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A Decision Support System for Joint Emission Reduction Investment and Pricing Decisions with Carbon Emission Trade

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Abstract

Carbon emission trade is one of the most common carbon emission regulation policies, manufactures must take measures to cope with this new situation. This paper dedicated to design a decision support system (DSS) based on our proposed model. We examined the manufacture's joint emission reduction effort and pricing decisions with carbon emission trade. We formulate this problem as a stackelberg game, the manufacture is leader, the retailer is follower, the optimal emission reduction effort and pricing decisions are derived. The impact of carbon emission trade on these decisions and profits is also investigated. A numerical example is also provided to verify our model and findings. We found that manufactures will invest to reduce emission and increase their wholesale price compared with the situation without carbon emission trade. A decision support system (DSS) integrating the proposed model and the analysis is developed as an efficient decision tool to help manufactures and retailers to optimize their decision. The visualized outputs of DSS allow the decision makers to gain better understanding the impact of carbon emission trade on decisions, facilitating their decision making process in carbon economics era.

Keywords: *Carbon emission trade; Stackelberg game; pricing decision; emission reduction effort; decision support system*

1. Introduction

Nowadays manufactures face different carbon emission regulation policies such as strict carbon caps, carbon tax, carbon emission trade, and carbon offsets. Carbon emission trade is one of the most common policies. Under this new competitive environment, manufactures must incorporate these carbon emission regulation policies into their strategic and operational decisions, for example facility location, technology selection, inventory, sourcing, pricing and routing.

In this paper we will focus on a supply chain consisting of a manufacture and a retailer, the manufacture will decide what extent of emission reduction effort he should make and the wholesale price. To the best our knowledge, there is no paper address this problem. Based on our model and analysis, we design a decision support system (DSS) for manufactures and retailers, which can help manufactures and retailers to optimize their decisions. To the best our knowledge, there is also no this kind type of DSS at present.

Our work is related to the carbon emission trade. Carbon emission trade means that a firm is allocated a carbon emission quota, if his carbon emission is higher than this quota, then he should buy carbon trust from a carbon trade market, otherwise, he can sell his surplus quota to a carbon trade market. There are some researches on this topic. Some papers dealt with

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strategic decisions in a supply chain with carbon emission trade. Chaabane et al. (2012) introduced a mixed-integer linear programming based framework for sustainable supply chain design under the emission trading scheme. Diabat et al. (2013) examined a multiechelon multicommodity closed-loop facility location problem with carbon emissions trade, model and algorithm were provided. Cachon (2014) discusses the impact of the new objective of reducing carbon footprints on supply chain operations and structures. Other papers examined operational decisions. Hua et al. (2011) examined how firms manage carbon footprints in inventory management with carbon emission trade, derived the optimal order sizing, and anal sized the impact of carbon emission trade on the decision, numerical experiment were conducted and managerial insights were presented. Hua et al. (2011) studied the optimal order lot sizing and pricing with carbon trade based on the EOQ model, and examined the impact of the carbon emission trade on the order lot sizing and pricing, some numerical examples were presented to show the managerial insights. Benjaafar et al. (2013) showed how carbon emission concerns could be integrated into operational decision-making using relatively simple and widely used models. Asbi et al. (2013) introduced carbon emission constraints, i.e., carbon emission trade, in multisourcing lot-sizing problems. Four types of constraints are proposed and analyzed in the single-item uncapacitated lot-sizing problem.

Our work is also related to the literature on emission reduction investment. The literature on this topic is sparse. Toptal et al. (2014) examined the joint decisions on inventory replenishment and emission reduction investment under different emission regulations, including cap-and-trade (i.e., carbon emission trade). Huang and Rust (2011) examined the implications of the three pillars of sustainability (environment, economy and social justice) on consumption in a wealthy country, the correlation between investment and carbon emission reduction was presented. Jiang and Klabjan (2012) studied joint production capacity and investment decisions with stochastic demand under command-and-control and market-based regulations such as carbon tax and cap-and- trade.

Our work is related to the literature on designing a decision support system for the optimal decisions under carbon emission policies. Mattiussi et al (2014) presented a framework for an energy supply decision support system (DSS) for sustainable plant design and production using multi-objective and multi-attribute decision-making modelling together with impact assessment of the emission outputs. Hunt et al (2013) proposed a new integrated tool and decision support framework for complex problems resulting from the interaction of many multi-criteria issues, and they applied this DSS to UK energy sector. Chang (2014) modelled the planning and coordination of hybrid renewable energy systems in uncertain environments and developed an efficient heuristic to solve their model, and developed a decision support system integrating their proposed model and the heuristic as an efficient decision tool to enable effective and efficient energy management of hybrid renewable energy systems. Based on a framework for integrated sustainability modelling and reporting, Ahmed and Sundaram (2012) proposed and implemented a generic sustainable business transformation roadmap, which leverages system dynamics, workflow modelling and adaptable system concepts.

There are other papers similar to this topic. Krishnan et al. (2004) examined the coordinating contracts for decentralized supply chains with retailer promotional effort. Wu (2013) investigated the bargaining equilibrium behavior of an industry with two competing supply chains with price and promotional effort dependent demand. De & Sana (2013) examined the backlogging EOQ model for promotional effort and selling price sensitive demand using an intuitionistic fuzzy approach. Giri, Bardhan & Maiti (2013) investigated the method to coordinate a two-echelon supply chain through different contracts under price and promotional effort-dependent demand.

The rest of this paper is organized as follows. Section 2 presents the retailer and manufacture's model, and derives the optimal emission reduction effort and pricing decisions. Section 3 is dedicated to the impact of carbon emission trade on the above decisions. A numerical example is presented in Section 4. And Section 5 is dedicated to developing a decision support system for decision makers, and Section 6 concludes the paper.

2. The Model

In this section, we consider a supply chain consisting of a manufacture and a retailer, the manufacture should decide the optimal emission reduction investment and wholesale price, the retailer should decide his retail price, please refer to Figure 1. We formulate this problem as a stackelberg game, i.e., the manufacture is the leader, the retailer is the follower.

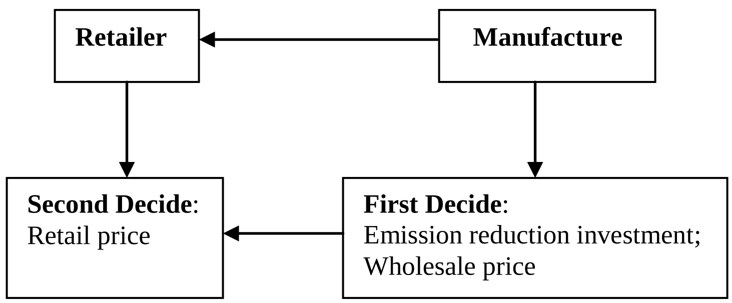

Figure 1. The Decision Sequence

2.1. Assumptions and Notation

C_0: the original carbon footprints of unit product;

α^0 : the carbon emission quota;

Q: the manufacture's carbon emission;

c: the production cost of unit product;

p^C : the carbon price per unit (ton);

w: the wholesale price;

p: the retail price ($p > w > c$);

X: the amount of emission reduction investment;

d: the customer demand;

π^m : the manufacture's profit;

π^r : the retailer's profit;

Obviously, the emission reduction investment results in the decrease of the manufacture's carbon footprints, it should be decreasing, concave function of the emission reduction investment, following Toptal et al. (2014), we assume that the decrease of the carbon footprint is

$$\alpha X - \beta X^2, 0 \le X \le \frac{\alpha}{2\beta},$$

where α, β are positive constants.

Following most of the related literature, it is assumed that the customer demand function decreases in the retail price, i.e., $d = a - bp$, where *a* and *b* are positive constants.

The manufacture's carbon emission is

$$Q = C_0 d - \alpha X + \beta X^2 = C_0(a - bp) - \alpha X + \beta X^2 \quad (1)$$

2.2. The retailer's Model

Given the manufacture's wholesale price *w*, the retailer should decide his retail price *p* to maximize his profit. The retailer's profit is

$$\pi^r = (p - w)d = (p - w)(a - bp) \quad (2)$$

Let $\frac{d\pi^r}{dp} = 0$, we have the following theorem.

Theorem 1. Given the manufacture's wholesale price *w*, the retailer's retail price and the customer's demand are

$$p = \frac{a + bw}{2b} \quad (3)$$

$$d = \frac{a - bw}{2} \quad (4)$$

The proof is omitted since it is obvious. From (2)-(4), we have

$$\pi^r = \frac{(a - bw)^2}{4b} \quad (5)$$

(3)-(5) indicate that the retailer's retail price, profit and the customer's demand only depends on the manufacture's wholesale price.

2.3. The Manufacture's Model

Given the optimal retailer's respond function, the manufacture should decide his emission reduction investment and wholesale price. The manufacture's profit is

$$\begin{aligned}\pi^m &= (w - c)d - p^C(Q - \alpha^0) - X \\ &= (w - c - C_0 p^C)\frac{a - bw}{2} - \beta p^C X^2 + (\alpha p^C - 1)X + \alpha^0 p^C\end{aligned} \quad (6)$$

Let $\frac{d\pi^m}{dw} = 0, \frac{d\pi^m}{dX} = 0,$ then we have the following theorem.

Theorem 2. The manufacture's optimal emission reduction effort and wholesale price are

$$w^* = c + C_0 p^C + \frac{\bar{a}}{2b} \quad (7)$$

$$X^* = \frac{\alpha}{2\beta} - \frac{1}{2\beta p^C} \quad (8)$$

Where $\bar{a} = a - b(c + C_0 p^C)$.

Since the proof is simply, it is also omitted. Theorem 2 indicates that the manufacture's optimal emission reduction effort and wholesale price only depends on the carbon price per unit. From (7), we see that the wholesale price includes two parts, one is production cost and carbon emission cost $c + C_0 p^C$, and another is the marginal profit $\frac{\bar{a}}{2b}$. And if the carbon price per unit approaches infinity, then the manufacture should invest $\frac{\alpha}{2\beta}$. The amount of the carbon reduction investment is the same as Toptal et al. (2014).

From Theorem 1 and Theorem 2, we have the following theorem.

Theorem 3. The retailer's optimal retail price and the customer's demand are

$$p^* = c + C_0 p^C + \frac{3\bar{a}}{4b} \tag{9}$$

$$d^* = \frac{\bar{a}}{4} \tag{10}$$

Substituting (7) and (8) into (3) and (4), we can prove Theorem 3, so the proof is omitted. Theorem 3 indicates that the retailer's optimal retail price and the customer's demand only depend on the carbon price per unit. From (7) and (9), we have $p^* > w^* > c + C_0 p^C$, which satisfies the assumption. And the retailer's marginal profit is $p^* - w^* = \frac{\bar{a}}{4b}$, which is half of the manufacture's.

Substituting (8) and (10) into (1), (7) into (5), (7) and (8) into (6), we have

$$Q^* = \frac{C_0 \bar{a}}{4} + \frac{1}{4\beta p^{C2}} - \frac{\alpha^2}{4\beta} \tag{11}$$

$$\pi^{r*} = \frac{\bar{a}^2}{16b} \tag{12}$$

$$\pi^{m*} = \frac{\bar{a}^2}{8b} + \frac{(\alpha p^C - 1)^2}{4\beta p^C} + \alpha_0 p^C \tag{13}$$

(11)-(13) indicate that the manufacture's optimal carbon emission, profit and the retailer's profit only depend on the carbon price per unit.

3. The impact of carbon emission trade on decisions and profits

In this section, we will examine the impact of carbon emission trade on the manufacture and retailer's decisions and profits.

Differentiating p^* with regard to p^C and α^0, we have the following theorem.

Theorem 4. $\frac{dp^*}{dp^C} > 0$, $\frac{dp^*}{d\alpha^0} = 0$.

Proof. From (9), we have $\frac{dp^*}{dp^C} = \frac{C_0}{4}$, so the results hold. The second result is straightforward.

Theorem 4 states that the retail price will increase with increasing the carbon price, and have nothing to do with the cap, which may be strange. In fact, the cap only effects the retailer's profit,

Differentiating w^* with regard to p^C and α^0, we have the following Theorem 5.

Theorem 5. $\frac{dw^*}{dp^C} > 0$, $\frac{dw^*}{d\alpha^0} = 0$.

Proof. From (7), $\frac{dw^*}{dp^C} = \frac{C_0}{2}$, so the results hold. The proof of the second result is omitted since it is straightforward.

Similar to Theorem 4, from Theorem 5, we see that the wholesale price will increase with increasing the carbon price, and have nothing to do with the cap. The wholesale price will increase $\frac{C_0}{2}$, but the retail price will increase $\frac{C_0}{4}$ with increasing one unit of the carbon price.

Differentiating d^*, Q^*, X^* with regard to p^C and α^0, we have Theorem 6.

Theorem 6. (1) $\frac{dd^*}{dp^C} < 0, \frac{dd^*}{d\alpha^0} = 0$,

(2) $\frac{dQ^*}{dp^C} < 0, \frac{dQ^*}{d\alpha^0} = 0$,

(3) $\frac{dX^*}{dp^C} > 0, \frac{dX^*}{d\alpha^0} = 0$.

Proof. From (9), $\frac{dd^*}{dp^C} = -\frac{bC_0}{4} < 0,$ from (8) and (11), $\frac{dX^*}{dp^C} = \frac{1}{2\beta p^{C2}} > 0,$ $\frac{dQ^*}{dp^C} = -\frac{bC_0^2}{4} - \frac{1}{2\beta p^{C3}} < 0$, and the rest of the results are obvious.

Theorem 6 states that with increasing the carbon price, the customer's demand and the amount of carbon emission decrease, and the emission reduction investment increases. But they all have nothing to do with the cap.

Theorem 7. (1) $\frac{d\pi^{r*}}{dp^C} < 0, \frac{d\pi^{r*}}{d\alpha^0} = 0, \frac{d\pi^{m*}}{d\alpha^0} > 0.$

(2) When $p^{C2}(4\alpha_0\beta + \alpha^2 - \bar{a}\beta C_0) > 1, \frac{d\pi^{m*}}{dp^C} > 0,$ otherwise, $\frac{d\pi^{m*}}{dp^C} < 0.$

Proof. From (12) and (13), we have $\frac{d\pi^{r*}}{dp^C} = -\frac{\bar{a}C_0}{8} < 0$, and $\frac{d\pi^{m*}}{dp^C} = \frac{p^{C2}(4\alpha_0\beta + \alpha^2 - \bar{a}\beta C_0) - 1}{4\beta p^{C2}}$, $\frac{d\pi^{m*}}{d\alpha^0} = p^C > 0$, so the results hold.

Theorem 7 indicates that the retailer's profit will decrease with increasing the carbon price, and the manufacture's profit may increase or decrease which depends on the carbon price. But the manufacture's profit will increase with increasing the cap, and retailer's profit has nothing to do with the cap, which is straightforward.

4. Developing a Decision Support System

In this section, we will develop a decision support system for retailers and manufactures to facilitate their decision making process. The DSS is not only to provide the optimal solution for retailers and manufactures such as the optimal retail price and emission reduction investment; wholesale price, but also to give decision makers more managerial insights into their decisions under carbon emission trade. In particular, the DSS has four major modules, “Input Parameters”, “Output Results”, “Model” and “Sensitivity Analysis”.

Our DSS is as Figure 2.

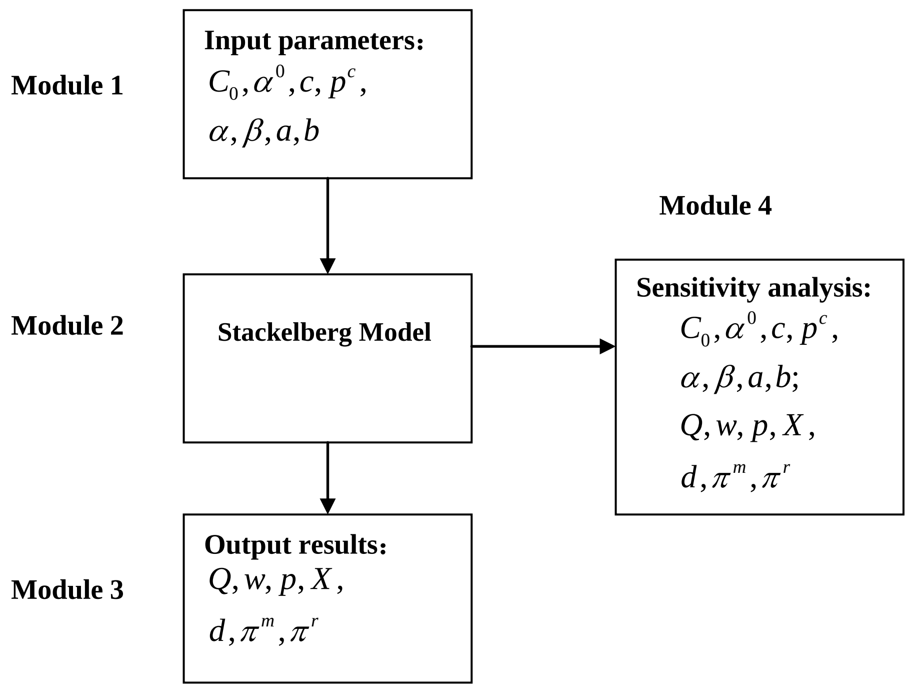

Figure 2. The four Modules of DSS

4.1. Input parameters

The DSS requires users to provide the following information, which can be obtained from the spot market and the carbon trade market.

- C_0: the original carbon footprints of unit product;
- α^0 : the carbon emission quota;
- c: the production cost of unit product;
- p^C : the carbon price per unit (ton);
- $\alpha, \beta : \alpha X - \beta X^2$;
- a, b: $d = a\text{-}bp$.

4.2. Output Results

When the retailer or maufacture inputs the required parameters, then the DSS will calculate the optimal decisions for retailer and manufacture based on our Stackelberg model, and show the output results, such as the optimal retail price, the optimal wholesale price, the amount of emission reduction investment, the amount of manufacture's carbon emission, the customer demand, the manufacture's profit and the retailer's profit.

- Q: the manufacture's carbon emission;
- w: the wholesale price;
- p: the retail price ($p > w > c$);
- X: the amount of emission reduction investment;
- d: the customer demand;
- π^m : the manufacture's profit;
- π^r : the retailer's profit;

4.3. Sensitivity analysis

This module shows how the optimal decisions change when one input parameter of the model varies, the optimal decisions include the optimal retail price, the optimal wholesale price, the amount of emission reduction investment, and the amount of manufacture's carbon emission, the customer demand, the manufacture's profit and the retailer's profit. One input parameter may be the carbon emission quota, the carbon price per unit, the original carbon footprints of unit product, the production cost of unit product or α, β, a, b. The results can be shown in number or bar chart in different colours, such as increasing in green and decreasing in red.

5. Numerical Example

In this section, we will present a numerical example to illustrate our model and results. There is a supply chain consisting of a manufacture and a retailer. They face the following market parameters, and should decide their wholesale price, the amount of investment, and the retail price.

C_0=1.5kg; $\alpha^0 = 1000$ kg; c=500; $p^C = \$0.2/kg$; $d = 10^6 - 800p$; $\alpha = 100$, $\beta = 0.01$, the results are summarized in Table 1 and Table 2.

From Tables 1 and 2, we can see that with increasing the carbon price, the retail price, the manufacture's wholesale price and the emission reduction investment will increase, the customer's demand and the amount of carbon emission decrease. The retailer and manufacture's profit will decrease with increasing the carbon price. With increasing the cap, the retail price, the wholesale price, the investment, customers' demand, the carbon emission and the retailer's profit have nothing to do with the cap, but the manufacture's profit will increase.

Table 1. The Impact of the Carbon Price

p^C	p	w	X	d	Q	π^{r*}	π^{m*}
0.01	1062.5	875	0	149997	225000	2.8124×10^7	5.6248×10^7
0.015	1062.5	875	1667	149995	86104	2.8123×107	5.6247×10^7
0.02	1062.4	875	2500	149993	37491	2.8123×107	5.6247×10^7
0.025	1062.4	875	3000	149991	14989	2.8122×107	5.6246×10^7
0.03	1062.3	875	3333	149990	2764	2.8122×107	5.6246×10^7

Table 2. The Impact of the Cap

α^0	p	w	X	d	Q	π^{r*}	π^{m*}
1000	1062.5	875	2500	149994	37491	2.8123×107	5.6247×10^7
60000	1062.5	875	2500	149994	37491	2.8123×107	5.6248×10^7
100000	1062.5	875	2500	149994	37491	2.8123×107	5.6249×10^7
200000	1062.5	875	2500	149994	37491	2.8123×107	5.6251×10^7
300000	1062.5	875	2500	149994	37491	2.8123×107	5.6253×10^7

6. Conclusion

In this paper, we examined the joint emission reduction investment and pricing decisions with carbon emission trade, and investigated the impact of carbon emission trade on these decisions and profits. The problem is formulated as a stackelberg game, the manufacture is leader, and the retailer is follower. A numerical example is presented to illustrate the proposed model and the results. Based on our model and analysis, we also designed a decision support system for retailers and manufactures to facilitate their decision making in practice.

We found that the retail price will increase with increasing the carbon price, and have nothing to do with the cap. And the retailer's profit will decrease with increasing the carbon price, and has nothing to do with the cap. The maufacture's wholesale price will increase with increasing the carbon price, and have nothing to do with the cap. The manufacture's profit may increase or decrease which depends on the carbon price, and will increase with increasing the cap. With increasing the carbon price, the customer's demand and the amount of carbon emission decrease, and the emission reduction investment increases.

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