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SUPPLY CHAIN EMISSION REDUCTION OPTIMIZATION UNDER CONSUMER CARBON SENSITIVITY AND CARBON TAX POLICY

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Abstract

This paper presents decentralized and centralized decision-making conditions based on consumer carbon sensitivity and carbon tax policy in a supplier-driven two echelons supply chain. The analysis shows that: 1) the optimal emission reduction amount under centralized decision-making is more than that under decentralized decision-making; 2) the carbon tax should be levied properly because the carbon emission reduction will decrease as the carbon tax is higher than a critical value; 3) the consumer carbon sensitivity is positively correlated with carbon emission reduction, but it may cause total mission rised in certain condition. Then an extensive numerical analysis is conducted to enrich the discussion and to draw some managerial insights on how to reduce carbon emission in the supply chain.

Key words: carbon emission reduction, consumer carbon sensitivity, carbon tax policy, Stackelberg game, supply chain

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1. Introduction

Since global warming has been widely concerned by the governments and companies, people concern more and more about carbon emission. Many governments apply relevant policies to address the issue of global warming. Amongst them, the carbon tax is the government's specific tax on companies to constrain carbon emissions. Owing to the obvious effect and low cost of carbon tax collection, the United States, Canada and Australia and other countries have adopted it (Lin and Li, 2011). In addition, due to global concern about environmental protection, consumer demand for products is not only concerned with the quality of products (Du et al., 2013). More and more, consumers are paying more attention to the social value and environmental value of products. In response to the different preferences of consumers with low carbon, the level of carbon emissions per unit of product has gradually become one of the most important attributes for consumers to pursue products. Scholars have discovered that when the products are sold within the form of carbon labels (Vanclay et al., 2011). Environmentally friendly consumers are more willing to make such purchases (Androniceanu and Dragulanescu, 2016; Michaud et al., 2012). At the same time, those consumers are more willing to pay higher prices for low-carbon product, which means that if companies reduce carbon emission in production process, then they can get their products better competitiveness in the market (Lu et al., 2007; Zhou et al., 2017). The low-carbon production decisions of companies in the production process have become serious business decision-making problems. On one hand, the government levying carbon taxes on companies will increase the operating costs of companies, while consumers' demand for low-carbon products will prompt companies to produce environmentally friendly products. On the other hand, low-carbon investments by companies can reduce carbon tax costs and meet the needs of environmentally friendly consumers but increase costs

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in the manufacturing process. Therefore, how the government levies the carbon tax and how they produce a reasonable preventive solution is a problem influenced both government and companies. Thus, questions about how the carbon tax and the consumer carbon sensitivity affect the carbon emission reduction decisions of companies, how the government formulates the optimal carbon tax considering consumer carbon sensitivity have become urgent problems to be solved.

In this paper, research focuses on the carbon tax levied on companies and consumer preferences for low-carbon products from the perspective of supply chain; the relevant literature review is hence done from two perspectives as following:

1) Carbon tax:

Carbon tax can induce companies to reduce their carbon emissions (Bruvoll and Larsen, 2002; Meng et al., 2013; Bjørner and Jensen, 2002), and different carbon tax rates result in different carbon emission reductions. In the supply chain, revenues of companies change under variable decision-making strategy. Tseng and Hung (2014) have established a decision-making model for the sustainable development of garment processing supply chain network under the carbon tax policy, and the strategic decision-making of companies under different carbon tax policies. Comas Martí et al. (2015) take demand uncertainty into account and includes decisions on supply chain responsiveness under different carbon policies for both functional and innovative products. Yue and Shuaihua (2016) have analyzed the manufacturers and supplier decisions under the carbon tax policy when suppliers involved and not involved in carbon emission and the impact of carbon tax on the two kinds of decision-making. Yang and Luo (2016) produce a model expressing both the emission reduction decisions of manufacturers within carbon tax constraints and the stochastic demand of the wholesale price of companies and their revenue sharing contract and announce that there only existed an emission reduction rate within two kinds of decision-making to maximize the supply chain revenue.

Besides the decision making, revenue distribution and are also analyzed. Yang et al. (2017) analyzed the revenue sharing and first-run advantage in manufacturers' carbon emission reduction efforts and firms' profitability in linear demand settings of a manufacture-driven supply chain.

These papers show that carbon tax play a significant role in reducing emissions and useful methods are also given, but joint influence of carbon tax and other related items such as are not mentioned.

2) Consumer carbon sensitivity:

The impact of consumer carbon sensitivity means that environmentally friendly consumers who cares about carbon emission are willing to pay high prices for low-carbon products (Chitra, 2007). Considering of the impact of consumers' preference to low carbon in an emission sensitive supply chain or market, both the channel profit and the emission reduction increase in the consumers' preference to low-carbon consumption simultaneously in particular cases (Du et al., 2015). Liu et al. (2012) analyzed the decision-making and profit-making of retailers and manufacturers in the supply chain, putting the emphasis on consumer environmental preferences. Ji et al. (2017) compared two emission reduction strategies, including single manufacturer's emission reduction in production strategy and joint emission reduction strategy. They indicated that when considering consumers' low-carbon preference, the retailer always has motivation to implement low carbon promotion though without the manufacturer's incentives. Yilei et al. (2017) focused their research on three contract models under low carbon preferences of consumers to analyze the cooperation and profit reduction in the supply chain. They concluded here that companies constraining the wholesale price can make the supply chain reduce emissions and optimize supply chain coordination. Wang et al. (2016) analyze by contracting emission reduction for supply chains considering market low-carbon preference. Therefore, we can get that consumer carbon sensitivity affects the revenue of the companies and the entire supply chain. Under different strategy, the effects are not the same.

To sum up, the papers reviewed make contribution to the carbon emission reduction to protect the environment, but seldom paper takes both of carbon tax and consumer carbon sensitivity. In this paper, we present a game theory model to assist companies facing these joint affect items, and analyze the revenue distribution to help them get proper decision to make the profits maximized for the entire supply chain. Suggestions of the carbon tax for the government are given as well. More precisely, we contribute to the literature with a two-echelon supply chain game model that simultaneously considers carbon tax and consumer sensitivity of low-carbon products. It also provide managerial implications for the companies to maximize revenue and the government to levy carbon at proper amount.

The structure of this paper is as follows. In Section 2, we present the game modal in both decentralized and centralized mode for the carbon emission reduction and the balance analysis. In Section 3, we present detailed numerical analyse to illustrate the influence of the carbon tax and consumer carbon sensitivity captured by the model and the type of managerial insights that it allows to derive. In Section 4, we conclude and discuss future research opportunities.

2. Material and methods

2.1. Problem description and model assumptions

This article aims at a supplier-driven two-echelon supply chain consisting of a supplier and a manufacturer. Both the supplier and the manufacturer are risk-neutral and the information between them is symmetrical. The manufacturer can only order generic or low-carbon raw materials from upstream, so the supplier is in the leading position in the supply chain.

Since the supply chain is driven by the supplier, which means the supplier is in the dominant position, the government charges carbon tax on the supplier is more feasible to get the influence of the entire supply chain. Consumers who are sensitive to low-carbon environmental protection also grow in number. Therefore, the supplier will implement carbon reduction technologies to reduce the carbon emissions per unit of product. Hence, several situations of the consumer carbon sensitivity are considered under the carbon tax: decentralized decision-making when demand is unrelated to emission reduction; centralized decision-making when the demand is related or unrelated to emission reduction; and how the supplier and the manufacturer will make the decision. The following assumptions have hence been made for the simplification and research convenience of the model:

Hypothesis 1: Assuming that upon the occasion the supplier does not invest in carbon emission reductions, the initial carbon emission reduction per unit of production is e_0. Then the government imposes a carbon tax on carbon dioxide emissions from the supplier at a rate of t yuan/ton CO_2.

Hypothesis 2: The wholesale price and production cost of the supplier's unit product are *w* and *c* respectively, as the wholesale price is the supplier's decision variable and the manufacturer sell their products with the price p per unit.

Hypothesis 3: Carbon emission reductions for the supplier after carbon reduction investment is *e*, $0 \leq e \leq e_0$ and *e* is the supplier's decision variable. The emission cost of the supplier after carbon emission reduction satisfies $c(e) = ke^2/2$, $k > 0$ (Ma et al., 2013; Peng et al., 2013), where k is the carbon emission reduction cost coefficient of the supplier; that is, $c(e)$ satisfies $c'(e) < 0$, $c''(e) < 0$. In the actual production process, the reduction of carbon emission e will lead to increasing marginal costs, indicating that the early stage emission reduction will be easy to carry on, but become more and more difficult later.

Hypothesis 4: When there is some demand for low-carbon products in the market, the supplier adopts the order-oriented production method with the same market demand without regard to stock-out and stock-extrusion problems. This article uses the symbols and their meanings as shown in Table 1.

2.2. Methods and models

2.2.1. Decentralized decision when demand unrelated to carbon emission reduction

In this situation, the product demand is expressed as $Q = a - p$. When the demand is unrelated with the consumers' sensitivities of carbon emission reduction, the game is normally a two-echelon game. In the game, the supplier first determines the wholesale price w and the emission reduction rate e, while the manufacturer determines the final retail price p according to the wholesale price and the emission reduction rate provided by the supplier (w,e) and the observed market information.

In the model, the government levies carbon tax *t* of the CO_2, which is generated by the supplier in the production process. At this point, we can model the profit maximization decision function of the supplier and the manufacturer as Eqs. (1-2):

$$\pi_s^N = (w - c - te_0)(a - p) - ke^2/2 \tag{1}$$

$$\pi_m^N = (p - w)(a - p) \tag{2}$$

Table 1. Symbol meaning summary

Variable	***Meaning***
w	whole sale price of a unit product
p	retail price of a unit of product
Q	market demand for products
π_s	supplier's revenue
π_m	manufacturer's revenue
π_c	supply chain's revenue
$*$	optimal decision-making
t	a unit of carbon tax levied by he government
c	supplier production costs
N	decentralized decision when demand isn't related to carbon emission reduction
D	decentralized decision when demand is related to carbon emission reduction
C	centralized decision-making when demand is related to carbon emission reduction
e	the amount of carbon emission reduction of the supplier
k	cost coefficient for carbon emission reduction
e_0	initial discharge of per unit product
E	discharge of supply chain
η	consumer sensitivity to low carbon products

Calculating the first-order partial derivative of π_r^N with respect to the retail price p in Eq.(1) and make $\partial\pi_m^N / \partial p = 0$, we can obtain the manufacturer's retail price relative to the wholesale price of the supplier as Eq. (1):

$$p = (a+w)/2 \tag{3}$$

Substituting Eq. (3) into Eq. (1) and calculating the first-order partial derivative of the wholesale price w and letting $\partial\pi_s^N / \partial w = 0$, we get the optimal wholesale price w of the supplier, as Eq. (4):

$$w^{N^*} = \frac{a+c+te_0}{2} \tag{4}$$

Substituting Eq. (4) into Eq. (3), we could yield the optimal retail price p^{N^*} as Eq. (5):

$$p^{N^*} = \frac{3a+c+te_0}{4} \tag{5}$$

Substitute the optimal decision of the supplier and the manufacturer into the demand function and revenue Eqs. (1-2), and then the market demand, the optimal revenue for the supplier and the manufacturer will be as Eq. (6):

$$Q^{N^*} = \frac{a-c-te_0}{4}$$

$$\pi_s^{N^*} = \frac{(a-c-te_0)^2 - 4ke^2}{8} \tag{6}$$

$$\pi_m^{N^*} = \frac{(a-c-t_0)^2}{16}$$

According to Eq. (1), we can get that when demand is unrelated to the initial emissions of the products, the optimal emission reduction of the supplier is $e = 0$. It means that the supplier will not be willing to reduce the carbon emission because emissions reduction has no effect on consumers' purchase of the product. However, if consumers' carbon sensitivity is related to the carbon emission of the product, which means when the manufacturer applies emission reductions, the demand of consumers will increase, the manufacturer will actively increase the carbon emission reduction investment.

The following study will thus focus on the impact of carbon tax and consumer carbon sensitivity on corporate emissions reduction, pricing and supply chain performance under both decentralized and centralized decision-making models when consumer demand is related to carbon emission reduction.

2.2.2. Decentralized decision when demand related to carbon emission reduction

Since consumers' sensitivity for low-carbon products will result in lower sales of products of carbon-laden companies, if companies want to sell more products, they will have to take active measures to deal with carbon emission. Energy-saving and emission reduction technology allows companies to reduce energy consumption in the process of production, and the manufacturer will invest in applying certain technology to achieve the reduction of carbon emissions rather than traditional production, which means the carbon emission of per unit product will decrease. The demand of consumers will thus increase because of the carbon sensitivity.

As long as the carbon emission varies, the carbon tax cost of companies, the increase of market demand and the revenue of the supply chain companies change. When companies reduce carbon emissions, the demand will be expressed as $Q = a - p + \eta e$ within the emission reduction amount e as the decision variable. The revenue functions for the supplier and manufacturer are constituted by Eqs. (7-8):

$$\pi_s^D = [w - c - t(e_0 - e)](a - p + \eta e) - ke^2/2 \tag{7}$$

$$\pi_m^D = (p - w)(a - p + \eta e) \tag{8}$$

We thus get the formation of the two-echelon Stackelberg game model between supplier and manufacturer. In the first stage, the supplier determines its own wholesale price and emission reduction amount according to the maximization of revenue. In the second stage, the manufacturer determines the retail price according to the emission reduction amount of the supplier and the wholesale price. Then we can use the inverse inductive method to solve the problem, while the supplier would offer the optimal wholesale price as Eq. (9):

$$w^{D^*} = \frac{a+c+te_0+(\eta - t)e}{2} \tag{9}$$

The optimal retail price is computed as Eq. (10):

$$p^{D^*} = \frac{3a+c+te_0+(3\eta - t)e}{4} \tag{10}$$

Hence, we can obtain the demand of the products, the benefit of supplier and manufacturer respectively as given by Eq. (11):

$$Q^{D^*} = \frac{a-c-te_0+(t+\eta)e}{4}$$

$$\pi_s^{D^*} = \frac{[a-c-te_0+(t+\eta)e]^2 - 4ke^2}{8} \tag{11}$$

$$\pi_m^{D^*} = \frac{[a-c-t_0+(t+\eta)e]^2}{16}$$

Considering that both the supplier and the manufacturer are rational, the emission reduction of the supplier needs to meet $\pi_s^{D^*} > \pi_s^{N^*}$, which means two possibilities should be considered as given by Eqs. (12-13):

$$4k-(t+\eta)^2 > 0,\quad e > \frac{2(t+\eta)(a-c-te_0)}{4k-(t+\eta)^2} \tag{12}$$

$$4k-(t+\eta)^2 < 0,\quad 0 < e < \frac{2(t+\eta)(a-c-te_0)}{4k-(t+\eta)^2} \tag{13}$$

Then we substitute the supplier's wholesale price (Eq. 9) and the retail price (Eq. 10) into Eq. (11), calculate the first-order partial derivative and let it be zero, as $\partial\pi_m^{N^*}/\partial e = 0$, entailing that we can then obtain the optimal emission reduction e^{D^*} expressed as Eq. (14):

$$e^{D^*} = \frac{(t+\eta)(a-c-te_0)}{4k-(t+\eta)^2} \tag{14}$$

and e^{N^*} satisfies Eq. (12).

Substitute the optimal emission reductions into Eq. (11), then the demand, the revenue of supplier and the manufacturer are computed as Eq. (15):

$$\begin{aligned} Q^{D^*} &= \frac{k(a-c-te_0)}{4k-(t+\eta)^2} \\ \pi_s^{D^*} &= \frac{k(a-c-te_0)^2}{2\left[4k-(t+\eta)^2\right]} \\ \pi_m^{D^*} &= \frac{k^2(a-c-te_0)^2}{\left[4k-(t+\eta)^2\right]^2} \end{aligned} \tag{15}$$

2.2.3. Centralized decision-making when demand is related to carbon emission reduction

In the centralized decision-making mode, the supplier and the manufacturer are an integrated system. The supplier and the manufacturer jointly determine the retail price p and the carbon emission reduction e in order to maximize the revenue of the entire supply chain system. We get the revenue function of the entire supply chain as Eq. (16):

$$\pi^C = [p-c-t(e_0-e)](a-p+\eta e)-ke^2/2 \tag{16}$$

The Hessian matrix of π^C on retail price p and carbon emission reduction e is:

$$H = \begin{bmatrix} \partial^2\pi^C/\partial e^2 & \partial^2\pi^C/\partial p\partial e \\ \partial^2\pi^C/\partial p\partial e & \partial^2\pi^C/\partial p^2 \end{bmatrix} = \begin{bmatrix} 2\eta t-k & t+\eta \\ t+\eta & -2 \end{bmatrix}$$

According to $\partial^2\pi^C/\partial p^2 = -2$ and $|H| = 2k-(t+\eta)^2 > 0$, π^C is a joint concave function with respect to the retail price p and carbon emission reduction e, so there will be an optimal solution. By calculating the first-order partial derivative of Eq. (1) of the retail price p and carbon emission reduction e respectively and making the results zero, we get Eqs. (17-18):

$$\frac{\partial\pi^C}{\partial p} = a-2p+c+te_0-(t+\eta)e = 0 \tag{17}$$

$$\frac{\partial\pi^C}{\partial e} = ta+\eta c-(t+\eta)p+\eta te_0-2\eta te-ke = 0 \tag{18}$$

According to the calculating of Eqs. (17-18), the retail price P^{C^*} and carbon emission reduction e^{C^*} are computed as Eq. (19):

$$\begin{aligned} P^{C^*} &= \frac{k(a+c+te_0)-(t+\eta)(at+\eta te_0+\eta c)}{2k-(t+\eta)^2} \\ e^{C^*} &= \frac{(t+\eta)(a-c-te_0)}{2k-(t+\eta)^2} \end{aligned} \tag{19}$$

Taking P^{C^*} and e^{C^*} into demand, we get that the total demand and revenue of the whole supply chain follow Eq. (20):

$$\begin{aligned} Q^{C^*} &= \frac{k(a-c-te_0)}{2k-(t+\eta)^2} \\ \pi^{C^*} &= \frac{k(a-c-te_0)^2}{2\left[2k-(t+\eta)^2\right]} \end{aligned} \tag{20}$$

Since the supplier and the manufacturer in the supply chain are rational, they would accept the profits only if they are more than that under decentralized decision-making as Eq. (21):

$$\begin{cases} \pi_s^{C^*} > \pi_s^{D^*} \\ \pi_m^{C^*} > \pi_m^{D^*} \end{cases} \tag{21}$$

Then, the optimal wholesale price under centralized decision satisfies $w_{min} < w^{C^*} < w_{max}$, and the result of calculating is Eq. (22):

$$w_{min} = \frac{\pi_s^{D^*} + ke^2/2 + cQ^{C^*} + t\left(e_0 - e^{C^*}\right)Q^{C^*}}{Q^{C^*}}$$

$$w_{\max} = \frac{p^{C^*}Q^{C^*} - \pi_m^{D^*}}{Q^{C^*}} \tag{22}$$

The retail price is obtained by bargaining between the supplier and the manufacturer. If the manufacturer's bargaining power is named as $\alpha, (0 < \alpha < 1)$, the supplier's bargaining power is 1-α correspondingly. According to the Nash bargaining model, the problem of seeking the best w then boils down to N is Eq. (23):

$$\underset{w}{N : Max} = \left(\pi_m^{C^*} - \pi_m^{D^*}\right)^{\alpha}\left(\pi_s^{C^*} > \pi_s^{D^*}\right)^{(1-\alpha)} \tag{23}$$

which means (Eq. 24):

$$\underset{w}{N : Max} = \left[\left(p^{C^*} - w\right)Q^{C^*} - \pi_m^{D^*}\right]^{\alpha}, \left\{\left[w - c - t\left(e_0 - e^{C^*}\right)\right]Q^{C^*} - k\left(e^{C^*}\right)^2/2 - \pi_s^{D^*}\right\}^{(1-\alpha)} \tag{24}$$

Then the best solution to the retail price follows Eq. (25):

$$w = \frac{p^{C^*} - \pi_m^{D^*} - \alpha\Delta\pi}{Q^{C^*}} \tag{25}$$

According to Eq. (25), the wholesale price is negatively related to the manufacturer's bargaining power, which means the stronger the bargaining power of the manufacturer is, the lower the wholesale price given by the supplier will be. On the contrary, it will be higher. By using the Shapley method to distribute the supply chain revenue under the centralized decision, the profitability of the manufacturer and the supplier should be expressed as Eqs. (26-27):

$$\pi_s^{C^*} = \frac{\pi_s^{D^*}}{2} + \frac{\pi^{C^*} - \pi_m^{D^*}}{2} \tag{26}$$

$$\pi_m^{C^*} = \frac{\pi_m^{D^*}}{2} + \frac{\pi^{C^*} - \pi_s^{D^*}}{2} \tag{27}$$

2.3. Balance results analysis

Proposition 1: If $2k - (t+\eta)^2 > 0$ and $a - c - te_0 > 0$, when the consumer demand is related to carbon emission reduction, then the emission reduction efficiency of the supplier is increased, and the carbon reduction in production is carried out. Moreover, when the supplier and the manufacturer take a centralized decision-making, the emission reduction amount is more than decentralized. It shows that under the precondition that the government levies carbon tax, the emission reduction effect will be more effective within the cooperation between the supplier and the manufacturer in the supply chain. Thus, when the carbon tax policy is levied, the government should promote the benefits of the corporation of the entire supply chain to reduce carbon emissions.

Proposition 2: Under the decentralized decision-making mode and the centralized decision-making mode, the optimal emission reduction will decrease as the carbon emission reduction coefficient of the supplier increases; that is $\partial e^{C^*}/\partial k < 0$, $\partial e^{D^*}/\partial k < 0$.

Therefore, no matter whether the supplier cooperates with the manufacturer to reduce emissions or not, the optimal emission reductions will decrease as the supplier's emission reduction coefficient increases. This movement demonstrates that there is scale diseconomy in the process of investment in emission reduction.

Proposition 3:
When

$$4e_0\left[4k - (t+\eta)^2\right]^2 - \left[4ke_0 - e_0(t+\eta)^2 - (t+\eta)(a - c - te_0)\right] > 0$$

we can know that under decentralized decision-making mode, carbon emission of the whole supply chain will decrease; and when:

$$2e_0\left[2k - (t+\eta)^2\right]^2 - \left[2ke_0 - e_0(t+\eta)^2 - (t+\eta)(a - c - te_0)\right] > 0$$

carbon emission of the whole supply chain will decrease under the centralized decision-making mode. When under the centralized and decentralized decision, if the values of t and η are satisfied, then the carbon emissions in the supply chain under the two decision-making modes both decrease. Due to the complexity of the inequality, the numerical analysis will be verified in the next chapter.

3. Results and discussion

When the government imposes carbon tax on the supplier, the supplier will consider the cost and revenue of emission reductions to make a comparative decision. Because when the increasing consumer's demand for low-carbon products brings more revenue than the cost, the supplier will actively invest in emission reduction. Conversely, it will lack of power to do this. Therefore, the carbon tax levied on the supplier needs to be considered with consumer carbon sensitivity. Only if a proper carbon tax is levied, it will it play an incentive role in reducing emissions.

At the meantime, the companies have to face carbon tax and consumers are carbon-sensitive at the same time, so that they need make the carbon emission decision to meet the low-carbon needs of both consumers and government, as well as try to get maximum revenue.

Owing to the complexity of solving the model, to verify the model conclusion and simplify the model calculation process, we use Matlab (R2016a) as a calculation tool to solve each equation in the model. To illustrate the effect of carbon tax and carbon-sensitive coefficient on emissions reductions, it is assumed that $a=100$, $c=60$, $k=2$, $\eta=0.4$, $e_0=40$, $t=0.1$, then compare companies revenue and total revenue on the supply chain under demand related/unrelated to carbon emission or not under centralized decision-making and decentralized decision-making, as shown in Table 2. This Table shows that, when consumers' demand is related to carbon emission reduction, companies have increased the revenue of both the supplier and the manufacturer by investment in emission reduction. At the same time, Nash bargaining constrains the wholesale price and the Shapley method to allocate companies revenue under centralized decision-making, so that the profits of all parties under decentralized decision-making have been improved and the supply chain participates are coordinated. We then analyze the impact of carbon tax changing demand, supply chain revenue, emission reductions and total emissions, as shown in Figs. (1-4). We set the consumer preference as $\eta=0.4$, while the range of variation of t is 0~1. In Fig. 1, we can get that no matter consumers are carbon-sensitive or not, the demand is negatively correlated with the carbon tax. In addition, consumers have the maximum demand when they are carbon-sensitive under centralized decision-making. Meanwhile, demands under decentralized decision-making only experience minor differences in demand both related and unrelated to carbon emission reduction. In Fig. 2, the supply chain revenue are all negatively related to the carbon tax in the three game models. The revenue under centralized decision making within carbon-intensive is the highest, and when the demand is unrelated to the emission reduction, the supply chain revenue is the lowest. Therefore, the emission reduction effect within supply chain cooperation is higher than that within individual emission reduction. When the government has levied a carbon tax, we should encourage upstream and downstream companies in the supply chain to cooperate in emission reduction.

According to Figs 1-2, when the government wants to levy carbon tax to protect the environment, it should carefully decide the tax amount. That’s because if the tax is too heavy, the market will decrease badly and even the supplier and manufacturer may quit the market leading to industry decline in the long term. It illustrates in Fig. 3 that when the tax rate is low, while the level of emission reduction of supply chain rises with the increase of carbon tax. When the tax rate exceeds a certain threshold, the optimal emission reduction will decrease with the increase in carbon tax.

Table 2. Revenues of companies and entire supply chain under different decision-making mode

Revenue	***Demand unrelated to carbon emission, decentralized decision-making***	***Demand related to carbon emission, decentralized decision-making***	***Demand related to carbon emission, centralized decision-making***
π_s^*	162	167.23	213.47
π_m^*	81	86.31	132.13
π_c^*	243	253.54	345.60

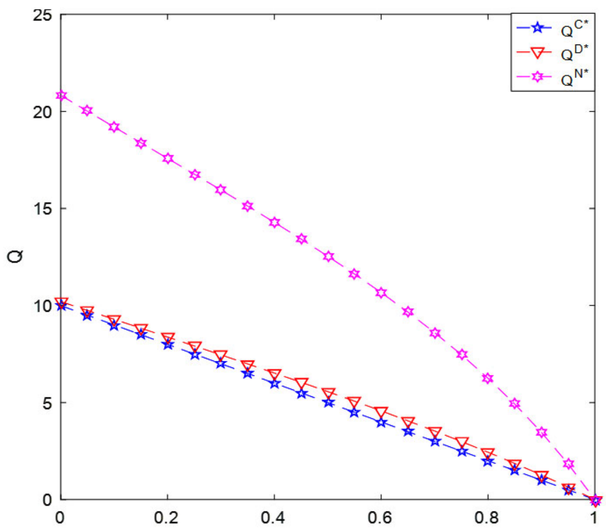

Fig. 1. Impact of carbon tax on demand

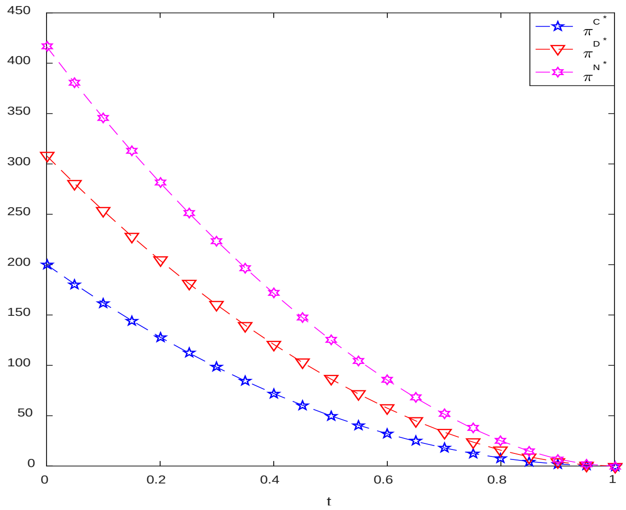

Fig. 2. Impact of carbon tax on supply chain revenue

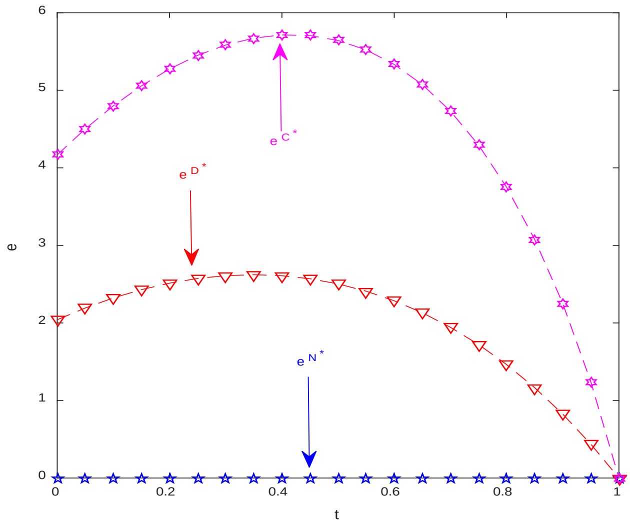

Fig. 3. Impact of carbon tax on emission reductions

In Fig. 4, it shows that the total carbon emissions under the three decision-making modes have a negative correlation to the carbon tax. When $0 < t < 0.33$, carbon emissions under decentralized decision-making within carbon-sensitive demand is larger than that within non-carbon-sensitive demand, which means that when $0 < t < 0.33$, the carbon tax rate is low and so does the carbon emission. When $0.33 < t < 1$, since the carbon tax rate rise, companies should sell more products to make up for carbon emission reduction costs and the carbon tax, while the total carbon emission is largest under centralized decision making.

Therefore, the government should not make the tax amount too low or too high when levying it because a high tax rate will decrease the enthusiasm of companies in emission reduction and a low tax rate will not achieve the purpose of emission reduction. The government needs to balance between industry and environment protection. Then we analyze the impact of the consumer changes on demand, supply chain revenue, emission reduction and total emissions, as shown in Fig. (5-8). We set carbon tax as $t = 0.5$, η range of 0 ~ 1. In Fig. 5 it is shown that, when consumers are carbon-sensitive, if carbon-sensitivity increases, the demand increases too, and will reach the top under centralized decision-making. Meanwhile, there is only a little difference of the demand under decentralized decision-making no matter the demand is related or unrelated to emission reduction.

Fig. 6 presents that when the demand is related to consumer carbon sensitivity, the supply chain revenue has a positive correlation to consumers' carbon sensitivity under both decentralized and centralized decision-making, and the revenue of the supply chain is higher under centralized rather than decentralized decision-making.

Therefore, we use Nash bargaining to restrict the wholesale price and then distribute the revenue under the centralized decision-making within the Shapley method. Hence, under decentralized decision-making, both of the supplier and the manufacturer can get more profit.

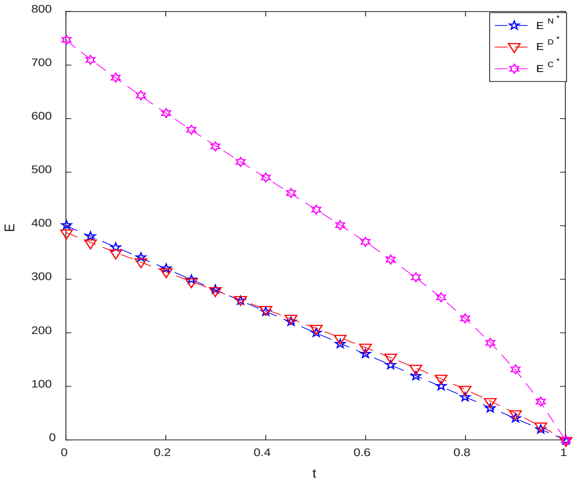

Fig. 4. Impact of carbon tax on total emissions

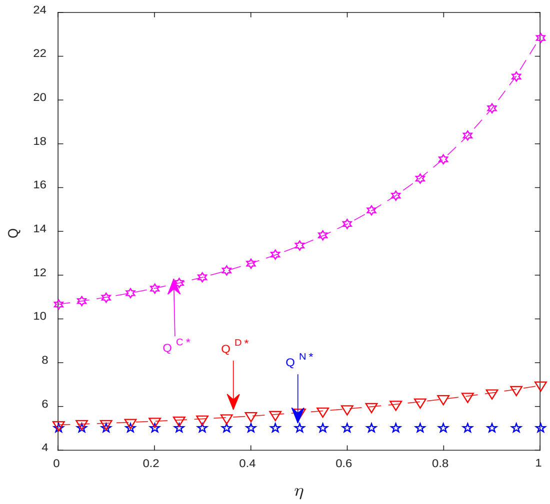

Fig. 5. Impact of consumers' carbon sensitivity differences on demand

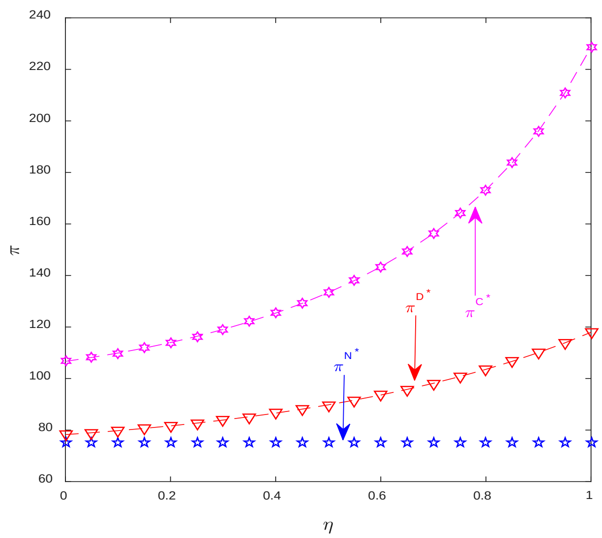

Fig. 6. Impact of consumers' carbon sensitivity differences on supply chain revenue

According to Figs. 5-6, the companies in the supply chain should improve the promotion of low-carbon products to increase consumer carbon sensitivity, then they can work together within centralized decision-making in order to sell more products and get more revenue.

In Fig. 7, we find out that with the increasing of consumer carbon sensitivity, the carbon emission reduction increases as well under both centralized decision-making mode and decentralized decision-making mode, which can be concluded that consumers' carbon sensitivity can push companies forward to reduce carbon emissions. In Fig. 8, the total carbon emissions under the three decision-making modes are positively correlated with the consumers' carbon sensitivities. Under decentralized decision-making, when $0<\eta<1$, the total carbon emissions amount within demand related to consumer carbon sensitivity is lower than demand unrelated to the sensitivity. When $\eta=1$, the level of emissions almost achieves zero. Under centralized decision-making, when $0<\eta<0.61$, the total carbon emissions amount within demand related to consumer carbon sensitivity is lower than demand unrelated to the sensitivity. When $0.61<\eta<1$, the emission is higher than the demand unrelated to carbon sensitivity, and when $\eta=1$, the carbon emission reaches the maximum value. It means that although the emission reduction increases, the increase of the consumers' carbon preference leads to the increase in sales and finally causes more emissions. Therefore, the consumer carbon sensitivity plays a vital role in carbon emission reduction of the supply chain.

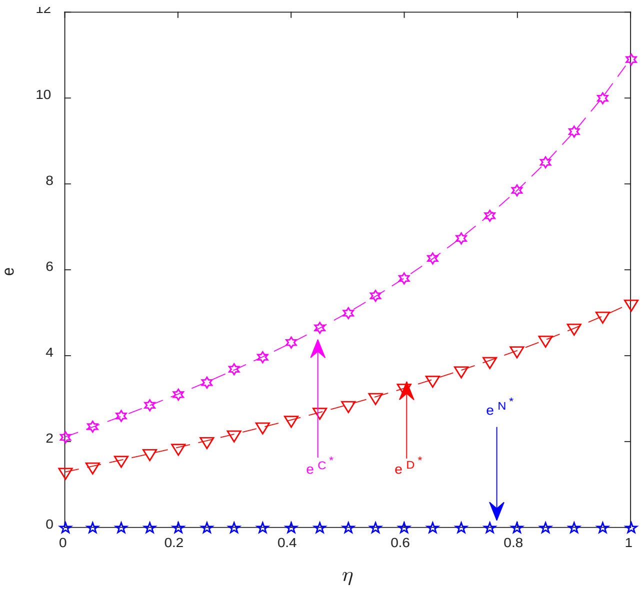

Fig. 7. Impact of consumers' carbon sensitivity differences on carbon emission reduction

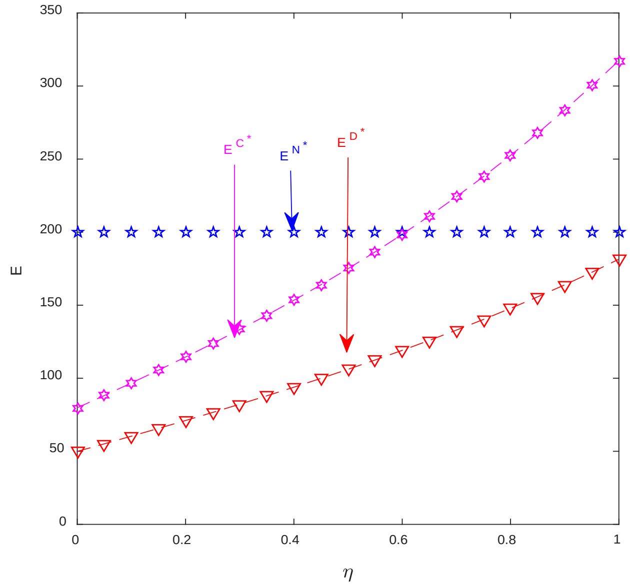

Fig. 8. Impact of consumers' carbon sensitivity differences on carbon emissions

On the basis of encouraging the supplier and the manufacturer to cooperate on emissions reduction, the government should try to keep the consumer carbon sensitivity at $0<\eta<0.61$, in order to get better environment protection.

4. Conclusions

This paper s presents the game model between the supplier and the manufacturer under the carbon tax policy and consumers' carbon-sensitive differences. By comparing the demand related or unrelated with the emission reduction under both decentralized and centralized modes of decision-making, we have provided optimal emission reduction decisions, profit decisions and optimal emissions in the supply chain within different decision-making situations.

Comparing with reviewed paper's conclusion as manufacturer's optimal carbon emissions per unit product the centralized channel, no matter whether the supply chain is coordinated or not, or when considering consumers' low-carbon preference, the retailer always has motivation to implement low-carbon promotion though without the manufacturer's incentives, we focus on more comprehensive effect by considering both carbon tax and consumer carbon sensitivity and finally, we get different conclusions by calculating the equilibrium solution and numerical analysis as below:

(1) Demand and supply chain revenue are negatively related to carbon tax, but positively related to consumers' carbon-sensitivity preferences. Besides, the demand and supply chain benefits are highest under centralized decision-making under both demand and carbon sensitivities;

(2) When demand is unrelated to carbon sensitivities, carbon tax and consumers' carbon sensitivities will not affect the emission reductions of companies. When demand is related to carbon sensitivities, emission reductions will first increase and then decrease with the carbon tax increases, meaning that emission reductions and consumer carbon sensitivity are positively correlated;

(3) When the carbon tax is considered, the total emission reductions in the supply chain decrease when $0<t<0.33$ under decentralized decision-making. Considering the carbon sensitivities of consumers, when $0<\eta<0.61$, the total emission reductions of the supply chain will increase under centralized decision-making. Therefore, the comprehensive consideration of the carbon tax and consumer carbon sensitivity is particularly important for the formulation of emission reduction strategies.

This paper is based on recognition of the reality that both the supplier and the manufacturer are risk-neutral and information symmetric. In fact, since the cost of the supplier's emission reduction investment is uncertain and affected by risk aversion, it is very difficult to realize the complete sharing of information on the supply chain, while uncertainty factors will also affect the cost and profit distribution between the supplier and the manufacturer. Therefore, considering the information uncertainty of both parties is one of the principal research directions to be taken in the future.

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We thank the support provided by the Project 691249 RUC-APS (EU H2020-MSCA-RISE-2015), National Natural Science Foundation of China: Urban Logistics Management (71390334).

Appendix

Certify of Proposition 1: If emission reduction is greater than zero, then the following inequalities would be satisfied:

$$4k-(t+\eta)^2>0,\ a-c-te_0>0,$$

which means, when

$2k-(t+\eta)^2>0$, $a-c-te_0>0$

the emission reduction is positive. From Table (1) we can get:

$$e^{N^*}=0,\ e^{D^*}=\frac{(t+\eta)(a-c-te_0)}{4k-(t+\eta)^2},\ e^{C^*}=\frac{(t+\eta)(a-c-te_0)}{2k-(t+\eta)^2}$$

Then $e^{C^*}>e^{N^*}$, $e^{D^*}>e^{N^*}$.

Since $e^{C^*}-e^{D^*}=\frac{2k}{\left[4k-(t+\eta)^2\right]\left[2k-(t+\eta)^2\right]}>0$, we can get $e^{C^*}>e^{D^*}$.

Certify of Proposition 2: Under centralized decision-making, the first-order partial derivative of optimal emission reduction e^{C^*} with respect to emission reduction coefficient k satisfies the following:

$$\partial e^{C^*}/\partial k=-2(t+\eta)(a-c-te_0)/\left[2k-(t+\eta)^2\right]$$

and we can conclude from Proposition 1 that $2k-(t+\eta)^2>0$, then obtain $\partial e^{D^*}/\partial k<0$,

$$\partial e^{C^*}/\partial k=-2(t+\eta)(a-c-te_0)/\left[2k-(t+\eta)^2\right]<0.$$

Certify of Proposition 3: When the demand is independent of carbon emissions, the carbon emissions per unit product is e_0, then the carbon emission of the whole supply of the supply chain is $E^N=e_0Q^N$; when the demand is related to carbon emissions in the decentralized decision-making mode, the total carbon emissions is $E^D=(e_0-e)Q^{D^*}$, and the emission reduction is:

$$\Delta E^D=E^N-E^D=e_0Q^N-(e_0-e)Q^{D^*}=$$
$$e_0(a-c-te_0)/4-\left[(e_0-e)k(a-c-te_0)\right]/\left[4k-(t+\eta)^2\right]$$

Then, if

$$4e_0\left[4k-(t+\eta)^2\right]^2-$$
$$\left[4ke_0-e_0(t+\eta)^2-(t+\eta)(a-c-te_0)\right]>0$$

we can get $\Delta E^D=E^N-E^D>0$.

Also, in centralized decision-making mode, we can obtain:

$$\Delta E^C=E^N-E^C=e_0Q^N-(e_0-e)Q^{C^*}=$$
$$e_0(a-c-te_0)/4-\left[(e_0-e)k(a-c-te_0)\right]/\left[2k-(t+\eta)^2\right]$$

If

$$2e_0\left[2k-(t+\eta)^2\right]^2-$$
$$\left[2ke_0-e_0(t+\eta)^2-(t+\eta)(a-c-te_0)\right]>0$$

we can conclude that the emission under the centralized decision is reduced.

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