Pricing and Carbon Emission Strategy of Supply Chain with Cap and Trade

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Abstract. Low-carbon economy is the trend of economic development in the future. It is gradually becoming a hot topic in academic and business circles that how to reduce carbon emissions. Cap and trade is one of the effective ways to reduce carbon emissions and has been adopted by many countries. We investigate a two-echelon supply chain that consists of a supplier and a manufacturer. This paper assumes a vertical Nash game between the two sides. We study three different models on cap and trade policy, which are the independent carbon reduction model and the concentrated models (only the supplier faces cap and trade and only the manufacturer faces cap and trade). We obtain the optimal decisions and unit carbon emissions of the supplier and the manufacturer. The optimal wholesale price, sale price, unit carbon emission and maximum profit under different cap and trade models have be compared by numerical analysis. We find that concentrated carbon reduction models are beneficial for supply chain enterprises, but as the price is creating more carbon emissions than the independent model. This study provides valuable managerial implications, which will be beneficial for firms to make an important strategy.

1. Introduction

Human production activities generate large quantities of greenhouse gas, and the global warming caused by carbon emissions has posed a serious threat to the world's ecosystem and human survival. With the rapid development of the low-carbon economy, reducing greenhouse gas emissions and alleviating the global warming are becoming the consistent goal of all countries. In response to global warming, many carbon emission policies, such as mandatory carbon emission cap, carbon emission tax, and cap and trade, have been adopted by governments[1]. Among them, cap and trade is one of the most effective market-based mechanisms that has been universally recognized. It is an economic measure that controls carbon emissions and carbon quotas based on market transaction[2]. At present, cap and trade is implemented in nearly 40 countries around the world. The implementation of cap and trade policy challenges firm pricing and also attracts firms' attention about carbon reduction efforts. Therefore, it is practically meaningful to examine firms' pricing and carbon reduction efforts with cap and trade policy.

Du et al.[3] proved that the operational optimization and supply chain collaboration could lead to more distinct emission reduction. Lee [4] analysed the role of low carbon supply chain in enhancing enterprise competitiveness and the necessity of implementing low carbon supply chain management by empirical research. Chen et al.[5] examined a two-echelon supply chain that consists of a retailer and a manufacturer whose customer demand was carbon emission sensitive. The optimal solutions under three supply chain power structures were derived. It showed that different power structure had a significant impact on the

carbon reduction decision. Jiang and Chen.[6] investigated the optimal production, pricing, carbon trading, and green technology investment strategies of the low carbon supply chain in centralized and decentralized carbon reduction model.

The literatures above mentioned laid the foundation for our study but did not consider the effect of the different modes of cap and trade policies on firm pricing and unit carbon emissions. In order to fill the gap presented by the literature review, this paper examines the pricing and carbon emissions strategy of the supply chain with different cap and trade policies.

2. Model descriptions and assumptions

We consider a two-echelon supply chain that is composed of a row materials supplier and a manufacturer. The manufacturer buys raw materials from the supplier and produces products. Then the manufacturer sells products to the customers. The supply chain faces cap and trade policy, which means the supplier and the manufacturer must input low carbon effort to reduce their products' carbon emissions. The demand is affected by product price. The decision variables of the supplier are wholesale price and unit carbon emissions after low carbon effort, and the decision variables of the manufacturer are sale price and unit carbon emissions after low carbon effort. Throughout this paper, we use the notations presented in Table 1.

Table 1. Notations of parameters and variables

Notation	Descriptions
c_s	Supplier's unit row material cost.
c_m	Manufacturer's unit production cost.
c	The supply chain's unit cost, $c = c_s + c_m$
$T(e_i)$	Supplier and manufacturer's carbon emission reduction cost, $i=s,m$
t_i	Supplier and manufacturer's carbon emission reduction cost coefficient, $i=s,m$
w	Supplier's unit wholesale price.
p	Unit price of the products
k	Unit price of carbon emission trading with the carbon trade market
K_s	Supplier's initial carbon allowances.
K_m	Manufacturer's initial carbon allowances.
K	The supply chain's total initial carbon allowances, $K = K_s + K_m$

In addition, the following assumptions are employed in this study:

(1) The product's demand function is: $q=\alpha-\beta p$ $(\alpha,\beta>0)$, where α is the initial market and β is the self-price sensitivity.

(2) $T(e_i) = t_i(e_0 - e_i)^2$ $(i=s,m)$. This assumption means that the supplier and manufacturer's carbon emission reduction cost is convexity on e_i $(i=s,m)$, which attributes to diminishing returns from expenditures. This setting is popular in the literature[7-8].

(3) $p>w>c>0$. This condition states that there is a positive profit margin for the supplier to sell raw materials to the manufacturer, and there is a positive profit margin for the manufacturer to sell products to the consumers.

(4) The supplier-manufacturer relationship is 1:1, which means that the manufacturer produces one unit of products at a time. Meanwhile the supplier consumes one unit of raw materials.

3. The independent carbon reduction model

In this section, we examine the optimal decisions of the supplier and the manufacturer. We followed Jiang et al.[9] by formulating the model.

The supplier's profit is $\Pi_s^I(w,e_s) = (w - c_s)q - t(e_0 - e_s)^2 - k(e_s q - K_s)$. The first term is the profit from product wholesale, the second term indicates the cost of carbon reduction, and the third term represents the

carbon trading cost (or profit if the carbon emissions of the supplier are lower than the initial carbon allowances).

In a similar way, the manufacturer's profit is $\Pi_m^I(p,e_m) = (p - w - c_m)(\alpha - \beta p) - t(e_0 - e_m)^2 - k[e_m(\alpha - \beta p) - K_m]$. The first term is the profit from products sale. The second term indicates the cost of carbon reduction. The third term represents the carbon trading cost (or profit if the carbon emissions of the manufacturer are lower than the initial carbon allowances).

The supplier's decision problem for the independent carbon reduction model is: $\max\limits_{w,e_s} \Pi_s^I(w,e_s)$ and the manufacturer's decision problem for the independent carbon reduction model is: $\max\limits_{p,e_m} \Pi_m^I(p,e_m)$. When $4t_s - \beta k^2 > 0$ and $4t_m - \beta k^2 > 0$, the Hessian Matrixes in the independent carbon reduction model is positive definite. We can obtain the optimal whole price and the optimal unit carbon emissions of the supplier, denoted by w^I and e_s^I, are: $w^I = c_s + e_0 k + \dfrac{(2t_m t_s - \beta k^2 t_m)(\alpha - \beta c - 2\beta e_0 k)}{\beta[6t_m t_s - \beta k^2(t_m + t_s)]}$, $e_s^I = e_0 - \dfrac{kt_m(\alpha - \beta c - 2\beta e_0 k)}{6t_m t_s - \beta k^2(t_m + t_s)}$. The optimal sale price and the optimal unit carbon emissions of the manufacturer, denoted by p^I and e_m^I, are:

$$p^I = \frac{\alpha}{\beta} - \frac{2t_m t_s(\alpha - \beta c - 2\beta e_0 k)}{\beta[6t_m t_s - \beta k^2(t_m + t_s)]} , \quad e_m^I = e_0 - \frac{kt_s(\alpha - \beta c - 2\beta e_0 k)}{6t_m t_s - \beta k^2(t_m + t_s)} .$$

4. The concentrated carbon reduction model

In this section, we investigate two types of cap and trade: Only the supplier faces cap and trade, and only the manufacturer faces cap and trade. We obtain the optimal decisions and unit carbon emissions of the supplier and the manufacturer.

4.1. The optimal decisions when only the supplier faces cap and trade

We firstly examine the concentrated model that the government applies cap and trade policy to the supplier. The sequence of events is as follows. Firstly, the government announces the initial carbon allowances to the supplier. Then the supplier determines row materials wholesale price and unit carbon emissions, and the manufacturer determines the product's sale price and unit carbon emissions simultaneously. Finally, when customer demand is realised, the supplier and the manufacturer obtain their revenues.

When only the supplier faces cap and trade, we can get the profit function of the supplier and manufacturer. The profit function of the supplier denoted by $\Pi_s^s(w,e_s)$, where the superscript s represents the concentrated model of only the supplier faces cap and trade and the subscript s represents the supplier.

$$\Pi_s^s(w,e_s) = (w - c_s)q - t(e_0 - e_s)^2 - k[e_s q - (K_s + K_m)] \tag{1}$$

The first term is the profit from row materials wholesale, the second term indicates the cost of carbon reduction, and the third term represents the carbon trading cost (or profit if the carbon emissions of the supplier are lower than the initial carbon allowances).

In a similar way, the manufacturer's profit is

$$\Pi_m^s(p,e_m) = (p - w - c_m)(\alpha - \beta p) - t(e_0 - e_m)^2 \tag{2}$$

The first term is the profit from products sale. The second term indicates the cost of carbon reduction. The supplier's decision problem when only the supplier faces cap and trade is: $\max\limits_{w,e_s} \Pi_s^s(w,e_s)$ and the manufacturer's decision problem when only the supplier faces cap and trade is: $\max\limits_{p,e_m} \Pi_m^s(p,e_m)$.

Proposition 1: When $4t_s - \beta k^2 > 0$, the optimal wholesale price and the optimal unit carbon emissions of the supplier, denoted by w^s and e_s^s, are: $w^s = c_s + \dfrac{2t_s(\alpha - \beta c + 2\beta e_0 k) - \beta k^2(\alpha - \beta c)}{\beta(6t_s - \beta k^2)}$, $e_s^s = e_0 - \dfrac{k(\alpha - \beta c - \beta e_0 k)}{6t_s - \beta k^2}$. The optimal sale price and the optimal unit carbon emissions of the manufacturer, denoted by p^s and e_m^s, are:

$$p^s = \frac{\alpha}{\beta} - \frac{2t_s(\alpha - \beta c - \beta e_0 k)}{\beta(6t_s - \beta k^2)} , \quad e_m^s = e_0 .$$

Proposition 1 shows that both the optimal sale price and unit carbon emissions of the manufacturer and the optimal wholesale price and unit carbon emissions of the supplier uniquely exist. We also show that the manufacturer will not make low-carbon investment in vertical Nash equilibrium mode when only the supplier faces cap and trade.

Proof: From eq.1, we get $\frac{\partial \Pi_s^s(w,e_s)}{\partial w} = \alpha - \beta(m+w) - \beta(w-c_s) + \beta e_s k$, $\frac{\partial \Pi_s^s(w,e_s)}{\partial e_s} = 2t_s(e_0 - e_s) - k[\alpha - \beta(m+w)]$. From

eq.2, we get $\frac{\partial \Pi_m^s(p,e_m)}{\partial p} = \alpha - 2\beta p + \beta(c_m + w)$, $\frac{\partial \Pi_m^s(p,e_m)}{\partial e_m} = 2t_m(e_0 - e_m)$ .we have $\frac{\partial^2 \Pi_s^s(w,e_s)}{\partial w^2} = -2\beta < 0$,

$\frac{\partial^2 \Pi_s^s(w,e_s)}{\partial e_s^2} = -2t_s < 0$ and $\frac{\partial^2 \Pi_s^s(w,e_s)}{\partial w \partial e_s} = \frac{\partial^2 \Pi_s^s(w,e_s)}{\partial e_s \partial w} = \beta k$. when $4t_s - \beta k^2 > 0$, we obtain

$\begin{vmatrix} \frac{\partial^2 \Pi_s^s(w,e_s)}{\partial e_s^2} & \frac{\partial^2 \Pi_s^s(w,e_s)}{\partial e_s \partial w} \\ \frac{\partial^2 \Pi_s^s(w,e_s)}{\partial w \partial e_s} & \frac{\partial^2 \Pi_s^s(w,e_s)}{\partial w^2} \end{vmatrix} = \beta(4t_s - \beta k^2) > 0$. Then we can get that $\Pi_s^s(w,e_s)$ is jointly concave in w and e_s . Ac-

cording to eq.2, we have $\frac{\partial^2 \Pi_m^s(p,e_m)}{\partial p^2} = -2\beta < 0$, $\frac{\partial^2 \Pi_m^s(p,e_m)}{\partial e_m^2} = -2t_m < 0$. Let the first derivatives are equal to 0

respectively, we can get proposition 1.

4.2. The optimal decisions when only the manufacturer faces cap and trade
We then examine the concentrated model when only the manufacturer faces cap and trade. The sequence of events is the same as section 4.1.

When only the manufacturer faces cap and trade, we can get the profit functions of the supplier and the manufacturer. The profit function of the supplier denoted by $\Pi_s^m(w,e_s)$, where the superscript m represents the concentrated model of only the manufacturer faces cap and trade and the subscript s represents the supplier.

$$\Pi_s^m(w,e_s) = (w-c_s)(\alpha - \beta p) - t(e_0 - e_s)^2 \tag{3}$$

In a similar way, the manufacturer's profit is

$$\Pi_m^m(p,e_m) = (p-w-c_m)(\alpha - \beta p) - t(e_0 - e_m)^2 - k[e_m(\alpha - \beta p) - (K_s + K_m)] \tag{4}$$

Proposition 2: When $4t_m - \beta k^2 > 0$, the optimal wholesale price and the optimal unit carbon emissions of the supplier, denoted by w^m and e_s^m , are: $w^m = c_s + \frac{2t_m(\alpha - \beta c - \beta e_0 k)}{\beta(6t_m - \beta k^2)}$, $e_s^m = e_0$ .The optimal sale price and

the optimal unit carbon emissions of the manufacturer, denoted by p^m and e_m^m , are:

$p^m = \frac{\alpha}{\beta} - \frac{2t_m(\alpha - \beta c - \beta e_0 k)}{\beta(6t_m - \beta k^2)}$, $e_m^m = e_0 - \frac{k(\alpha - \beta c - \beta e_0 k)}{6t_m - \beta k^2}$.

Proof: From eq.3, we get $\frac{\partial \Pi_s^m(w,e_s)}{\partial w} = \alpha - \beta(m+w) - \beta(w-c_s)$, $\frac{\partial \Pi_s^m(w,e_s)}{\partial e_s} = 2t_s(e_0 - e_s)$. From eq.4, we get

$\frac{\partial \Pi_m^m(p,e_m)}{\partial p} = \alpha - 2\beta p + \beta(c_m + w + k e_m)$, $\frac{\partial \Pi_m^m(p,e_m)}{\partial e_m} = 2t_m(e_0 - e_m) - k(\alpha - \beta p)$. We also get $\frac{\partial^2 \Pi_m^m(p,e_m)}{\partial p^2} = -2\beta < 0$,

$\frac{\partial^2 \Pi_m^m(p,e_m)}{\partial e_m^2} = -2t_m < 0$ and $\frac{\partial^2 \Pi_m^m(p,e_m)}{\partial p \partial e_m} = \frac{\partial^2 \Pi_m^m(p,e_m)}{\partial e_m \partial p} = \beta k$ .when $4t_m - \beta k^2 > 0$, the proof is similar to the proof of

Proposition 1, the Hessian Matrix is positive definite, we can get proposition 2.

5. Discussion
In this section, numerical analysis is provided to examine the impact of manufacturer's low carbon cost coefficient (t_m) on the optimal wholesale price, sale price and unit carbon emissions. We set $\alpha = 400$, $\beta = 5$, $e_0 = 20$, $k = 1$, $t_s = 8$, $c = 2$, $c_s = c_m = 1$, $K_s = K_m = 15$, $K = 30$. In order to observe the change of the decision variables and profits of the supplier, the manufacturer and the supply chain, we set $t_m \in [6,10]$.

The effect of different cap and trade mode on the price is analysed in figure 1.
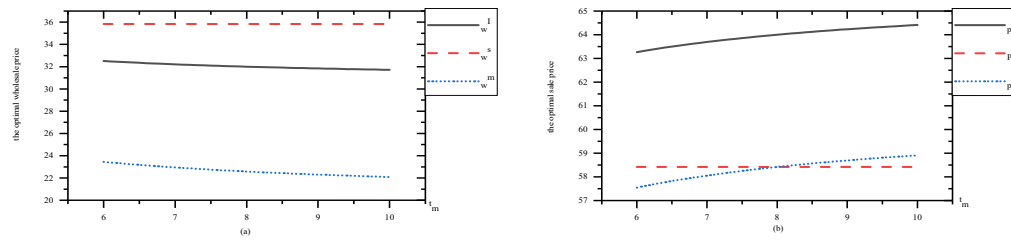
Figure 1: The effect of carbon reduction mode on the price

From figure 1(a), we observe that the optimal wholesale price when only the supplier faces cap and trade is independent of t_m. It also shows that the optimal wholesale price when only the supplier faces cap and trade is the highest and it means the supplier needs to increase the wholesale price of raw materials to obtain profits when the supplier faces cap and trade. From figure 1(b), we observe that the optimal sale price in concentrated carbon reduction model is lower than that in independent carbon reduction model. It means that concentrated carbon reduction benefits customers. We also find when $t_m \in [6,8]$, the optimal wholesale price in the mode which only the manufacturer faces cap and trade is lower than the mode which only the supplier faces cap and trade. When $t_m \in [8,10]$, the result is the opposite. It means that the manufacturer must increase the sales price to achieve profitability when $t_m > t_s$.

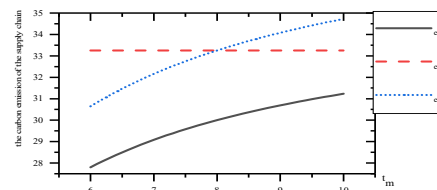The effect of carbon reduction mode on the unit carbon emissions is analysed in figure 2.

Figure 2: The effect of carbon reduction mode on the unit carbon emissions

From figure 2, we observe that the unit carbon emission of the supply chain on the concentrated model is higher than that on the independent model. The government's pursuit of environmental performance will be sacrificed at the expense of the company's economic profits. The government should balance the economic performance and environmental performance of the company

The effect of different cap and trade modes on the profit of the supplier, the manufacturer and the supply chain are shown in figure 3.
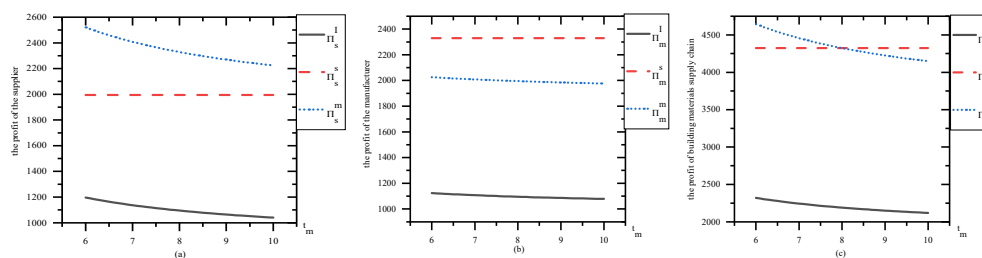

Figure 3: The effect of carbon reduction mode on the profit

From figure 3, we observe that the profit of the supplier, manufacturer and the supply chain in concentrated carbon reduction model are higher than these in independent carbon reduction model. It means that concentrated carbon reduction benefits the supply chain. From figure 3(a), when only the manufacturer faces cap and trade, the supplier's profit is highest. The profit of supplier is not related to t_m when only the supplier faces cap and trade. From fig 3(b), it shows the manufacturer get the highest profit when only the supplier faces cap and trade. From fig 3(c), when $t_m \in [6,8]$, the profit of the supply chain when only the manufacturer faces cap and trade is higher than the profit when only the supplier faces

cap and trade. The result is the opposite when $t_m \in [8,10]$. The reasonable profit distribution mechanism or cooperative R&D mechanism should be designed to achieve Pareto optimality.

6. Conclusions and future researches

This paper studies the pricing and carbon emission decision model of two-stage supply chain composed of suppliers and manufacturers under cap and trade policy. Firstly, we formulate the model of independent cap and trade, and drive the optimal decisions and unit carbon emissions of the supply chain. Secondly, we formulate the model that only the supplier faces cap and trade. We obtain the optimal wholesale price, sale price and unit carbon emissions of the supply chain. Thirdly, we formulate the model that only the manufacturer faces cap and trade. We obtain the optimal wholesale price, sale price and unit carbon emissions of the supply chain. Finally, we analyse the effect of t_m on the optimal decisions and the profit of the supplier, the manufacturer and the supply chain by a numerical study. We show that the profits of the concentrated model are higher than the profit of the independent model. The government should balance the economic performance and environmental performance of the company. The supply chain enterprises could cooperate in low-carbon technology research and development. This paper provides a reference for the government's decisions on how to design a carbon policy and the supply chain enterprises' decisions on how to price and reduce carbon with cap and trade.

The paper assumes that the demand is only price dependent. Actually, the customer demand may become price and carbon emissions sensitive. Therefore, one of the future directions is considering price and carbon dependent demand. The paper assumes that the supplier and the manufacturer are vertical Nash power structure. Later we will study the influence of power structure on the company's decision in the future.

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