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Carbon Reduction Technology Investment of Supply Chain under Quota Trading and Government Subsidy

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This paper aims to improve government and enterprise decision-making on emission reduction. Focusing on the carbon emission reduction (CER) technology investment of manufacturers and the cost sharing of retailers, the government policies on carbon quota, carbon trading and emission reduction subsidy were taken into consideration. The game theory was adopted to build an expected profit model between the retailer and the manufacturer, and the impacts of the government policies on four decision-making scenarios for emission reduction, namely, decentralized decision-making, cooperative game, centralized decision-making and social planning. Through modelling, comparative analysis and parametric sensitivity analysis, it is concluded that the CER level, the optimal order quantity and the optimal social benefit are highest under social planning, followed by centralized decision-making, decentralized decision-making and cooperative game. The research findings shed new light on energy conservation and emission reduction in two-level supply chain.

1. Introduction

Global warming, a common challenge to the world, concerns the survival and development of mankind. To solve the problem, the Kyoto Protocol was adopted in 1997 to control greenhouse gas emissions through the concerted efforts of countries around the world. Since then, some countries have stepped up their efforts on energy conservation and emission reduction, while some have laid down a series of policies to support low-carbon development and emission reduction among enterprises. These efforts and policies have won an active response from the enterprises. Much research has been done on the carbon emission reduction (CER) behaviours of the supply chain in the low-carbon environment. For instance, Liu et al. (2012) suggested that enterprises on a two-level low-carbon supply chain generally invest a lot on emission reduction technologies. Jaber et al. (2013) investigated the cooperative emission reduction in a two-level supply chain. Luo et al. (2014) discussed the effect of consumer carbon footprint on optimal decision-making after modelling the decentralized, centralized and cooperative decision-making processes of supply chain enterprises. Yang and Wang (2016) constructed a Stackelberg game model to analyse the economic effect of supply chain emission reduction under three conditions. Based on low carbon preference of consumers, Wang and Zhao (2014) examined the optimal decision-making of supply chain members. Zhang et al. (2015) created a game model for cooperative emission reduction in supply chain and applied the model to analyse the optimal emission reduction under carbon tax. From the angle of carbon tax, Yang et al. (2016) probed into the optimal decision-making of CER among supply chain enterprises. Meng (2010) explored the impact of government subsidy on emission reduction, considering exogenous carbon emission tax. Cao et al. (2013) verified the effectiveness of government subsidy and enterprise cooperation with a game model between government and enterprises. Gong and Zhou (2013) identified the most cost-effective decision-making behaviours of enterprises on the purchase of carbon quota. Yang and Yu (2016) proposed and solved a game model of two-level low-carbon supply chain, laying the basis for determining the optimal emission reduction rate. To improve government and enterprise decision-making, this paper targets the emission reduction technology investment of manufacturers and the cost sharing of retailers, considering the government policies on carbon quota, carbon trading and emission reduction subsidy.

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2. Problem description and hypotheses

It is assumed that the low-carbon supply chain consists of only one manufacturer and one retailer, the carbon trading price is determined by exogenous variables in the carbon market, and the unit carbon emission at the current technology level is constant. Besides, the manufacturer produces products at the unit cost of c_m, while the retailer purchases the intermediate products from the manufacturer at the wholesale price of p_m according to the market demand. The quantity of the purchased products is denoted as q, and the production cost of these products is denoted as c_d. There is no overstock or understock. In addition, the consumers are willing to buy low-carbon products if the retail price is $p_d = a + \alpha - bq$ (a>0, b>0 and a>c_m). To support the emission reduction among enterprises, the government grants them a certain amount of carbon quota g_m, allows them to trade the quota at the unit price of pc, and subsidizes their investment on emission reduction technologies at the rate of*t*. Considering the consumers' preference to low-carbon products and the $g_m p_c$ introduction of carbon trading system, the manufacturer is more inclined to produce low-carbon products, increase investment in emission reduction technologies. The unit initial carbon emissions and the unit CER are denoted as e_m and Δe_m, respectively. Theemission reduction technology investment is a function of CER $C(\Delta e_m) = \frac{\beta \Delta {e_m}^2}{2}$, C' $(\Delta e_m) \geqslant 0$with β (β>0) is the emission reduction cost coefficient.

3. Model analysis of emission reduction technology investment

There are four different decision-making scenarios for CER technology investment of supply chain enterprises: decentralized decision-making, the cooperative game, centralized decision-making and social planning.

3.1 Model of decentralized decision-making

Under decentralized decision-making, the manufacturer and the retailer make their own decisions to maximize their own profits. The decision-making process is as follows: the government determines the subsidy rate for emission reduction; the manufacturer determines the wholesale price and the CER level; the retailer determines the order quantity. The three-stage process was discussed below by backward induction.
In the third stage, the retailer determines the order quantity based on the market demand and the wholesale price p_m to maximize its profit. The retailer's strategy can be expressed as:

$$p_m max \pi_d = [p_d - (p_m + c_d)]q \tag{1}$$

The optimal order quantity is:

$$q = \frac{A + c_m - p_m}{2b} \tag{2}$$

where$A = a + \alpha - c_m - c_d$.

In the second stage, the manufacture makes the decision $(p_m, \Delta e_m)$ to maximize its profit. The manufacturer's strategy can be expressed as:

$$p_m \max_{p_m, \Delta e_m} \pi_m = (p_m - c_m)q + p_c[g_m - (e_m - \Delta e_m)]q - \frac{1}{2}(1-t)\beta {\Delta e_m}^2 \tag{3}$$

Substituting equation (2) into equation (3), the optimal wholesale price can be derived from the first-order optimal condition:$p_m = \frac{A + 2c_m - p_c(g_m - e_m + \Delta e_m)}{2}$,the optimal CER level $\Delta e_m = \frac{p_c(A + p_c g_m - p_c e_m)}{4b\beta(1-t) - {p_c}^2}$.
In the first stage, the government determines the subsidy rate for CER investment to maximize the social benefit. The government's strategy can be expressed as:

$$maxG = \frac{1}{2}bq^2 + \pi_m + \pi_d - \frac{1}{2}t\beta {\Delta e_m}^2 \tag{4}$$

Substituting equation (5) into equations (1), (2), (3), (4) and (6), the optimal strategy for social benefit can be derived from the first-order optimal condition. Thus, it is possible to put forward Proposition 1.

Proposition 1: Under decentralized decision-making, the maximum social benefit is the goal of setting the subsidy rate for CER investment. If$0 < 7{p_c}^2 < 16b\beta$, the optimal values of relevant parameters are as follows:

The optimal subsidy rate for CER investment ${t_1}^* = \frac{3}{7}$,the optimal CER level ${\Delta e_{m1}}^* = \frac{7p_c(A + p_c g_m - p_c e_m)}{16b\beta - 7{p_c}^2}$,the optimal wholesale price: ${p_{m1}}^* = \frac{8b\beta[A + 2c_m - p_c(g_m - e_m)] - 7{p_c}^2(A + c_m)}{16b\beta - 7{p_c}^2}$, and the optimal order quantity ${q_1}^* = \frac{4\beta(A + p_c g_m - p_c e_m)}{16b\beta - 7{p_c}^2}$.

The manufacturer's profit $\pi_{m1}{}^* = \frac{2\beta(A+p_c g_m - p_c e_m)^2}{16b\beta - 7p_c{}^2}$,The retailer's profit $\pi_{d1}{}^* = \frac{16b\beta^2(A+p_c g_m - p_c e_m)^2}{(16b\beta - 7p_c{}^2)^2}$,the supply chain profit $\pi_{T1}{}^* = \frac{(48b\beta^2 - 14\beta p_c{}^2)(A+p_c g_m - p_c e_m)^2}{(16b\beta - 7p_c{}^2)^2}$,and the social benefit $G_1{}^* = \frac{7\beta(A+p_c g_m - p_c e_m)^2}{2(16b\beta - 7p_c{}^2)}$.

The following conclusion can be drawn from Proposition 1:

Conclusion 1: When CER cost coefficient and carbon trading price remain constant, both the CER level and order quantity increase with carbon quota, while the wholesale price decreases. When the carbon quota and carbon trading price remain constant, the CER level is negatively correlated with the CER cost coefficient.

3.2 Model of cooperative game

Under the cooperative game, the manufacturer and the retailer look for cooperation in that the CER investment cost is partially allocated to the retailer at the ratio of k. The decision-making process is as follows: the government determines the subsidy rate for emission reduction investment; the retailer determines the cost-sharing ratio; the manufacturer determines the wholesale price and the CER level; the retailer determines the order quantity. The four-stage process was discussed below by backward induction.

In the fourth stage, the retailer determines the order quantity based on the market demand and the wholesale price$p_m$to maximize its profit. The retailer's strategy can be expressed as:

$$p_m max \pi_d = [p_d - (p_m + c_d)]q - \frac{1}{2}k(1-t)\beta \Delta e_m{}^2 \quad (5)$$

The optimal order quantity is $q = \frac{A+c_m-p_m}{2b}$

In the third stage, the manufacture makes the decision ($p_m, \Delta e_m$) to maximize its profit. The manufacturer's strategy can be expressed as:

$$\max_{p_m, \Delta e_m} \pi_m = (p_m - c_m)q + p_c[g_m - (e_m - \Delta e_m)]q - \frac{1}{2}(1-k)(1-t)\beta \Delta e_m{}^2 \quad (6)$$

The optimal wholesale price can be derived from the first-order optimal condition:$p_m = \frac{A+2c_m - p_c(g_m - e_m + \Delta e_m)}{2}$, the optimal CER level $\Delta e_m = \frac{p_c(A+p_c g_m - p_c e_m)}{4b\beta(1-k)(1-t) - p_c{}^2}$.

In the second stage, the retailer determines the cost-sharing ratio of the CER investment to maximize its own profit.

In the first stage, the government determines the subsidy rate for CER investment to maximize the social benefit. The government's strategy can be expressed as:

$$maxG = \frac{1}{2}bq^2 + \pi_m + \pi_d - \frac{1}{2}t\beta \Delta e_m{}^2 \quad (7)$$

The optimal strategy for social benefit can be derived from the first-order optimal condition. Thus, it is possible to put forward Proposition 2.

Proposition 2: Under cooperative game, the maximum social benefit is the goal of setting the subsidy rate for CER investment. If $0 < 7p_c{}^2 < 16b\beta$, the optimal values of relevant parameters are as follows:

The optimal subsidy rate for CER investment $t_2{}^* = \frac{24b\beta - 7p_c{}^2}{56b\beta}$,the optimal cost-sharing ratio $k_2{}^* = \frac{7p_c{}^2}{32b\beta + 7p_c{}^2}$, the optimal CER level $\Delta e_{m2}{}^* = \frac{7p_c(A+p_c g_m - p_c e_m)}{16b\beta - 7p_c{}^2}$,the optimal wholesale price $p_{m2}{}^* = \frac{8b\beta[A+2c_m - p_c(g_m - e_m)] - 7p_c{}^2(A+c_m)}{16b\beta - 7p_c{}^2}$,and the optimal order quantity $q_2{}^* = \frac{4\beta(A+p_c g_m - p_c e_m)}{16b\beta - 7p_c{}^2}$.

The manufacturer's profit $\pi_{m2}{}^* = \frac{2\beta(A+p_c g_m - p_c e_m)^2}{16b\beta - 7p_c{}^2}$,the retailer's profit $\pi_{d2}{}^* = \frac{(16b\beta + 7p_c{}^2)(A+p_c g_m - p_c e_m)^2}{16b(16b\beta - 7p_c{}^2)}$,the supply chain profit $\pi_{T2}{}^* = \frac{(48b\beta + 7p_c{}^2)B^2}{16b(16b\beta - 7p_c{}^2)}$, and the social benefit $G_2{}^* = \frac{7\beta(A+p_c g_m - p_c e_m)^2}{2(16b\beta - 7p_c{}^2)}$

The following conclusion can be drawn from Proposition 2:

Conclusion 2: When CER cost coefficient and carbon trading price remain constant, both the CER level and order quantity increase with carbon quota, while the wholesale price decreases. When the carbon quota and carbon trading price remain constant, the cost-sharing ratio and CER level are negatively correlated with the CER cost coefficient.

3.3 Model of centralized decision-making

Under centralized decision-making, the manufacturer and the retailer aim to maximize the overall profit of the supply chain. The decision-making process is as follows: the government determines the subsidy rate for emission reduction; the supply chain enterprises determine the CER level and the order quantity. The two-

stage process was discussed below by backward induction.
In the second stage, the order quantity q and the CER level Δe_m are the bases for decision-making. The strategy of the two enterprises can be expressed as:

$$max\pi_T = \pi_m + \pi_d = [p_d - (c_m + c_d)]q + p_c[g_m - (e_m - \Delta e_m)]q - \frac{1}{2}(1-t)\beta\Delta e_m{}^2 \quad (8)$$

Find the partial derivatives of$q$andΔe_maccording to equation (9). Then, the following equations can be derived from the first-order optimal condition:

$$\frac{\partial\pi_T}{\partial q} = A - 2bq + p_c(g_m - e_m) + p_c\Delta e_m = 0 \quad (9)$$

$$\frac{\partial\pi_T}{\partial\Delta e_m} = p_c q - \beta(1-t)\Delta e_m = 0 \quad (10)$$

Then, the optimal CER level $\Delta e_m = \frac{p_c(A+p_c g_m - p_c e_m)}{2b\beta(1-\mathrm{t})-p_c{}^2}$,the optimal order quantity $q = \frac{\beta(1-t)(A+p_c g_m - p_c e_m)}{2b\beta(1-\mathrm{t})-p_c{}^2}$.
In the first stage, the government determines the subsidy rate for CER investment to maximize the social benefit. The government's strategy can be expressed as:

$$maxG = \frac{1}{2}bq^2 + \pi_T - \frac{1}{2}t\beta\Delta e_m{}^2 \quad (11)$$

We can obtain the optimal strategy for social benefit according to the first-order optimal condition. Thus, it is possible to put forward Proposition 3.
Proposition 3: Under centralized decision-making, the maximum social benefit is the goal of setting the subsidy rate for CER investment. If $0 < 3p_c{}^2 < 4b\beta$, the optimal values of relevant parameters are as follows:
The optimal subsidy rate for CER investment$t_3{}^* = \frac{1}{3}$,the optimal CER level $\Delta e_{m3}{}^* = \frac{3p_c(A+p_c g_m - p_c e_m)}{4b\beta-3p_c{}^2}$,the optimal order quantity $q_3{}^* = \frac{2\beta(A+p_c g_m - p_c e_m)}{4b\beta-3p_c{}^2}$.The supply chain profit $\pi_{T3}{}^* = \frac{\beta(A+p_c g_m - p_c e_m)^2}{4b\beta-3p_c{}^2}$, the social benefit $G_3{}^* = \frac{3\beta(A+p_c g_m - p_c e_m)^2}{2(4b\beta-3p_c{}^2)}$.
The following conclusion can be drawn from Proposition 3:
Conclusion 3: When CER cost coefficient and carbon trading price remain constant, both the CER level and order quantity increase with carbon quota, while the wholesale price decreases. When the carbon quota and carbon trading price remain constant, the CER level is negatively correlated with the CER cost coefficient.

3.4 Model of social planning

Under social planning, the manufacturer and the retailer aim to achieve the best social benefit through implementing CER activities. In other words, the two enterprises pursue the optimal social benefit in their decisions on order quantity q and the CER level Δe_m.The strategy of the two enterprises can be expressed as:

$$e_m max\pi = [p_d - (c_m + c_d)]q + p_c[g_m - (e_m - \Delta e_m)]q - \frac{1}{2}(1-t)\beta\Delta e_m{}^2 \quad (12)$$

$$maxG = \frac{1}{2}bq^2 + \pi - \frac{1}{2}t\beta\Delta e_m{}^2 \quad (13)$$

Find the partial derivatives of$q$ and Δe_m according to equation (13). Then, the following equations can be derived from the first-order optimal condition:

$$\frac{\partial G}{\partial q} = A - bq + p_c(g_m - e_m) + p_c\Delta e_m = 0 \quad (14)$$

$$\frac{\partial G}{\partial\Delta e_m} = p_c q - \beta\Delta e_m = 0 \quad (15)$$

The optimal solution can be determined by solving two equations. The solution is summed up as Proposition 4.
Proposition 4: $p_c{}^2$Under social planning, the maximum social benefit is the goal of both the manufacture and the retailer. If$0 < p_c{}^2 < b\beta$, the optimal values of relevant parameters are as follows:
The optimal CER level $\Delta e_{m4}{}^* = \frac{p_c(A+p_c g_m - p_c e_m)}{b\beta-p_c{}^2}$,the optimal order quantity $q_4{}^* = \frac{\beta(A+p_c g_m - p_c e_m)}{b\beta-p_c{}^2}$,the supply chain profit $\pi_{T4}{}^* = -\frac{\beta p_c{}^2(A+p_c g_m - p_c e_m)^2}{2(b\beta-p_c{}^2)^2}$, and the social benefit $G_4{}^* = \frac{\beta(A+p_c g_m - p_c e_m)^2}{2(b\beta-p_c{}^2)}$.
The following conclusion can be drawn from Proposition 4:
Conclusion 4: When CER cost coefficient and carbon trading price remain constant, both the CER level and order quantity increase with carbon quota, while the wholesale price decreases. When the carbon quota and carbon trading price remain constant, the CER level is negatively correlated with the CER cost coefficient.

4. Comparative Analysis

To disclose the utility differences among the above four different decision-making scenarios, the optimal solutions of these scenarios were subjected to comparative analysis. Under $0 < p_c{}^2 < b\beta$ and $B = A + p_c g_m - p_c e_m$, we have the following proposition:

Proposition 5: When $16b\beta < 21p_c{}^2$, the four scenarios can be ranked in descending order below by the government subsidy: decentralized decision-making, centralized decision-making, social planning and cooperative game; when $16b\beta > 21p_c{}^2$, the ranking can be expressed as: decentralized decision-making, cooperative game, social planning and centralized decision-making. In other words, if $16b\beta < 21p_c{}^2$,then $t_1{}^* > t_3{}^* > t_2{}^*$; if $16b\beta > 21p_c{}^2$, then $t_1{}^* > t_2{}^* > t_3{}^*$.

Proof: $t_1{}^* = \frac{3}{7} = \frac{24b\beta}{56b\beta} > t_2{}^* = \frac{24b\beta-7p_c{}^2}{56b\beta}$, and $t_1{}^* = \frac{3}{7} > t_3{}^* = \frac{1}{3}, \frac{t_2{}^*}{t_3{}^*} = \frac{72b\beta-21p_c{}^2}{56b\beta} = 1 + \frac{16b\beta-21p_c{}^2}{56b\beta}$

If $16b\beta < 21p_c{}^2, \frac{t_2{}^*}{t_3{}^*} < 1$, then $t_2{}^* < t_3{}^*$; If $16b\beta > 21p_c{}^2, \frac{t_2{}^*}{t_3{}^*} > 1$, then $t_2{}^* > t_3{}^*$.

Hence, if $16b\beta < 21p_c{}^2$, then $t_1{}^* > t_3{}^* > t_2{}^*$; if $16b\beta > 21p_c{}^2$, then $t_1{}^* > t_2{}^* > t_3{}^*$.Q.E.D.

Proposition 6: The CER level is the highest under social planning, followed by that under centralized decision-making, decentralized decision-making and cooperative game. In other words, $\Delta e_{m4}{}^* > \Delta e_{m3}{}^* > \Delta e_{m1}{}^* = \Delta e_{m2}{}^*$.

Proof: Since $\Delta e_{m4}{}^* - \Delta e_{m3}{}^* = \frac{p_c B}{b\beta-p_c{}^2} - \frac{3p_c B}{4b\beta-3p_c{}^2} = \frac{b\beta p_c B}{(b\beta-p_c{}^2)(4b\beta-3p_c{}^2)} > 0$, we have $\Delta e_{m4}{}^* > \Delta e_{m3}{}^*$

Whereas $\Delta e_{m3}{}^* - \Delta e_{m1,2}{}^* = \frac{3p_c B}{4b\beta-3p_c{}^2} - \frac{7p_c B}{16b\beta-7p_c{}^2} = \frac{20b\beta p_c B}{(4b\beta-3p_c{}^2)(16b\beta-7p_c{}^2)} > 0$,

Thus, $\Delta e_{m3}{}^* > \Delta e_{m1,2}{}^*$, Therefore, $\Delta e_{m4}{}^* > \Delta e_{m3}{}^* > \Delta e_{m1}{}^* = \Delta e_{m2}{}^*$. Q.E.D.

Proposition 7: The optimal order quantity is the highest under social planning, followed by that under centralized decision-making, decentralized decision-making and cooperative game. In other words, $q_4{}^* > q_3{}^* > q_1{}^* = q_2{}^*$.

Proof: Since $q_4{}^* - q_3{}^* = \frac{\beta B}{b\beta-p_c{}^2} - \frac{2\beta B}{4b\beta-3p_c{}^2} = \frac{\beta(2b\beta-p_c{}^2)B}{(b\beta-p_c{}^2)(4b\beta-3p_c{}^2)} > 0$, we have $q_4{}^* > q_3{}^*$

Since $q_3{}^* - q_{1,2}{}^* = \frac{2\beta B}{4b\beta-3p_c{}^2} - \frac{4\beta B}{16b\beta-7p_c{}^2} = \frac{2\beta(8b\beta-p_c{}^2)B}{(4b\beta-3p_c{}^2)(16b\beta-7p_c{}^2)} > 0$, we have $q_3{}^* > q_{1,2}{}^*$.

Therefore, $q_4{}^* > q_3{}^* > q_1{}^* = q_2{}^*$.Q.E.D.

Proposition 9: The supply chain profit is the highest under centralized decision-making, followed by that under decentralized decision-making, cooperative game and social planning. In other words, $\pi_{T3}{}^* > \pi_{T1}{}^* > \pi_{T2}{}^* > \pi_{T4}{}^*$.

Proof: Since $\frac{\pi_{T1}{}^*}{\pi_{T3}{}^*} = \frac{\frac{(48b\beta^2-14\beta p_c{}^2)B^2}{(16b\beta-7p_c{}^2)^2}}{\frac{\beta B^2}{4b\beta-3p_c{}^2}} = \frac{192b^2\beta^2-200b\beta p_c{}^2+42p_c{}^4}{(16b\beta-7p_c{}^2)^2}$ and $b, \beta > 0$, we have

$\frac{192b^2\beta^2-200b\beta p_c{}^2+42p_c{}^4}{(16b\beta-7p_c{}^2)^2} < \frac{192b^2\beta^2-180b\beta p_c{}^2+42p_c{}^4}{(16b\beta-7p_c{}^2)^2} = \frac{(16b\beta-7p_c{}^2)(12b\beta-6p_c{}^2)}{(16b\beta-7p_c{}^2)^2} = \frac{12b\beta-6p_c{}^2}{16b\beta-7p_c{}^2}$.

Since $(12b\beta - 6p_c{}^2) - (16b\beta - 7p_c{}^2) = p_c{}^2 - 4b\beta < 0$, we have $\frac{12b\beta-6p_c{}^2}{16b\beta-7p_c{}^2} < 1$. Thus, $\frac{192b^2\beta^2-200b\beta p_c{}^2+42p_c{}^4}{(16b\beta-7p_c{}^2)^2} < 1$, and $\pi_{T3}{}^* > \pi_{T1}{}^*$.

Since $\pi_{T1}{}^* - \pi_{T2}{}^* = \frac{(48b\beta^2-14\beta p_c{}^2)B^2}{(16b\beta-7p_c{}^2)^2} - \frac{(48b\beta+7p_c{}^2)B^2}{16b(16b\beta-7p_c{}^2)} = \frac{(27b\beta+49p_c{}^2)p_c{}^2B^2}{16b(16b\beta-7p_c{}^2)^2} > 0$, we have $\pi_{T1}{}^* > \pi_{T2}{}^*$ and $\pi_{T4}{}^* = -\frac{\beta p_c{}^2 B^2}{2(b\beta-p_c{}^2)^2} < 0$. Therefore, $\pi_{T3}{}^* > \pi_{T1}{}^* > \pi_{T2}{}^* > \pi_{T4}{}^*$. Q.E.D.

Proposition 9: The social benefit is the highest under social planning, followed by centralized decision-making, decentralized decision-making and cooperative game. In other words, $G_4{}^* > G_3{}^* > G_1{}^* = G_2{}^*$.

Proof: Since $\frac{G_4{}^*}{G_3{}^*} = \frac{\frac{\beta B^2}{2(b\beta-p_c{}^2)}}{\frac{3\beta B^2}{2(4b\beta-3p_c{}^2)}} = \frac{4b\beta-3p_c{}^2}{3b\beta-3p_c{}^2} > 1$, we have $G_4{}^* > G_3{}^*$ .Since $\frac{G_3{}^*}{G_{1,2}{}^*} = \frac{\frac{3\beta B^2}{2(4b\beta-3p_c{}^2)}}{\frac{7\beta B^2}{2(16b\beta-7p_c{}^2)}} = \frac{48b\beta-21p_c{}^2}{28b\beta-21p_c{}^2} > 1$, we have $G_3{}^* > G_{1,2}{}^*$.Therefore, $G_4{}^* > G_3{}^* > G_1{}^* = G_2{}^*$.Q.E.D.

5. Parametric Sensitivity Analysis

The decision-making of supply chain enterprises hinges on carbon quota, carbon trading price and CER cost coefficient. Based on the previous studies, the values of the relevant parameters are configured as follows: $a = 100, \alpha = 3, b = 5, c_m = 4.5$, $c_d = 3$ and $e_m = 2.3$. With these parameters, a parametric sensitivity analysis was performed, and the results are recorded in Figure 1.

As shown in Figure 1, in all four decision-making scenarios, the optimal emission reduction level $\Delta e_m{}^*$ decreases with the increase in CER cost coefficient β when $\Delta e_{m4}{}^* > \Delta e_{m3}{}^* > \Delta e_{m1}{}^* = \Delta e_{m2}{}^*$,and increases with $\Delta e_m{}^*$ carbon trading price P_c and carbon quota g_m when $\Delta e_{m4}{}^* > \Delta e_{m3}{}^* > \Delta e_{m1}{}^* = \Delta e_{m2}{}^*$.

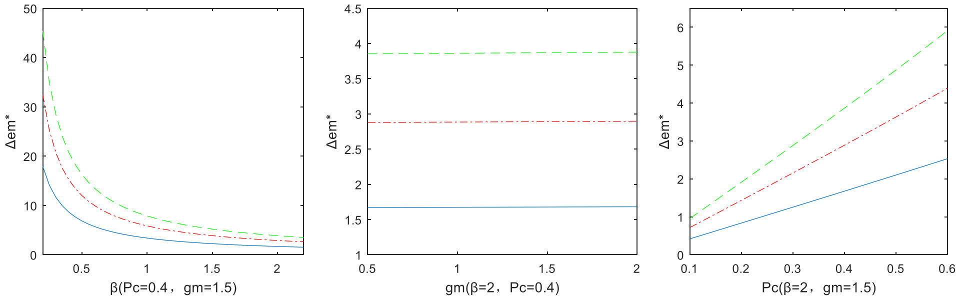

Figure 1: Parametric sensitivity analysis

6. Conclusions

Based on carbon quota, carbon trading and subsidy for emission reduction, this paper constructs an expected profit model between the retailer and the manufacturer under four decision-making scenarios. The modelling results show that the CER level, the optimal order quantity and the optimal social benefit are highest under social planning, followed by centralized decision-making, decentralized decision-making and cooperative game. When the unit carbon quota is below a certain threshold, the optimal supply chain profit is the highest under decentralized decision-making, followed by cooperative game, centralized decision-making and social planning. Under social planning, the optimal supply chain profit is always negative. When the unit carbon quota is above a certain threshold, the optimal supply chain profit is the highest under centralized decision-making, followed by decentralized decision-making, cooperative game and social planning. Under social planning, the optimal supply chain profit is always negative. In addition, the optimal CER level is negatively correlated with the CER cost coefficient and positively with the unit carbon quota under all four decision-making scenarios.

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