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Carbon emissions reduction and transfer in supply chains under A cap-and-trade system with emissions-sensitive demand

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ABSTRACT

Although 'Cap-and-trade' mainly constrains the manufacturer, the decision of the manufacturer's emission reduction will affect the decision of the whole supply chain. In this paper, we investigate manufacturer and retailer's decision under decentralized decision and centralized decision and taking into account the impact of carbon price and consumer environmental consciousness. Specially, we analyse the condition of whether a manufacturer transfers the emission reduction task to retailer. Besides, we use computational experiments to analyse the sensitivity by changing the cost function. Through the research, we have some findings: under a decentralized decision, manufacturer transfers emissions reduction task in more times, if the manufacturer transfers the emissions reduction task, the effectiveness of the emissions reduction, demand, retailer's revenue per product and consumer welfare decrease. Under centralized decision, the manufacturer does not transfer emissions reduction task all time, which is affected by emissions reduction cost of the manufacturer and retailer, carbon price and consumer environmental consciousness. In addition, emissions reduction cost function is not the sensitivity factor.

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KEYWORDS

Carbon emission; supply chain; cap-and-trade; carbon price; consumer environmental consciousness

1. Introduction

In the face of both academic and practitioner concerns about greenhouse gas as a major contributor to global warming, the EU and other countries have established various regulations to control carbon emissions. Governments have also supplemented traditional 'command and control' with market-based instruments (Aidt & Dutta, 2004), the most influential of which is the 'cap-and-trade' system whereby the government allocates a carbon emissions cap to each firm. If the company's carbon emissions exceed this cap, it must buy the quota from the market; if they are lower than the cap, it can sell the surfeit on the market. Although such a system may be a key point to ease the environmental burden and possibly be a basic module of future climate policy (Stern, 2008), it has a definite effect on firms' operational decisions (Du, Zhu, Liang, & Ma, 2013) and region selection (Wu, Jin, Shi, & Shyu, 2018).

The firm's decision of emissions reduction is also influenced by consumers' environmental consciousness: the growing number of consumers who are aware of products' environmental impacts and opt for greener choices constrains firms' negative environmental externality. If a

product's emission is high, a firm's social responsibility is low, and it can expect consumer punishment from production through sale; for example, by paying a high price to attract and motivate employees, which raises production costs and impacts sales (Heyes & Kapur, 2012). If the product is green, on the other hand, because of the consumer's environment preference, consumer demand is linked with carbon emissions of per product unit (Li et al., 2018), consumers may be willing to pay a premium price (Arora & Gangopadhyay, 1995), which means that the manufacturer's efforts to reduce carbon emissions are also enjoyed by the retailer, who becomes a free rider. As a result, some firms are calling for other stakeholders to also reduce related carbon emissions so as to lower emissions overall. Nike, for instance, has reported that it will focus on the energy footprint of its retail channel (NIKE, FY07-FY09).

The literature relevant to this research primarily comes from three streams: (i) green supply chain design focused on optimizing the carbon footprint in a product's whole life cycle (Benjaafar, Li, & Daskin, 2013; Chaabane, Ramudhin, & Paquet, 2012; Hoen, Tan, Fransoo, & Houtum, 2014; Mohammed, Selim, Hassan, & Syed, 2017), (ii) the impact

on supply chains of environmental policy (e.g. carbon taxes, carbon disclosure, and ‘cap-and-trade’ systems) (Bazan, Jaber, & Zanoni, 2017; Fischer & Springborn, 2011; Hoen et al., 2014; Mackenzie & Ohndorf, 2012; Song, Govindan, Xu, Du, & Qiao, 2017), and (iii) the impact on supply chains of corporate social responsibility and consumer environmental consciousness (Geffen & Rothenberg, 2000; Laroche, Bergeron, & Guido, 2001; Liu, Anderson, & Cruz, 2012; O’Brien, 1999; Sarkis, Zhu, & Lai, 2011; Sengupta, 2012; Yalabik & Fairchild, 2011; Zhu & Sarkis, 2007).

Yet, despite these emerging trends, little academic literature addresses the joint reduction of carbon emissions along the supply chain and/or the allocation of reduction tasks among different partners. To help fill this void, we develop a theoretical game model for analysing these factors in what, to the best of our knowledge, is the first paper on joint emissions reduction in the supply chain.

Our model captures three characteristics of a low-carbon supply chain: First, consumer choices based on environmental consciousness force manufacturers to reduce their carbon emissions. Second, such reduction can increase demand, which can also benefit the retailer, which means that manufacturers may transfer some emission reduction task to retailers (Caro, Corbett, Tan, & Zuidwijk, 2011). Third, this convenient transfer, referred to as ‘green wash’ in the literature, is facilitated by the fact that emissions from transportation and inventory make up a large portion of the product’s whole life cycle (Cachon, 2011). Our game model therefore focuses on the whole supply chain and, unlike the many studies that investigate emissions reduction by firms only, assumes that the manufacturer can transfer all or part of the carbon emissions reduction task to the retailer.

Our overall contributions are therefore twofold: First, our model not only considers the decision of joint emissions reduction of the whole supply chain under a carbon price constraint but also compares these decisions under both a decentralized and a centralized mode. Second, our paper focuses heavily on how carbon price and consumer environmental consciousness affect a manufacturer’s decision, an aspect little studied in the related literature.

2. Problem description and model assumptions

In this paper, we study a two-echelon supply chain with one dominant manufacturer who can control the supply chain and one retailer (see Figure 1). In the presence of policy and consumer pressure, the manufacturer always ascertains and declares a goal of emissions reduction in order to signal its corporate social responsibility and attract more consumers. That is, the manufacturer

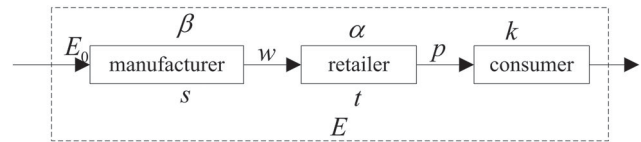


Figure 1. Emissions allocation in a low-carbon supply chain.

informs consumers that the per product carbon emissions will be reduced from E_0 to E . The decision sequence is as follows: The manufacturer first decides the optimal emissions E associated with the product, the proportion of emissions reduction task allocated to the retailer β , and the wholesale price w , based on which the retailer decides the retail price p .

Under the cap-and-trade system, the government sets an emissions cap E_{cap} . If the firm’s total emissions exceed this limit, the excess must be bought on the market; if not, the surfeit can be sold on the market. Since the carbon price is beyond the company’s control, we assume that it is an exogenous variable denoted by p_c . In our analysis, although in current practice the cap-and-trade system applies mainly to manufacturers, we make the following assumption:

Assumption 2.1: *The manufacturer can allocate part but not all of the emissions reduction goal to the retailer, making the retailer’s portion $\alpha \in [0, 1)$ and the manufacturer’s portion $\beta \in (0, 1]$.*

The rationale underlying this assumption is that the entire supply chain should be responsible for the overall emissions not simply the supply chain leader (Caro et al., 2011). And some other literature reveals that there exists greenwashing in a green supply chain (Eun-Hee & Thomas, 2011). It is therefore reasonable to assume that the retailer has a part in the emissions reduction; for example, by reducing the emissions during inventory and transportation. If the manufacturer (retailer) were to undertake all emissions reduction, then $\alpha = 0$ and $\beta = 1$ ($\alpha = 1$ and $\beta = 0$); however, this situation is rare in practice, so we omit these scenarios. We also assume that the manufacturer and retailer have different marginal costs of dealing with emissions reduction and express the manufacturer’s marginal cost as t , with a linear function $C_c = t\beta(E_0 - E)$, and the retailer’s as s , with linear function $C_r = s\alpha(E_0 - E)$. This assumption is general enough to give our model the flexibility to capture different situations. In some cases, the retailer cannot reduce the product’s carbon emissions directly but must still bear some related cost, which corresponds to the case of $t = s$. Although this linear cost function assumption may seem a little strict, our numerical experiment shows that our results are highly robust to it.

The research also provides clear evidence that when consumers' environmental consciousness increases, carbon emissions have a negative effect on demand, which leads to our second assumption:

Assumption 2.2: *The demand function decreases with an increase in emissions per product unit or price.*

In this case, following (Yalabik & Fairchild, 2011), the demand function can be given as

$$Q = a - p - kE \quad (1)$$

where Q is the demand, a is the potential market, and k is a coefficient denoting consumer sensitivity to carbon emissions. In the presence of an environmentally conscious consumer, however, if the emissions are high, consumer demand will decrease, so the retailer will appreciate the manufacturer's reducing the carbon emissions per product unit. Some literatures give the conclusion through their studies (Heyes & Kapur, 2012; Li et al., 2018; Yalabik & Fairchild, 2011), but some research thinks that consumer are concerned with price more than carbon emissions. For example, the BIS(2010) report indicates that consumers pay more attention to cost savings than carbon emissions.

In terms of manufacturer's cost, assume the following:

Assumption 2.3: *The manufacturer's cost is made up of two parts: production cost C_m , which is assumed to be a constant, and emissions-related costs, which include the reduction cost C_c and the carbon quota purchasing cost $p_c(EQ - E_{cap})$.*

The variable cost of manufacturing, besides being affected by production quantity, is also affected by demand when price or emissions per product unit change. We eliminate this effect by adding $p_c(EQ - E_{cap})$ to the revenue function, allowing us to focus primarily on the cost of emissions reduction. To simplify the calculation, we write the cost of emissions reduction as $C_r = \alpha E_r = \alpha(E_0 - E)$ and the manufacturing cost as $C_c = t\beta(E_0 - E)$, whose potential effect on the revenue function we neutralize through a subsequent analysis of cost sensitivity. Since a constant variable cost does not change our results, we assume a constant production cost equivalent to zero variable production cost, allowing us to make the above assumption without loss of generality. The notations used in the model are summarized in Table 1.

Within this modelling framework, we can write from Assumptions 2.2 and 2.3 that the retailer's and manufacturer's revenue functions are as follows: the retailer's

Table 1. Model notations.

Symbol	Definition
Q	Consumer demand
p	Retail price
k	Market sensitivity to the emissions of the firm's product
C_r	Retailer's cost of dealing with the emissions
C_m	Manufacturing cost
w	Wholesale price
C_c	Manufacturer's cost of emissions reduction
p_c	Carbon price
E_{cap}	Emissions cap
α	Proportion undertaken by the retailer
β	Proportion undertaken by the manufacturer
E	Emissions per product unit
E_0	Original emissions per product unit
E_r	Quantity of emissions reduction
s	Retailer's treatment cost for emissions per unit
t	Manufacturer's treatment cost for emissions per unit

revenue function is

$$\begin{aligned} \Pi_r(p) &= pQ - wQ - C_r \\ &= (p - w)(a - p - kE) - \alpha(E_0 - E), \end{aligned} \quad (2)$$

and the manufacturer's revenue function is

$$\Pi_m(w, E) = wQ - C_m - C_c - p_c(EQ - E_{cap}). \quad (3)$$

Under a cap-and-trade system, when $EQ > E_{cap}$ (i.e. when emissions are higher than the cap), the manufacturer must buy the excess on the market, whereas when $EQ < E_{cap}$ (i.e. when emissions are lower than the cap), the manufacturer can sell the surfeit on the trade market and earn extra benefits.

3. Analysis

To examine the condition under which the retailer will undertake a portion of the emissions reduction, we use backward induction to solve the model and achieve a Stackelberg game Nash equilibrium between the manufacturer and retailer in the supply chain. We also consider the opposite condition ($\alpha = 0$) as a special case. To increase the number of insights, we analyse both the decentralized and centralized decision model.

3.1. Decentralized decision model

Under a condition of decentralized decisions, from (1), (2) and (3), we can get that the optimal decisions for the manufacturer and retailer are thus

$$E^* = \frac{a(p_c + k) - 4t\beta_d}{(p_c + k)^2}, \quad (4)$$

$$w^* = \frac{p_c a(p_c + k) - 2t\beta_d(p_c - k)}{(p_c + k)^2}, \quad (5)$$

$$p^* = \frac{p_c a(k + p_c) - t\beta_d(p_c - 3k)}{(p_c + k)^2}, \quad (6)$$

$$Q^* = \frac{t\beta_d}{p_c + k}. \quad (7)$$

When the retailer undertakes no portion of the emissions reduction, the optimal decision is

$$E^0 = \frac{a(p_c + k) - 4t}{(p_c + k)^2}, \quad (8)$$

$$w^0 = \frac{p_c a(p_c + k) - 2t(p_c - k)}{(p_c + k)^2}, \quad (9)$$

$$p^0 = \frac{p_c a(k + p_c) - t(p_c - 3k)}{(p_c + k)^2}, \quad (10)$$

$$Q^0 = \frac{t}{p_c + k}. \quad (11)$$

In the following, we analyse the manufacturer's strategy for allocating the emissions reduction task, which yields the following results:

Theorem 3.1: *The manufacturer's emissions reduction allocation strategy is as follows:*

- (i) If $\frac{a - \sqrt{a^2 - 8tE_0}}{2E_0} \leq p_c + k \leq \frac{a + \sqrt{a^2 - 8tE_0}}{2E_0}$,
then $\Pi_m^* \leq \Pi_m^0$,
- (ii) If $\frac{a + \sqrt{a^2 - 8tE_0}}{2E_0} < p_c + k < \frac{a}{E_0}$ or $0 < p_c + k < \frac{a - \sqrt{a^2 - 8tE_0}}{2E_0}$, then $\Pi_m^* > \Pi_m^0$,

where $\Pi_m^* = \frac{at\beta_d(p_c+k) - 2(t\beta_d)^2}{(p_c+k)^2} - C_m + p_c E_{cap} - t\beta_d E_0$, which denotes the manufacturer's revenue when the manufacturer undertakes the whole emissions reduction and transfers to the retailer, $\Pi_m^0 = \frac{at(p_c+k) - 2t^2}{(p_c+k)^2} - C_m + p_c E_{cap} - tE_0$, which denotes the manufacturer's revenue when the manufacturer undertakes the whole emissions reduction and transfers none to the retailer.

For the proof, see the appendix.

Theorem 3.1 also suggests that when the sum $p_c + k$ of the carbon price p_c and consumer sensitivity k is very low, reducing carbon emissions results in increased cost, meaning that the manufacturer gains little benefit from selling either the emissions quota or environmentally friendly products. In that case, the manufacturer has no incentive to eliminate emissions and will transfer the task to the retailer. When the carbon price and consumer sensitivity pressure is high, the manufacturer should avoid the high carbon price penalty by reducing carbon emissions and passing the related costs onto the consumer. As

this pressure increases, however, the manufacturer faces a high penalty for further eliminating carbon emissions and cannot pass the cost on to the consumer because the higher price may result in less demand. In this case, the manufacturer can allocate the emissions reduction so that the retailer shares the cost (see Yalabik & Fairchild, 2011). So, government should establish the threshold of the carbon price to promote the manufacturer to invest technology to reduce carbon emission of per product unit.

Theorem 3.2: *Under a decentralized decision, if the manufacturer decides to transfer part $1 - \beta_d$ of the emissions reduction task, the effectiveness of the emissions reduction, E , demand, Q , retailer's revenue per product, $p - w$, and consumer welfare, $\int_0^Q (a - Q - kE)dQ$, all decrease.*

For the proof, see the appendix.

According to Theorem 3.1, if the manufacturer transfers the emissions reduction under a decentralized decision, both retailer revenue and activity decrease, which may result in decreased demand. As a result, the overall emissions, EQ , decrease, which means that the manufacturer does not invest more in technology. For instance, when a number of emissions credits are available in the carbon market (as in the EU), the carbon price can plummet to a record low, leading many firms to buy emissions credits instead of investing in environmental technology. Moreover, effective emissions reduction implies that emissions per product are high, so not only $p - w$ and consumer welfare but also demand decreases, affecting both the retail and wholesale price. From Theorem 3.2, we can know that the policy of cap of total emission associated with the policy of carbon disclosure is better.

3.2. Centralized decision model

To examine conditions under a centralized decision, we consider emissions and revenue in the entire supply chain. According to Assumption 2.2, the consumer is willing to pay a premium on low-carbon products, which means that both emissions and price affect demand and the supplier can transfer the emissions reduction cost to the consumer (Cachon, 2011). In the centralized decision mode, therefore, we must consider the price of revenue-integrating product and emissions per product. Because $\alpha \in [0, 1)$ and $\beta \in (0, 1]$ in Assumption 2.1, we also assume the following revenue function, in which we consider $\alpha = 0$ and $\beta = 1$ as a special condition:

$$\Pi_t = pQ - C_r - C_m - C_c - p_c(EQ - E_{cap}). \quad (12)$$

The optimal decision in the centralized control mode, therefore, is

$$E_t^* = \frac{a(p_c + k) - 2(s\alpha_c + t\beta_c)}{(p_c + k)^2}, \quad (13)$$

$$p_t^* = \frac{p_c a(p_c + k) - (p_c - k)(s\alpha_c + t\beta_c)}{(p_c + k)^2}, \quad (14)$$

$$Q_t^* = \frac{s\alpha_c + t\beta_c}{p_c + k}. \quad (15)$$

Theorem 3.3: Under the manufacturer who chooses a centralized control mode, the optimal decision is as follows:

- (i) If $\frac{a - \sqrt{a^2 - 8sE_0}}{2E_0} < p_c + k \leq \frac{a - \sqrt{a^2 - 8tE_0}}{2E_0}$ or $\frac{a + \sqrt{a^2 - 8tE_0}}{2E_0} \leq p_c + k < \frac{a + \sqrt{a^2 - 8sE_0}}{2E_0}$ for $t > s$, then the manufacturer transfers the emissions reduction to the retailer,

$$\beta_c = \frac{a(p_c + k) - E_0(p_c + k)^2 - 2s}{2(t - s)},$$

and the optimal revenue is

$$\prod_t^* = \frac{E_0^2(p_c + k)^2 - 2E_0(p_c + k)}{4} + \frac{2a - a^2}{4} + p_c E_{cap} - C_m.$$

- (ii) If $\frac{a - \sqrt{a^2 - 8tE_0}}{2E_0} \leq p_c + k < \frac{a - \sqrt{a^2 - 8sE_0}}{2E_0}$ or $\frac{a + \sqrt{a^2 - 8sE_0}}{2E_0} < p_c + k \leq \frac{a + \sqrt{a^2 - 8tE_0}}{2E_0}$ for $t > s$, then the manufacturer transfers the emissions reduction to the retailer,

$$\beta_c = \frac{a(p_c + k) - E_0(p_c + k)^2 - 2s}{2(t - s)},$$

and the optimal revenue is

$$\prod_t^* = \frac{E_0^2(p_c + k)^2 - 2E_0(p_c + k)}{4} + \frac{2a - a^2}{4} + p_c E_{cap} - C_m.$$

- (iii) When $t = s$, no matter what the proportion of emissions reduction allocated, the revenue under a centralized decision is

$$\prod_t^* = \frac{at(p_c + k) - t^2}{(p_c + k)^2} - tE_0 + p_c E_{cap} - C_m.$$

For the proof, see the appendix.

4. Numerical example

For our numerical example, we perform a sensitivity analysis of the emissions reduction cost function. We test whether our original results are robust by changing the linear emissions reduction cost function into a quadratic one.

In the above, we have considered the case that the cost of emissions reduction as $C_r = s\alpha(E_0 - E)$ and the manufacturing cost as $C_c = t\beta(E_0 - E)$. If the cost of emissions reduction C_r and the manufacturing cost C_c are considered as $C_r = s\alpha^2(E_0 - E)^2$ and $C_c = t\beta^2(E_0 - E)^2$, respectively, then the manufacturer's revenue given transfer and non-transfer of the emissions reduction task, respectively, are

$$\prod_{m0}^*(w, E) = \frac{8t^2(p_c E_0 + kE_0 - a)^2}{[(p_c + k)^2 - 8t]^2} - C_m - t \left(E_0 - \frac{a(p_c + k) - 8tE_0}{(p_c + k)^2 - 8t} \right)^2 + p_c E_{cap},$$

and

$$\prod_m^*(w, E) = \frac{8t^2\beta^2(p_c E_0 + kE_0 - a)^2}{[(p_c + k)^2 - 8t\beta]^2} - C_m - t\beta \left(E_0 - \frac{a(p_c + k) - 8t\beta E_0}{(p_c + k)^2 - 8t\beta} \right)^2 + p_c E_{cap}.$$

From above mathematical deduction, we know that it is difficult to analyse the decentralized decision and centralized decision. In the following, we use simulation to analyse the functional sensitivity.

Setting $a = 600$, $t = 20$, $E_0 = 55$, $C_m = 100$, $\beta = 0.6$, $E_{cap} = 40$, $p_c = 12$ and $k = 12$ which refers to (Subramanian, Gupta, & Talbot, 2007), then the simulation status of the manufacturer's optimal revenue is shown in Figures 2 and 3, where Figure 2 shows that the comparison of the revenue between carbon emissions transfer and no transfer, while Figure 3 shows the optimal revenue no matter whether the manufacturer transfers emissions or not. From Figure 2, we clearly see that $\prod_m^* \leq \prod_{m0}^*$ when $\frac{a - \sqrt{a^2 - 8tE_0}}{2E_0} \leq p_c + k \leq \frac{a + \sqrt{a^2 - 8tE_0}}{2E_0}$ and $\prod_m^* > \prod_{m0}^*$ holds too when $\frac{a + \sqrt{a^2 - 8tE_0}}{2E_0} < p_c + k < \frac{a}{E_0}$ or $0 < p_c + k < \frac{a - \sqrt{a^2 - 8tE_0}}{2E_0}$. So, it demonstrates that the emissions cost assumption in the model assumption is rational.

With regard to the manufacturer's revenue, when the carbon price and consumer penalty pressure are low, their impact is almost negligible, so the manufacturer's revenue is high. With these constraints increasing, even though the manufacturer transfers part of the emissions burden to the retailer, the manufacturer's cost also increases and revenue decreases. If the pressure increases

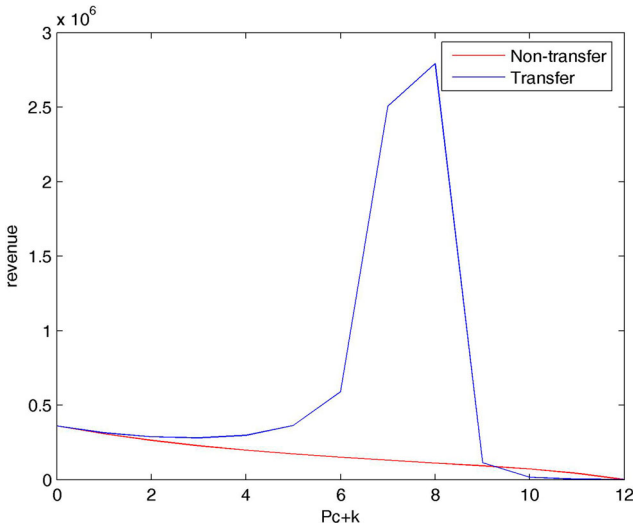


Figure 2. Optimal manufacturer's revenue given Emissions burden transfer or non-transfer for a certain $p_c + k$.

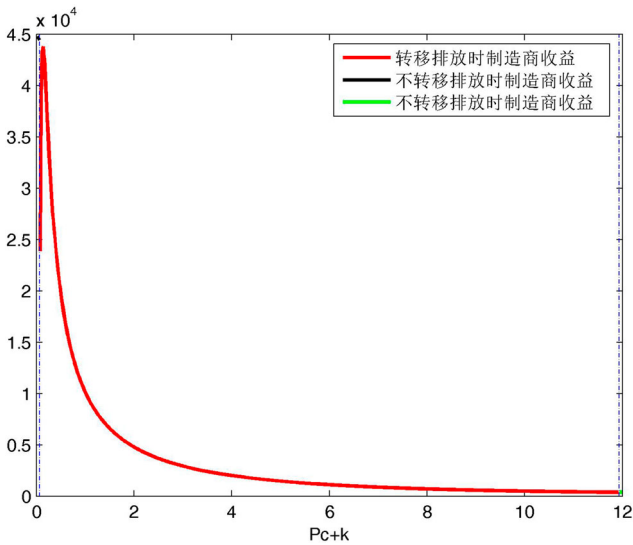


Figure 3. Manufacturer's revenue under the optimal decision.

further, but the manufacturer still transfers the emissions burden to the retailer, the retailer's revenue is so low that it may have no desire to be an agent for the product, which also impacts the manufacturer's revenue. In this case, the manufacturer's strategy is to use price to transfer the cost to the consumer. As Figure 2 illustrates, however, the carbon price and consumer environmental consciousness pressures are seldom too small or too large, so most of the time, the manufacturer transfers the emissions reduction to the retailer.

5. Conclusions

By analysing the decision of one manufacturer and one retailer under carbon price and consumer environmental

consciousness constraints, we offer several important insights into the allocation of carbon emissions reduction and how such decisions affect the consumer. One major finding is that, when the carbon price and consumer consciousness constraints are present in certain intervals, a centralized decision is better than a decentralized decision and, in most cases, it is the optimal manufacturer choice. Nonetheless, even when choosing this mode, the manufacturer is likely to transfer part of the emissions reduction to the retailer, so that, even though demand and consumer welfare increases in the centralized mode, the emissions reduction effectiveness is the same as that in the decentralized mode. Our analysis also points to the following conclusions:

- (1) Under the decentralized decision, whether the manufacturer transfers emission to the retailer which depends on the scope of values of the constraint of carbon price and consumer, in some conditions, the manufacturer is willing to undertake the whole allocation of emission reduction. And the initiative of emission reduction is not always increasing with the high constraint of carbon price and consumer, according to Theorem 3.1, when the pressure from the carbon price and consumer consciousness exceeds a certain level, the manufacturer's motivation to reduce emissions decreases.
- (2) Under the decentralized decision, the manufacturer transfers emissions reduction to the retailer and both demand and consumer welfare decrease, which bears out (Carmona, Fehr, Hinz, & Porchet, 2010; Subramanian et al., 2007) claim that the socially optimal is not always good for the consumer. That is, by undertaking emissions reduction, no matter to what extent, the retailer suffers a loss of revenue, so the amount of emissions reduction undertaken has a baseline.
- (3) Even though the effectiveness of emissions reduction is the same under both a centralized and decentralized decision, demand and consumer welfare is higher under the former. Moreover, when the manufacturer undertakes the entire emissions reduction, there is no improvement in the reduction's effectiveness in either the centralized or decentralized decision, because the entire supply chain collectively is subject to an emissions cap that constrains only one firm.
- (4) Under a centralized decision, a firm considers not only the emissions cost but also its price strategy, enough concern about the minimum cost of emissions reduction may result in decreased demand and prices and thus a reduction in gross revenue. In fact, the BIS(2010) report indicates that consumers pay more attention to cost savings than carbon

emissions, which means that even low-carbon products require the use of a price strategy. Thus, although a centralized decision is good for the manufacturer and consumer, it is not beneficial for the environment.

The demand function in our paper could be affected by consumer preference. In the future, the study will consider the stochastic demand of the model and the effect of threshold of carbon price on the manufacturer's decision.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix

Proof of Theorem 3.1: Substituting (4), (5), (6) and (7) into (2) and (3) yields

$$\begin{aligned} \Pi_r^* &= \frac{(t\beta_d)^2}{(p_c+k)^2} - s\alpha_d(E_0 - E) \\ &= \frac{(t^2+4st)\beta_d^2 - 4st\beta_d - sa(p_c+k)\beta_d + sa(p_c+k)}{(p_c+k)^2} + sE_0\beta_d - sE_0, \end{aligned} \quad (A1)$$

and

$$\Pi_m^* = \frac{at\beta_d(p_c + k) - 2(t\beta_d)^2}{(p_c + k)^2} - C_m + p_c E_{cap} - t\beta_d E_0. \quad (A2)$$

Substituting (8), (9), (10) and (11) into (2) and (3) gives

$$\Pi_r^0 = \frac{t^2}{(p_c + k)^2}, \quad (A3)$$

and

$$\Pi_m^0 = \frac{at(p_c + k) - 2t^2}{(p_c + k)^2} - C_m + p_c E_{cap} - tE_0. \quad (A4)$$

Hence

$$\Pi_m^* - \Pi_m^0 = \frac{t(1 - \beta_d)[E_0(p_c + k)^2 - a(p_c + k) + 2t(1 + \beta_d)]}{(p_c + k)^2}.$$

- (i) When $\frac{a - \sqrt{a^2 - 8tE_0(1 - \beta_d)}}{2E_0} \leq p_c + k \leq \frac{a + \sqrt{a^2 - 8tE_0(1 - \beta_d)}}{2E_0}$, we have from Assumption 2.1 that

$$\Pi_m^* \leq \Pi_m^0.$$

- (ii) When $\frac{a + \sqrt{a^2 - 8tE_0(1 - \beta_d)}}{2E_0} < p_c + k$ or $0 < p_c + k < \frac{a - \sqrt{a^2 - 8tE_0(1 - \beta_d)}}{2E_0}$, we get from Assumption 2.1 that

$$\Pi_m^* > \Pi_m^0.$$

The proof is complete. \blacksquare

Proof of Theorem 3.2: According to (4) and (8), we can obtain that

$$E^* - E^0 = \frac{4t - 4t\beta_d}{(p_c + k)^2} = \frac{4t(1 - \beta_d)}{(p_c + k)^2} \geq 0,$$

hence

$$E^* \geq E^0.$$

According to (7) and (11), we can get that

$$Q^* - Q^0 = -\frac{t(1 - \beta_d)}{p_c + k} \leq 0,$$

therefore

$$Q^* \leq Q^0.$$

According to (5) and (6), when the retailer undertakes the emissions reduction, its revenue per product unit is

$$p^* - w^* = \frac{t\beta_d}{p_c + k}.$$

According to (9) and (10), when the retailer undertakes no emissions reduction, its revenue per unit product is

$$p^0 - w^0 = \frac{t}{p_c + k}.$$

Hence

$$(p^* - w^*) - (p^0 - w^0) = -\frac{t(1 - \beta_d)}{p_c + k} < 0.$$

When the retailer undertakes emissions reduction, consumer welfare can be written as

$$\int_0^{Q^*} (a - Q - kE^*)dQ = \frac{1}{2}(Q^*)^2 = \frac{(t\beta_d)^2}{2(p_c + k)^2}. \quad (A5)$$

When it does not, consumer welfare can be expressed as

$$\int_0^{Q^0} (a - Q - kE^0)dQ = \frac{1}{2}(Q^0)^2 = \frac{t^2}{2(p_c + k)^2}. \quad (A6)$$

A comparison of (A5) and (A6) shows that if the manufacturer decides to transfer the emissions reduction to the retailer, consumer welfare decreases.

The proof is complete. \blacksquare

Proof of Theorem 3.3: Substituting (13), (14) and (15) into (12) yields

$$\prod_t^* = \frac{a(p_c + k)(s\alpha_c + t\beta_c) - (s\alpha_c + t\beta_c)^2}{(p_c + k)^2} - (s\alpha_c + t\beta_c)E_0 + p_c E_{cap} - C_m. \quad (A7)$$

Let $X = s\alpha_c + t\beta_c$, then $\prod_t^* = \frac{a(p_c + k)X - X^2}{(p_c + k)^2} - XE_0 + p_c E_{cap} - C_m$.

It is easy to compute that

$$\frac{d^2 \prod_t^*}{dX^2} < 0.$$

Hence, \prod_t^* has a maximum. Let $\frac{d\prod_t^*}{dX} = 0$, which yields

$$X = \frac{a(p_c + k) - E_0(p_c + k)^2}{2} = (s\alpha_c + t\beta_c). \quad (A8)$$

So,

$$\beta_c = \frac{a(p_c + k) - E_0(p_c + k)^2 - 2s}{2(t - s)}. \quad (A9)$$

It follows from $0 < \beta_c \leq 1$ that

$$0 < \frac{a(p_c + k) - E_0(p_c + k)^2 - 2s}{2(t - s)} \leq 1. \quad (A10)$$

- (i) If $\frac{a - \sqrt{a^2 - 8sE_0}}{2E_0} < p_c + k \leq \frac{a - \sqrt{a^2 - 8tE_0}}{2E_0}$ or $\frac{a + \sqrt{a^2 - 8tE_0}}{2E_0} \leq p_c + k < \frac{a + \sqrt{a^2 - 8sE_0}}{2E_0}$ for $t > s$, then we can get from (A10) that the optimal revenue is

$$\prod_t^* = \frac{E_0^2(p_c + k)^2 - 2E_0(p_c + k)}{4} + \frac{2a - a^2}{4} + p_c E_{cap} - C_m.$$

- (ii) If $\frac{a - \sqrt{a^2 - 8tE_0}}{2E_0} \leq p_c + k < \frac{a - \sqrt{a^2 - 8sE_0}}{2E_0}$ or $\frac{a + \sqrt{a^2 - 8sE_0}}{2E_0} < p_c + k \leq \frac{a + \sqrt{a^2 - 8tE_0}}{2E_0}$ for $t > s$, then we can get from (A10) that the optimal revenue is

$$\prod_t^* = \frac{E_0^2(p_c + k)^2 - 2E_0(p_c + k)}{4} + \frac{2a - a^2}{4} + p_c E_{cap} - C_m.$$

- (iii) When $t = s$, we can get from (A10) that centralized decision revenue is

$$\prod_t^* = \frac{at(p_c + k) - t^2}{(p_c + k)^2} - tE_0 + p_c E_{cap} - C_m.$$

The proof is complete. \blacksquare