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The role of co-opetition in low carbon manufacturing

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Abstract: Low carbon manufacturing has become a strategic objective for many developed and developing economies. This study examines the role of co-opetition in achieving this objective. We investigate the pricing and emissions reduction policies for two rival manufacturers with different emission reduction efficiencies under the cap-and-trade policy. We assume that the product demand is price and emission sensitive. Based on non-cooperative and cooperative games, the optimal solutions for the two manufacturers are derived in the purely competitive and co-opetitive market environments respectively. Through the discussion and numerical analysis, we uncovered that in both pure competition and co-opetition models, the two manufacturers' optimal prices depend on the unit price of carbon emission trading. In addition, higher emission reduction efficiency leads to lower optimal unit carbon emissions and higher profit in both the pure competition and co-petition models. Interestingly, compared to pure competition, co-opetition will lead to more profit and less total carbon emissions. However, the improvement in economic and environmental performance is based on higher product prices and unit carbon emissions.

Keywords: Low carbon manufacturing, co-opetition, carbon emission reduction, green technology investment, game theory.

1 Introduction

Decades of research has demonstrated that the fossil fuel leads to a higher carbon dioxide and greenhouse gases in the atmosphere which poses threats and challenges to human lives (Tang and Zhou, 2012; Chen and Hao, 2015). The recent economic recovery of many industrialized countries and the continuing industrialization of emerging economies have contributed to further global carbon emissions. Across different industry sectors, the manufacturing industry is often the single largest contributor to carbon emissions in many developed and developing economies (Fysikopoulos *et al.*, 2014). Carbon footprint, historically defined as the total set of greenhouse gas emissions caused by an organization, event, product or person, has become a key evaluation factor when companies choose suppliers or customers make a purchase decision. For example, Walmart, Tesco, Hewlett Packard, and Patagonia require their suppliers to complete the carbon footprint certification and to guide customers to consider carbon footprint index rather than just the price and quality (Sundarakani *et al.*, 2010). Faced with novel realities, new generation of manufacturing process technologies has emerged (Chryssolouris *et al*., 2008; Fysikopoulos *et al.*, 2014). Low carbon manufacturing defined as the manufacturing process that produces low carbon emission intensity through the effective and efficient use of energy and resources during the process (Tridech and Cheng, 2011; Chryssolouris, 2013). It has therefore become an important area of public policy and scholarly enquiry set against the background of increasing political and societal concerns about carbon emissions.

One response from regulatory and policy makers is to introduce various carbon emissions reduction policies such as mandatory carbon emission capacity and carbon emission taxes. In addition, many governments have also supplemented traditional “command and control” with emission trade schemes through which creating financial incentives for companies to invest in green innovations (Adit and Dutta, 2004; Stavins, 2008; Chaabane *et al.*, 2012; Lukas and Welling, 2014). Among these schemes, cap-and-trade is one of the most influential regulatory policies, which provides the manufacturing sector a flexible market mechanism and a viable carbon emission reduction method. Manufacturers are motivated to reduce their carbon emissions level by improving energy efficiency of production process through green technology investment. While this policy may play a key role in achieving low carbon manufacturing, it will certainly affect firms' decisions at both strategic and operational levels.

In similar vein, the general public has also become increasingly sensitive to environmental issues. Buying low carbon products has become an irreversible trend. More importantly, this trend is no longer simply the choice of a few eco-conscious consumers, but has now shifted into the mainstream market (Tsen *et al*., 2006; Fraj and Martinez, 2007; Kanchanapibul *et al*., 2014). For example, Echeverría *et al.* (2014) indicated that consumers are willing to pay a premium price to products with carbon footprint. Consequently, carbon emission attribute of products has become an important factor influencing purchasing decisions and product demands. The growing number of environmental consciousness consumers gives manufacturing firms an economic incentive to invest in green technologies and to achieve low carbon manufacturing. At least, the emission sensitive demand should be considered when making the product pricing and emission reduction decisions.

From manufacturers' perspective, there is increasing realisation of the importance of carbon emissions reduction. One important strategic response from the manufacturing sector is cooperation between autonomous firms such as supply chain collaboration, strategic alliances, and eco-industrial parks, focusing on inter-organizational interactions to reduce carbon emissions and other negative environmental effects (Kolk and Pinkse, 2004; Tudor *et al.*, 2007; Theißen and Spinler, 2014). The cooperation between competing firms for low carbon manufacturing is closely associated to the notion of co-opetition introduced by Brandenburger and Nalebuff (1996), which refers to the interdependence that entails competing and collaborating elements, with rivalry as well as collaborative mechanisms to maximize individual profits. Although the benefits of environmental collaboration have been widely discussed in the literature, to the best of our knowledge, no research has examined the role of co-opetition in low carbon manufacturing. Our research aims to fill this gap in the literature by examining the following key questions:

(1) Under the cap-and-trade policy, what effect does the manufacturers' carbon emission reduction efficiency have on their optimal prices, optimal green technology investments, and maximum profits?

(2) How to develop a pricing policy and green technology investment strategy to help

manufacturers to maximize their economic benefit while minimizing the negative environmental impact?

(3) What effect does the purely competitive and co-opetitive relationships have on low carbon manufacturing?

To answer these questions, we consider two competing manufacturers with different emission reduction efficiencies under the cap-and-trade policy. They produce a same product and sell to end-users with a deterministic demand which is influenced by their own and competing manufacturer’s prices and unit carbon emissions. Using the non-cooperative and cooperative games, our analysis attempts to derive the optimal pricing policies and green technology investment decisions for the two manufacturers in purely competitive and co-opetitive environments respectively. We also examine the effect of emission reduction efficiency and unit price of carbon emission trading on the manufacturers’ optimal policies and maximum profits. Through a comparison of the optimal solutions between the purely competitive scenario and the co-opetitive scenario, this research intends to understand the role that co-opetition has in low carbon manufacturing.

The rest of this paper is organized as follows. A survey of related literature is presented in Section 2. Section 3 provides the model formulation and assumptions. In Section 4 and 5, we investigate the pricing and emission reduction policies for two competing manufacturers in a purely competitive scenario and a co-opetitive scenario respectively. In Section 6, we focus on the effect of emission reduction efficiency on the two competing manufacturers’ optimal decisions. The numerical examples presented in Section 7 analyse the effect of co-opetition on the optimal policies, total carbon emissions and maximum profits. Finally, we conclude our research findings and highlight possible future work in Section 8.

2 Literature review

The literature reviewed here primarily relates to three streams of research: (i) effect of cap-and-trade policy on firms’ decisions, (ii) models with price and emission sensitive demand, and (iii) the impact of cooperation on environmental and organizational performances.

The first relevant stream of literature looks into impact of cap-and-trade policy on green operations and supply chain management. Among the earlier works, Dobos (2005) studied the effect of cap-and-trade policy on firms' decision and then obtained the optimal production quantity. Letmathe and Balakrishnan (2005) constructed two models with mandatory carbon emissions capacity, carbon emissions tax and cap-and-trade policies. They obtained the optimal product structure and production quantity, and then analysed the effects of cap, tax and trade price on optimal structure and optimal product quantity. Rong and Lahdelma (2007) developed a production model of a thermal power plant under cap-and-trade policy, and the optimal production quantity was obtained using stochastic optimization methods. More recently, Hua *et al.* (2011) studied a firm's optimal order quantity under deterministic demand with cap-and-trade. They analysed the effects of carbon cap-and-trade policy on optimal order quantity, total carbon emissions and total cost. Bouchery *et al*. (2012) expanded the traditional EOQ model to multi-objective decision model and obtained optimal order quantity under carbon emissions constraint. In addition, they discussed the effect of carbon emissions policies on optimal order quantity. Song and Leng (2012) investigated the single-period newsvendor problem with carbon emissions policies and analysed the effect of different emissions policies on firm's order quantity. Their findings indicate that the optimal condition increase profits and reduce carbon emissions. Zhang and Xu (2013) studied a multi-item production firm which faced a stochastic demand and obtained the optimal product quantity. Their research also discussed the impact of carbon cap and trade price on optimal policy and profits. Similarly, Rosic and Jammernegg (2013) studied a single retailer with dual sourcing model and obtained the optimal order quantity and optimal order sourcing under cap-and-trade and carbon tax. Benjaafar *et al.* (2013) illustrated the impact of operation decisions on carbon emissions through a series of models. Their findings demonstrate that adjustments to the ordering policy can significantly reduce emissions without considerably increasing cost whereas the choice of pollution control mechanisms e.g. cap-and-trade can achieve the same emission reduction but incurring substantial differing costs. Toptal *et al.* (2014) studied a single manufacturer's joint decisions on inventory replenishment and emission reduction investment under condition of carbon cap, tax and cap-and-trade policies. Although the literature on firms' optimal decisions under cap-and-trade policy is rich as illustrated above, most of them do not take price and emission sensitive demand into consideration.

Among the few studies that consider price and emission sensitive demand, Arora and Gangopadhyay (1995), Bansal and Gangopadhyay (2003) found that when a product has low-carbon attribute, consumers are willing to pay additional prices for the product.as a result, the manufacturer is willing to win customers by reducing carbon emissions. Other studies such as Geffen and Rothenberg (2000), Laroche *et al.* (2001), Innes and Robert (2006), Zhu and Sarkis (2007), Liu *et al.* (2012) and Zhang (2015) also demonstrated that carbon emission reduction strategy is influenced by customer environmental consciousness. Yalabik and Fairchild (2011) and Choudhary *et al.* (2015) discussed a manufacturer who faces the pressure of regulatory penalties and reduced demand as a result of emissions and obtained the optimal price and optimal emissions level. Sengupta (2012) studied the pricing behaviour of a firm with environmentally conscious consumers. The research findings pointed out that when firms realize that consumers are environmentally sensitive, they would directly disclose their environmental performance to obtain better market response. Nouira *et al.* (2014) examined the effect of emission sensitive customers on manufactures' profits with conditions of price sensitive demand and price and emission sensitive demand. Du *et al.* (2015) studied a two-stage supply chain consisting of one single emission dependent manufacturer and one single emission permit supplier under cap-and-trade policy but not mention price sensitive demand. Although there are a few studies taking price and emission sensitive demand into account, often only one manufacturer is considered in these models without mentioning the market competition between rival manufacturers.

Another relevant stream of literature looks into the impact of environmental collaboration on environmental and organizational performance. For instance, Geffen and Rothenberg (2000) examined the role of strategic partnership between manufacturers and their suppliers in accomplishing the environmental performance targets through three case studies of US assembly plants. They concluded that the strongest coordination between the supply chain partners achieves the greatest success. Through the research on a sample of Canadian manufacturing plants, Klassen and Vachon (2003) revealed that supply chain collaboration significantly affect both the level and form of investment in environmental technologies. Vachon and Klassen (2008) examined the relationship between supply chain environmental collaboration and manufacturing performance. Their findings indicate that environmental collaboration can have a significant positive impact on both environmental and manufacturing performances. Through the investigation on environmental-oriented supply chain cooperation in China, Zhu *et al.* (2010) emphasized the importance of intensive cooperation with supply chain partners for a circular economy initiative to succeed. The findings from Green *et al.* (2012) also supported the view that environmental collaboration and monitoring among supply chain partners can lead to improved environmental performance and organizational performance. Nevertheless, the above mentioned literatures on environmental collaboration mainly focus on the supply chain vertical cooperation between manufacturers and their suppliers or between manufacturers and their customers. In addition, very few studies have attempted to examine the effort of the horizontal environmental collaboration between the competing manufacturers, i.e., co-opetition on the environmental and organisational performance. Many studies (Gnyawali and He, 2006; Gurnani *et al*., 2007; Gnvawali and Park, 2011; Li *et al*., 2011; Zhang and Frazier, 2011) have examined the impact of co-opetition on firms' strategic and operational decisions and their organizational performance. However, the co-opetition may also play an important role in achieving carbon efficient economy. This research seeks to address this gap.

3 Model descriptions and assumption

We consider two competing manufacturers who have different emission reduction efficiencies. We denote our parameters and variables for model development as the notations shown in Table 1. The green technology investment is assumed as a disposable (one-off) investment to improve the production process which turns raw material into product. Unit product consumes unit practical raw material. Through that, we aim to make initial unit carbon emissions e_0 decrease to e_i $(i = 1, 2)$ per product to achieve greener product. For example, the carbon footprint for the production of a hamburger adds 2.5 kg (5.5lbs) CO_2e (Berners-Lee, 2011). The investment is $I_i = t_i(e_0 - e_i)^2$ (Yalabik and Fairchild, 2011; Choudhary *et al.*, 2015). It is easy to see that the investment is convexity on e_i, which is attributed to diminishing returns from expenditures (Tsay and Agrawal, 2000; Chen, 2001; Bhaskaran and Krishnan, 2009; Ghosh and Shah, 2011). Without loss of generality, we assume that the emission reduction efficiency of manufacturer 1 is higher than that of manufacturer 2, namely $0 < t_1 < t_2$. The demand faced by the manufacturer i is price and emissions sensitive, that is, $q_i = a - b_1 p_i + b_2 p_j - k_1 e_i + k_2 e_j$ ($i = 1, 2, j = 3 - i$), where $b_1 > b_2 > 0$ and $k_1 > k_2 > 0$. $b_1 > b_2 > 0$ means the influence of the self-price sensitivity is higher than cross-price sensitivity, and $k_1 > k_2 > 0$ means that self-carbon emission sensitivity is higher than cross-carbon emission sensitivity. The manufacturers' revenues include sale revenues and carbon emission trading revenues (if $E_i < 0$), and the costs include manufacturing costs, green technology investments and carbon emission trading costs (if $E_i > 0$). To avoid trivial, we assume that the parameters satisfy the conditions: $X_i > 0$, $Y_i > 0$ and $M_1 M_2 - N_1 N_2 > 0$ ($i = 1,2$). These assumptions are simply mathematical conditions to ensure non-negativity of the decision variables.

Table 1. Parameters and variables

Notation	Descriptions
q_1 , q_2	Production quantity or customer demand of manufacturer 1 and 2 respectively
p_1 , p_2	Unit retail price of manufacturer 1 and 2 respectively
e_0	Initial unit carbon emissions of manufacturer 1 and 2, $e_0 > 0$
e_1 , e_2	Unit carbon emissions after green technology investment of manufacturer 1 and 2 respectively, $0 < e_1 < e_0$ and $0 < e_2 < e_0$ (Zhang and Xu, 2013; Yalabik and Fairchild, 2011; Choudhary *et al.*, 2015; Du *et al.*, 2015)
c	Unit production cost, $0 < c < p_1$ and $0 < c < p_2$
a	The primary market size, $a > 0$
b_1 , b_2	Self-price sensitivity and cross-price sensitivity, $b_1 > b_2 > 0$
k_1 , k_2	Self-carbon emission sensitivity and cross-carbon emission sensitivity, $k_1 > k_2 > 0$
t_1 , t_2	An investment parameter and a function of emission reduction efficiency of manufacturer 1 and 2 respectively, $0 < t_1 < t_2$
I_1 , I_2	The green technology investment of manufacturer 1 and 2 respectively
K_1 , K_2	Total carbon emissions of manufacturer 1 and 2 respectively
K	Initial carbon emission allowances of government, $K > 0$
λ	Unit price of carbon emission trading, $\lambda > 0$
E_1 , E_2	Total carbon emissions trading, $E_i > 0$ means buying carbon emission quotas and $E_i < 0$ means selling carbon emission quotas
M_i	$4b_1 t_i - (k_1 + \lambda b_1)^2$
N_i	$2b_2 t_i - (k_1 + \lambda b_1)(k_2 + \lambda b_2)$
A_i	$\frac{[a - (b_1 - b_2)(c + \lambda e_0) - (k_1 - k_2)e_0](M_j + N_j)}{M_1 M_2 - N_1 N_2}, i = 1,2, \ j = 3 - i$
X_i	$M_i - (k_2 + \lambda b_2)^2$
Y_i	$2N_i$

B_i	$\dfrac{[a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0]\big(X_j+Y_j\big)}{X_1X_2-Y_1Y_2}, i=1,2，j=3-i$
C	$\dfrac{2[a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0](t_2-t_1)(k_2+\lambda b_2)(k_1+\lambda b_1+k_2+\lambda b_2)}{X_1X_2-Y_1Y_2}$

Base on the above assumptions, the manufacturer 1's profit, denoted $\pi_1(p_1, e_1)$, is

$$\pi_1(p_1, e_1) = (p_1 - c)(a - b_1p_1 + b_2p_2 - k_1e_1 + k_2e_2) - t_1(e_0 - e_1)^2 - \lambda E_1 \qquad (1)$$

The first term is the profit from product sale. The second term means the green technology investment. And the last term represents the cost or revenue from buying or selling carbon emission quotas from or to the carbon market. Similarly, the manufacturer 2's profit, denoted $\pi_2(p_2, e_2)$, is

$$\pi_2(p_2, e_2) = (p_2 - c)(a - b_1p_2 + b_2p_1 - k_1e_2 + k_2e_1) - t_2(e_0 - e_2)^2 - \lambda E_2 \qquad (2)$$

Then, the total profit of manufacturer 1 and 2, denoted $\pi_c(p_1, e_1, p_2, e_2)$, is

$$\pi_c(p_1, e_1, p_2, e_2) = \pi_1(p_1, e_1) + \pi_2(p_2, e_2) \qquad (3)$$

4 Pure competition model

In a purely competitive market environment, manufacturer 1 and manufacturer 2 make their decisions separately to maximize their own profits. The decision problem faced by manufacturer 1 is

$$max\ \pi_1(p_1, e_1)$$
$$s.t.\ e_1q_1 - E_1 = K$$

And the decision problem faced by manufacturer 2 is

$$max\ \pi_2(p_2, e_2)$$
$$s.t.\ e_2q_2 - E_2 = K$$

As to the manufacturers' optimal prices (p_i^n) and unit carbon emissions (e_i^n) with cap-and-trade policy in the pure competition model, the following proposition is obtained.

Proposition 1 ***In the pure competition model, with cap-and-trade policy,*** $\boldsymbol{p_1^n = c + \lambda e_0 + [2t_1 - (k_1 + \lambda b_1)\lambda]A_1}$, $\boldsymbol{p_2^n = c + \lambda e_0 + [2t_2 - (k_1 + \lambda b_1)\lambda]A_2}$, $\boldsymbol{e_1^n = e_0 - (k_1 + \lambda b_1)A_1}$ ***and*** $\boldsymbol{e_2^n = e_0 - (k_1 + \lambda b_1)A_2}$.

From proposition 1, we obtain manufacturer 1's optimal production quantity (q_1^n) and manufacturer 2's optimal production quantity (q_2^n) in the pure competition model as following:

$$q_1^n = 2b_1 t_1 A_1 \tag{4}$$

$$q_2^n = 2b_1 t_2 A_2 \tag{5}$$

From proposition 1, we obtain the optimal green technology investments of manufacturer 1 (I_1^n) and manufacturer 2 (I_2^n) in the pure competition model respectively as following:

$$I_1^n = t_1(k_1 + \lambda b_1)^2 A_1^2 \tag{6}$$

$$I_2^n = t_2(k_1 + \lambda b_1)^2 A_2^2 \tag{7}$$

Then, we get the following corollary.

Corollary 1 ***In the pure competition model,*** $\boldsymbol{p_1^n}$***,*** $\boldsymbol{p_2^n}$***,*** $\boldsymbol{q_1^n}$***,*** $\boldsymbol{q_2^n}$***,*** $\boldsymbol{I_1^n}$***,*** $\boldsymbol{I_2^n}$***,*** $\boldsymbol{\pi_1(p_1^n, e_1^n)}$ ***and*** $\boldsymbol{\pi_2(p_2^n, e_2^n)}$ ***all increase in*** $\boldsymbol{a}$***, both*** $\boldsymbol{e_1^n}$ ***and*** $\boldsymbol{e_2^n}$ ***decrease in*** $\boldsymbol{a}$***.*** $\boldsymbol{q_1^n}$***,*** $\boldsymbol{q_2^n}$***,*** $\boldsymbol{I_1^n}$***,*** $\boldsymbol{I_2^n}$***,*** $\boldsymbol{\pi_1(p_1^n, e_1^n)}$ ***and*** $\boldsymbol{\pi_2(p_2^n, e_2^n)}$ ***all decrease in c, both*** $\boldsymbol{e_1^n}$ ***and*** $\boldsymbol{e_2^n}$ ***all increase in c.***

Corollary 1 explores manufacturers' optimal decisions and the corresponding economic and environmental performances when facing the changing external environment e.g. primary market size (a) in purely competitive scenario. From the economics standpoint, it is not difficult to understand that an increase in the primary market size of goods will result in higher price and production quantity, which is an effective mechanism to balance the supply and demand. From manufacturers' perspective, as the primary market size increases, the two manufacturers may adopt low-price strategy to gain market share in the short term. However, it is not a sustainable solution in the long term. A manufacturer who wants to maintain competitive advantage and capture more orders would like to invest more on green technology to decrease unit carbon emission. Because of an increased investment, manufacturers will pass on the additional costs to the end consumers, which contribute to higher prices. Therefore, facing an increasing primary market size, the manufacturers can gain more profit by raising price and increasing green technology investment. Use carbon-intensive sectors like steel industry in China as an example, most steel manufacturers use low pricing strategy to compete in order to gain market share. In contrast to other big steel manufacturers, Baosteel employs a completely different strategy. They invest heavily on technologies including green technologies to improve production processes and product quality while keep the premium price of their products. Although most steel manufacturers grew their sales and profits during the economic boom time, Baosteel is one of very few Chinese steel manufacturers that still performs well and remains competitive while others are struggling in the current economic slowdown in China.

5 Co-opetition model

In a co-opetitive market environment, manufacturer 1 and manufacturer 2 jointly make their decision and aim to maximize their total profits. The decision problem faced by manufacturer 1 and 2 is

$$max\ \pi_c(p_1, e_1, p_2, e_2)$$
$$s.t.\ e_1 q_1 - E_1 = K$$
$$e_2 q_2 - E_2 = K$$

As to the manufacturers' optimal prices (p_i^c) and unit carbon emissions (e_i^c) with cap-and-trade policy in the co-opetition model, the following proposition is obtained.

Proposition 2 ***In the co-opetition model, with cap-and-trade policy,*** $\boldsymbol{p_1^c = c + \lambda e_0 + [2t_1 - (k_1 - k_2 + \lambda b_1 - \lambda b_2)\lambda]B_1 - C}$, $\boldsymbol{p_2^c = c + \lambda e_0 + [2t_2 - (k_1 - k_2 + \lambda b_1 - \lambda b_2)\lambda]B_2 + C}$, $\boldsymbol{e_1^c = e_0 - [(k_1 - k_2) + (b_1 - b_2)\lambda]B_1}$ ***and*** $\boldsymbol{e_2^c = e_0 - [(k_1 - k_2) + (b_1 - b_2)\lambda]B_2}$**.**

From proposition 2, we obtain manufacturer 1's optimal production quantity (q_1^c) and manufacturer 2's optimal production quantity (q_2^c) in the co-opetition model as following:

$$q_1^c = 2b_1 t_1 B_1 - 2b_2 t_2 B_2 - (b_1 + b_2)C \tag{8}$$

$$q_2^c = 2b_1 t_2 B_2 - 2b_2 t_1 B_1 + (b_1 + b_2)C \tag{9}$$

From proposition 2, we obtain the optimal green technology investments of manufacturer 1 (I_1^c) and manufacturer 2 (I_2^c) in the co-opetition model respectively is

$$I_1^c = t_1[(k_1 - k_2) + (b_1 - b_2)\lambda]^2 B_1^2 \tag{10}$$

$$I_2^c = t_2[(k_1 - k_2) + (b_1 - b_2)\lambda]^2 B_2^2 \tag{11}$$

Then, we get the following corollary.

Corollary 2 ***In the co-opetition model,*** $\boldsymbol{p_1^c}$, $\boldsymbol{p_2^c}$, $\boldsymbol{q_1^c}$, $\boldsymbol{q_2^c}$, $\boldsymbol{I_1^c}$ ***and*** $\boldsymbol{I_2^c}$ ***all increase in a,*** $\boldsymbol{e_1^c}$ ***and*** $\boldsymbol{e_2^c}$ ***decrease in a.*** $\boldsymbol{q_1^c}$, $\boldsymbol{q_2^c}$, $\boldsymbol{I_1^c}$ ***and*** $\boldsymbol{I_2^c}$ ***all decrease in c,*** $\boldsymbol{e_1^c}$ ***and*** $\boldsymbol{e_2^c}$ ***all increase in c.***

Similar to Corollary 1, Corollary 2 also explore effect of primary market size and unit production cost on the two manufacturers' optimal solutions as well as economic performance in the co-opetitve scenario. From this corollary, we know that with cap-and-trade policy, when the primary market size is big, the manufacturers will set higher prices, produce more products with lower unit carbon emissions, and increase green technology investments in a co-opetitive market environment. When the unit production cost is high, the manufacturers will decrease the production quantities and green technology investments. As a result, the unit carbon emissions are higher. Therefore, it is critical for manufacturers in the co-opetitive environment to reduce unit production cost, which will lead to lower unit carbon emissions and increased production quantity. Ultimately, it will enable manufacturers to gain more market share. From the above analysis, we can see the way how the primary market size (a) and the unit product cost (c) affect the two manufacturers' decisions and associated economic performance shows some common attributes in both the purely competitive and co-opetitive relationships. Nevertheless, in order to examine the role of co-opetition in low carbon manufacturing, we will explore the key differences how the competitive and co-opetitive relationships between the two manufacturers affect their operational and strategic decisions as well as the associated economic and environmental performances in the following sections.

6 Discussions

In this section, we discuss the effects of emission reduction efficiency on the two competing manufacturers' optimal prices, optimal unit carbon emissions, optimal production quantities and optimal green technology investments in the purely competitive and co-opetitive scenarios. The following two propositions can be obtained.

Proposition 3 ***With cap-and-trade policy, (1) in the pure competition model, if*** $\lambda \leq \frac{k_1+k_2}{b_1}$***, then*** $p_1^n \geq p_2^n$***; if*** $\lambda > \frac{k_1+k_2}{b_1}$***, then*** $p_1^n < p_2^n$***;*** $e_1^n < e_2^n$***. (2) In the co-opetition model, if*** $\lambda \leq \frac{k_1+k_2}{b_1+b_2}$***, then*** $p_1^c \geq p_2^c$***; if*** $\lambda > \frac{k_1+k_2}{b_1+b_2}$***, then*** $p_1^c < p_2^c$***;*** $e_1^c < e_2^c$***.***

It is easy to see that with cap-and-trade policy, the optimal unit carbon emission of manufacturer with high emission reduction efficiency (manufacturer 1) is lower than that of manufacturer with low emission reduction efficiency (manufacturer 2) in both pure competition and co-opetition models. That is, in a sort of sense, how green a product is depends on the emission reduction efficiency of green technology. Therefore, emission reduction efficiency is an important factor that should be considered in firms' decision on green technology adoption. On the other hand, the pricing decision is influenced not only by the emission reduction efficiency (t_i) but also the unit price of carbon emission trading (λ). In both purely competitive and co-opetitive scenarios, if unit price of carbon emission trading (λ) is lower than certain ratios, then the optimal price of the manufacturer with high emission reduction efficiency (manufacturer 1) is higher than that of the manufacturer with low emission reduction efficiency (manufacturer 2). Otherwise, as unit price of carbon emission trading (λ) is higher than these ratios, the relationship between the two optimal prices will change in an opposite direction. This ratio in the purely competition model is decided by carbon emission sensitivities of both manufacturers and self-price sensitivity of manufacturer 1. In contrast, this ratio in the co-opetition model is decided by carbon emission sensitivities and price sensitivities of both manufacturers.

Proposition 4 ***With cap-and-trade policy, (1)*** $\boldsymbol{q_1^n > q_2^n}$ ***and*** $\boldsymbol{I_1^n > I_2^n}$ ***in the pure competition model. (2)*** $\boldsymbol{q_1^c > q_2^c}$ ***and*** $\boldsymbol{I_1^c > I_2^c}$ ***in the co-opetition model.***

This proposition means that with cap-and-trade polity, the optimal production quantity and optimal investment in green technology of manufacturer with high emission reduction efficiency are both higher than that of manufacturer with low emission reduction efficiency in both the purely competition and co-opetition models.

7 Numerical examples

In this section, we develop two numerical analyses: effect of emission reduction efficiency (t_1) and unit price of carbon emission trading (λ). Through a comparison of the optimal solutions between the purely competitive scenario and the co-opetitive scenario, we aim to analyse the effect of co-opetition on manufacturers' optimal solutions, total carbon emissions ($K_i = e_i q_i$, $i = 1, 2$) and maximum profits.

According to the model description and assumption in Section 3, the values must satisfy $a > 0$, $b_1 > b_2 > 0$, $k_1 > k_2 > 0, q_i > 0$, $e_0 > 0$, $c > 0$, $\lambda > 0$, $K > 0$ and $0 < t_1 < t_2$. In addition, the above ranges must satisfy $a - (b_1 - b_2)(c + \lambda e_0) - (k_1 - k_2)e_0 > 0$, $X_i > 0$, $Y_i > 0$ and $M_1 M_2 - N_1 N_2 > 0$ ($i = 1, 2$), so that to ensure non-negativity of the decision variables. Therefore, we specify that $a = 800$, $b_1 = 50$, $b_2 = 30$, $k_1 = 60$, $k_2 = 30$, $e_0 = 5$, $c = 5$ $\lambda = 4$ and $K = 100$. Due to the symmetry of manufacturer 1 and 2, we hold

$t_2 = 1500$ to explore the effect of emission reduction efficiency (t_1); and then, we specify another numerical example which includes $a = 800, b_1 = 30, b_2 = 20, k_1 = 30, k_2 = 10$, $e_0 = 5$, $c = 5$, $K = 100$, $t_1 = 1500$ and $t_2 = 2000$, to explore the effect of unit price of carbon emission trading (λ). Through these two numerical examples, we attempt to explore the effect of co-opetition on low carbon manufacturing. The results are given in Figure 1-12.

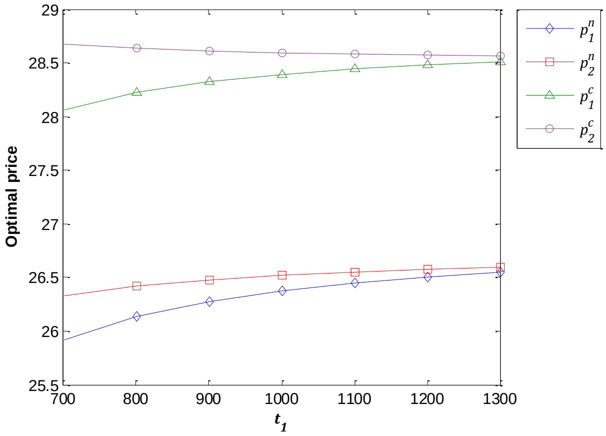

Figure 1. Effect of t_1 on optimal price

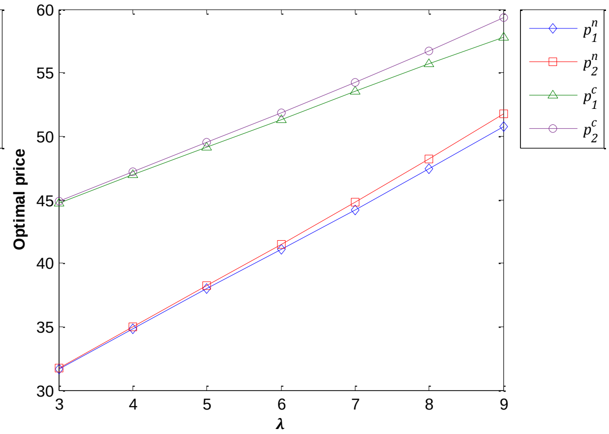

Figure 2. Effect of λ on optimal price

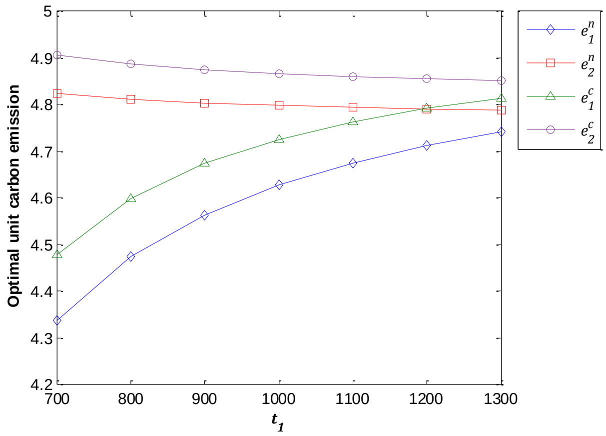

Figure 3. Effect of t_1 on optimal unit carbon emissions

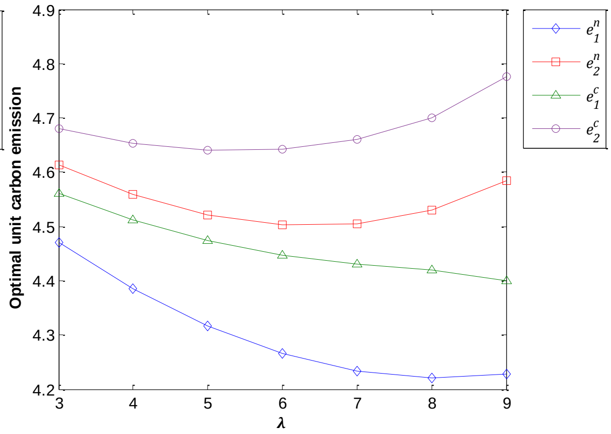

Figure 4. Effect of λ on optimal unit carbon emissions

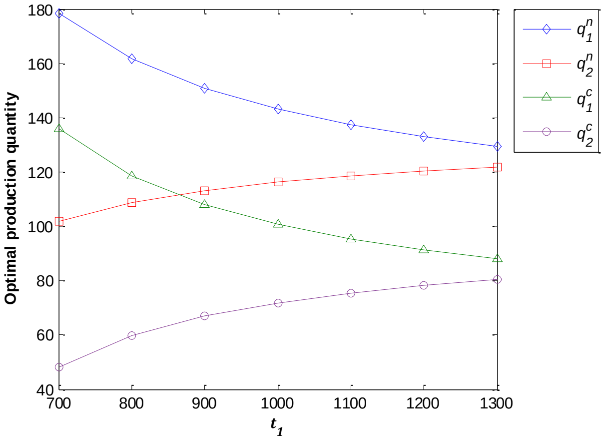

Figure 5. Effect of t_1 on optimal production quantity

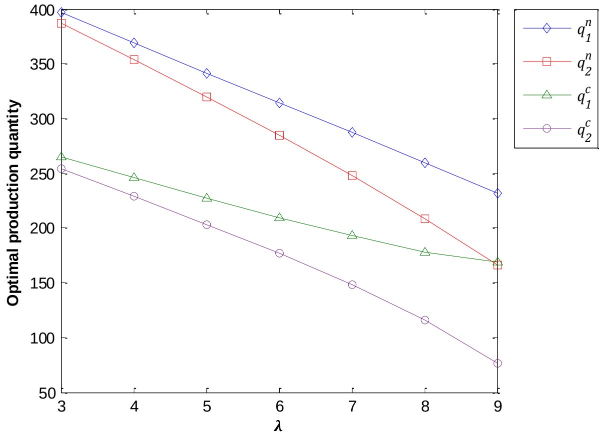

Figure 6. Effect of λ on optimal production quantity

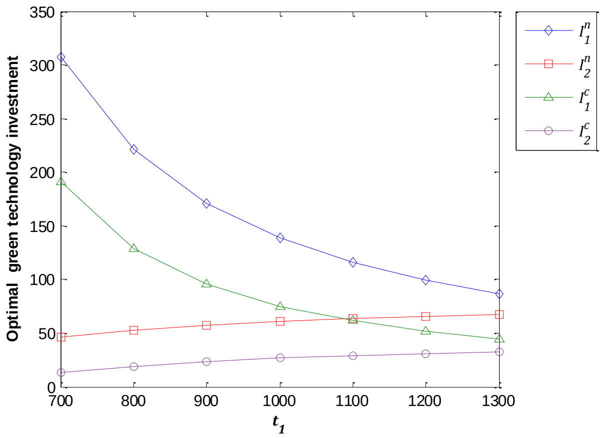

Figure 7. Effect of t_1 on optimal investment

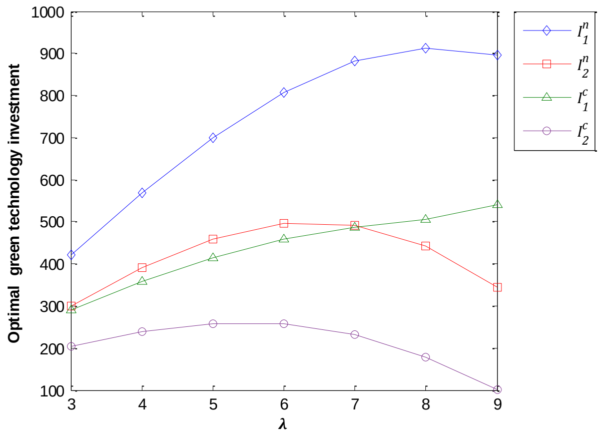

Figure 8. Effect of λ on optimal investment

For the effect of emission reduction efficiency (t_1), Figure 1-8 indicate that in both purely competition and co-opetition models, manufacturers can apply green technology with high emission reduction efficiency by increasing investments, which will bring manufacturers more competitive advantages. For the effect of unit price of carbon emission trading (λ), the increase of unit price of carbon emission trading will result in higher prices in both purely competition and co-opetition models. Because of the high unit price of carbon emission trading, the manufacturers tend to increase the green technology investments and reduce the carbon emissions to lower the carbon emission trading fees. And the investments and the carbon emission trading fees (if $E_i > 0$) will pass on to customers, which lead to higher prices. Figure 4 and 8 reveal that when the unit price of carbon emission trading increase from low to moderate, the manufacturers are willing to invest more to reduce unit carbon emissions.

But, when the unit price of carbon emission trading increase to a certain high level, the manufacturers tend to decrease green technology investments because the cost exceeds the marginal profit brought by green technology investments.

From Figure 1, 2, 5 and 6, it is clear that the manufacturers' optimal prices in the co-opetition model (p_1^c,p_2^c) are higher than those in the purely competition model (p_1^n,p_2^n), and the manufacturers' optimal production quantities in the co-opetition model (q_1^c,q_2^c) are accordingly less than those in the purely competition model (q_1^n,q_2^n). From Figure 3, 4, 7 and 8, we get that the manufacturers' optimal unit carbon emissions in the co-opetition model (e_1^c,e_2^c) are higher than those in the purely competition model (e_1^n,e_2^n), and the manufacturers' optimal green technology investments in the co-opetition model (I_1^c,I_2^c) are accordingly less than those in the purely competition model (I_1^n,I_2^n).

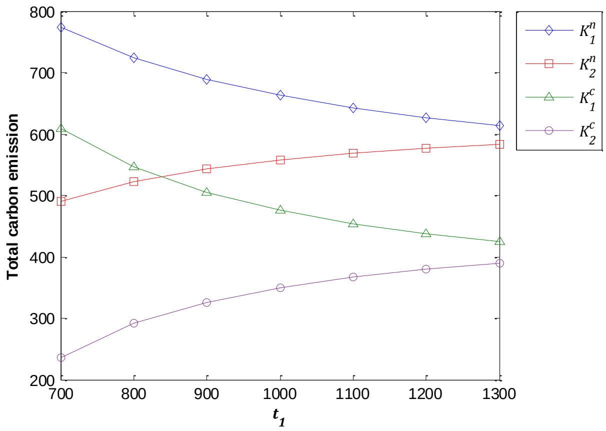

Figure 9. Effect of t_1 on total carbon emissions

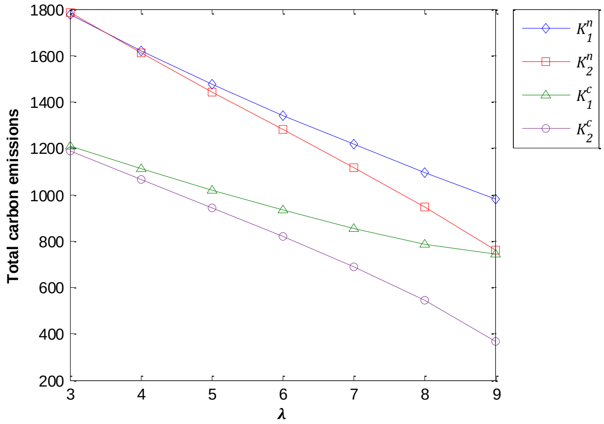

Figure 10. Effect of λ on total carbon emissions

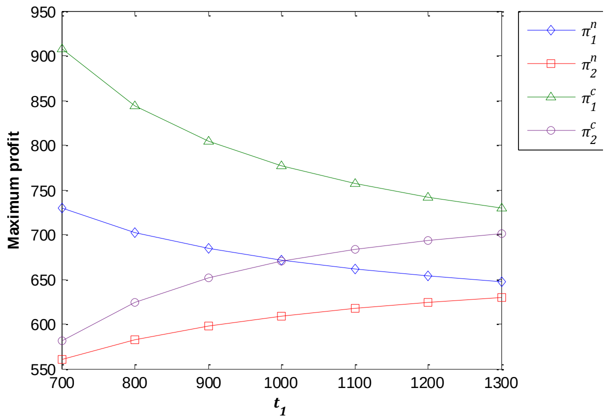

Figure 11. Effect of t_1 on maximum profit

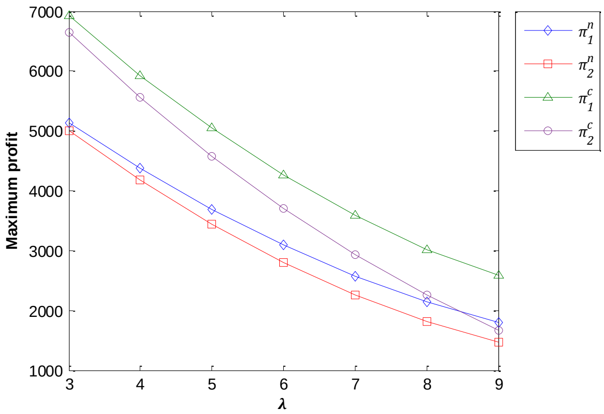

Figure 12. Effect of λ on maximum profit

Figure 9 shows that in both purely competitive scenario and co-opetitive scenario, the total carbon emissions of the manufacturer with high emission reduction efficiency (manufacturer 1) is higher than that of the manufacturer with low emission reduction efficiency (manufacturer 2). Namely, high emission reduction does not mean low total carbon emissions, because low price and low unit carbon emissions will increase demand. To meet the product demand, the manufacturers have to increase outputs. So the carbon emissions of additional production quantity may exceed the amount of emission reduction from the decreased unit carbon emission which in turn increases the total emissions. One way to decrease total carbon emissions is the pricing mechanism of carbon emission trading as shown in Figure 10. A high unit price of carbon emission trading, which is determined by carbon market, will force manufacturers to cut total carbon emissions. From Figure 11, we get that the profit of the manufacturer with high carbon emission reduction efficiency (π_1^n,π_1^c) is higher than those with low carbon emission reduction efficiency (π_2^n,π_2^c) in both the pure completion and the co-operation models. As shown in Figure 12, manufacturers will also gain more profit in the situation of low unit price of carbon emission trading. That is, higher carbon emissions reduction efficiency and low carbon emission trading fees will benefit the manufacturer.

From Figure 9-12, it is clear that in the co-opetition model, the manufacturers' total carbon emissions (K_1^c, K_2^c) are lower and maximum profits (π_1^c, π_2^c) are higher than those in the pure competition model ($K_1^n, K_2^n;\ \pi_1^n, \pi_2^n$).

Intuitively, it seems that co-opetition can improve both environmental and economic performances for manufacturers with less green technology investments compared with that of pure competition. However, these improvements are at the expense of higher product prices and unit carbon emissions, and lower production quantities. The above findings have some interesting implications and may vary between different product categories. For instance, co-opetition can be useful to achieve sustainability objectives for the luxury goods. In a co-opetitive market environment, although the manufacturers will decrease green technology investments leading to higher unit carbon emissions, the overall environmental performance is improved because of suppressed demand whereas the total profits are increased as higher products prices are set. While the co-opetition may be suitable for the luxury goods manufacturers to achieve its sustainability objectives, it may not work for other product categories especially considering long-term sustainability. Since the co-opetition between manufacturers will decrease their green technology investments and increase unit carbon emissions as illustrated in Figure 3, 4, 7 and 8, which is against the fundamental principle of low carbon manufacturing (Tridech and Cheng, 2011). Such a strategy will weaken their environmental competitiveness and therefore attract manufacturers with higher carbon emission reduction efficiency to entry the market. In contrast, a competitive market environment is more appropriate in succeeding low carbon manufacturing in a long run. From the environmental perspective, more green technology investments enable manufacturers to improve their carbon emission reduction efficiencies which lead to lower unit carbon emissions. From the economic perspective, although manufacturers' profits may be decreased in a short term, they can still gain financial benefits in future from the stimulated demand by lower retail prices and reduced unit carbon emissions. From the social perspective, consumers can enjoy more environmental friendly products at affordable prices.

8 Conclusions and suggestions for further research

In this paper, we examined two competing manufacturers' optimal pricing and emission reduction policies with different emission reduction efficiencies under cap-and-trade policy. Using the non-cooperative and cooperative games, we developed competition and co-opetition models with price and emission sensitive demand, and then derived the manufacturers' optimal prices and optimal unit carbon emissions in the purely competitive and co-opetitive market environments respectively. The main results are as follows:

(1) The relationship between the two manufacturers' optimal prices is not only influenced by their emission reduction efficiencies but also unit price of carbon emission trading in both pure competition and co-opetition models. When unit carbon emission trading price is higher than certain ratio, the optimal price of the manufacturer with low emission reduction efficiency is higher than that with high emission reduction efficiency. That is, the manufacturer with low emission reduction efficiency may sell products at a higher price.

(2) In both the pure competition and co-petition models, higher emission reduction efficiency will result in lower optimal unit carbon emissions and higher profit. This means higher emission reduction efficiency will benefit both the manufacturers and the environment.

Consequently, lower unit carbon emissions will lead to more market demand and larger market share. The market mechanism induces the manufacturers to improve emission reduction efficiency.

(3) Compared to pure competition, co-opetition will lead to more profit and less total carbon emissions for the manufacturers. However, this may just be a temporary solution given that such an improvement in economic and environmental performances is not built on green technological innovation driven low carbon manufacturing but based on inflated retail prices and suppressed consumer demand. Surprisingly, the co-opetition between two manufacturers will decrease their green technology investments and increase their unit carbon emissions. Although both manufacturers can gain economic benefits through the co-opetition in the short term, such environmental collaboration will weaken their market competitiveness in the long run.

This research makes the following key contributions. Theoretically, first, our research extends the existing carbon efficient manufacturing literature by looking at the effects of horizontal co-opetition has on manufacturers' strategic and operational decisions and their environmental and economic performances. It is different to most studies in the existing literature that mainly focus on the vertical supply chain cooperation on carbon emissions reduction (Geffen and Rothenberg, 2000; Klassen and Vachon, 2003; Vachon and Klassen, 2008; Green *et al.*, 2012). Second, our research incorporates the product unit carbon emissions into a price and emission sensitive demand as a decision variable in a competitive market environment. This complements to the existing literature that often use the carbon emissions attribute as a constraint or only consider the demand of single manufacturer. Methodologically, through applying non-cooperative and cooperative games to study the purely competitive and co-opetitive relationships respectively, our research extends the existing literature on co-opetition by demonstrating how such a game-theoretical approach can be used to explore the impact of co-opetition on firms' operational decisions and their performance in relation to different market environments.

Furthermore, our research findings have many important managerial and policy implications. We derive the optimal solutions for the manufacturers' pricing and emissions reduction policies in the competitive and co-opetitive market environments, which will be beneficial for the manufacturing firms to make strategic and operational decisions on low carbon manufacturing. For instance, to overcome the challenge of squeezed demand, excessive capacity, and more restrict carbon emission regulations facing by the steel industry globally, it is more critical than ever for steel manufacturers to invest on green technologies to transform the industry to low carbon manufacturing. This has also been demonstrated by other sectors as a viable way to move towards low carbon economy. In addition, we discuss the implications of the pure competition and co-opetition from the perspectives of manufacturers, consumers, and the environment. Co-opetition may be suitable for the luxury goods industry to achieve sustainability objective. It is more applicable to many other sectors to have a competitive market environment to achieve a long term economic, environmental and social sustainability. It is valuable for policy makers to create a more sustainable market environment that can promote low carbon manufacturing for different industrial sectors.

The findings can be extended in several directions. First, two competing manufacturers are discussed in this research, and multiple manufacturers can be taken into consideration in the future. Similarly, the research can be extended from manufacturers to supply chains. Another extension of our work is to examine the role of co-operation in low carbon manufacturing under other carbon emissions policies such as mandatory carbon emissions capacity and carbon tax, and discuss the effect of different carbon emissions reduction policies on manufacturers' decisions and their performances. In addition, the demand is assumed to be deterministic in the paper and using deterministic models does not consider the cost associated with supply and demand uncertainty. One future extension is to investigate the research problem using stochastic models. Finally, our research does not consider the intensity of coopetition such as low competition and low cooperation, high competition and low cooperation, high competition and high cooperation, and low competition and high cooperation in models. Another future extension is to incorporate the intensity of coopetition in the model and examine its impacts on firms' decisions and performances.

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Appendix

Proof of Proposition 1

From (1), we get $\frac{\partial\pi_1(p_1,e_1)}{\partial p_1} = (a - b_1p_1 + b_2p_2 - k_1e_1 + k_2e_2) - b_1(p_1 - c) + \lambda e_1 b_1$ and $\frac{\partial\pi_1(p_1,e_1)}{\partial e_1} = -k_1(p_1 - c) + 2t_1(e_0 - e_1) - \lambda(a - b_1p_1 + b_2p_2 - k_1e_1 + k_2e_2) + \lambda e_1$. Then, we obtain $\frac{\partial\pi_1^2(p_1,e_1)}{\partial p_1^2} = -2b_1$, $\frac{\partial\pi_1^2(p_1,e_1)}{\partial e_1^2} = -2(t_1 - \lambda k_1)$ and $\frac{\partial\pi_1^2(p_1,e_1)}{\partial p_1\partial e_1} = \frac{\partial\pi_1^2(p_1,e_1)}{\partial e_1\partial p_1} = -k_1 + \lambda b_1$, then $\begin{vmatrix} -2b_1 & -k_1 + \lambda b_1 \\ -k_1 + \lambda b_1 & -2(t_1 - \lambda k_1) \end{vmatrix} = 4b_1(t_1 - \lambda k_1) - (-k_1 + \lambda b_1)^2 = M_1 > 0$. Therefore, $\pi_1(p_1, e_1)$ is a concave function of p_1 and e_1.

Let $\frac{\partial \pi_1(p_1,e_1)}{\partial p_1} = 0$ and $\frac{\partial \pi_1(p_1,e_1)}{\partial e_1} = 0$, we get

$$(a - b_1p_1 + b_2p_2 - k_1e_1 + k_2e_2) - b_1(p_1 - c) + \lambda e_1 b_1 = 0 \quad (1\text{-}1)$$

$$-k_1(p_1 - c) + 2t_1(e_0 - e_1) - \lambda(a - b_1p_1 + b_2p_2 - k_1e_1 + k_2e_2) + \lambda e_1 = 0 \quad (1\text{-}2)$$

From (2), we can obtain $\frac{\partial \pi_2(p_2,e_2)}{\partial p_2} = (a - b_1p_2 + b_2p_1 - k_1e_2 + k_2e_1) - b_1(p_2 - c) + \lambda e_2 b_1$ and $\frac{\partial \pi_2(p_2,e_2)}{\partial e_2} = -k_1(p_2 - c) + 2t_2(e_0 - e_2) - \lambda(a - b_1p_2 + b_2p_1 - k_1e_2 + k_2e_1) + \lambda e_2 k_1$. Then, $\frac{\partial \pi_2^2(p_2,e_2)}{\partial p_2^2} = -2b_1$, $\frac{\partial \pi_2^2(p_2,e_2)}{\partial e_2^2} = -2(t_2 - \lambda k_1)$ and $\frac{\partial \pi_2^2(p_2,e_2)}{\partial p_2 \partial e_2} = \frac{\partial \pi_2^2(p_2,e_2)}{\partial e_2 \partial p_2} = -k_1 + \lambda b_1$. So, $\begin{vmatrix} -2b_1 & -k_1 + \lambda b_1 \\ -k_1 + \lambda b_1 & -2(t_2 - \lambda k_1) \end{vmatrix} = 4b_1(t_2 - \lambda k_1) - (-k_1 + \lambda b_1)^2 = M_2 > 0$. Therefore, $\pi_2(p_2, e_2)$ is a concave function of p_2 and e_2.

Let $\frac{\partial \pi_2(p_2,e_2)}{\partial p_2} = 0$ and $\frac{\partial \pi_2(p_2,e_2)}{\partial e_2} = 0$, we have

$$(a - b_1p_2 + b_2p_1 - k_1e_2 + k_2e_1) - b_1(p_2 - c) + \lambda e_2 b_1 = 0 \quad (1\text{-}3)$$

$$-k_1(p_2 - c) + 2t_2(e_0 - e_2) - \lambda(a - b_1p_2 + b_2p_1 - k_1e_2 + k_2e_1) + \lambda e_2 k_1 = 0 \quad (1\text{-}4)$$

From (1-1), (1-2), (1-3) and (1-4), we get $p_1^n = c + \lambda e_0 + [2t_1 - (k_1 + \lambda b_1)\lambda]A_1$, $p_2^n = c + \lambda e_0 + [2t_2 - (k_1 + \lambda b_1)\lambda]A_2$, $e_1^n = e_0 - (k_1 + \lambda b_1)A_1$ *and* $e_2^n = e_0 - (k_1 + \lambda b_1)A_2$. This completes the proof.

Proof of Corollary 1

Proposition 1 shows $\frac{dp_1^n}{da} = [2t_1 - (k_1 + \lambda b_1)\lambda]\frac{\partial A_1}{\partial a} = [2t_1 - (k_1 + \lambda b_1)\lambda]\frac{M_2 + N_2}{M_1M_2 - N_1N_2}$. Recalling assumption, $0 < Y_1 = 2[2b_2t_1 - (k_1 + \lambda b_1)(k_2 + \lambda b_2)] < 2b_2[2t_1 - (k_1 + \lambda b_1)\lambda]$, then we get $2t_1 - (k_1 + \lambda b_1)\lambda > 0$ and $M_1M_2 - N_1N_2 > 0$, so $\frac{dp_1^n}{da} > 0$. That is, p_1^n increases in a.

Proposition 1 shows $\frac{dp_2^n}{da} = [2t_2 - (k_1 + \lambda b_1)\lambda]\frac{\partial A_2}{\partial a} = [2t_2 - (k_1 + \lambda b_1)\lambda]\frac{M_1 + N_1}{M_1M_2 - N_1N_2}$. Recalling assumption, $0 < Y_2 = 2[2b_2t_2 - (k_1 + \lambda b_1)(k_2 + \lambda b_2)] < 2b_2[2t_2 - (k_1 + \lambda b_1)\lambda]$ and $M_1M_2 - N_1N_2 > 0$, so $\frac{dp_2^n}{da} > 0$. That is, p_2^n increases in a.

Proposition 1 shows $\frac{de_1^n}{da} = -(k_1 + \lambda b_1)\frac{\partial A_1}{\partial a} = -(k_1 + \lambda b_1)\frac{M_2 + N_2}{M_1M_2 - N_1N_2}$ and $\frac{de_1^n}{dc} = -(k_1 + \lambda b_1)\frac{\partial A_1}{\partial a} = (b_1 - b_2)(k_1 + \lambda b_1)\frac{M_2 + N_2}{M_1M_2 - N_1N_2}$. Recalling assumption, $X_2 > 0$, $Y_2 > 0$ and $M_1M_2 - N_1N_2 > 0$, we get $M_2 > 0$, $N_2 > 0$, so $\frac{de_1^n}{da} < 0$ and $\frac{de_1^n}{dc} > 0$. That is, e_1^n decreases in a and increases in c.

Proposition 1 shows $\frac{de_2^n}{da} = -(k_1 + \lambda b_1)\frac{\partial A_2}{\partial a} = -(k_1 + \lambda b_1)\frac{M_1+N_1}{M_1M_2-N_1N_2}$ and $\frac{de_2^n}{dc} = -(k_1 + \lambda b_1)\frac{\partial A_2}{\partial a} = (b_1 - b_2)(k_1 + \lambda b_1)\frac{M_1+N_1}{M_1M_2-N_1N_2}$. Recalling assumption, $X_1 > 0$, $Y_1 > 0$ and $M_1M_2 - N_1N_2 > 0$, we get $M_1 > 0$, $N_1 > 0$, so $\frac{de_2^n}{da} < 0$ and $\frac{de_2^n}{dc} > 0$. That is, e_2^n decreases in a and increases in c.

From (4), we get $\frac{dq_1^n}{da} = 2b_1t_1\frac{dA_1}{da} = 2b_1t_1\frac{M_2+N_2}{M_1M_2-N_1N_2}$ and $\frac{dq_1^n}{dc} = 2b_1t_1\frac{\partial A_1}{\partial a} = -2b_1t_1(b_1 - b_2)\frac{M_2+N_2}{M_1M_2-N_1N_2}$. Recalling assumption, so $\frac{dq_1^n}{da} > 0$ and $\frac{dq_1^n}{dc} < 0$. That is, q_1^n increases in a and increases in c.

From (5), we get $\frac{dq_2^n}{da} = 2b_1t_2\frac{dA_2}{da} = 2b_1t_2\frac{M_1+N_1}{M_1M_2-N_1N_2}$ and $\frac{dq_2^n}{dc} = 2b_1t_2\frac{\partial A_2}{\partial a} = -2b_1t_2(b_1 - b_2)\frac{M_1+N_1}{M_1M_2-N_1N_2}$. Recalling assumption, so $\frac{dq_2^n}{da} > 0$ and $\frac{dq_2^n}{dc} < 0$. That is, q_2^n increases in a and increases in c.

From (6), we get $\frac{dI_1^n}{da} = 2t_1(k_1 + \lambda b_1)^2A_1\frac{dA_1}{da} = 2t_1(k_1 + \lambda b_1)^2A_1\frac{M_2+N_2}{M_1M_2-N_1N_2}$ and $\frac{dI_1^n}{dc} = 2t_1(k_1 + \lambda b_1)^2A_1\frac{dA_1}{da} = -2t_1(b_1 - b_2)(k_1 + \lambda b_1)^2A_1\frac{M_2+N_2}{M_1M_2-N_1N_2}$. Recalling proposition 1, $e_1^n < e_0$, we get $A_1 > 0$, so $\frac{dI_1^n}{da} > 0$ and $\frac{dI_1^n}{dc} < 0$. That is, I_1^n decreases in a and increases in c.

From (7), we get $\frac{dI_2^n}{da} = 2t_2(k_1 + \lambda b_1)^2A_2\frac{dA_2}{da} = 2t_2(k_1 + \lambda b_1)^2A_2\frac{M_1+N_1}{M_1M_2-N_1N_2}$ and $\frac{dI_2^n}{dc} = 2t_2(k_1 + \lambda b_1)^2A_2\frac{dA_2}{da} = -2t_2(b_1 - b_2)(k_1 + \lambda b_1)^2A_2\frac{M_1+N_1}{M_1M_2-N_1N_2}$. From proposition 1, $e_2^n < e_0$, we get $A_2 > 0$, so $\frac{dI_2^n}{da} > 0$ and $\frac{dI_2^n}{dc} < 0$. That is, I_2^n decreases in a and increases in c.

From proposition 1 and (1), we get $\frac{d\pi_1(p_1^n,e_1^n)}{da} = \frac{d[(p_1^n-\mathrm{c})q_1^n-I_1^n-\lambda(q_1^ne_1^n-K)]}{da} = [2t_1 - (k_1 + \lambda b_1)\lambda]q_1^n\frac{M_2+N_2}{M_1M_2-N_1N_2} + 2(p_1^n - \mathrm{c})b_1t_1\frac{M_2+N_2}{M_1M_2-N_1N_2} - 2t_1(k_1 + \lambda b_1)^2A_1\frac{M_2+N_2}{M_1M_2-N_1N_2} - \lambda q_1^n\left(-(k_1 + \lambda b_1)\lambda\frac{M_2+N_2}{M_1M_2-N_1N_2}\right) - 2\lambda e_1^nb_1t_1\frac{M_2+N_2}{M_1M_2-N_1N_2} = \frac{2t_1[a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0](M_2+N_2)^2M_1}{(M_1M_2-N_1N_2)^2}$. From proposition 1 and assumption, we get $a - (b_1 - b_2)(c + \lambda e_0) - (k_1 - k_2)e_0 > 0$, so $\frac{d\pi_1(p_1^n,e_1^n)}{da} > 0$. That is, $\pi_1(p_1^n, e_1^n)$ increases in a. From proposition 1 and (1), we get $\frac{d\pi_1(p_1^n,e_1^n)}{dc} = \frac{d[(p_1^n-\mathrm{c})q_1^n-I_1^n-\lambda(q_1^ne_1^n-K)]}{dc} = -(b_1 - b_2)[2t_1 - (k_1 + \lambda b_1)\lambda]\frac{M_2+N_2}{M_1M_2-N_1N_2}q_1^n - 2(b_1 - b_2)(p_1^n - \mathrm{c})b_1t_1\frac{(M_2+N_2)}{M_1M_2-N_1N_2} + 2t_1(b_1 - b_2)(k_1 + \lambda b_1)^2A_1\frac{M_2+N_2}{M_1M_2-N_1N_2} - \lambda q_1^n(b_1 - b_2)(k_1 +$

$\lambda b_1)\lambda\frac{(M_2+N_2)}{M_1M_2-N_1N_2}+2(b_1-b_2)\lambda e_1^n b_1 t_1\frac{M_2+N_2}{M_1M_2-N_1N_2}=-\frac{2t_1(b_1-b_2)(M_2+N_2)M_1A_1}{M_1M_2-N_1N_2}<0$. That is, $\pi_1(p_1^n,e_1^n)$ decreases in c.

Similarly, from proposition 1 and (2), we can get $\pi_2(p_2^n,e_2^n)$ increases in a and decreases in c.

Hence, p_1^n, p_2^n, q_1^n, q_2^n, I_1^n, I_2^n, $\pi_1(p_1^n,e_1^n)$ and $\pi_2(p_2^n,e_2^n)$ all increase in a, e_1^n and e_2^n decrease in a. q_1^n, q_2^n, I_1^n, I_2^n $\pi_1(p_1^n,e_1^n)$ and $\pi_2(p_2^n,e_2^n)$ all decrease in c, e_1^n and e_2^n all increase in c. This completes the proof.

Proof of Proposition 2

From (3), we get $\frac{\partial\pi_c(p_1,e_1,p_2,e_2)}{\partial p_1}=(a-b_1p_1+b_2p_2-k_1e_1+k_2e_2)-b_1(p_1-c)+\lambda e_1b_1+b_2(p_2-c)-\lambda e_2b_2$ and $\frac{\partial\pi_c(p_1,e_1,p_2,e_2)}{\partial e_1}=-k_1(p_1-c)+2t_1(e_0-e_1)-\lambda(a-b_1p_1+b_2p_2-k_1e_1+k_2e_2)+\lambda e_1k_1+k_2(p_2-c)-\lambda e_2k_2$. Then, we get $\frac{\partial\pi_c^2(p_1,e_1,p_2,e_2)}{\partial p_1^2}=-2b_1$, $\frac{\partial\pi_c^2(p_1,e_1,p_2,e_2)}{\partial e_1^2}=-2(t_1-\lambda k_1)$ and $\frac{\partial\pi_c^2(p_1,e_1,p_2,e_2)}{\partial p_1\partial e_1}=\frac{\partial\pi_c^2(p_1,e_1,p_2,e_2)}{\partial e_1\partial p_1}=-k_1+\lambda b_1$. So, we get $\begin{vmatrix}-2b_1 & -k_1+\lambda b_1\\ -k_1+\lambda b_1 & -2(t_1-\lambda k_1)\end{vmatrix}=4b_1(t_1-\lambda k_1)-(-k_1+\lambda b_1)^2=M_1>0$. Therefore, $\pi_c(p_1,e_1,p_2,e_2)$ is a concave function of p_1 and e_1.

Let $\frac{\partial\pi_c(p_1,e_1,p_2,e_2)}{\partial p_1}=0$ and $\frac{\partial\pi_c(p_1,e_1,p_2,e_2)}{\partial e_1}=0$, we get

$$(a-b_1p_1+b_2p_2-k_1e_1+k_2e_2)-b_1(p_1-c)+\lambda e_1b_1+b_2(p_2-c)-\lambda e_2b_2=0 \quad \text{(2-1)}$$

$$-k_1(p_1-c)+2t_1(e_0-e_1)-\lambda(a-b_1p_1+b_2p_2-k_1e_1+k_2e_2)+\lambda e_1k_1+k_2(p_2-c)-\lambda e_2k_2=0 \quad \text{(2-2)}$$

Similarly, from (3), we get $\frac{\partial\pi_c(p_1,e_1,p_2,e_2)}{\partial p_2}=b_2(p_1-c)-\lambda e_1b_2(a-b_1p_2+b_2p_1-k_1e_2+k_2e_1)-b_1(p_2-c)+\lambda e_2b_1$ and $\frac{\partial\pi_c(p_1,e_1,p_2,e_2)}{\partial e_2}=k_2(p_1-c)-\lambda e_1k_2-k_1(p_2-c)+2t_2(e_0-e_2)-\lambda(a-b_1p_2+b_2p_1-k_1e_2+k_2e_1)+\lambda e_2k_1$. Then, we get $\frac{\partial\pi_c^2(p_1,e_1,p_2,e_2)}{\partial p_2^2}=-2b_1$, $\frac{\partial\pi_c^2(p_1,e_1,p_2,e_2)}{\partial e_2^2}=-2(t_2-\lambda k_1)$ and $\frac{\partial\pi_c^2(p_1,e_1,p_2,e_2)}{\partial p_2\partial e_2}=\frac{\partial\pi_c^2(p_1,e_1,p_2,e_2)}{\partial e_2\partial p_2}=-k_1+\lambda b_1$. So, we get $\begin{vmatrix}-2b_1 & -k_1+\lambda b_1\\ -k_1+\lambda b_1 & -2(t_2-\lambda k_1)\end{vmatrix}=4b_1(t_2-\lambda k_1)-(-k_1+\lambda b_1)^2=M_2>0$. Therefore, $\pi_c(p_1,e_1,p_2,e_2)$ is a concave function of p_2 and e_2.

Let $\frac{\partial\pi_c(p_1,e_1,p_2,e_2)}{\partial p_2}=0$ and $\frac{\partial\pi_c(p_1,e_1,p_2,e_2)}{\partial e_2}=0$, we have

$$b_2(p_1-c)-\lambda e_1 b_2(a-b_1p_2+b_2p_1-k_1e_2+k_2e_1)-b_1(p_2-c)+\lambda e_2 b_1=0 \quad (2\text{-}3)$$

$$k_2(p_1-c)-\lambda e_1 k_2-k_1(p_2-c)+2t_2(e_0-e_2)-\lambda(a-b_1p_2+b_2p_1-k_1e_2+k_2e_1)+\lambda e_2 k_1=0 \quad (2\text{-}4)$$

From (2-1), (2-2), (2-3) and (2-4), we get $p_1^c=c+\lambda e_0+[2t_1-(k_1-k_2+\lambda b_1-\lambda b_2)\lambda]B_1-C$, $p_2^c=c+\lambda e_0+[2t_2-(k_1-k_2+\lambda b_1-\lambda b_2)\lambda]B_2+C$, $e_1^c=e_0-[(k_1-k_2)+(b_1-b_2)\lambda]B_1$ and $e_2^c=e_0-[(k_1-k_2)+(b_1-b_2)\lambda]B_2$. This completes the proof.

Proof of Corollary 2

From proposition 2, we get $\frac{dp_1^c}{da}=[2t_1-(k_1-k_2+\lambda b_1-\lambda b_2)\lambda]\frac{dB_1}{da}-\frac{d\mathrm{C}}{da}=\frac{[2t_1-(k_1-k_2+\lambda b_1-\lambda b_2)\lambda](X_2+Y_2)-2(t_2-t_1)(k_2+\lambda b_2)(k_1+\lambda b_1+k_2+\lambda b_2)}{X_1\mathrm{X}_2-Y_1Y_2}$. Recalling assumption, $0<Y_1=2[2b_2t_1-(k_1+\lambda b_1)(k_2+\lambda b_2)]<2b_2[2t_1-(k_1-k_2+\lambda b_1-\lambda b_2)\lambda]$, then we get $2t_1-(k_1-k_2+\lambda b_1-\lambda b_2)\lambda>0$, Recalling proposition 2, $X_1\mathrm{X}_2-Y_1Y_2>0$, so $\frac{dp_1^c}{da}>0$. That is, p_1^c increases in a.

From proposition 2, we get $\frac{dp_2^c}{da}=[2t_2-(k_1-k_2+\lambda b_1-\lambda b_2)\lambda]\frac{dB_2}{da}+\frac{d\mathrm{C}}{da}=\frac{[2t_1-(k_1-k_2+\lambda b_1-\lambda b_2)\lambda](X_1+Y_1)+2(t_2-t_1)(k_2+\lambda b_2)(k_1+\lambda b_1+k_2+\lambda b_2)}{X_1X_2-Y_1Y_2}$. Recalling assumption, $0<Y_2=2[2b_2t_2-(k_1+\lambda b_1)(k_2+\lambda b_2)]<2b_2[2t_2-(k_1-k_2+\lambda b_1-\lambda b_2)\lambda]$, then we get $2t_2-(k_1-k_2+\lambda b_1-\lambda b_2)\lambda>0$, From proposition 2, $e_1^c<e_0$, we get $B_1>0$. Recalling assumption, $X_1\mathrm{X}_2-Y_1Y_2>0$, so $\frac{dp_2^c}{da}>0$. That is, p_2^c increases in a.

From (8), we get $\frac{dq_1^c}{da}=2b_1t_1\frac{dB_1}{da}-2b_2t_2\frac{dB_2}{da}-(b_1+b_2)\frac{dC}{da}=\frac{q_1^c}{a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0}>0$ and $\frac{dq_1^c}{dc}=-(b_1-b_2)\left[2b_1t_1\frac{dB_1}{da}-2b_2t_2\frac{dB_2}{da}-(b_1+b_2)\frac{dC}{da}\right]=-\frac{(b_1-b_2)q_1^c}{a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0}<0$. That is, q_1^c increase in a and decreases in c.

From (9), we get $\frac{dq_2^c}{da}=2b_1t_2\frac{dB_2}{da}-2b_2t_1\frac{dB_1}{da}+(b_1+b_2)\frac{dC}{da}=\frac{q_2^c}{a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0}>0$ and $\frac{dq_2^c}{dc}=-(b_1-b_2)\left[2b_1t_2\frac{dB_2}{da}-2b_2t_1\frac{dB_1}{da}+(b_1+b_2)\frac{dC}{da}\right]=-\frac{(b_1-b_2)q_2^c}{a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0}<0$. That is, q_2^c increase in a and decreases in c.

From proposition 2, we get $\frac{de_1^c}{da} = -[(k_1 - k_2) + (b_1 - b_2)\lambda]\frac{dB_1}{da} = -[(k_1 - k_2) + (b_1 - b_2)\lambda]\frac{X_2+Y_2}{X_1\mathrm{X}-Y_1Y_2} < 0$ and $\frac{de_1^c}{dc} = -[(k_1 - k_2) + (b_1 - b_2)\lambda]\frac{dB_1}{da} = (b_1 - b_2)[(k_1 - k_2) + (b_1 - b_2)\lambda]\frac{X_2+Y_2}{X_1\mathrm{X}-Y_1Y_2} > 0$. That is, e_1^c decreases in a and increases in c.

From proposition 2, we get $\frac{de_2^c}{da} = -[(k_1 - k_2) + (b_1 - b_2)\lambda]\frac{dB_2}{da} = -[(k_1 - k_2) + (b_1 - b_2)\lambda]\frac{X_1+Y_1}{X_1\mathrm{X}-Y_1Y_2} < 0$ and $\frac{de_2^c}{dc} = -[(k_1 - k_2) + (b_1 - b_2)\lambda]\frac{dB_2}{da} = (b_1 - b_2)[(k_1 - k_2) + (b_1 - b_2)\lambda]\frac{X_1+Y_1}{X_1\mathrm{X}-Y_1Y_2} > 0$. That is, e_2^c decreases in a and increases in c.

From (10), we get $\frac{dI_1^c}{da} = 2t_1[(k_1 - k_2) + (b_1 - b_2)\lambda]^2 B_1\frac{dB_1}{da} = 2t_1[(k_1 - k_2) + (b_1 - b_2)\lambda]^2 B_1\frac{X_2+Y_2}{X_1\mathrm{X}-Y_1Y_2} > 0$ and $\frac{dI_1^c}{dc} = 2t_1[(k_1 - k_2) + (b_1 - b_2)\lambda]^2 B_1\frac{dB_1}{da} = -2(b_1 - b_2)t_1[(k_1 - k_2) + (b_1 - b_2)\lambda]^2 B_1\frac{X_2+Y_2}{X_1\mathrm{X}-Y_1Y_2} < 0$. That is, I_1^c increases in a and decreases in c.

From (11), we get $\frac{dI_2^c}{da} = 2t_2[(k_1 - k_2) + (b_1 - b_2)\lambda]^2 B_2\frac{dB_2}{da} = 2t_2[(k_1 - k_2) + (b_1 - b_2)\lambda]^2 B_2\frac{X_1+Y_1}{X_1\mathrm{X}-Y_1Y_2}$ and $\frac{dI_2^c}{dc} = 2t_2[(k_1 - k_2) + (b_1 - b_2)\lambda]^2 B_2\frac{dB_2}{da} = -2(b_1 - b_2)t_2[(k_1 - k_2) + (b_1 - b_2)\lambda]^2 B_2\frac{X_1+Y_1}{X_1\mathrm{X}-Y_1Y_2}$. From proposition 2, $e_2^c < e_0$, we get $B_2 > 0$ so $\frac{dI_2^c}{da} > 0$ and $\frac{dI_2^c}{dc} < 0$. That is, I_2^c increases in a and decreases in c.

Hence, p_1^c, p_2^c, q_1^c, q_2^c, I_1^c and I_2^c all increase in a, both e_1^c and e_2^c decrease in a. q_1^c, q_2^c, I_1^c and I_2^c all decrease in c, e_1^c and e_2^c all increase in c. This completes the proof.

Proof of Proposition 3

(1) With cap-and-trade and pure competition, from proposition 1, we get $p_1^n - p_2^n = \{(c + \lambda e_0) + [2t_1 - (k_1 + \lambda b_1)\lambda]A_1\} - \{(c + \lambda e_0) + [2t_2 - (k_1 + \lambda b_1)\lambda]A_2\} = \frac{2[a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0]}{M_1M_2-N_1N_2}(t_2 - t_1)(k_1 + k_2 - \lambda b_1)(k_1 + \lambda b_1)$. So, if $\lambda \le \frac{k_1+k_2}{b_1}$, then $p_1^n \ge p_2^n$; if $\lambda > \frac{k_1+k_2}{b_1}$, then $p_1^n < p_2^n$.

(2) With cap-and-trade and pure competition, from proposition 1, we get $e_1^n - e_2^n = [e_0 - (k_1 + \lambda b_1)A_1] - [e_0 - (k_1 + \lambda b_1)A_2] = (k_1 + \lambda b_1)(B_2 - B_1) = \frac{[a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0](k_1+\lambda b_1)}{M_1M_2-N_1N_2}(4b_1 + 2b_2)(t_1 - t_2) < 0$. That is, $e_1^n < e_2^n$.

(3) With cap-and-trade and co-opetition, from proposition 2, we get $p_1^c - p_2^c = [c + 2t_1B_1 +$

$2t_2C_1 - [(k_1 - k_2) + (b_1 - b_2)\lambda]\lambda D_{1]} - [c + 2t_2B_2 + 2t_1C_2 - [(k_1 - k_2) + (b_1 - b_2)\lambda]\lambda D_2] = \frac{2[a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0][(k_1-k_2)+(b_1-b_2)\lambda][(k_1+k_2)-(b_1+b_2)\lambda](t_2-t_1)}{X_1X_2-Y_1Y_2}$. So, if $\lambda \le \frac{k_1+k_2}{b_1+b_2}$, then $p_1^c \ge p_2^c$; if $\lambda > \frac{k_1+k_2}{b_1+b_2}$, then $p_1^c < p_2^c$.

(4) With cap-and-trade and co-opetition, from proposition 2, we get $e_1^c - e_2^c = [e_0 - [(k_1 - k_2) + (b_1 - b_2)w]D_1] - [e_0 - [(k_1 - k_2) + (b_1 - b_2)w]D_2] = -\frac{4[a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0](b_1+b_2)[(k_1-k_2)+(b_1-b_2)\lambda](t_2-t_1)}{X_1X_2-Y_1Y_2} < 0$. That is, $e_1^c < e_2^c$. This completes the proof.

Proof of Proposition 4

(1) With cap-and-trade and pure competition, from (4) and (5), we get $q_1^n - q_2^n = 2b_1t_1A_1 - 2b_1t_2A_2 = \frac{2b_1(t_2-t_1)(k_1+\lambda b_1)(k_1+\lambda b_1+k_2+\lambda b_2)[a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0]}{M_1M_2-N_1N_2} > 0$. That is, $q_1^n > q_2^n$.

From (6) and (7), we get $I_1^n - I_2^n = t_1(e_0 - e_1^e)^2 - t_2(e_0 - e_2^e)^2 = t_1(k_1 + \lambda b_1)^2A_1^2 - t_2(k_1 + \lambda b_1)^2A_2^2$ and $t_1A_1 - t_2A_2 = \frac{a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0}{M_1M_2-N_1N_2}[(M_2 + N_2)t_1 - (M_1 + N_1)t_2] = \frac{a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0}{M_1M_2-N_1N_2}(t_2 - t_1)(k_1 + \lambda b_1)(k_1 + k_2 + \lambda b_1 + \lambda b_2) > 0$, so $t_1A_1 > t_2A_2$. Because $e_1^n < e_2^n$, then $A_1 > A_2$, therefore $t_1A_1^2 > t_2A_2^2$, and then we can get $t_1(k_1 + \lambda b_1)^2A_1^2 > t_2(k_1 + \lambda b_1)^2A_2^2$, that is, $I_1^n > I_2^n$. So, with cap-and-trade and pure competition, $q_1^n > q_2^n$ and $I_1^n > I_2^n$.

(2) With cap-and-trade and co-opetition, from (8) and (9), we get $q_1^c - q_2^c = \frac{2[a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0][(k_1-k_2)+(b_1-b_2)\lambda][(k_1+k_2)+(b_1+b_2)\lambda](t_2-t_1)}{X_1X_2-Y_1Y_2} > 0$. That is, $q_1^c > q_2^c$.

From (10) and (11), we get $I_1^c - I_2^c = t_1(e_0 - e_{c1}^e)^2 - t_2(e_0 - e_{c2}^e)^2 = [(k_1 - k_2) + (b_1 - b_2)\lambda)^2(t_1B_1^2 - t_2B_2^2)$ and $t_1B_1 - t_2B_2 = \frac{a-(b_1-b_2)(c+\lambda e_0)-(k_1-k_2)e_0}{X_1X_2-Y_1Y_2}(t_2 - t_1)(k_1 + k_1 + \lambda b_1 + \lambda b_2)^2 > 0$, so $t_1B_1 > t_2B_2$. Because $e_1^c < e_2^c$, then $B_1 > B_2$, therefore $t_1B_1^2 > t_2B_2^2$, $[(k_1 - k_2) + (b_1 - b_2)\lambda)^2(t_1B_1^2 - t_2B_2^2) > 0$, that is, $I_1^c > I_2^c$. So, with cap-and-trade and co-opetition, $q_1^c > q_2^c$ and $I_1^c > I_2^c$. This completes the proof.