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Research Article

Pricing and Carbon Emission Reduction Decisions in a Supply Chain with a Risk-Averse Retailer under Carbon Tax Regulation

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Carbon tax is an emission regulation, which widely used to curb the carbon emissions generated from firms. In the context of carbon tax policy, firms need to determine an optimal carbon reduction level and optimal product prices. To address firms' decision-making challenges, this paper considers a two-echelon supply chain consisting of a single manufacturer and a single retailer under carbon tax policy; it establishes a Stackelberg game model with a risk-averse retailer and a risk-neutral manufacturer who is the leader of the game. The paper studies the influence of the government's carbon tax policy and retailer's risk-averse attitude on the optimal decision of the supply chain. The result shows that when the retailer is risk aversion, the degree of risk aversion of the retailer is positively correlated with the wholesale price of the manufacturer and unit carbon emission reduction, and within a certain range of carbon emission reduction cost coefficient, it is positively correlated with the price of products; with the increase of the carbon tax rate imposed by the government, the retail price of unit products, the wholesale price of the manufacturer, and the carbon emission reduction of unit products also increase. Finally, the results are verified by numerical examples.

1. Introduction

The continuous increase of carbon dioxide and other greenhouse gas emissions have brought huge influence to human life and nature. In order to deal with the catastrophic climate change caused by greenhouse gas emissions, more than 100 countries and regions in the world signed the "the United Nations framework convention on climate change" Kyoto Protocol in 1997 and decided to face environmental challenges together. For example, during "the 11th Five-Year Plan" period, the Chinese government set the target of reducing energy consumption unit GDP by about 20% and achieved the goal of reducing energy consumption unit GDP by 19.1% and saving 630 million tons of energy at the end of the deadline. In addition, at the 15th United Nations climate change conference, the Chinese government made commitments to reduce carbon dioxide emissions based on unit GDP by 40–45% in 2020 as opposed to 2005. At the same time, many countries in the world have issued corresponding carbon emission reduction plans one after another.

In order to achieve the goal of reducing carbon emission, many countries have implemented some low-carbon policies, such as carbon tax policy, carbon emission cap-and-trade mechanism (cap-and-trade), and carbon emission reduction subsidy policy. Among them, cap-and-trade mechanism and carbon tax policy are widely adopted and implemented in practice. Under cap-and-trade mechanism, the government allocates a predetermined amount of carbon emissions (a carbon cap) for a firm. If the firm's actual amount of carbon emissions exceeds the carbon cap, it can buy carbon emission permits on a carbon trading market such as the European Union Emissions Trading System (EU ETS). If a firm's actual amount of carbon emissions is less than the carbon cap, it can sell its surplus emission permits on the same market. Under carbon tax policy, a firm is charged for its carbon emissions through taxes. A number of European countries have implemented carbon taxes, including Denmark, Finland, the Netherlands, Norway, Sweden, Switzerland, and the UK. Because these two regulation schemes have different effects on operational decisions of a firm, some researchers have studied this issue and compared the effects of cap-and-trade mechanism and carbon tax policy. For example, Hu et al. [1] analyzed the tradeoffs between carbon tax and cap-and-trade with a series of numerical studies; their research shows that, while keeping carbon emissions under control, cap-and-trade demonstrates a better fit to remanufacturing. Weitzman [2] compared the carbon tax policy and carbon emission trading policy; his research shows that, if the marginal revenue curve is flat, the carbon tax policy is better than carbon emission right trade policy. If the marginal cost curve is flat, the carbon emission right trade policy is better than a carbon tax. Recently, a researcher who comes from the International Monetary Fund (IMF) said that a carbon tax is the most effective way to combat climate change [3]. In addition, governments of the world also educate their citizens to enhance their low-carbon awareness in various ways. Therefore, more and more consumers are inclined to buy low-carbon products, so firms must reduce carbon emissions to meet consumers' demand for low-carbon products.

In reality, the consumer market is full of uncertainties. The market demand is affected by commodity prices, services, popular trends, seasons, and many other factors. The uncertainties of the market make the profits of the members in the supply chain full of uncertainties, so the ability of enterprises to bear risks will affect the expected returns. We all know different enterprises have different preferences for risks. For example, the risk seekers usually pursue risks actively and prefer the volatility of returns to the stability of returns. For risk evaders, they usually take the initiative to avoid risks, prefer the stability of returns, and choose more conservative decision-making behavior. Therefore, it is the most important that risk attitude of member enterprises should be fully considered in the supply chain research. The enterprises' risk attitude will have an impact on the optimal decision of the supply chain. It is well known that there are three major formulations that are widely used in the literature: mean-variance and its variants, Value-at-Risk (VaR), and Conditional Value-at-Risk (CVaR). All of them have been widely applied although each of them has certain strengths as well as limitations. For example, in Li et al.'s [4] establishment of the game model of risk-averse retailers and risk-neutral manufacturers' dual-channel pricing, the optimal decision-making of the decentralized and centralized supply chain under VaR and CVaR was studied, respectively, and the research on price and order quantity of retailers' risk aversion coefficient was further explored. Fang and Ren [5] used the mean-variance method to study the pricing strategy of the dual-channel supply chain of risk-averse retailers.

In this paper, we intend to address three questions as follows:

(1) What are the optimal decisions of the manufacturer and retailer in the case of risk neutrality and risk averse?

(2) What are the impacts of the retailer's risk aversion degree on the optimal retail price, wholesale price, and unit carbon emission reduction under the carbon tax policy?

(3) What is the relationship between the carbon tax rate and the optimal retail price, wholesale price, and unit carbon emission reduction?

This research makes two contributions to the literature. First, this research considers both the carbon tax policy and supply chain members' risk aversion characteristics in a paper, to make it more in line with the actual and more practical. Second, this research integrates the retailer's risk aversion into the green supply chain models and explores how the retailer's risk aversion characteristics affect the optimal decision of the supply chain, which enriches the theory of green supply chain management.

The paper is organized as follows. The relevant literature is reviewed in Section 2. Section 3 gives the problem description and describes the assumptions about the model. Then, we consider the different structure about retailer risk neutral and risk averse in Section 4. In Section 5, we carry out numerical analysis on all the conclusions of this paper to further verify the research results. Finally, we conclude in Section 6.

2. Literature Review

Recently, the literature on the carbon tax policy and the impact of risk aversion characteristics is growing. In fact, some scholars have carried out some research on this issue; here, we review the studies highly related to this paper. Thus, the related literature can be divided into two streams, as reviewed in the following.

2.1. Carbon Tax Policy and Green Supply Chain Management. The research on the carbon tax policy can be divided into two parts. The first part is about the impact of the carbon tax policy and related carbon emission reduction policy on the government and enterprises. Zhou et al. [6] constructed a social welfare model considering carbon tax emission and discussed the theoretical characteristics of the proposed carbon tax policy based on the Stackelberg game. Then, the differences and similarities between a flat carbon tax and an increasing block carbon tax are analyzed using a numerical simulation. Zhang and Baranzini [7] found that increasing the rate of carbon tax did not support the development of enterprises. The carbon tax makes carbon emissions valuable, resulting in increasing costs for enterprises, and the high carbon tax will inhibit the economic development and production behavior of enterprises. Kuo et al. [8] discussed the interactions between a government and enterprise for implementing carbon taxes over time or level of tax, considering greenhouse gas emission. Wesseh and Lin [9] found the Chinese government is poised to commit to a low-carbon economy and study how optimal the carbon tax is for enterprises and implications for power generation, welfare, and the environment. The second part is the relationship with the carbon tax policy and supply chain, the cost of carbon emission reduction of supply chain members, and the impact on product price and output, as well as the impact on retailers and consumers in the supply chain. Yi and Li [10] thought government subsidy and carbon tax policies can promote the cooperation of both the upstream and downstream enterprises of the supply chain, as subsidy policy can always drive energy saving and emissions reduction, while a carbon tax policy does not always exert positive effects, as it depends on the initial level of pollution and level of carbon tax. Haddadsisakht and Ryan [11] proposed a model of a three-stage hybrid robust/stochastic program that combines probabilistic scenarios for the demands and return quantities with uncertainty for the carbon tax rates in the closed-loop supply chain. Gao et al. [12] considered a two-echelon supply chain system of the cooperative emission reduction model consisting of a manufacture and a retailer under the carbon tax policy. Kumar et al. [13] presented a remanufacturing supply chain tactical planning model that integrates economic and carbon emission objectives with a carbon tax policy consideration.

As consumers' preference for low-carbon products increases, green supply chain management has become an important academic research topic. Du et al. [14] studied the impact of consumers' preference to low carbon in a green supply chain, and they adopted a novel emission-sensitive demand function and introduced an emission-sensitive cost function to capture the deviation production cost caused by emission reduction. Swami and Shah [15] studied the coordination problem of a green supply chain, coordinated the green supply chain, and found that the optimal effort level had a lot to do with greening sensitivity and greening cost. He et al. [16] studied a green supply chain composed of one manufacturer and two complementary suppliers and analyzed the impact of governmental taxes over production emissions of firms. Heydari et al. [17] studied the problem of optimal and coordinated decision making for a three-tier dual-channel green supply chain, built three different decision-making structures, and developed a coordinated environmentally friendly decision model for a multitier dual-channel supply chain structure. Aslani and Heydari [18] addressed the issue of pricing, product greenness, and coordination in a dual-channel supply chain under channel disruption. Their research illustrates that the proposed contract is capable of coordinating the supply chain and guaranteeing the members' profitability. Xu et al. [19] offered a comparative study of pressures that impact the adoption of the Green Supply Chain Management and examined pressure impact differences in Green Supply Chain Management implementation in different sectors and varying scales of production in Indian industries.

2.2. The Impact of Risk Aversion Characteristics. In real life, with increasing market uncertainty and fierce competition, the increasing diversification of consumer demand gradually increases the uncertainty of market demand, thus increasing the risks brought to enterprises. Faced with all kinds of potential risks in the market, and decision makers show a risk-averse attitude. Among the numerous literatures on risk attitudes, there are some studies on the risk attitudes of one of the retailers or manufacturers in the supply chain. For example, Hafezalkotob et al. [20] considered a supply chain including a manufacturer and a population of retailers and intended to investigate how the population of retailers tends to evolve toward risk-averse behavior. Ke et al. [21] investigated the impacts of the risk sensitivity on the performances of the closed-loop supply chain members are given by the comparison of different degrees of the retailer's risk aversion, and numerical studies found that only the manufacturer makes more profit while the retailer is more risk sensitivity. Li and Jiang [22] investigated the effect of consumer returns and retailer's risk aversion on the behavior of supply chain members under supplier encroachment. There are also some literatures on the risk attitude of retailers or suppliers and manufacturers or risk aversion management of the whole supply chain. Choi et al. [23] analyzed the optimal pricing decisions in a mass customization supply chain with one risk-averse manufacturer and two risk-averse competing retailers and focused on exploring how the degree of risk aversion of each supply chain agent affects the optimal prices as well as consumer welfare, supply chain profitability, and credit deposit under a competitive setting. Wang and He [24] compared the supply chain performances of the case under risk neutrality and risk aversion and investigated the impact of risk aversion of the supplier and the manufacturers and the low-carbon supply chain performances, respectively. Basu et al. [25] studied the problem of hedging demand uncertainty in a supply chain consisting of a risk-neutral supplier and a risk-averse retailer under a buyback contract and found it is too costly for the supplier to manage risk. Cannella et al. [26] studied the impact of risk aversion on the supply chain and implied that a company facing problems of high inventory should favor low-risk aversion managers, as instrumental to lowering stock and improving net working capital.

3. Model Assumptions

In this section, we consider a two-echelon supply chain system consisting of a single manufacturer and a single retailer. The manufacturer produces a product and supplies it to the retailer at a certain wholesale price, and then the retailer sells the product to the consumer. The manufacturer emits carbon dioxide gas in the process of producing products. For the carbon dioxide gas emitted by the manufacturer, the government will levy a carbon tax on the manufacturer. In order to reduce carbon emissions in the production process of products, the manufacturer will take some technical measures to reduce carbon emissions per unit product, and the manufacturer has to pay some carbon emission reduction costs. The main notations used in this paper are shown in Table 1.

In this paper, we made the following model assumptions:

(1) Assumed that the manufacturer's risk attitude is neutral and the retailer is risk averse.

(2) Assumed that the market demand is $D = a - bp + \lambda e + \varepsilon$ and both the manufacturer and the retailer know the distribution of the demand [27]; here, a is the maximum market capacity, p is the product retail price, b is the price sensitivity coefficient, e is the carbon emission reduction per unit product, λ is the elasticity coefficient of carbon emission reduction per unit product affecting demand, ε is the random uncertainty of the market; assuming $\varepsilon \in N(0, \delta^2)$, the mean value is 0 and the variance is δ^2, there have been extensive papers using the similar demand mode to capture the impacts of the carbon emission reduction level on the demand, e.g., [27–29].

(3) Assumed that the low-carbon control of products mainly comes from the emission reduction of the manufacturer, so the manufacturer bears the cost of carbon emission reduction $g(e) = 1/2ke^2$, where k is the cost coefficient of carbon emission reduction. Such a quadratic cost function has been adopted in the existing literature on carbon reduction efforts investment, such as [30, 31].

(4) Assumed that in the absence of carbon emission reduction technology input, the carbon emission per unit product is e_0, the carbon tax imposed by the government on the carbon emission per unit of the manufacturer is t, the wholesale price of the manufacturer's unit product is w, and the retail price per unit product is p.

Let π_r and π_m are the profits of the retailer and manufacturer, according to the literature [28, 29, 31],

$$\begin{aligned} \pi_r &= (p - w)(a - bp + \lambda e + \varepsilon), \\ \pi_m &= (w - c)(a - bp + \lambda e + \varepsilon) - \frac{1}{2}ke^2 - t(e_0 - e). \end{aligned} \tag{1}$$

The risk attitude of the retailer will affect the utility of the manufacturer and retailer. Therefore, in the following paragraphs, we take the utility as the operation standard of the supply chain in different models and use "rn" and "ra" superscript to indicate that the retailer is risk-neutral and risk-aversion models.

4. Model Construction and Analysis

4.1. Retailer Is the Risk-Neutral Decision Maker. When the retailer is risk neutral, the Stackelberg game model is established and the optimal solutions of the retailer and manufacturer can be solved by the reverse induction method.

Table 1: Notations.

Notation	Description
a	Maximum market capacity
b	Coefficient of sensitivity of price
p	Product retail price
e_0	Initial unit carbon emission
λ	The elasticity coefficient of carbon emission reduction per unit product affecting demand
ε	The random uncertainty of the market
e	Unit carbon emission reduction
k	Carbon emission reduction cost factor
t	Carbon tax rate
w	Unit product wholesale price
c	Unit product cost
π_r	The profit of retailer
π_m	The profit of manufacturer
U_r	The utility of retailer
U_m	The utility of manufacturer

Theorem 1. *Under the carbon tax policy, when the retailer is risk neutral, the manufacturer's utility function U_m is concave in both w and e if $2bk - \lambda^2 > 0$; hence, by holding the condition, the optimal retail price and the optimal wholesale price are*

$$\begin{aligned} p^{rn} &= \frac{3ak + bck - c\lambda^2 + 3t\lambda}{4bk - \lambda^2}, \\ w^{rn} &= \frac{2ak + 2bck - c\lambda^2 + 2t\lambda}{4bk - \lambda^2}. \end{aligned} \tag{2}$$

The optimal unit carbon emission reduction of the manufacturer is

$$e^{rn} = \frac{(a - bc)\lambda + 4bt}{4bk - \lambda^2}. \tag{3}$$

Proof. See Appendix A. □

4.2. Retailer Is the Risk-Averse Decision Maker. In the actual production of enterprises, retailers should have the characteristics of risk aversion, so we need to consider the risk aversion factors. There are many ways to measure the risk-averse attitudes of manufacturers and retailers. According to the research conducted by [32, 33], retailers with risk-averse characteristics will comprehensively consider the variance of expected returns. In this paper, we use the mean-variance method to establish the retailer's expectation function. Let η be the risk aversion coefficient of the retailer; the greater the value of this coefficient, the greater the retailer's risk aversion, and $\eta = 0$ means the retailer is risk neutral.

Theorem 2. *Under the carbon tax policy when the retailer is risk averse, the manufacturer's utility function U_m is concave in both w and e if $2bk - \lambda^2 > 0$; hence, by holding the condition, the optimal retail price and the optimal wholesale price are*

$$p^{ra} = \frac{(bk-\lambda^2)(bc+2c\eta\delta^2)+(ak+t\lambda)(3b+2\eta\delta^2)}{4kb^2+4bk\eta\delta^2-b\lambda^2-2\lambda^2\eta\delta^2},$$
$$w^{ra} = \frac{(b+\eta\delta^2)(2ak+2t\lambda+2kbc)-c\lambda^2(b+2\eta\delta^2)}{4kb^2+4bk\eta\delta^2-b\lambda^2-2\lambda^2\eta\delta^2}, \quad (4)$$

the optimal unit carbon emission reduction of the manufacturer is

$$e^{ra} = \frac{(2\eta\delta^2+b)(a-bc)\lambda+4bt(b+\eta\delta^2)}{4kb^2+4bk\eta\delta^2-b\lambda^2-2\lambda^2\eta\delta^2}. \quad (5)$$

Proof. See Appendix B. □

Corollary 1. *The manufacturer's wholesale price and carbon emission reduction per unit product are positively correlated with the retailer's risk aversion coefficient. When the manufacturer's carbon emission reduction cost coefficient k satisfies $k > \lambda^2/b$, the retailer's selling price is negatively correlated with the retailer's risk avoidance degree, and when k satisfies $\lambda^2/2b < k < \lambda^2/b$, the retailer's selling price is positively correlated with the retailer's risk avoidance degree.*

Proof. See Appendix C. □

Corollary 2. *Under the condition that the retailer is risk averse and the manufacturer is risk neutral, when the manufacturer's carbon emission reduction cost coefficient k satisfies $k > \lambda^2/2b$, the manufacturer's wholesale price w, the unit product carbon emission reduction e, and the retailer's retail price p are positively correlated with the carbon tax rate t.*

Proof. See Appendix D. □

5. Numerical Analysis

5.1. The Impact of Retailer's Risk Aversion on Unit Carbon Emission Reduction and Wholesale Price. The correctness of these inferences is verified by numerical analysis. Under the influence of the government's carbon tax policy, manufacturers take the approach of reducing carbon emissions to reduce carbon emissions and consider the impact of carbon emission cost coefficient and retailers' risk aversion characteristics on enterprises. In order for the discussion to be meaningful and for each optimal decision to exist, let $k > \lambda^2/2b$. Assumed that the relevant parameters of the model are $a = 100$, $b = 4$, $c = 10$, $\lambda = 2$, and $\delta = 2$, the risk aversion coefficient of the retailer is $\eta \in [0, 1]$, the impacts of retailer's risk aversion on unit carbon emission reduction and wholesale price under different carbon taxes are shown in Figures 1 and 2.

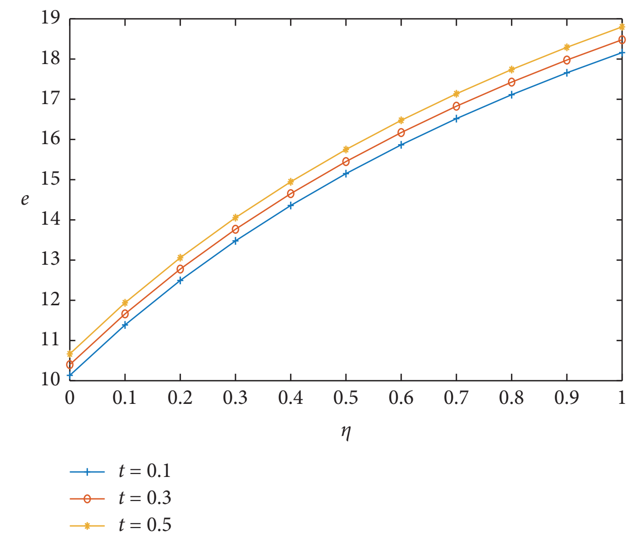

Figure 1: The impact of retailer's risk aversion on unit carbon emission reduction under different carbon taxes.

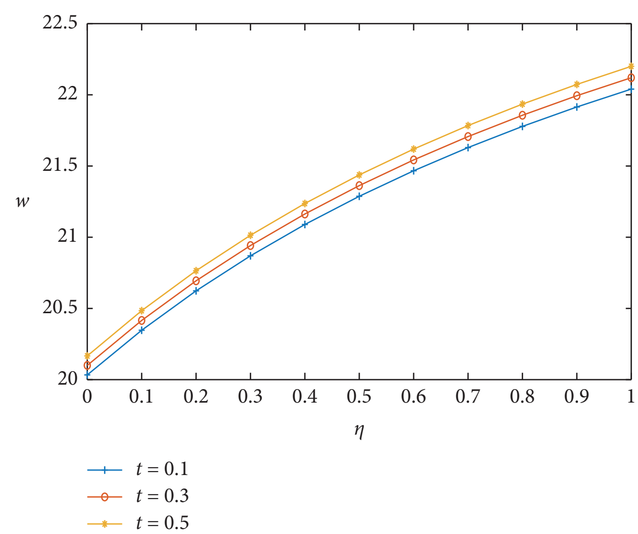

Figure 2: The impact of retailers' risk aversion degree on the wholesale price of products under different carbon taxes.

It can be concluded from Figure 1 that when the retailer has the risk aversion characteristics, the carbon emission reduction per unit product of the manufacturer will increase with the increase of the retailer's risk aversion degree under a certain carbon tax. This is because when faced with risks brought by market uncertainty, the retailer is more afraid of risks. In order to increase the market demand of products, the manufacturer will increase carbon emission reduction efforts, which will increase the carbon emission reduction per unit of products. In the same degree of risk aversion of the retailer, the carbon emission reduction per unit also increases with the increase of carbon tax. This is because the increase of carbon tax increases the production cost of the manufacturer. The manufacturer will increase the unit carbon emission of products to offset the increased cost caused by the increase of carbon tax.

From Figure 2 we can find that, when the risk aversion degree of the retailer increases, the wholesale price of the manufacturer also increases with a certain carbon tax. This is because the higher the degree of risk aversion of the retailer, more afraid the retailer and more prudent the decision, so the manufacturer will slightly increase the wholesale price to make more profits. With the same degree of risk aversion of the retailer, the increase of the carbon tax will increase the wholesale price of products. This is because as carbon taxes rise, so does the cost to the manufacturer of making products, which is offset by higher wholesale prices.

5.2. The Impact of Retailer's Risk Aversion on the Retail Price under Different Carbon Taxes. Based on the assumptions in this chapter, we know that $\lambda^2/b = 1$, and let the parameters k take different values separately, for example, $k = 0.8 < 1$ and $k = 2 > 1$, and perform numerical simulation, as shown in Figures 3 and 4.

As can be seen from Figures 3 and 4, when the manufacturer's unit carbon emission reduction cost coefficient $k < \lambda^2/b = 1$, the retail price increases with the increase of the retailer's risk aversion under a certain carbon tax. As the risk coefficient is $k > \lambda^2/b = 1$, with the increase of risk aversion of the retailer the retail price decrease. This shows that when the manufacturer's unit cost of carbon emissions coefficient is larger, the manufacturer's unit carbon emission reduction will reduce. It will affect the market demand for products and the retailer will be afraid of the uncertainty of market risk; in order to compensate for the reduced demand, the retailer will reduce the retail price of the products to promote the sales of products, expanding market demand. When the unit carbon emission reduction cost coefficient of the manufacturer is small, the unit carbon emission reduction of the manufacturer will increase and the retailer will raise the price of the product to earn more profits. Under the fixed degree of risk aversion of the retailer, no matter the unit carbon emission reduction cost coefficient of the manufacturer is large or small, with the increase of the carbon tax, the product price will also increase. This is because the increase of the carbon tax increases the production cost of the manufacturer; to turn a profit, the manufacturer will increase the wholesale price, then the retail price of the products also increases.

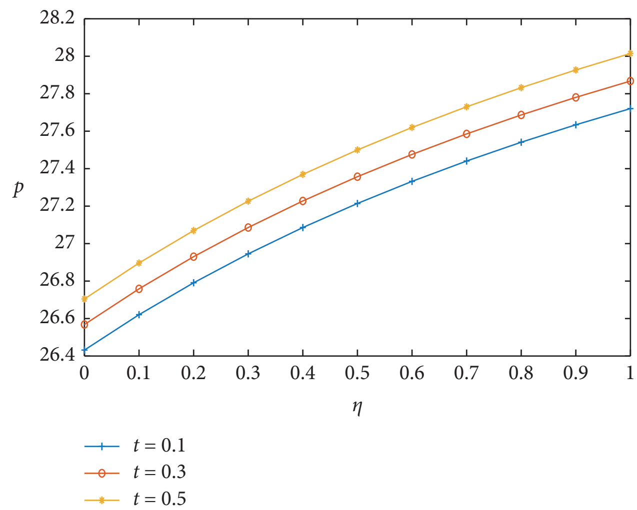

FIGURE 3: The impact of retailer's risk aversion on the retail price under different carbon taxes as $k = 0.8$.

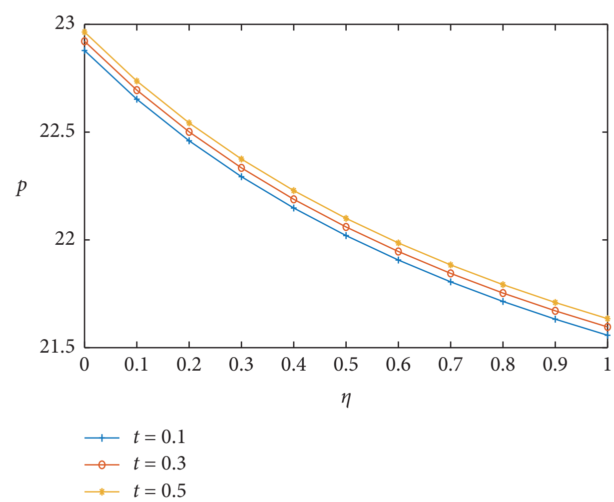

FIGURE 4: The impact of retailer's risk aversion on the retail price under different carbon taxes as $k = 2$.

6. Conclusion

This paper constructs a two-echelon supply chain composed of a single manufacturer and a single retailer and considers the impact of carbon tax policy and retailer's risk aversion characteristics on the supply chain. The results show the following. (1) When the retailer has the risk aversion characteristics, the wholesale price of the manufacturer and the carbon emission reduction per unit of the product are positively correlated with the risk aversion coefficient of the retailer and the cost coefficient of carbon emission reduction per unit of the manufacturer will affect the retail price of the product. (2) Under a certain degree of risk aversion of the retailer, with the increase of carbon tax, the wholesale price of the manufacturer, the carbon emission reductions of the unit product, and the retail price of the unit product also increase. The main managerial implications of our research are obtained as follows: (1) when the retailer is risk averse, under certain conditions, for example $k > \lambda^2/2b$, an increase in carbon taxes would encourage manufacturers to reduce carbon emissions per unit of production; (2) when the manufacturer's unit carbon emission reduction cost increases, a high carbon tax would increase the retail price of products.

This paper can be extended as follows: first, in this paper, we only consider the secondary retailer in a supply chain risk aversion attitude, in the real supply chain operation, not only the retailer has the characteristics of risk aversion, but also the manufacturer has the characteristics of risk aversion. Future research studies can consider the condition that the manufacturer has the characteristics of risk aversion. Second, in this paper, we did not consider the fair attitude of the supply chain members; future research studies can also consider the fair attitude of the supply chain members.

Appendix

A. Proof of Theorem 1

As the retailer and the manufacturer are both risk neutral, the enterprise's deterministic utility are their expected return. In this case, utility of the manufacturer and the retailer are

$$U_r = E(\pi_r) = (p - w)(a - bp + \lambda e), \tag{A.1}$$

$$U_m = E(\pi_m) = (w - c)(a - bp + \lambda e) - \frac{1}{2}ke^2 - t(e_0 - e). \tag{A.2}$$

We use backward sequential decision-making approach to solve the Stackelberg game. From (A.1), we can obtain

$$\frac{dU_r}{dp} = a - 2bp + \lambda e + wb, \tag{A.3}$$

$$\frac{d^2U_r}{dp^2} = -2b < 0. \tag{A.4}$$

So U_r has maximum, and from first order condition of (A.3), we can obtain

$$p = \frac{a + \lambda e + wb}{2b}. \tag{A.5}$$

Taking (A.5) into (A.2), we can obtain

$$\frac{\partial U_m}{\partial w} = \frac{1}{2}(a + bc + \lambda e - 2bw), \tag{A.6}$$

$$\frac{\partial U_m}{\partial e} = \frac{1}{2}\lambda(w - c) + t - ke. \tag{A.7}$$

Let H be the Hessian matrix of U_m:

$$H = \begin{pmatrix} \frac{\partial^2 U_m}{\partial w^2} & \frac{\partial^2 U_m}{\partial w\,\partial e} \\ \frac{\partial^2 U_m}{\partial e\,\partial w} & \frac{\partial^2 U_m}{\partial e^2} \end{pmatrix} = \begin{bmatrix} -b & \frac{\lambda}{2} \\ \frac{\lambda}{2} & -k \end{bmatrix}. \tag{A.8}$$

When the matrix is negative definite, the first principal minor is negative and the second principal minor is positive, U_m is concave in both w and e, and the utility function will have a maximum. For $\partial^2 U_m/\partial w^2 = -b < 0$, $(\partial^2 U_m/\partial w^2)\cdot(\partial^2 U_m/\partial e^2) - (\partial^2 U_m/\partial e\,\partial w)^2 = bk - (\lambda^2/4)$, if $2bk - \lambda^2 > 0$, then $bk - (\lambda^2/4) > 0$, the Hessian matrix is negative definite, and U_m have maximum. From (A.6) and (A.7), we can obtain

$$w^{rn} = \frac{2ak + 2bck - c\lambda^2 + 2t\lambda}{4bk - \lambda^2}, \tag{A.9}$$

$$e^{rn} = \frac{(a - bc)\lambda + 4bt}{4bk - \lambda^2}. \tag{A.10}$$

Taking (A.9) and (A.10) into (A.5), we can obtain the retailer's optimal retail price:

$$p^{rn} = \frac{3ak + bck - c\lambda^2 + 3t\lambda}{4bk - \lambda^2}. \tag{A.11}$$

B. Proof of Theorem 2

The retailer's utility is

$$U_r = E(\pi_r) - \eta \mathrm{Var}(\pi_r) = (p - w)(a - bp + \lambda e) - \eta(p - w)^2\delta^2. \tag{B.1}$$

The manufacturer's utility is

$$U_m = (w - c)(a - bp + \lambda e) - \frac{1}{2}ke^2 - t(e_0 - e). \tag{B.2}$$

From (B.1), we can obtain

$$\frac{dU_r}{dp} = a - b(2p - w) - 2(p - w)\delta^2\eta + \lambda e, \tag{B.3}$$

$$\frac{d^2U_r}{dp^2} = -2b - 2\delta^2\eta < 0. \tag{B.4}$$

So U_r has maximum, and from first-order condition of (B.3), we can obtain

$$p = \frac{a + bw + \lambda e + 2\eta w\delta^2}{2(b + \eta\delta^2)}. \tag{B.5}$$

Substituting equation (B.5) into (B.2), we can obtain

$$\frac{\partial U_m}{\partial w} = \frac{(b + 2\delta^2\eta)(a - b(c - 2w) + \lambda e)}{2(b + \delta^2\eta)}, \tag{B.6}$$

$$\frac{\partial U_m}{\partial e} = \frac{2\delta^2\eta(\lambda(w - c) - ke + t) + b(\lambda(w - c) - 2ke + 2t)}{2(b + \delta^2\eta)}. \tag{B.7}$$

Let H be the Hessian matrix of U_m:

$$H = \begin{pmatrix} \frac{\partial^2 U_m}{\partial w^2} & \frac{\partial^2 U_m}{\partial w\,\partial e} \\ \frac{\partial^2 U_m}{\partial e\,\partial w} & \frac{\partial^2 U_m}{\partial e^2} \end{pmatrix} = \begin{pmatrix} -\frac{b(b + 2\delta^2\eta)}{b + \delta^2\eta} & \frac{\lambda(b + 2\delta^2\eta)}{2(b + \delta^2\eta)} \\ \frac{\lambda(b + 2\delta^2\eta)}{2(b + \delta^2\eta)} & -k \end{pmatrix}. \tag{B.8}$$

When the matrix is negative definite, the first principal minor is negative and the second principal minor is positive, U_m is concave in both w and e and the utility function will have a maximum. For $\partial^2 U_m/\partial w^2 = -(b(b + 2\delta^2\eta)/b + \delta^2\eta) < 0$, $(\partial^2 U_m/\partial w^2)\cdot(\partial^2 U_m/\partial e^2) - (\partial^2 U_m/\partial e\,\partial w)^2 = ((b + 2\delta^2\eta)(4bk(b + \delta^2\eta) - \lambda^2(b + 2\delta^2\eta)))/(4(b + \delta^2\eta)^2)$, if $2bk$

$-\lambda^2 > 0$, $4bk(b+\delta^2\eta) - \lambda^2(b+2\delta^2\eta) > 2\lambda^2(b+\delta^2\eta) - \lambda^2(b+2\delta^2\eta) = b\lambda^2 > 0$, then $(\partial^2 U_m/\partial w^2)\cdot(\partial^2 U_m/\partial e^2) - (\partial^2 U_m/\partial e\,\partial w)^2 > 0$, the Hessian matrix is negative definite and U_m have maximum. From (B.6) and (B.7), we can obtain

$$e^{ra} = \frac{\left(2\eta\delta^2 + b\right)(a-bc)\lambda + 4bt\left(b+\eta\delta^2\right)}{4kb^2 + 4bk\eta\delta^2 - b\lambda^2 - 2\lambda^2\eta\delta^2}, \tag{B.9}$$

$$w^{ra} = \frac{\left(b+\eta\delta^2\right)(2ak + 2t\lambda + 2kbc) - c\lambda^2\left(b+2\eta\delta^2\right)}{4kb^2 + 4bk\eta\delta^2 - b\lambda^2 - 2\lambda^2\eta\delta^2}. \tag{B.10}$$

Substitute equations (B.9) and (B.10) into (B.5), we can obtain the retailer's optimal retail price:

$$p^{ra} = \frac{\left(bk-\lambda^2\right)\left(bc + 2c\eta\delta^2\right) + (ak+t\lambda)\left(3b+2\eta\delta^2\right)}{4kb^2 + 4bk\eta\delta^2 - b\lambda^2 - 2\lambda^2\eta\delta^2}. \tag{B.11}$$

If $\eta = 0$, the retailer's risk aversion coefficient is zero, the optimal wholesale price, optimal retail price, and optimal carbon emission reductions are the same as that when the retailer's risk attitude is neutral.

C. Proof of Corollary 1

Proof. From (B.6), (B.7), and (B.9), we can obtain

$$\frac{\partial w^{ra}}{\partial \eta} = \frac{2kb\lambda^2\delta^2(a-bc) + 2tb\lambda^3\delta^2}{\left(4kb^2 + 4bk\eta\delta^2 - b\lambda^2 - 2\lambda^2\eta\delta^2\right)^2}, \tag{C.1}$$

$$\frac{\partial e^{ra}}{\partial \eta} = \frac{4kb^2\lambda\delta^2(a-bc) + 4tb^2\delta^2\lambda^2}{\left(4kb^2 + 4bk\eta\delta^2 - b\lambda^2 - 2\lambda^2\eta\delta^2\right)^2}, \tag{C.2}$$

$$\frac{\partial p^{ra}}{\partial \eta} = \frac{\left(bk-\lambda^2\right)\left[4bk\delta^2(bc-a) - 4bt\lambda\delta^2\right]}{\left(4kb^2 + 4bk\eta\delta^2 - b\lambda^2 - 2\lambda^2\eta\delta^2\right)^2}. \tag{C.3}$$

Because $D = a - bp + \lambda e + \varepsilon > 0$, then $a - bp > 0$, and because $p > c$, we can get $a - bc > 0$, then we can get $(\partial w^{ra}/\partial \eta) > 0$ and $(\partial e^{ra}/\partial \eta) > 0$. We have known that $bc - a < 0$, when $k > (\lambda^2/b)$, then $(\partial p^{ra}/\partial \eta) < 0$; when $(\lambda^2/2b) < k < (\lambda^2/b)$, then $(\partial p^{ra}/\partial \eta) > 0$. With the increase of the retailer's risk aversion coefficient η, the manufacturer's wholesale price and unit carbon emission reduction will also increase. When the manufacturer's carbon emission reduction cost coefficient k satisfies $k > (\lambda^2/b)$, the retailer's price is negatively correlated with the retailer's risk avoidance degree, and when k satisfies $(\lambda^2/2b) < k < (\lambda^2/b)$, the retailer's selling price is positively correlated with the retailer's risk avoidance degree. □

D. Proof of Corollary 2

Proof. From (B.6), (B.7), and (B.9), we can obtain

$$\frac{\partial w^{ra}}{\partial t} = \frac{2b\lambda + 2\lambda\eta\delta^2}{4kb^2 + 4bk\eta\delta^2 - b\lambda^2 - 2\lambda^2\eta\delta^2}, \tag{D.1}$$

$$\frac{\partial e^{ra}}{\partial t} = \frac{4b^2 + 4b\eta\delta^2}{4kb^2 + 4bk\eta\delta^2 - b\lambda^2 - 2\lambda^2\eta\delta^2}, \tag{D.2}$$

$$\frac{\partial p^{ra}}{\partial t} = \frac{3b\lambda + 2\lambda\eta\delta^2}{4kb^2 + 4bk\eta\delta^2 - b\lambda^2 - 2\lambda^2\eta\delta^2}. \tag{D.3}$$

We make $4kb^2 + 4bk\eta\delta^2 - b\lambda^2 - 2\lambda^2\eta\delta^2 = 0$ and obtain $k = \lambda^2(b+2\eta\delta^2)/4b(b+\eta\delta^2)$, we know $k > (\lambda^2/2b)$, because $(\lambda^2(b+2\eta\delta^2)/4b(b+\eta\delta^2)) < (\lambda^2/2b)$, and then when $k > (\lambda^2/2b)$, we can get $(\partial w^{ra}/\partial t) > 0$, $(\partial e^{ra}/\partial t) > 0$, and $(\partial p^{ra}/\partial t) > 0$. Therefore, the wholesale price, carbon emission reduction per unit product, and retail price of the manufacturer increase with the increase of the carbon tax. □

Data Availability

The numerical experiment in this paper is mainly based on the inferred conclusion in this paper, the data used to support the findings of this paper are included within the paper. If readers need related data, they can contact the authors.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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