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Research Article

Pricing and Coordination Decisions in a Low-Carbon Supply Chain with Risk Aversion under a Carbon Tax

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Under a carbon tax, with the constraint of carbon emissions reduction, by establishing game theoretical models for a low-carbon supply chain, the article investigates how the carbon tax rate and risk aversion degree may affect retail price, product carbon emission degree, and profits of the manufacturer, the retailer, and the entire supply chain. The results show that product carbon emission degree and supply chain profit in a centralized supply chain are higher than those in a decentralized supply chain. With a risk-averse manufacturer, the product's carbon emission degree and supply chain profit will further decrease. With increased risk aversion, the manufacturer's profit and total channel profit will decrease, but the retailer's profit will be affected by the carbon tax rate. Carbon reduction investment cost-sharing contracts can contribute to the implementation of increased demand for low-carbon products and decreased retail prices. Regardless of whether the manufacturer is risk-averse, a carbon reduction investment cost-sharing contract can increase the overall efficiency and profit of the supply chain. Finally, the results are verified by numerical examples.

1. Introduction

With the rapid economic development, environmental damage and pollution have become increasingly severe and greenhouse gas emissions have seriously exceeded standards. Many countries are facing the difficult challenge of reducing air pollution and carbon emissions while developing their economies. Reducing and controlling carbon emissions are a global problem that urgently needs to be solved. The signing and entry into force of the "United Nations Framework Convention on Climate Change" and the "Kyoto Protocol" indicate that carbon emissions reduction has become a consensus and the inevitable trend of all involved parties. With a low-carbon economy as the development background, how to reduce carbon emissions and achieve sustainable economic development has become one of the hot issues. To effectively control carbon emissions, countries have successively introduced a series of policies, such as standard mandatory emission reduction policies, carbon tax policies, quota trading policies, and emission reduction subsidy policies. Among them, the carbon tax policy is a control method established by the government to directly price the carbon dioxide emissions of enterprises, following the taxation principle of "who consumes, who pays." On the other hand, a large number of empirical studies have shown that consumers are increasingly aware of environmental protection and prefer to purchase more environmentally friendly and lower-carbon products. The British Carbon Trust [1] found that most consumers are more willing to buy low-carbon products and are willing to pay higher prices for them. Vanclay et al. [2] found through empirical analysis that the sales volume of low-carbon products in Australia is higher than that of ordinary products of the same type. Through mining and analysis of consumer data in Nanjing, Zhou et al. [3] found that consumers are more willing to pay for low-carbon products.

At present, the issue of carbon emission reduction in the supply chain has attracted the attention of many scholars. Benjaafar et al. [4] were the first to incorporate carbon emission factors into a simple supply chain system to conduct research, introduce different forms of carbon constraints into the inventory problem, and analyze the impact of inventory decisions on carbon emissions. Zhang et al. [5] compared the emission reduction effects under the carbon tax mechanism and the carbon trading mechanism in the case of random demand. Zhao et al. [6] used game theory to study the pricing and decision-making strategies of supply chain enterprises with the dual criteria of carbon emission reduction and profit maximization under the two situations of government supervision and voluntary emission reduction of supply chain enterprises. Yalabik and Fairchild [7] studied the impact of a carbon tax and consumer awareness on corporate environmental innovation. Li et al. [8] studied the impact of a carbon tax on the carbon dioxide emission reduction effects of enterprises and social welfare. Li [9] studied the incentive effect of a carbon tax on enterprises' emission reduction behavior by establishing a game model between the government and enterprises. Zhao et al. [10] used game theory methods to study the optimal equilibrium strategies of manufacturers and suppliers and, on this basis, deduced the optimal trajectory of product carbon emissions over time. Kroes et al. [11] believed that enterprises' environmental compliance leverage includes two methods: investment in carbon emission reduction technology and purchase of carbon emission rights. Enterprises need to weigh their investment in carbon emission reduction and purchase of carbon emission rights. Xiong et al. [12] analyzed the impacts of a carbon tax and consumer environmental awareness on manufacturers' unit carbon emissions and supply chain members' profits under two different channel structures. Cheng Yonghong and Xiong [13] discussed the optimal carbon dioxide emission reduction and pricing strategies of manufacturers and retailers under a carbon tax policy from the perspective of the supply chain and the impact of tax rates on carbon dioxide emission reduction per unit product and sales price. Yu et al. [14] compared carbon emission, the manufacturer's profit, and social welfare for reselling and marketplace modes under cap-and-trade and carbon tax regulation. Chen et al.[15] examined the optimal carbon tax design with different power structures and green technology investment efficiencies. Zhang et al. [16] simultaneously considered competition and cooperation within companies and developed four Stackelberg game theory-based models for a coopetition supply chain consisting of two manufacturers to explore the production and operation strategies in the context of a carbon tax mechanism. Meng et al. [17] conducted an analytical examination of the effect of power structure on the product selection strategy of the firm over various levels of the carbon tax rate.

In summary, an increasing number of scholars have begun to pay attention to the issues of carbon emission reduction and supply chain decision-making and to pursue the dual optimization of environmental friendliness and economic benefits. Most of the current papers on low-carbon supply chains are based on entirely rational assumptions of researchers. However, in the real world, individual attributes of decision-makers, such as risk aversion, overconfidence, and fairness concerns, will affect their rational decision-making behavior, and decision-makers cannot make decisions under the premise of complete rationality. To expand and supplement the research content of low-carbon supply chains, this article introduces the risk aversion attributes of decision-makers on the basis of existing low-carbon supply chain research. This article studies the decision-makers' risk aversion attributes on low-carbon supply chain pricing strategies, reduction levels of product carbon emission, the profits of supply chain members, and the overall profits of the supply chain.

The behaviors of decision-makers often show certain characteristics of risk aversion [18, 19]. At present, many scholars have introduced the risk aversion characteristics of decision-makers into traditional supply chain research. Choi [20] studied the ordering problem under random demand through the mean-variance method and noted that when the retailer can return excess inventory, the manufacturer can achieve coordination of the supply chain by adjusting the wholesale price. Wu et al. [21] established a risk-averse newsboy model using the mean-variance method. They noted that when the out-of-stock cost is considered, the order quantity of newsboys is not necessarily lower than the quantity under risk-neutral conditions. He et al. [22] used an exponential utility function to simulate the characteristics of risk aversion and noted that when the supplier and the manufacturer implement a wholesale contract and the manufacturer and the retailer implement a repurchase contract, the supply chain can achieve coordination. Xu et al. [23] studied the impact of risk aversion on the parameters of a two-way revenue-sharing contract. Lin et al. [24] used CVaR to establish a supply chain model in which both suppliers and retailers are risk-averse and noted that revenue-sharing contracts can coordinate supply chains in most cases. Li et al. [25] used CVaR criteria to study two different supply chain rebate and penalty contracts. Dai et al. [26] further studied the coordination of supply chain repurchase contracts with promotion effects and risk aversion decision-makers and examined two types of improved repurchase contract arrangements that can coordinate the risk aversion supply chain. Tao et al. [27] developed an integrated optimization model to study supply chain procurement and distribution decisions incorporating the manufacturer's aversion to risk and the distributors' concern for fairness in a climate of uncertain supply and demand. Mauro et al. [28] investigated the impact of individual risk aversion on replenishment decisions in a multi-echelon supply chain and explored whether this impact is affected by experiential learning. Adhikari et al. [29] proposed an analytical model for a textile supply chain by adopting a five-level structure that comprises an apparel retailer, an apparel manufacturer, a textile firm, a fiber firm, and a cotton firm under simultaneous demand and supply uncertainty using a wholesale price contract. The above articles considered the influence of risk-averse participants on the supply chain in a traditional supply chain. However, few articles have studied and discussed risk aversion attributes in low-carbon supply chains.

Based on this research gap, different from the existing article, this article considers a two-level low-carbon supply chain composed of a manufacturer and a retailer under a carbon tax policy. Manufacturers produce low-carbon products and sell them to the market through retailers. The low-carbon supply chain is modeled and analyzed in three different decision-making modes: centralized decision-making, manufacturer risk-neutral decentralized decision-making, and manufacturer risk aversion decentralized decision-making. The impacts of manufacturers' risk aversion coefficients and carbon tax rates on low-carbon supply chain pricing strategies, product carbon emission reduction levels, the profits of supply chain members, and the overall profits of the supply chain are studied.

The article is organized as follows. Section 2 gives the symbol description and basic assumptions about the model. Then, we consider the different structures about risk-neutral and risk-averse manufacturers in Section 3. Section 4 is about investment cost-sharing contracts under risk-neutral and risk-averse manufacturers. Section 5 is a numerical analysis of all the conclusions of this article and further verifies the research results. Finally, we conclude in Section 6.

2. Symbol Description and Basic Assumptions

Under a carbon tax policy, a two-level supply chain consisting of a manufacturer and a retailer is considered. The manufacturer produces low-carbon products and sells them to the market through the retailer. Carbon emissions from supply chain systems are only considered in the manufacturing process, and manufacturers use low-carbon technologies to reduce carbon emissions in the production process. Every unit of carbon emission reduction has a certain cost for carbon emission reduction technology. Before the sales season, suppliers act as leaders in the Stackelberg game, determining the wholesale price and low-carbon level of the product based on the costs of carbon reduction and production. Retailers, as followers, determine the retail price of products based on their forecasts of market demand information and wholesale prices issued by upstream suppliers in pursuit of maximizing their profits.

The symbols used in this article are described as follows:

$\tilde{a}$: an uncertain market demand size; the average value is a, and the variance is σ^2.

c: production costs per unit of product.

w: the wholesale price of the unit product provided by the manufacturer to the retailer.

p: the unit retail price of low-carbon products.

e: carbon emissions per unit product before carbon emission reduction.

τ: carbon emission reduction level of low-carbon products.

α: consumer low-carbon preference coefficient.

β: manufacturer's carbon emission reduction investment cost coefficient;

t: tax per unit of carbon emissions.

k: manufacturer's risk aversion coefficient.

ϕ: the proportion of low-carbon emission reduction investment costs borne by retailers.

π_m: manufacturer's profit.

π_r: retailer's profit.

π_{sc}: the overall profit of the supply chain.

U: utility function. Tables r and m represent the utility of the retailer and the manufacturer, respectively.

Superscript c represents the decision-making mode under the implementation of the supply chain contract, and superscripts D and k represent the manufacturer's risk-neutral and risk-averse decentralized decision-making models, respectively.

For the convenience of the following discussion, we make the following assumptions:

(1) The information about the market involving the manufacturer and retailer is symmetrical and complete, which is a complete information game between the manufacturer and retailer, such as [30–32].

(2) Manufacturers adopt carbon reduction technologies to reach the carbon reduction degree of low-carbon products for τ; refer to [33]. We assume that the cost of reducing emissions is $C = 1/2\beta\tau^2$, where τ is the manufacturer's decision variable. Such a quadratic cost function has been adopted in the existing literature on carbon reduction efforts investment, such as [7, 34].

(3) At reasonable prices, consumers are more likely to buy low-carbon products. The variables that affect product demand are not just prices, so we suppose that product demand is a function of the product's price and carbon reduction degree $D = \tilde{a} - p + \alpha\tau$, where $\tilde{a} = a + \varepsilon$ and $\varepsilon \sim N(0, \sigma^2)$, the density function is $f(x)$, and the distribution function is $F(x)$, such as [33, 35–37].

(4) To ensure that carbon reduction investments by manufacturers after carbon taxes are profitable, it is always assumed that the following constraints are true: $a - c - et > 0$.

3. Models Establishing and Results Analysis

3.1. Centralized Decision-Making. In the centralized decision-making process of the supply chain, it is assumed that there is a unique decision-maker. The manufacturer and retailer are taken as a whole to make decisions; that is, the retail price p of the product and the low-carbon emission reduction level τ of the product are determined with the goal of maximizing the overall profit of the supply chain. The overall expected profit of the supply chain is as follows:

$$E(\pi_{sc}) = (p - c - t(e - \tau))(a - p + \alpha\tau) - \frac{1}{2}\beta\tau^2. \quad (1)$$

The Hesse matrix of the overall expected profit function of the supply chain concerning the retail price p and the product's low-carbon emission reduction level τ is

$$H_{\pi_{sc}} = \begin{pmatrix} -2 & \alpha - t \\ \alpha - t & 2\alpha t - \beta \end{pmatrix}. \quad (2)$$

Observing the Hesse matrix, when $t < \sqrt{2\beta} - \alpha$, the Hesse matrix $H_{\pi_{sc}}$ is negative definite. At this point, the overall expected profit of the supply chain is a joint concave function of the retail price of the product and the low-carbon emission reduction level of the product; therefore, there exist unique p^* and τ^* to make the overall profit function of the supply chain achieve great value. To maximize the overall profit function of the supply chain, the first-order partial derivatives of equation (1) are found concerning p and τ, and they are set equal to 0. The simultaneous solution to obtain the best retail price and the best product low-carbon emission reduction level when the overall profit of the supply chain is maximized is as follows:

$$p^* = \frac{\left(\beta - \alpha t - \alpha^2\right)et + \left(\beta - t^2 - \alpha t\right)(a - c)}{2\beta - (\alpha + t)^2} + c, \quad (3)$$

$$\tau^* = \frac{(\alpha + t)(a - c - et)}{2\beta - (\alpha + t)^2}. \quad (4)$$

3.2. Manufacturer Risk-Neutral Decentralized Decision-Making. Under decentralized decision-making, the game process between manufacturers and retailers is a typical complete information dynamic game. As the leaders of the Stackelberg game, manufacturers act first based on their market forecast information and the information provided by retailers, targeting profit maximization. Manufacturers determine the optimal wholesale price and low-carbon emission reduction levels of products. Downstream retailers make decisions based on the wholesale prices and low-carbon emission reduction levels for products determined by upstream manufacturers and determine the optimal retail prices for products based on their profit maximization. The expected profits of manufacturers and retailers under the decentralized decision-making model, respectively, are as follows:

$$E(\pi_m) = (w - c - t(e - \tau))(a - b + \alpha\tau) - \frac{1}{2}\beta\tau^2, \quad (5)$$

$$E(\pi_s) = (p - w)(a - p + \alpha\tau). \quad (6)$$

The inverse induction method is used to solve the game process. In the second stage of the Stackelberg game, as a follower, the retailer determines the optimal retail price based on the wholesale price and the low-carbon emission reduction level of the product given by the upstream manufacturer to maximize its profit. To maximize the retailer's profit function, the response function of the retail price to the wholesale price and the product's low-carbon emission reduction level is as follows:

$$p = \frac{a + w + \alpha\tau}{2}. \quad (7)$$

Substituting equation (7) into equation (5), the manufacturer's expected profit is obtained as a function of the wholesale price and the product's low-carbon emission reduction level τ:

$$E(\pi_m) = \frac{1}{2}(w - c - t(e - \tau))(a - w + \alpha\tau) - \frac{1}{2}\beta\tau^2. \quad (8)$$

The Hesse matrix of the manufacturer's expected profit function about the wholesale price w and the product's low-carbon emission reduction level τ is as follows:

$$H_{\pi_m} = \begin{pmatrix} -1 & \dfrac{\alpha - t}{2} \\ \dfrac{\alpha - t}{2} & \alpha t - \beta \end{pmatrix}. \quad (9)$$

Observe the Hesse matrix in the above formula; when $t < 2\sqrt{\beta} - \alpha$, the matrix H_{π_m} is negative. The manufacturer's profit function is a joint concave function of the wholesale price w and the product's low-carbon emission reduction level τ. Maximizing (8), we set the first-order partial derivative of $E(\pi_m)$ concerning w and τ equal to zero, and the simultaneous solution to obtain the optimal wholesale price and low-carbon emission reduction levels of the products identified by the manufacturer in the case of the manufacturer's risk-neutral decentralized decision-making are as follows:

$$w^D = \frac{\left(2\beta - \alpha t - \alpha^2\right)et + \left(2\beta - t^2 - \alpha t\right)(a - c)}{4\beta - (\alpha + t)^2} + c, \quad (10)$$

$$\tau^D = \frac{(\alpha + t)(a - c - et)}{4\beta - (\alpha + t)^2}. \quad (11)$$

Substituting (10) and (11) into (7), we obtain the optimal retail price determined by the retailer under the manufacturer's risk-neutral decentralized decision-making model:

$$p^D = \frac{\left(\beta - \alpha t - \alpha^2\right)et + \left(3\beta - t^2 - \alpha t\right)(a - c)}{4\beta - (\alpha + t)^2} + c. \quad (12)$$

3.3. Decentralized Decision-Making When the Manufacturer Is Risk-Averse. Under the carbon tax policy, manufacturers in a low-carbon supply chain should bear not only the investment cost of carbon emission reduction but also the carbon tax. The upfront costs and investments are enormous, and therefore, the manufacturer will be more sensitive to risks because of external uncertainties, such as market demand. When the manufacturer has the attribute of risk aversion, the manufacturer will comprehensively consider the size of the expected profit and expected profit variance; therefore, the manufacturer's utility function can be constructed using the mean-variance method, and the manufacturer's expected return variance is

$$\mathrm{var}(\pi_m) = (w - c - t(e - \tau))^2\sigma^2. \quad (13)$$

Then, the utility function of the risk-averse manufacturer is as follows:

$$U_m = (w - c - t(e-\tau))(a - p + \alpha\tau) - \frac{1}{2}\beta\tau^2 - k(w - c - t(e-\tau))^2\sigma^2. \quad (14)$$

In the above equation, k represents the manufacturer's risk aversion coefficient. The retailer in this article does not have the attribute of risk aversion, so the retailer's utility function is expressed by its expected profit:

$$U_s = (p - w)(a - p + \alpha\tau). \quad (15)$$

Similar to Section 3.2, we can get when $t < \sqrt{8\beta k\sigma^2 + 4\beta} - \alpha$,

$$w^k = \frac{\left(8\beta k\sigma^2 + 2\beta - \alpha t - \alpha^2\right)et + \left(2\beta - t^2 - \alpha t\right)(a-c)}{8\beta k\sigma^2 + 4\beta - (\alpha+t)^2} + c, \quad (16)$$

$$\tau^k = \frac{(\alpha+t)(a-c-et)}{8\beta k\sigma^2 + 4\beta - (\alpha+t)^2}. \quad (17)$$

$$p^k = \frac{\left(4\beta k\sigma^2 + \beta - \alpha t - \alpha^2\right)et + \left(4\beta k\sigma^2 + 3\beta - t^2 - \alpha t\right)(a-c)}{8\beta k\sigma^2 + 4\beta - (\alpha+t)^2} + c. \quad (18)$$

3.4. Result Analysis. This section analyzes and discusses the equilibrium results obtained from the previous theoretical modeling to better analyze and explain the internal reasons behind some real business phenomena and attempts to identify innovative and reference value management enlightenment.

Proposition 1. *In a low-carbon supply chain under a carbon tax policy, the overall profit of the supply chain under the centralized decision-making model is greater than the overall profit of the supply chain under the manufacturer's risk-neutral decentralized decision-making model, and the latter is greater than the overall profit of the supply chain under the manufacturer's risk aversion decentralized decision-making model.*

Proof: from the previous solution, the overall profits of the supply chain under the manufacturer's risk neutrality and manufacturer's risk aversion decentralized decision-making are as follows:

$$\pi_{sc}^D = \pi_m^D + \pi_r^D = \frac{1}{2}\frac{\beta\left(6\beta - (+t)^2\right)(a-c-et)^2}{\left(4\beta - (\alpha+t)^2\right)^2}, \quad (19)$$

$$\pi_{sc}^k = \pi_m^k + \pi_r^k = \frac{1}{2}\frac{\beta\left(\left(32k^2\sigma^4 + 32k\sigma^2 + 6\right)\beta - (\alpha+t)^2\right)(a-c-et)^2}{\left(8\beta k\sigma^2 + 4\beta - (\alpha+t)^2\right)^2}. \quad (20)$$

Comparison of the overall profit of the supply chain under three different decision-making modes,

$$\frac{\pi_{sc}^*}{\pi_{sc}^D} = \frac{\left(4\beta - (\alpha+t)^2\right)^2}{\left(2\beta - (\alpha+t)^2\right)\left(6\beta - (\alpha+t)^2\right)} = \frac{\left(4\beta - (\alpha+t)^2\right)^2}{\left(4\beta - (\alpha+t)^2\right)^2 - 4\beta}, \quad (21)$$

can obtain $\pi_{sc}^*/\pi_{sc}^D > 1$; that is, $\pi_{sc}^* > \pi_{sc}^D$; $\pi_{sc}^D/\pi_{sc}^k = (6\beta - (\alpha+t)^2)(8\beta k\sigma^2 + 4\beta - (\alpha+t)^2)^2/\ (4\beta - (\alpha+t)^2)^2((32k^2\sigma^4 + 32k\sigma^2 + 6)\beta - (\alpha+t)^2)$, it is easy to find $\pi_{sc}^D/\pi_{sc}^k > 1$; that is, $\pi_{sc}^D > \pi_{sc}^k$.

In summary, we can obtain $\pi_{sc}^* > \pi_{sc}^D > \pi_{sc}^k$.

Proposition 1 shows that the profit of the supply chain under centralized decision-making is greater than that under decentralized decision-making, which is consistent with the conclusion of the existing traditional supply chain [38]. When members of the low-carbon supply chain take their profit maximization as their decision-making goal, the overall profit of the low-carbon supply chain will be harmed. Under the decentralized decision-making model, each member of the low-carbon supply chain only makes decisions based on maximizing their profits, making the low-carbon supply chain unable to achieve coordination of the optimal low-carbon supply chain system, which damages the overall profit of the supply chain. For the two different decentralized models, when the manufacturer is a risk-averse decision-maker, it will maximize its utility as the decision-making goal, and decisions made by low-carbon manufacturers are bound to be more conservative, further damaging the overall profits of the supply chain. On the other hand, the upstream and downstream members of the low-carbon supply chain can coordinate the supply chain through alliances to improve the efficiency of the supply chain. In contrast, the supply chain with the participation of risk-averse manufacturers is more coordinated, and the cooperation of upstream and downstream members can increase profits.

Proposition 2. *When the manufacturer is risk-averse, the manufacturer's profit is smaller than the manufacturer's profit under the risk-neutral decentralized decision-making model and decreases with the increase of the risk aversion coefficient. The relationship between the retailer's profits under the two decision models is determined by the carbon tax rate. When the carbon tax rate is low, the retailer's profit* *under the risk-averse manufacturer's participation in the supply chain decision-making model is greater than the retailer's profit under the manufacturer's risk-neutral decentralized decision-making, and at this time, the retailer's profit increases as the manufacturer's risk aversion coefficient increases. When the carbon tax rate is high, the retailer's profit under the risk-averse manufacturer's participation in the supply chain decision-making model is smaller than that under the manufacturer's risk-neutral decentralized decision-making; at this time, the retailer's profit decreases as the manufacturer's risk aversion coefficient increases.*

Proof: $\pi_m^D - {\pi_m}^k = 32\beta^3 k^2\sigma^4 (a-c-et)^2/(4\beta-(\alpha+t)^2)(8\beta k\sigma^2+4\beta-(\alpha+t)^2)^2$; from the previous discussion, π_m^D, ${\pi_m}^k$, and the feasible conditions are $4\beta-(\alpha+t)^2>0$; then, ${\pi_m}^D-{\pi_m}^k>0$; that is, ${\pi_m}^D>{\pi_m}^k$. ${\pi_r}^D-{\pi_r}^k = 32\beta^2 k\sigma^2 (2(6\beta-(\alpha+t)^2)+4\beta-((\alpha+t)^2)((\alpha+t)^2-2\beta)(a-c-e\ t)^2/(4\beta-(\alpha+t)^2)^2(8\beta k\sigma^2+4\beta-(\alpha+t)^2)^2\ 4\beta-(\alpha+t)^2>0$; then, the sign of ${\pi_r}^D-{\pi_r}^k$ is determined by $(\alpha+t)^2-2\beta$. When $(\alpha+t)^2-2\beta>0$, that is, when $\sqrt{2\beta}-\alpha<t$, ${\pi_r}^D>{\pi_r}^k$; when $(\alpha+t)^2-2\beta<0$, that is, when $t<\sqrt{2\beta}-\alpha$, ${\pi_r}^D<{\pi_r}^k$. Because the carbon tax rate is greater than 0 and $4\beta-(\alpha+t)^2>0$, in summary, when $\sqrt{2\beta}-\alpha<t<2\sqrt{\beta}-\alpha$, ${\pi_r}^D>{\pi_r}^k$; when $0<t<\sqrt{2\beta}-\alpha$, $\pi_r^D<\pi_r^k$.

The first-order partial derivative of k from ${\pi_m}^k$ is taken to obtain $\partial{\pi_m}^k/\partial k = -64\beta^3 k\sigma^4/(8\beta k\sigma^2+4\beta-(\alpha+t)^2)^3$; then, $\partial{\pi_m}^k/\partial k<0$. That is, the profit of the manufacturer decreases as the risk aversion coefficient increases.

The first partial derivative of k on π_r^k is $\partial\pi_r^k/\partial k = 8\beta^2(4k\sigma^2+1)\sigma^2(2\beta-(\alpha+t)^2)(a-c-et)^2/(8\beta k\sigma^2+4\beta-(\alpha+t)^2)^3$; that is, when $2\beta-(\alpha+t)^2>0$, $\partial{\pi_r}^k/\partial k>0$; when $2\beta-(\alpha+t)^2<0$, $\partial{\pi_r}^k/\partial k<0$. In summary, when $0<t<\sqrt{2\beta}-\alpha$, the retailer's profits increase as the manufacturer's risk aversion coefficient increases; when $\sqrt{2\beta}-\alpha<t<2\sqrt{\beta}-\alpha$, the retailer's profit decreases as the manufacturer's risk aversion coefficient increases.

Proposition 3. *Under the carbon tax policy, the carbon emission reduction level of low-carbon products under centralized decision-making in the low-carbon supply chain is greater than that of products in the decentralized decision-making supply chain; when the manufacturer is risk-averse, the carbon emission reduction level of its products is further reduced and decreases as the manufacturer's risk aversion coefficient increases.*

Proposition 2 shows that the manufacturer's risk-averse behavior will affect the manufacturer's profit, and as the manufacturer's risk-averse degree becomes higher, the manufacturer's profit will become smaller. In reality, under the uncertainty of market risks and low-carbon investment risk, manufacturing companies that are more afraid of risks dare not arbitrarily adjust production decisions, which will lead to loss of opportunities to make greater profits. For retailers, the manufacturer's risk-averse behavior will affect retailers' profits, but the carbon tax rate determines the changes in retailers' profits. When the carbon tax rate is small, the manufacturer's risk aversion behavior makes the retailer's profit increase, and when the carbon tax rate is higher, the manufacturer's risk aversion behavior makes the retailer's profit decrease. Combining Proposition 1, Proposition 2, and Proposition 3, we can find that risk aversion will further increase the double marginal effect of the supply chain and affect the profits of all parties in the supply chain. However, in the low-carbon supply chain, due to the impact of carbon tax policies, retailers' profits will not necessarily be damaged; they will be affected by the carbon tax rate. Therefore, the government can adjust or slow down the double marginal effect of the supply chain by setting up a reasonable carbon policy.

Proposition 4. *In the low-carbon supply chain under the carbon tax policy, the retail price is smaller in the decentralized decision model when the manufacturer is risk-averse than in the manufacturer's risk-neutral decentralized decision model. In the two decision-making modes, the wholesale price is determined by the carbon tax rate. When the carbon tax rate is low, the wholesale price under the manufacturer's risk aversion decentralized decision is smaller than the wholesale price under the manufacturer's risk-neutral decentralized decision; when the carbon tax rate is high, the wholesale price under the manufacturer's risk aversion decentralized decision is greater than the wholesale price under the manufacturer's risk-neutral decentralized decision.*

Proof: $p^D-p^k = 2\beta(2\beta+\alpha^2-t^2)(a-c-et)/(4\beta-(\alpha+t)^2)(8\beta k\sigma^2+4\beta-(\alpha+t)^2)$

According to the previous assumptions, $a-c-et>0$; we can obtain $p^D>p^k$. $w^D-w^k = 8\beta k\sigma^2(2\beta+\alpha t-t^2)(a-c-et)/(4\beta-(\alpha+t)^2)(8\beta k\sigma^2+4\beta-(\alpha+t)^2)$, and it can be concluded that the magnitudes of w^D and w^k are determined by the sign of $2\beta+\alpha t-t^2$, when $2\beta+\alpha t-t^2>0$, that is, when $t<\sqrt{2\beta+\alpha^2/4}+\alpha/2$, $w^D>w^k$; when $2\beta+\alpha t-t^2<0$, that is, when $t<\sqrt{2\beta+\alpha^2/4}+\alpha/2$, $w^D<w^k$.

Corollary 1. *Under the manufacturer's decentralized risk aversion decision-making model, the retail price of products decreases as the manufacturer's risk aversion coefficient increases. The trend of the wholesale price changes is determined by the carbon tax rate; when the carbon tax rate is low, the wholesale price decreases as the risk aversion coefficient increases; when the carbon tax rate is high, the wholesale price increases as the risk aversion coefficient increases.*

Finding the first derivative of k for p^k and w^k, the conclusion can be obtained directly.

Similar to [39], Proposition 4 shows that in two different decentralized decision-making modes, the retail price under the decentralized decision-making model with the participation of risk-averse manufacturers is lower than that with the participation of risk-neutral manufacturers. The manufacturer's risk aversion is bound to affect downstream companies in the supply chain, which makes retailers make more conservative decisions, adopt a strategy of small profits but with quick turnover to meet the manufacturer's risk aversion attributes. In contrast to [39], under the two decision-making models, the wholesale price determined by the manufacturer is determined by the carbon tax rate; when the carbon tax rate is low, the wholesale price determined by risk-averse manufacturers is lower than that determined by risk-neutral manufacturers; when the carbon tax rate is high, the wholesale price determined by risk-averse manufacturers is higher than that determined by risk-neutral manufacturers. Similar to [40], Corollary 1 indicates that the retail price and wholesale price of low-carbon products are affected by the manufacturer's risk aversion coefficient. Through Corollary 1, it can be found that as manufacturers become more afraid of risk, supply chain decisions become more conservative. That is, as the risk aversion coefficient increases, retail prices continue to decrease. In contrast to [40], manufacturers determine that the wholesale price is affected by the risk aversion coefficient and is also affected by the carbon tax rate. When the carbon tax rate is low, as the manufacturer's risk aversion coefficient increases, the wholesale price continues to decrease; when the carbon tax rate is relatively high, as the manufacturer's risk aversion coefficient increases, the wholesale price continues to increase. Combining Proposition 4 and Corollary 1, it can be found that the comparison of the retail price size and the influence of the retail price on the risk aversion coefficient in two different decentralized decision-making modes are independent of the carbon tax rate size. In contrast, the comparison of the wholesale price size and the influence of the wholesale price on the risk aversion coefficient are related to the carbon tax rate. Because the manufacturer has to pay the carbon tax directly, when the carbon tax rate is low, the manufacturer's decision is consistent with the traditional supply chain. In contrast, when the carbon tax rate is higher, a high carbon tax will cause manufacturers to increase the wholesale price only for immediate benefits and increase the wholesale price as the risk aversion coefficient increases.

4. Investment Cost-Sharing Contract

In a low-carbon supply chain under a low-carbon policy, manufacturers producing low-carbon products need to invest large low-carbon emission reduction costs in the early stage, and with the increase of the level of low-carbon emission reduction, the initial investment cost increases, and a large amount of upfront investment and carbon emission taxes will invisibly depress manufacturers' enthusiasm for production. To promote the enthusiasm of manufacturers to produce products with lower-carbon levels, expand consumer demand, and achieve a win-win situation between manufacturers and their profits, retailers will take the initiative to bear part of the investment cost of low-carbon emissions, reaching a low-carbon emission reduction investment cost-sharing contract with manufacturers. After introducing the low-carbon emission reduction investment cost-sharing contract, the retailer determines the sharing rate of the investment cost and the manufacturer's sharing rate. At this time, the expected profits of the manufacturer and the retailer, respectively, are as follows:

$$E(\pi_m) = (w - c - t(e-\tau))(a - p + \alpha\tau) - \frac{1-\varphi}{2}\beta\tau^2, \quad (22)$$

$$E(\pi_r) = (p - w)(a - p + \alpha\tau) - \frac{\varphi}{2}\beta\tau^2. \quad (23)$$

Observing the above two formulas, we find that after introducing the investment cost-sharing contract, the overall profit of the supply chain will not change, which is still expressed by (1).

4.1. Manufacturer's Risk-Neutral Decentralized Decision-Making. After introducing the investment cost-sharing contract, in the case of decentralized decision-making when the manufacturer's risk is neutral, the game process between the manufacturer and the retailer is still a typical complete information dynamic game. Reverse induction is used to solve the game process. We can obtain the following:

$$\tau^{Dc} = \frac{(\alpha+t)(a-c-et)}{4(1-\varphi)\beta - (\alpha+t)^2}, \quad (24)$$

$$w^{Dc} = \frac{\left(2\beta - 2\varphi\beta - \alpha t - \alpha^2\right)et + \left(2\beta - 2\varphi\beta - t^2 - \alpha t\right)(a-c)}{4(1-\varphi)\beta - (\alpha+t)^2} + c, \quad (25)$$

$$p^{Dc} = \frac{\left(\beta - \varphi\beta - \alpha t - \alpha^2\right)et + \left(3\beta - 3\varphi\beta - t^2 - \alpha t\right)(a-c)}{4(1-\varphi)\beta - (\alpha+t)^2} + c. \quad (26)$$

4.2. Decentralized Decision-Making for Risk-Averse Manufacturers. After implementing the investment cost-sharing contract, in the decentralized decision-making mode when the manufacturer is risk-averse, manufacturers and retailers will play games based on maximizing their utility, and the game process is still a dynamic game with complete information. After introducing the investment cost-sharing contract, the profit function of both the manufacturer and the retailer changes. Referring to the previous description of the utility function of manufacturers' risk aversion, the utility functions of the manufacturer and the retailer when investment cost-sharing can be obtained are as follows:

$$U_m = (w - c - t(e-\tau))(a - p + \alpha\tau) - \frac{1-\varphi}{2}\beta\tau^2 - k(w - c - t(e-\tau))^2\sigma^2, \quad (27)$$

$$U_s = (p - w)(a - p + \alpha\tau) - \frac{\varphi}{2}\beta\tau^2, \quad (28)$$

Similar to the previous section, the reverse induction method is used to solve the game process. We obtain the following:

$$w^{kc} = \frac{\left((1-\varphi)\left(8\beta k\sigma^2 + 2\beta\right) - \alpha t - \alpha^2\right)et + \left(2(1-\varphi)\beta - t^2 - \alpha t\right)(a-c)}{(1-\varphi)\left(8\beta k\sigma^2 + 4\beta\right) - (\alpha+t)^2} + c, \tag{29}$$

$$\tau^{kc} = \frac{(\alpha+t)(a-c-et)}{(1-\varphi)\left(8\beta k\sigma^2 + 4\beta\right) - (\alpha+t)^2}, \tag{30}$$

$$p^{kc} = \frac{\left((1-\varphi)\left(4\beta k\sigma^2 + \beta\right) - \alpha t - \alpha^2\right)et + \left((1-\varphi)\left(4\beta k\sigma^2 + 3\beta\right) - t^2 - \alpha t\right)(a-c)}{(1-\varphi)\left(8\beta k\sigma^2 + 4\beta\right) - (\alpha+t)^2} + c. \tag{31}$$

Corollary 2. *After introducing the low-carbon emission reduction investment cost-sharing contract, regardless of whether the manufacturer is risk-averse, the supply chain will provide a lower-carbon emission product.*

Proposition 5. *Under the manufacturer's risk-neutral decentralized decision-making model, when* $0 < \varphi < (4\beta - (\alpha + t)^2)(\alpha + t)^2/2\beta(8\beta - (\alpha + t)^2)$*, the carbon emission reduction investment cost-sharing contract can achieve Pareto improvement of the profits of supply chain members; under the manufacturer's risk aversion decentralized decision-making model, the carbon emission reduction investment cost-sharing contract can achieve Pareto improvement of the profits of supply chain members.*

Proof: When the manufacturer is risk-neutral, when ${\pi_m}^{Dc} > {\pi_m}^{D}$, ${\pi_r}^{Dc} > {\pi_r}^{D}$, which shows that the investment cost-sharing contract has achieved a Pareto improvement of the profit of supply chain members.

From $\pi_m^{Dc} > \pi_m^{D}$, there is $1/2\beta(1-\varphi)(a-c-et)^2/4(1-\varphi)\beta - (\alpha+t)^2 - 1/2\beta(a-c-et)^2/4\beta - (\alpha+t)^2 > 0$; we can obtain $\varphi > 0$. From ${\pi_r}^{Dc} > {\pi_r}^{D}$, there is $1/2\beta(2\beta(1-\varphi)^2 - (\alpha+t)^2\varphi)(a-c-et)^2/(4(1-\varphi)\beta - (\alpha+t)^2)^2 - \beta^2(a-c-et)^2/(4\beta-(\alpha+t)^2)^2 > 0$; we can obtain $0 < \varphi < (4\beta - (\alpha+t)^2)(\alpha+t)^2/2\beta(8\beta-(\alpha+t)^2)$. In summary, when $0 < \varphi < (4\beta - (\alpha+t)^2)(\alpha+t)^2/2\beta(8\beta-(\alpha+t)^2)$, $\pi_m^{Dc} > \pi_m^{D}$, $\pi_r^{Dc} > \pi_r^{D}$.

When the manufacturer is risk-averse, when $\pi_m^{kc} > \pi_m^{k}$, $\pi_r^{kc} > \pi_r^{k}$, the investment cost-sharing contract has achieved a Pareto improvement of the profit of supply chain members.

From $\pi_m^{kc} > \pi_m^{k}$, there is

$$\frac{1}{2}\frac{(1-\varphi)\beta(a-c-et)^2\left((1-\varphi)\left(16\beta k\sigma^2+4\beta\right)-(\alpha+t)^2\right)}{\left((1-\varphi)\left(8\beta k\sigma^2+4\beta\right)-(\alpha+t)^2\right)^2} - \frac{1}{2}\frac{\beta(a-c-et)^2\left(16\beta k\sigma^2+4\beta-(\alpha+t)^2\right)}{\left(8\beta k\sigma^2+4\beta-(\alpha+t)^2\right)^2} > 0 \tag{32}$$

Then, when $0 < \varphi < \varphi_1$, $\pi_m^{kc} > \pi_m^{k}$, where φ_1 is the solution satisfying $\pi_m^{kc} = \pi_m^{k}$; from $\pi_r^{kc} > \pi_r^{k}$, there is $1/2\beta\ ((1-\varphi)^2(1+4k\sigma^2)^2\beta - (\alpha+t)^2\varphi)(a-c-et)^2/((1-\varphi)\ (8\beta k\sigma^2+4\beta)-(\alpha+t)^2)^2 - \beta^2(1+4k\sigma^2)^2\ (a-c-et)^2/((8\beta k\sigma^2+4\beta)-(\alpha+t)^2)^2 > 0$ Then, when $0 < \varphi < \varphi_2$, $\pi_r^{kc} > \pi_r^{k}$, where φ_2 is the solution satisfying $\pi_r^{kc} = \pi_r^{k}$. In summary, when, $\pi_m^{kc} > \pi_m^{k}$, $\pi_r^{kc} > \pi_r^{k}$.

Similar to [41], Proposition 5 shows that considering risk aversion and carbon tax, the investment cost-sharing contract can realize the Pareto improvement of the supply chain, and by adjusting the contract parameters, the manufacturer and the retailer can achieve the maximum profit for a win-win situation. In practice, if companies in the supply chain can cooperate effectively to reach a strategic alliance, they can better respond to market risks and obtain greater benefits and then improve the efficiency of the supply chain.

5. Example Analysis

This section studies the abovementioned models through numerical analysis methods, supposing the supply chain parameters are $\alpha = 2$, $\alpha = 2$, $\alpha = 2$, $\beta = 10$, $e = 2.5$, and $\sigma^2 = 1$. That is, we assume that ε obeys the standard normal distribution.

First, we consider the impact of carbon tax rates on product low-carbon emission reduction levels, retail prices, wholesale prices, and the profits of all parties in the supply chain. Without considering the influence of the risk aversion coefficient, $k = 0.5$, the impact of the carbon tax rate on the product low-carbon emission reduction levels, retail prices, wholesale prices, and profits of all parties in the supply chain can be obtained, as shown in Figures 1–3.

Figure 1 shows that the product carbon emission reduction level in the case of centralized decision-making is significantly greater than that in the case of decentralized decision-making. When manufacturers are risk-averse, the product carbon emission reduction level will be further reduced. Figure 2 also shows that with the increase in the carbon tax rate, the average carbon emission reduction level of products under the three different decision-making modes will increase, and the increase rate in the case of centralized decision-making is significantly greater than that of decentralized decision-making. These findings show that with the continuous increase in the carbon tax rate, the marginal profit generated by the manufacturer's investment in product carbon emission reduction is increasing; that is, manufacturers will be more willing to provide low-carbon and higher products to control the carbon emissions generated during the production process.

Figure 2 shows that regardless of whether the manufacturer is risk-averse, the wholesale price of products will continue to decrease as the carbon tax rate increases, and the wholesale price decreases more when the manufacturer's risk is neutral than when the manufacturer is risk-averse. As

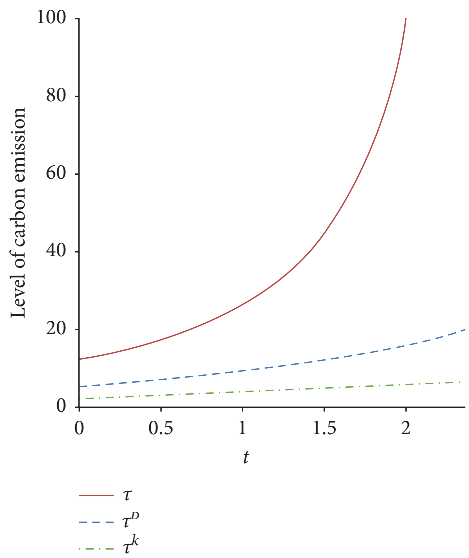

FIGURE 1: Level of carbon emission reduction is affected by the carbon tax rate.

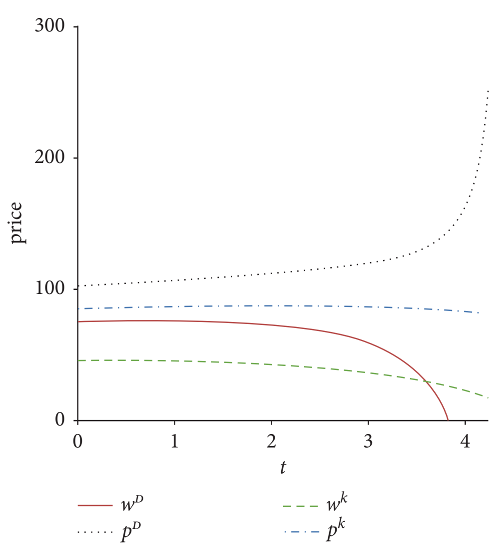

FIGURE 2: Price is affected by the carbon tax rate.

the carbon tax rate continues to increase, the wholesale price gradually changes from $w^D > w^k$ to $w^D < w^k$. Figure 2 also shows that when the manufacturer's risk is neutral, the retail price of the product is greater than when the manufacturer is risk-averse and sets the retail price, which is irrelevant to the amount of the carbon tax rate; however, with the increase in the carbon tax rate, the retail price gap under the two decision-making modes increases.

Figure 3 shows the impact of carbon tax rates on the profits of manufacturers and retailers under two decentralized decision-making models. Figure 3 shows that under the two decision-making modes, with the continuous increase in the carbon tax rate, the profits of both retailers and manufacturers will continue to increase. For the manufacturer's profit, when the manufacturer is risk-averse, the manufacturer's profit will decrease; that is, ${\pi_m}^D > {\pi_m}^k$, and

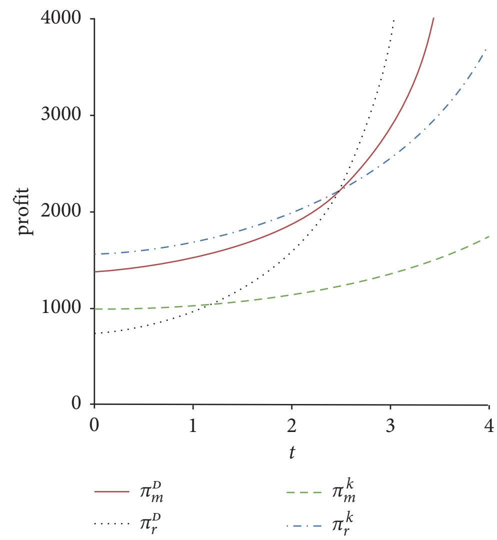

FIGURE 3: Profits are affected by the carbon tax rate.

as carbon tax rates increase, the gap between them will widen. For retailer profits, looking at Figure 3, we can find that when the carbon tax rate is low, that is, ${\pi_r}^D < {\pi_r}^k$, with the increase in the carbon tax rate, the retailer's profit under the two decision-making modes will gradually change to ${\pi_r}^D > {\pi_r}^k$.

Second, we analyze the influence of the manufacturer's risk aversion coefficient on supply chain pricing and decision-making. In Figure 4, $t = 1$ and $t = 4.5$ are taken to study the influence of the risk aversion coefficient on the wholesale price and retail price, respectively. As shown in Figure 4, regardless of whether t is larger or smaller, the retail price of the product will continue to decrease as the manufacturer's risk aversion coefficient increases, eventually infinitely approaching $a + c + et/2$. For the wholesale price of products, when the carbon tax rate t is low, the wholesale price will continue to decrease as the manufacturer's risk aversion coefficient increases; when the carbon tax rate t is relatively high, the wholesale price will continue to increase as the manufacturer's risk aversion coefficient increases and will eventually approach $c + et$. This finding is consistent with the conclusion of Corollary 1.

In Figure 5, $t = 1$ and $t = 3$ are taken to study the impact of the risk aversion coefficient on the profits of manufacturers and retailers, respectively. As shown in Figure 5, for the retailer's profits, when the carbon tax rate is low, the retailer's profits will continue to increase as the manufacturer's risk aversion coefficient increases. When the carbon tax rate is high, the retailer's profit will continue to decrease as the manufacturer's risk aversion coefficient increases, and the retailer's profit will infinitely approach $(a + c + et)^2/4$ as the manufacturer's risk aversion coefficient increases. The manufacturers' profits have nothing to do with the carbon tax rate. The profit of the manufacturer decreases with the increase of the risk aversion coefficient and eventually approaches 0. Because the existence of risk aversion attributes makes manufacturers more afraid of risks, as the risk aversion coefficient increases, the decisions made by manufacturers will become more conservative.

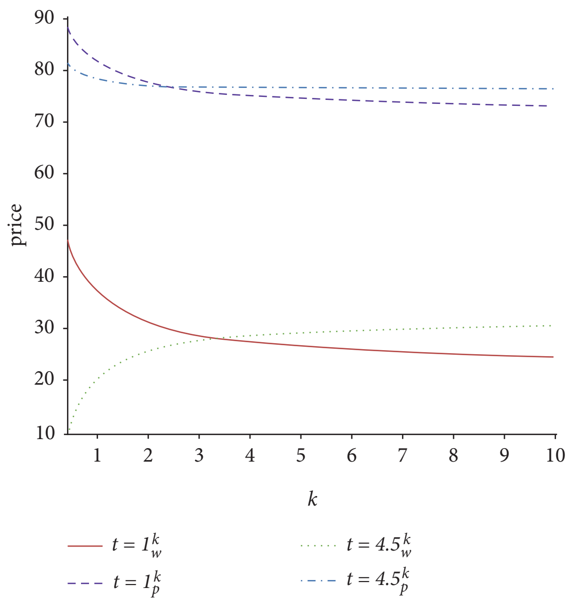

FIGURE 4: Price is affected by the risk aversion coefficient.

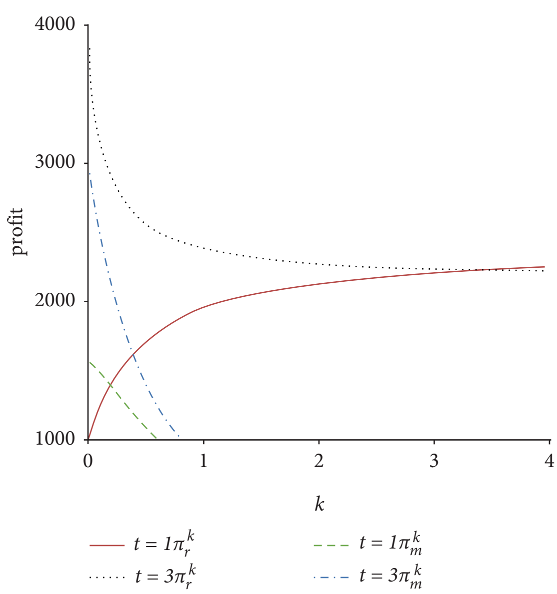

FIGURE 5: Profit is affected by the risk aversion coefficient.

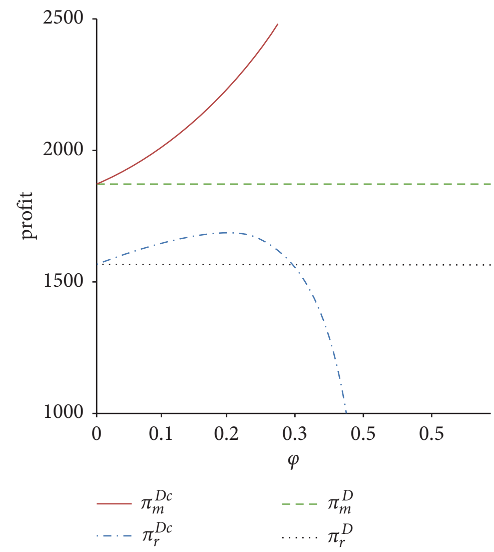

FIGURE 6: Impact of the cost-sharing coefficient on profit when risk is neutral.

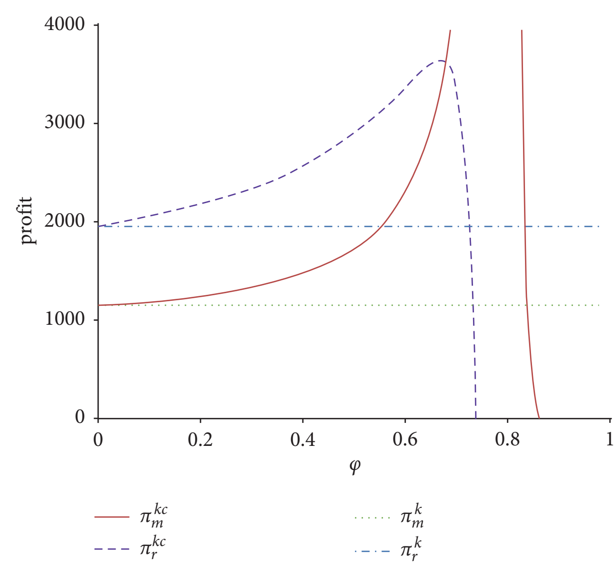

FIGURE 7: Impact of the cost-sharing coefficient on profit during risk aversion.

Finally, we study and analyze the impact of the low-carbon emission reduction investment cost allocation coefficient φ on the profit trend of supply chain members. Take $k = 0.5$, $t = 2$. The profits of manufacturers and retailers under the low-carbon emission reduction investment cost-sharing contract when the manufacturer's risk is neutral and the manufacturer is risk-averse are shown in Figures 6 and 7, respectively.

Figure 6 shows that when the manufacturer is risk-neutral, after the implementation of the cost-sharing contract, within a feasible region $\varphi_1 = 0.85$, as the cost-sharing coefficient $\varphi_1 = 0.85$ increases, the manufacturer's profit increases gradually, and the retailer's profit first increases and then decreases as the cost-sharing coefficient increases. This conclusion is in line with the research results of traditional cost-sharing contracts. When the cost-sharing coefficient is small, although the retailer bears part of the investment cost of the carbon emission reduction, the retailer's profit will not be reduced. However, the retailer's profit will increase first because the retailer bears part of the investment cost of carbon emission reduction and can promote manufacturers' with production enthusiasm, reduce product production costs, and improve product carbon emission reduction levels. The market expansion effects of lower product wholesale prices and increased carbon emission reduction levels will bring greater profits to retailers. Figure 6 also shows that when $\varphi_1 = 0.85$, the low-carbon emission reduction investment cost-sharing contract can increase the profits of both retailers and manufacturers, that is, realizing Pareto improvement of the profits of supply chain members.

Figure 7 shows that when the manufacturer is risk-averse, after implementation of the carbon emission reduction investment cost-sharing contract, within the feasible range of $\varphi_1 = 0.85$, as the cost-sharing coefficient $\varphi_1 = 0.85$ increases, the retailer's profit and the manufacturer's profit will firstly increase and then decrease. Analyzing Figure 7, we obtain, $\varphi_1 = 0.85$ and $\varphi_2 = 0.73$, according to Proposition 5, when the cost-sharing coefficient $\varphi \in (0, 0.73)$ is satisfied $\varphi \in (0, 0.73)$, that is, when $\varphi \in (0, 0.73)$, implementing a low-carbon emission reduction investment cost-sharing contract in a low-carbon supply chain where manufacturer's risk aversion can achieve a Pareto improvement of the profits of supply chain members. Combining Figures 6 and 7, it can be seen that after the implementation of carbon emission reduction investment cost-sharing, by adjusting the cost-sharing coefficient, the overall profit of the supply chain can be increased and Pareto improvement of the supply chain profit can be achieved; that is, the implementation of investment cost-sharing can improve the efficiency of the supply chain.

6. Conclusion

Under a carbon tax policy, this article considers a two-level low-carbon supply chain composed of manufacturers and retailers, where manufacturers produce low-carbon products and sell them to the market through retailers. We model and analyze a low-carbon supply chain under three different decision-making modes: centralized decision-making, manufacturer risk-neutral decentralized decision-making, and manufacturer risk-averse decentralized decision-making. We study the impact of carbon tax rates and manufacturers' risk-averse on low-carbon supply chain pricing strategies, product carbon emission reduction levels, the profits of the supply chain members, and the overall profits of the supply chain; then, the article builds a low-carbon emission reduction investment cost-sharing contract to coordinate and optimize the low-carbon supply chain and obtain the following conclusions.

(1) In the low-carbon supply chain, the product carbon emission reduction level and the overall profit of the supply chain under the centralized decision-making model are higher than under the decentralized decision-making; in decentralized decision-making, when the manufacturer is risk-averse, the level of product carbon emission reduction and the overall profit of the supply chain will be further reduced; under three different decision-making modes, the average carbon emission reduction level will increase with the increase of the carbon tax rate, and the increase in the centralized decision-making model is greater than that of the manufacturer's risk-neutral decentralized decision-making. The latter's increase is greater than under the manufacturer's risk-averse decentralized decision-making.

(2) When low-carbon product manufacturers are risk-averse, as the degree of risk aversion increases, the overall profit of the supply chain and the profit of the manufacturer will decrease, while the trend of the retailer's profit will be determined by the carbon tax rate: when the carbon tax rate is low, the retailer's profit will increase, and at this time, the retailer's profit will increase as the manufacturer's risk aversion coefficient increases; when the carbon tax rate is high, the retailer's profit will decrease; at this time, the retailer's profit will decrease as the manufacturer's risk aversion coefficient increases. In addition, with the increase in manufacturers' risk aversion, the retail prices of low-carbon products continue to decrease; when the carbon tax rate is low, the wholesale price is continuously decreasing; and when the carbon tax rate is high, the wholesale price is constantly increasing.

(3) In the low-carbon supply chain, implementation of the carbon emission reduction investment cost-sharing contract can promote an increase in the level of carbon emission reduction of low-carbon products, and the sharing coefficient will increase the profits of manufacturers and retailers at the same time under certain conditions. Regardless of whether the manufacturer is risk-averse, product carbon emission reduction investment cost-sharing can improve the overall efficiency of the supply chain and increase the profit of the supply chain.

In the future, studies should consider that all members of the supply chain are risk-averse, and it is also possible to introduce more behavioral characteristics, such as considering the combined or cross-effects of multiple behavioral preferences on the low-carbon supply chain. In addition, the impact of various carbon emission policies on the supply chain decision-making system can also be considered in the low-carbon supply chain. On this basis, by expanding the complexity of the supply chain structure to carry out more in-depth research, the constructed model is more in line with the real decision-making environment and better reveals social phenomena and laws.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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