

## COMPARISON OF COMPETING SUPPLY CHAINS WITH DIFFERENT STRUCTURES UNDER CAP-AND-TRADE REGULATION

YUYU CHEN<sup>1</sup>, QINGGUO BAI<sup>2</sup> AND JIANTENG XU<sup>2,\*</sup>

**Abstract.** To reduce carbon emissions, many countries and regions have implemented carbon cap-and-trade regulation. The main objective of this paper is to explore the economic and environmental impacts of carbon cap-and-trade regulation on two competing supply chains. This paper considers two cases: (i) in the absence of cap-and-trade regulation and (ii) with carbon cap-and-trade regulation. For each case, there are three structures: centralized-centralized (C-C) structure, decentralized-decentralized (D-D) structure, and hybrid centralized-decentralized (C-D) structure. First, this paper analyzes the optimal pricing decisions of two competing supply chains for the two cases, and then explores the impacts of cap-and-trade regulation on the sale price, market demand, economy (include enterprise profits and consumer surplus), environment (*i.e.*, carbon emission) and total social welfare. Finally, numerical examples are provided to illustrate the theoretical results. By comparing the two cases, the main conclusions are as follows: (i) cap-and-trade regulation leads to the increase of unit price and the decrease of the market demand, (ii) cap-and-trade regulation leads to the reduction of both carbon emission and the consumer surplus, (iii) the impacts of cap-and-trade regulation on the profit and social welfare depend on the carbon cap.

**Mathematics Subject Classification.** 91A40.

Received September 22, 2022. Accepted February 11, 2024.

### 1. INTRODUCTION

With the development of economic globalization and the intensification of market competition, enterprises have to reform the traditional operation system to improve their competitiveness. Currently, modern business competition channels are no longer limited to enterprises, but competition between the entire supply chain. This is the conclusion of the Deloitte Consulting Report (1999) based on a survey of more than 200 large manufacturers and distributors in the United States and Canada, covering industries including aerospace, telecommunications, automotive, consumer products, high-tech products, and more. In this scenario, chain-to-chain competition has received widespread concern from scholars and practitioners. Chain-to-chain competition mainly refers to the direct or indirect competition between multiple nodes composed of multiple enterprises and professional intermediaries. In China's home appliance industry, there is a competition model between a manufacturer, a retailer and a customer chain led by Changhong and Haier. Another real case is that BYD's manufacturer-retailer-customer

---

*Keywords.* Competitive supply chains, carbon emission, cap-and-trade regulation, implications analysis.

<sup>1</sup> School of Business, Changshu Institute of Technology, Changshu, P.R. China.

<sup>2</sup> School of Management, Qufu Normal University, Rizhao, P.R. China.

\*Corresponding author: [jiantengxu@163.com](mailto:jiantengxu@163.com)

chain competes with Tesla's supplier–manufacturer–customer chain. BYD independently developed and manufactured the core part of automobile battery while Contemporary Amperex Technology Co., Limited (CATL) is the main battery supplier of Tesla. These real cases motivate us to investigate how should enterprises make pricing decisions when faced with the competition of chain and chain.

Chain-to-chain competition has produced many challenges for the supply chain management while it also affected by the supply chain structure. Tesla mentioned earlier, the leading manufacturer of new energy vehicle, has taken the price-cutting strategy to maintain the market share under the current fierce market competition. Consequently, BYD began to sell its own batteries to other competitors such as Dongfeng Motor Corporation in 2018. It is also announced in 2022 that BYD will become the battery supplier of Tesla<sup>1</sup>. In this scenario, the supply chain of BYD is transformed from a vertically integrated structure to an innovative and open model while the channel structures of BYD's competitors are also changed. As the supply chain structure changes, the operations performance has become a key issue for the competitive supply chain. Hence, it is necessary to study the influence of structure on competitive supply chain.

Enterprises and their supply chain are the principal parts of carbon dioxide emissions. With global warming and the resulting harsh environment, more and more countries and regions have introduced and implemented a large number of emission regulations to reduce the carbon emissions. This paper focuses on carbon cap-and-trade regulation, which is an effective market-based mitigation mechanism [3, 8, 11]. First, the carbon cap-and-trade regulation means that regulators set emission caps for enterprises. For example, the U.S. government has set an emissions cap for the auto industry. Second, cap-and-trade regulation means that regulators use market mechanisms to allow companies to buy and sell emission shares to comply with emission regulations. According to the statistics of the National Development and Reform Commission of China, in the pilot provinces and cities of carbon emission trading, as of September 2017, the cumulative trading volume of allowances reached 197 million tons of carbon dioxide equivalent.

With the implementation of cap-and-trade regulation, the operational decisions and goals of enterprises have fundamentally influenced. Moreover, the goal of supply chain management is changed to improve both environmental and economic performances, which arises new serious challenges. In the competitive market, making operational decisions under different supply structures play a key role in balancing the profit and carbon emissions. Therefore, how to effectively carry out pricing and production optimization under the constraints of cap-and-trade regulation has become a research hotspot in the field of current operation management. These new challenges also motivate us to research how pricing and production decisions should be adjusted when considering cap-and-trade regulation in the competitive supply chains under different structures.

The above goals can be translated into the following research questions: How the competitive supply chains should make production and pricing decisions in the absence of cap-and-trade regulation? How does the competitive supply chains adjust the decisions when consider cap-and-trade regulation? How will cap-and-trade regulation affect the enterprise profit, the environment, consumer surplus, and social welfare? These are the questions that this article aims to explore.

Motivated by the above questions, this paper explores a system of two supply chains under competition of product price. The main objective of this paper is to explore the economic and environmental impacts of cap-and-trade regulation on two competing supply chains. Each supply chain consists of one supplier and one manufacturer. The product demand is decreasing in the price of the particular supply chain while increasing with its opponent. To study the impacts of cap-and-trade regulation on the competing supply chains. This paper considers two cases: in the absence of cap-and-trade regulation and with carbon cap-and-trade regulation. First, we analyze the optimal decisions of two competing supply chains for the two cases, and then explore the impacts of cap-and-trade regulation on the sale price, market demand, economy (include enterprise profits and consumer surplus), environment (*i.e.*, carbon emission) and total social welfare.

---

<sup>1</sup>[https://www.sohu.com/a/555425861\\_121124362](https://www.sohu.com/a/555425861_121124362).

The novelties of this paper are: (1) The competition among different supply chain structures is investigated under cap-and-trade regulation. (2) The implications of supply chain structures on economic, environmental and social welfare under cap-and-trade regulation are analyzed.

The remainder of this paper is organized as follows: In Section 2, we briefly review the related literature. The problem description and notations are presented in Section 3. In Section 4, we develop the model formulation and conduct decision analysis. Section 5 analyzes the impacts of cap-and-trade regulation on the sales prices, market demands, economy, environment and social welfare. In Section 6, we present a numerical study and analyze the results. Finally, we present the conclusions and potential future studies.

## 2. LITERATURE REVIEW

Our study is related to two streams of research. The first stream studies chain-to-chain competition supply chains; the second stream investigates operational decision under carbon emissions regulation.

### 2.1. Chain-to-chain competition

Recently, many studies focus on the competition between supply chains. Li and Li [17] develop the model of two sustainable supply chains under competition in product sustainability, and derive the equilibrium structures of the two-chain system. Tao *et al.* [24] consider a newsvendor model for the two competing supply chains that are subject to inventory inaccuracy, and analyze equilibrium contracting strategies. Guan *et al.* [10] examine the effects of sharing demand information in two competing supply chains. Li *et al.* [18] investigate partial vertical centralization in two supply chains each with one manufacturer and one retailer competing with substitutable products. Chen *et al.* [6] construct multiple competing supply chains, each consisting of a manufacturer and a retailer and investigate the influences of the factoring decision in one supply chain on other chains. Taleizadeh *et al.* [23] study two collecting reverse supply chains consist of a retailer and a manufacture, and analyze the pricing strategies in the competitive reverse supply chains with traditional and e-channels. Wang *et al.* [25] explore the competitive and sustainable supply chain network design problem for the chain-to-chain competition between two supply chains. Sadeghi *et al.* [20] study the coordination and competition problem for two reverse supply chains each having its own exclusive retailer and manufacturer. Xu *et al.* [28] study the innovation information sharing problem between two competing supply chains with one supplier and one manufacturer each. Ha *et al.* [12] consider two competing supply chains, each consisting of a manufacturer and a retailer, and explore the problem of sharing demand information for the competing supply chains. Zhang and Wang [30] study the impact of government incentive on the two competing supply chains consisting of one manufacturer and one retailer respectively.

Unlike above research, this paper considers the carbon emission under government carbon emission regulation, and analyze the impact of cap-and-trade regulation on two competing supply chains.

### 2.2. Carbon emission regulation

The related research on supply chain operation management under carbon regulation has received extensive attention from scholars. Some scholars study the operation optimization and coordination of supply chain under the constraints of carbon emission regulation. Yang *et al.* [29] construct a supply chain system, consisting of a manufacturer and a retailer, and analyze the role of revenue sharing and first-mover advantage in carbon emission reduction and the profit under carbon regulation. Bai *et al.* [1] develop one-manufacturer and two-competing-retailer low carbon supply chain models for deteriorating products under VMI to study the effects of carbon emission reduction on supply chain coordination. Dong *et al.* [7] study the sustainability investment on sustainable product with emission regulation consideration for decentralized and centralized supply chains. Xu *et al.* [27] explore the optimal total emissions and production quantities of the two products, and explore the impact of the cap-and-trade regulation on the production decisions and the profits. Feng *et al.* [9] analyze profit allocation rules for joint replenishment among retailers under a carbon cap-and-trade regulation. Considering consumer environmental awareness, Sun and Yang [22] study the carbon emission reduction of two

TABLE 1. Overview of recent literature.

Reference	CCC	CER	EcI	EnI	SWI
Li and Li [17]	✓		✓		✓
Tao <i>et al.</i> [24]	✓		✓		
Guan <i>et al.</i> [10]	✓		✓		
Li <i>et al.</i> [18]	✓		✓		
Chen <i>et al.</i> [6]	✓		✓		
Taleizadeh and Sadeghi [23]	✓		✓		
Wang <i>et al.</i> [25]	✓		✓		
Yang <i>et al.</i> [29]		✓	✓	✓	
Bai <i>et al.</i> [1]		✓	✓	✓	
Dong <i>et al.</i> [7]		✓	✓		
Xu <i>et al.</i> [27]		✓	✓	✓	
Feng <i>et al.</i> [9]		✓	✓		
Sun and Yang [22]		✓	✓	✓	✓
Liu <i>et al.</i> [19]		✓	✓	✓	✓
Sarkar <i>et al.</i> [21]		✓	✓	✓	
The present study	✓	✓	✓	✓	✓

competitive manufacturers given the carbon tax and cap-and-trade regulations. Liu *et al.* [19] develop a supply chain system, consisting of a manufacturer and a retailer, and explore the optimal choice of emission reduction mode under the carbon cap-and-trade regulation. Cai *et al.* [4] analyze the choice of design-for-environment under environmental taxation. Zhu *et al.* [33] explore the effect of carbon regulation on automobile industry in China. Halat and Hafezalkotob [14] study inventory management of a multi-stage green supply chain under carbon emission regulations. Zhang *et al.* [31] analyze the impact of carbon cap-and-trade regulation on green technology innovation.

There are also some scholars who compare the impact of different carbon regulations on supply chain decision-making. Bai *et al.* [2] examine the effects of mandatory emission capacity and emission tax regulations on the optimal production decisions of a manufacturer facing stochastic demand with partial distribution information. Xu *et al.* [26] explore the joint production and pricing decisions of a manufacturer with multiple products under cap-and-trade and carbon tax regulations, and compare the effects of the two regulations on the environment, the profit and social welfare. For the case of new energy vehicles Zhu *et al.* [34] explore whether carbon regulation is better than cash subsidy. Hu *et al.* [15] investigate the effects of carbon tax and cap-and-trade for Chinese remanufacturing industry. Hafezalkotob [13] studies the effects of various governmental regulations on competition of green supply chains. Zhou *et al.* [32] compare the cost-effectiveness between carbon cap-and-trade regulation and carbon tax regulation.

Unlike above research, this paper contributes to the literature by constructing a model of two supply chains competing product price and exploring the equilibrium structures for such a two-chain system. In addition, we explore the impacts of carbon cap-and-trade regulation on the economy (include enterprise profits and consumer surplus), environment (*i.e.*, carbon emission) and total social welfare. Sarkar *et al.* [21] Joint study the economic and environmental performance of sustainable supply chain. The difference between our paper and existing studies are shown in Table 1 from the aspects of chain-to-chain competition (CCC), carbon emission regulation (CER), economic implication (EcI), environmental implication (EnI) and social welfare implication (SWI).

TABLE 2. The major parameters and notations.

Notation	Definition
Parameters	
$c_s$	Unit cost for making raw material for the supplier
$c_m$	Unit manufacturing cost for the manufacturer
$a$	Carbon emission of unit product
$K$	Carbon cap of cap-and-trade regulation
$\theta$	Competition degree of products on price
$\varepsilon$	Unit carbon emission trading price
$\eta$	The economic value of unit environmental impact
Decision variables	
$p_i$	The unit sales price of the supply chain $i$ , $i = 1, 2$
$\omega_i$	The wholesale price of the supplier in supply chain $i$ , $i = 1, 2$
Auxiliary variables	
$q_i^{X-Y}$	Demand for supply chain $i$ , $X \in \{N, R\}, Y \in \{C, D, H\}, i = 1, 2$
$\Pi_i^{X-Y}$	Total profit for supply chain $i$ , $X \in \{N, R\}, Y \in \{C, D, H\}, i = 1, 2$
$\Pi_{Mi}^{X-Y}$	Profit for the manufacturer $i$ , $X \in \{N, R\}, Y \in \{C, D, H\}, i = 1, 2$
$\Pi_{Si}^{X-Y}$	Profit for the supplier $i$ , $X \in \{N, R\}, Y \in \{C, D, H\}, i = 1, 2$
$E^{X-Y}$	Carbon emission, $X \in \{N, R\}, Y \in \{C, D, H\}$
$CS^{X-Y}$	Consumer surplus, $X \in \{N, R\}, Y \in \{C, D, H\}$
$W^{X-Y}$	Social welfare, $X \in \{N, R\}, Y \in \{C, D, H\}$

### 3. NOTATIONS AND PROBLEM DESCRIPTION

#### 3.1. Notations

The notations in this paper are shown in Table 2. The superscript  $X$  indicates the carbon cap-and-trade regulation,  $X \in \{N, R\}$ .  $N$  (No Regulation) and  $R$  (Regulation) indicate not considering carbon cap-and-trade regulation and considering carbon cap-and-trade regulation, respectively. The superscript  $Y$  indicates the structure of two competing supply chains,  $Y \in \{C, D, H\}$ .  $C$  represents centralized-centralized (*i.e.*, C-C) structure,  $D$  represents decentralized-decentralized (*i.e.*, D-D) structure,  $H$  represents hybrid centralized-decentralized (*i.e.*, C-D) structure.

#### 3.2. Problem description

In order to explore the impacts of cap-and-trade regulation on the two competing supply chains, we comprehensively analyze the economic (profits, consumer surplus), environmental (carbon emission) and social welfare between models with and without cap-and-trade regulation.

This paper considers two supply chains, each one consisting of one supplier and one manufacturer. In each supply chain, the supplier first provides raw material to the manufacturer at wholesale price  $\omega_i$ , then the manufacturer produces and sells product to market at price  $p_i$ . Their interaction constitutes a leader–follower Stackelberg game. The unit cost of making raw material is  $c_s$  for the supplier, and the unit manufacturing cost is  $c_m$  for the manufacturer. The normalized market base is assumed to be 1. The two chains compete on the price of the product. That is, the demand of the product is increased with its selling price and decreased with the selling price of its opponent product sold by the competing supply chain. Hence, the demand function for

supply chain  $i$  is

$$q_i = 1 - p_i + \theta p_j, j = 3 - i \text{ and } i = 1, 2. \quad (1)$$

In the above equation, 1 is the normalized market base,  $p_i$  is the selling price of product  $i$  and  $\theta$  ( $\theta \in [0, 1]$ ) denotes the competition degree of the two products on selling price;  $\theta = 0$  implies two independent supply chains without any price competition.

Now we consider the supply chain structures. There are 3 structures for a two-chain system: centralized-centralized (C-C) structure, decentralized-decentralized (D-D) structure, and hybrid centralized-decentralized (C-D) structure. The centralized-centralized (C-C) structure corresponds to a 2-player Nash game, in which two centralized chains determine the selling prices of their products simultaneously. On the other hand, in decentralized-decentralized (D-D) structure, a complex 4-player game is conducted in the following way: The suppliers simultaneously and uncooperatively determine the wholesale prices within each supply chain, and accordingly, the suppliers simultaneously determine the selling prices for their products. Hence, two Nash game connected with a Stackelberg game should be formulated for the D-D structure. Finally, in hybrid centralized-decentralized (C-D) structure, the supplier in the decentralized chain first proposes the wholesale price, and then her manufacturer and its opponent chain simultaneously determine the selling prices to maximize their own profits, respectively. Therefore, a Nash game connected with a Stackelberg game should be formulated for the C-D structure.

To reduce carbon emissions, many countries and regions have implemented cap-and-trade regulation, which is an effective market-based mitigation mechanism. Under cap-and-trade regulation, the carbon cap is  $K$ , and the unit carbon emission trading price is  $\varepsilon$ . If the carbon emissions exceed the carbon cap, the manufacturer should buy carbon permits in the carbon trading market. Conversely, the manufacturer can sell the extra carbon permits in the carbon trading market [1, 5].

The carbon emission of unit product is  $a$ , hence the total carbon emission (*i.e.*, environment impact) for the two chains is  $E = aq_1 + aq_2$  [19, 27]. The consumer surplus is  $CS = \frac{q_1^2 + q_2^2}{2}$ . The total social welfare is  $W = \Pi_1 + \Pi_2 + CS - \eta E$ ,  $\eta$  is the economic value of unit environmental impact [18].

In this paper, we study the impacts of cap-and-trade regulation on two competing supply chains. Therefore, in order to highlight our research focus, we assume sufficient resources, that is, there are no resource constraints in the models. In addition, this paper is based on the assumption of complete information and demand determination. Similar assumptions can be found in [16]. The main research methods are convex optimization theory and game theory, which is a combination of Nash games and Stackelberg games. We consider two cases: (i) in the absence of cap-and-trade regulation and (ii) with carbon cap-and-trade regulation. For each case, there are three structures: centralized-centralized (C-C) structure, decentralized-decentralized (D-D) structure, and hybrid centralized-decentralized (C-D) structure. First, we analyze the optimal pricing decisions of two competing supply chains for the two cases, and then explore the impacts of carbon cap-and-trade regulation on the sale price, market demand, economy (include enterprise profits and consumer surplus), environment (*i.e.*, carbon emission) and total social welfare.

#### 4. MODEL FORMULATION AND DECISION ANALYSIS

This section formulates models for two different cases: not considering carbon cap-and-trade regulation and considering carbon cap-and-trade regulation. Consequently, for each case, we derive equilibrium results for three 2-chain structures: centralized-centralized (C-C) structure, decentralized-decentralized (D-D) structure, and hybrid centralized-decentralized (C-D) structure.

##### 4.1. Models in the absence of cap-and-trade regulation

To study the effect of cap-and-trade regulation on competitive supply chains, the optimal decisions in the absence of cap-and-trade regulation (*i.e.*,  $X = N$ ) are first analyzed.

4.1.1. C-C structure

For the C-C structure (*i.e.*,  $Y = C$ ), each chain  $i$  determines the price  $p_i$  to maximize the total profit of the supply chain. In the absence of cap-and-trade regulation, the profit for the supply chain  $i$  is as follows:

$$\max_{p_i} \Pi_i^{N-C} = (p_i - c_m - c_s)q_i, \quad i = 1, 2. \tag{2}$$

**Proposition 4.1.** *In the C-C structure in the absence of cap-and-trade regulation, the optimal sales price for the supply chain  $i$  is  $p_i^{N-C} = \frac{1+c_m+c_s}{2-\theta}, i = 1, 2.$*

Proposition 4.1 provides the analytic expressions of the optimal sales prices for the C-C structure in the absence of cap-and-trade regulation. From Proposition 4.1, we easily have that the sales price increases with  $c_m, c_s$  and  $\theta$ . The main realistic reasons regarding this finding are (i) an increase in the cost of raw material or manufacturing will cause an increase in the sales price; (ii) in the competitive market, when the competitive degree of channel prices is relatively high, each supply chain as a whole always increases the sales price to maintain its competitive advantage.

From Proposition 4.1 and using equations (1) and (2), we have that for the C-C structure in the absence of cap-and-trade regulation, the market demand and profit of the supply chain  $i$  are  $q_i^{N-C} = \frac{1-(c_m+c_s)(1-\theta)}{2-\theta}$  and  $\Pi_i^{N-C} = \frac{[1-(c_m+c_s)(1-\theta)]^2}{(2-\theta)^2}$ . We also have the corresponding consumer surplus and carbon emissions as  $CS^{N-C} = \frac{[1-(c_m+c_s)(1-\theta)]^2}{(2-\theta)^2}$  and  $E^{N-C} = \frac{2a[1-(c_m+c_s)(1-\theta)]}{2-\theta}$ . The total social welfare for the C-C structure in the absence of cap-and-trade regulation is  $W^{N-C} = \frac{3[1-(c_m+c_s)(1-\theta)]^2}{(2-\theta)^2} - \frac{2a\eta[1-(c_m+c_s)(1-\theta)]}{2-\theta}$ .

4.1.2. D-D structure

For the D-D structure (*i.e.*,  $Y = D$ ) in the supply chain  $i$ , the supplier  $i$  foresees the responses from the manufacturer and chooses the wholesale price  $\omega_i$  to maximize his profit

$$\max_{\omega_i} \Pi_{S_i}^{N-D} = (\omega_i - c_s)q_i, \quad i = 1, 2. \tag{3}$$

As the Stackelberg follower, for a given wholesale price  $\omega_i$ , the manufacturer determines the price  $p_i$  to maximize his profit,

$$\max_{p_i} \Pi_{M_i}^{N-D} = (p_i - \omega_i - c_s)q_i, \quad i = 1, 2. \tag{4}$$

**Proposition 4.2.** *In the D-D structure in the absence of cap-and-trade regulation, the following holds.*

- (i) *As the Stackelberg leader, there exists a unique optimal wholesale price  $\omega_i^{N-D}$  to maximize the profit of the supplier, whereby*

$$\omega_i^{N-D} = \frac{2 + (1 + c_m)\theta + (c_s - c_m)(2 - \theta^2)}{4 - \theta - 2\theta^2}, \quad i = 1, 2.$$

- (ii) *As the Stackelberg follower, there exists a unique optimal sales price such that the total profit of the manufacturer is maximized, whereby*

$$p_i^{N-D} = \frac{2 + (2 + c_m + c_s)(2 - \theta^2)}{(2 - \theta)(4 - \theta - 2\theta^2)}, \quad i = 1, 2.$$

Proposition 4.2 provides the analytic expressions of the optimal equilibrium strategies for the D-D structure in the absence of cap-and-trade regulation. From Proposition 4.2, we observe that the sales price increases with  $c_m, c_s$  and  $\theta$ . This finding is similar to that of the C-C structure. In addition, we have that the wholesale price increases with  $c_s$  and  $\theta$ , while decreases with  $c_m$ . The main realistic reasons regarding this finding are (i) an

increase in the cost of raw material will cause an increase in the wholesale price; (ii) in the competitive market, increasing the competitive degree of channel prices yields an increase in the sales price, which eventually leads to an increase in the wholesale price; (iii) for each supply chain, when the supplier increases the wholesale price of the raw material, the manufacturer always decreases the manufacturing cost to gain the revenue.

From Proposition 4.2 and using equations (3) and (4), we have that for the supply chain  $i$  with D-D structure in the absence of cap-and-trade regulation, the market demand and profits of the manufacturer and the supplier are  $q_i^{N-D} = \frac{[1-(c_m+c_s)(1-\theta)](2-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)}$ ,  $\Pi_{Mi}^{N-D} = \frac{[1-(c_m+c_s)(1-\theta)]^2(2-\theta^2)^2}{(2-\theta)^2(4-\theta-2\theta^2)^2}$ , and  $\Pi_{Si}^{N-D} = \frac{[1-(c_m+c_s)(1-\theta)]^2(2+\theta)(2-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)^2}$ .

We also have the corresponding consumer surplus and carbon emissions as  $CS^{R-D} = \frac{[1-(c_m+c_s)(1-\theta)]^2(2-\theta^2)^2}{(2-\theta)^2(4-\theta-2\theta^2)^2}$  and  $E^{N-D} = \frac{2a[1-(c_m+c_s)(1-\theta)](2-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)}$ . The total social welfare for the D-D structure without cap-and-trade regulation is

$$W^{N-D} = \frac{[1-(c_m+c_s)(1-\theta)]^2(2-\theta^2)(14-5\theta^2)}{(2-\theta)^2(4-\theta-2\theta^2)^2} - \frac{2a\eta[1-(c_m+c_s)(1-\theta)](2-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)}.$$

4.1.3. C-D structure

For the C-D (hybrid) structure (*i.e.*,  $Y = H$ ), we suppose the supply chain 1 is centralized and supply chain 2 is decentralized. In the absence of cap-and-trade regulation, the profit supply chain 1 is as follows

$$\max_{p_1} \Pi_1^{N-H} = (p_1 - c_m - c_s)q_1. \tag{5}$$

In supply chain 2, supplier 2 foresees the responses from the supply chain 1 and manufacture 2, and chooses the wholesale price  $\omega_2$  to maximize his profit,

$$\max_{\omega_2} \Pi_{S2}^{N-H} = (\omega_2 - c_s)q_2. \tag{6}$$

In supply chain 2, as the follower, for the given wholesale price  $\omega_2$ , manufacturer 2 determines the price  $p_2$  to maximize his profit,

$$\max_{p_2} \Pi_{M2}^{N-H} = (p_2 - \omega_2 - c_s)q_2. \tag{7}$$

**Proposition 4.3.** *In the C-D (hybrid) structure in the absence of cap-and-trade regulation, the following holds.*

- (i) *As the Stackelberg leader, there exists a unique optimal wholesale price  $\omega_2^{B-H}$  to maximize the profit of the supplier 2, whereby*

$$\omega_2^{N-H} = \frac{(2+\theta) + c_s(2+\theta-\theta^2) - c_m(2-\theta-\theta^2)}{2(2-\theta^2)}.$$

- (ii) *There exist unique optimal sales prices such that the profits of the supply chain 1 and manufacturer 2 are maximized, whereby*

$$p_1^{N-H} = \frac{4(1+c_m+c_s) + (1-c_m-c_s)\theta - (2+c_m+c_s)\theta^2}{2(2-\theta)(2-\theta^2)},$$

$$p_2^{N-H} = \frac{3+c_m+c_s + (c_m+c_s)\theta - (1+c_m+c_s)\theta^2}{(2-\theta)(2-\theta^2)}.$$

Proposition 4.3 provides the analytic expressions of the optimal equilibrium strategies for the C-D structure in the absence of cap-and-trade regulation. Proposition 4.3 yields that the wholesale price increases with  $c_s$  and decreases with  $c_m$ , and the sales price in each supply chain increases with  $c_s$  and  $c_m$ . The main realistic reasons regarding this finding are (i) when the cost of raw material is relatively high, the supplier increases

the wholesale price to sell the manufacture of each supply chain. This eventually results in a reduction of the manufacturing cost because of profit acquisition.

From Proposition 4.3 and using equations (5)–(7), we have that for the supply chain  $i$  with C-D structure in the absence of cap-and-trade regulation, the market demand of supply chains 1 and 2 are  $q_1^{N-H} = \frac{[1-(c_m+c_s)(1-\theta)](4+\theta-2\theta^2)}{2(2-\theta)(2-\theta^2)}$  and  $q_2^{N-H} = \frac{1-(c_m+c_s)(1-\theta)}{2(2-\theta)}$ , and the profits of the supply chain 1 is  $\Pi_1^{N-H} = \frac{[1-(c_m+c_s)(1-\theta)]^2(4+\theta-2\theta^2)^2}{4(2-\theta)^2(2-\theta^2)^2}$ . The profits of the manufacture and the supplier in the supply chain 2 are  $\Pi_{M2}^{N-H} = \frac{[1-(c_m+c_s)(1-\theta)]^2}{4(2-\theta)^2}$  and  $\Pi_{S2}^{N-H} = \frac{(2+\theta)[1-(c_m+c_s)(1-\theta)]^2}{4(2-\theta)(2-\theta^2)}$ . Moreover, we have that the consumer surplus and the carbon emissions are  $CS^{N-H} = \frac{[1-(c_m+c_s)(1-\theta)]^2[20+\theta(8-19\theta)-\theta^3(4-5\theta)]}{8(2-\theta)^2(2-\theta^2)^2}$  and  $E^{N-H} = \frac{a[1-(c_m+c_s)(1-\theta)][6+\theta(1-3\theta)]}{2(2-\theta)(2-\theta^2)}$ . Hence, the total social welfare is given by

$$W^{N-H} = -\frac{[1-(c_m+c_s)(1-\theta)]^2\{76+\theta[24-69\theta-\theta^2(12-17\theta)]\}}{8(2-\theta)^2(2-\theta^2)^2} - \frac{a\eta[1-(c_m+c_s)(1-\theta)][6+\theta(1-3\theta)]}{2(-2+\theta)(-2+\theta^2)}.$$

**Corollary 4.4.** For  $i = 1, 2$ , the followings hold: (i)  $p_i^{N-D} \geq p_2^{N-H} > p_1^{N-H} \geq p_i^{N-C}$ ; (ii)  $q_1^{N-H} \geq q_i^{N-C} \geq q_i^{N-D} \geq q_2^{N-H}$ ; (iii)  $\omega_i^{N-D} \geq \omega_2^{N-H}$ .

Corollary 4.4 compares the sales and wholesaler prices and the market demand of the C-C, D-D, and C-D structures in the absence of cap-and-trade regulation. From Corollary 4.4(i), we observe that among the three structures, the sales prices of the D-D structure are the largest and those of C-D structure are the smallest. This phenomenon occurs because when the members of the supply chain make decisions independently, the manufacturer increases the sales prices to maximize its profit. When the members of the supply chain fully cooperate with each other, the system reduces the sales prices to increase the demands. Corollary 4.4(ii) shows the relationship of market demands of the three structures. Corollary 4.4(iii) compares the wholesale prices of the D-D and C-D structure. These findings imply that when the supplier and the manufacturer make decision independently, the supplier always increase the wholesale price to maximize its own profit.

**Corollary 4.5.**  $E^{N-C} \geq E^{N-H} \geq E^{N-D}$ .

Corollary 4.5 compares the carbon emissions of the C-C, D-D, and C-D structures in the absence of cap-and-trade regulation. From Corollary 4.5, we observe that the carbon emissions of the C-C structure are higher than or equal to those of the C-C structure while the latter are higher than the carbon emissions of the D-D structure. The main realistic reasons are that when the supplier cooperate with the manufacturer, a reduction in the sales prices is used to increase the market demand. An increase in the production quantity yields an increase in the carbon emissions. Moreover, for the three structures, the degree of cooperation play a key role in comparing the amount of carbon emissions of the three structures.

### 4.2. Models with cap-and-trade regulation

In this subsection, we study how the optimal sale price, market demand, economy (include enterprise profits and consumer surplus), environment (*i.e.*, carbon emission) and total social welfare will be adjusted when the government implements carbon cap-and-trade regulation (*i.e.*,  $X = R$ ).

#### 4.2.1. C-C structure

For the C-C structure (*i.e.*,  $Y = C$ ), each chain  $i$  determines the price  $p_i$  to maximize the total profit of the supply chain. Under cap-and-trade regulation, the profit of the supply chain  $i$  is as follows:

$$\max_{\{p_i\}} \Pi_i^{R-C} = (p_i - c_m - c_s)q_i - \varepsilon(aq_i - K), \quad i = 1, 2. \tag{8}$$

**Proposition 4.6.** *In the C-C structure under cap-and-trade regulation, the optimal sales price for the supply chain  $i$  is  $p_i^{R-C} = \frac{1+c_m+c_s+a\varepsilon}{2-\theta}$ ,  $i = 1, 2$ .*

Proposition 4.6 provides the analytic expressions of the optimal sales prices for the C-C structure under cap-and-trade regulation. From Proposition 4.6, we easily have that the sales price increases with  $c_m$ ,  $c_s$  and  $\theta$ . This finding is similar to that of C-C structure in the absence of cap-and-trade regulation. It also means that the implementation of cap-and-trade regulation does not change the influences of manufacturing and raw material costs and price competitive degree on the price decisions of the competitive supply chain. From Proposition 4.6, we also have that the sales price increases with  $\varepsilon$ . This finding holds because when the system emits more carbon emission than the carbon cap under cap-and-trade regulation, an increase of the unit carbon emission trading price easily leads to an increase of the sales price because of profit acquisition.

From Proposition 4.6 and using equation (8), we have that for the C-C structure under cap-and-trade regulation, the market demand and profit of supply chain  $i$  are  $q_i^{R-C} = \frac{1-(c_m+c_s+a\varepsilon)(1-\theta)}{2-\theta}$  and  $\Pi_i^{R-C} = K\varepsilon + \frac{[1-(c_m+c_s+a\varepsilon)(1-\theta)]^2}{(2-\theta)^2}$ . The consumer surplus and carbon emissions are  $CS^{R-C} = \frac{[1-(c_m+c_s+a\varepsilon)(1-\theta)]^2}{(2-\theta)^2}$  and  $E^{R-C} = \frac{2a[1-(c_m+c_s+a\varepsilon)(1-\theta)]}{2-\theta}$ . Hence, the total social welfare for the C-C structure under cap-and-trade regulation is

$$W^{R-C} = 2K\varepsilon + \frac{3[1-(c_m+c_s+a\varepsilon)(1-\theta)]^2}{(2-\theta)^2} - \frac{2a\eta[1-(c_m+c_s+a\varepsilon)(1-\theta)]}{2-\theta}.$$

4.2.2. D-D structure

For the D-D structure (*i.e.*,  $Y = D$ ) under cap-and-trade regulation, as the Stackelberg leader, the supplier  $i$  foresees the responses from the manufacturer and chooses the wholesale price  $\omega_i$  to maximize his profit,

$$\max_{\{\omega_i\}} \Pi_{S_i}^{R-D} = (\omega_i - c_s)q_i, \quad i = 1, 2. \tag{9}$$

As the follower, under cap-and-trade regulation, for a given wholesale price  $\omega_i$ , the manufacturer determines the price  $p_i$  to maximize his profit,

$$\max_{\{p_i\}} \Pi_{M_i}^{R-D} = (p_i - \omega_i - c_s)q_i - \varepsilon(aq_i - K), \quad i = 1, 2. \tag{10}$$

**Proposition 4.7.** *In the D-D structure under cap-and-trade regulation, the following holds.*

- (1) *As the Stackelberg leader, there exists a unique optimal wholesale price  $\omega_i^{N-D}$  to maximize the profit of the supplier, whereby*

$$\omega_i^{R-D} = \frac{[1 - a\varepsilon(1 - \theta)](2 + \theta) + c_s(2 - \theta^2) - c_m(2 - \theta - \theta^2)}{4 - \theta - 2\theta^2}, \quad i = 1, 2.$$

- (2) *As the Stackelberg follower, there exists a unique optimal sales price such that the total profit of the manufacturer is maximized, whereby*

$$p_i^{R-D} = \frac{2 + (2 - \theta^2)(2 + c_m + c_s + a\varepsilon)}{(2 - \theta)(4 - \theta - 2\theta^2)}, \quad i = 1, 2.$$

Proposition 4.7 provides the analytic expression of the optimal equilibrium strategies for the D-D structure under cap-and-trade regulation. Proposition 4.2 shows that the sales price increases with  $c_m$ ,  $c_s$  and  $\theta$  while the wholesale price increases with  $c_s$  and decreases with  $c_m$ . Similar phenomenon occurs for the D-D structure in the absence of cap-and-trade regulation. These findings imply that the implementation of cap-and-trade regulation does not change the influences of manufacturing and raw material costs on the equilibrium strategies.

From Proposition 4.7 and using equations (9) and (10), we have that for the D-D structure under cap-and-trade regulation, the market demand of the supply chain  $i$  is  $q_i^{R-D} = \frac{[1-(c_m+c_s+a\varepsilon)(1-\theta)](2-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)}$ , and the profits for the manufacturer and the supplier of the supply chain  $i$  are  $\Pi_{Mi}^{R-D} = K\varepsilon + \frac{[1-(c_m+c_s+a\varepsilon)(1-\theta)]^2(2-\theta^2)^2}{(2-\theta)^2(4-\theta-2\theta^2)^2}$  and  $\Pi_{Si}^{R-D} = \frac{[1-(c_m+c_s+a\varepsilon)(1-\theta)]^2(2+\theta)(2-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)^2}$ . Furthermore, the consumer surplus and carbon emissions are  $CS^{R-D} = \frac{[1-(c_m+c_s+a\varepsilon)(1-\theta)]^2(2-\theta^2)^2}{(2-\theta)^2(4-\theta-2\theta^2)^2}$  and  $E^{R-D} = \frac{2a[1-(c_m+c_s+a\varepsilon)(1-\theta)](2-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)}$ . Hence, the total social welfare is

$$W^{R-D} = \frac{[1-(c_m+c_s+a\varepsilon)(1-\theta)]^2(2-\theta^2)(14-5\theta^2)}{(2-\theta)^2(4-\theta-2\theta^2)^2} + 2K\varepsilon - \frac{2a\eta[1-(c_m+c_s+a\varepsilon)(1-\theta)](2-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)}.$$

4.2.3. C-D structure

For the C-D (hybrid) structure (*i.e.*,  $Y = H$ ), we assume that supply 1 is centralized and supply 2 is decentralized. Under cap-and-trade regulation, the profit supply chain 1 is as follows,

$$\max_{\{p_1\}} \Pi_1^{R-H} = (p_1 - c_m - c_s)q_1 - \varepsilon(aq_1 - K). \tag{11}$$

In supply chain 2, supplier 2 foresees the responses from the supply chain 1 and manufacture 2, and chooses the wholesale price  $\omega_2$  to maximize his profit,

$$\max_{\{\omega_2\}} \Pi_{S2}^{R-H} = (\omega_2 - c_s)q_2. \tag{12}$$

In supply chain 2, under cap-and-trade regulation, as the follower, for the given wholesale price  $\omega_2$ , manufacturer 2 determines the price  $p_2$  to maximize his profit,

$$\max_{\{p_2\}} \Pi_{M2}^{R-H} = (p_2 - \omega_2 - c_s)q_2 - \varepsilon(aq_2 - K). \tag{13}$$

**Proposition 4.8.** *In the C-D (hybrid) structure under cap-and-trade regulation, the following holds.*

- (1) *As the Stackelberg leader, there exists a unique optimal wholesale price  $\omega_2^{R-H}$  to maximize the profit of the supplier 2, whereby*

$$\omega_2^{R-H} = \frac{[1 - a\varepsilon(1 - \theta)](2 + \theta) + c_s(2 + \theta - \theta^2) - c_m(2 - \theta - \theta^2)}{2(2 - \theta^2)}.$$

- (2) *There exist unique optimal sales prices such that the profits of the supply chain 1 and manufacturer 2 are maximized, whereby*

$$p_1^{R-H} = \frac{4 + \theta - 2\theta^2 + (c_m + c_s + a\varepsilon)(4 - \theta - \theta^2)}{2(2 - \theta)(2 - \theta^2)},$$

$$p_2^{R-H} = \frac{3 - \theta^2 + (c_m + c_s + a\varepsilon)(1 + \theta - \theta^2)}{2(2 - \theta)(2 - \theta^2)}.$$

Proposition 4.8 provides the analytic expression of the optimal equilibrium strategies for the C-D structure under cap-and-trade regulation. Proposition 4.8 yields that the wholesale price increases with  $c_s$  and decreases with  $c_m$ , and the sales price in each supply chain increases with  $c_s$  and  $c_m$ . This finding is similar to that of the C-D structure in the absence of cap-and-trade regulation.

From Proposition 4.8 and using equations (12) and (13), we have that for the C-D structure under cap-and-trade regulation, the market demands of supply chains 1 and 2 are  $q_1^{R-H} = \frac{[1-(c_m+c_s+a\varepsilon)(1-\theta)](4+\theta-2\theta^2)}{2(2-\theta)(2-\theta^2)}$

and  $q_2^{R-H} = \frac{1-(c_m+c_s+a\varepsilon)(1-\theta)}{2(2-\theta)}$ . The profit of supply chain 1 is  $\Pi_1^{R-H} = K\varepsilon + \frac{[1-(c_m+c_s+a\varepsilon)(1-\theta)]^2(4+\theta-2\theta^2)^2}{4(2-\theta)^2(2-\theta^2)^2}$ , and the profits for the manufacturer and the supplier of supply chain 2 are  $\Pi_{M2}^{R-H} = \varepsilon K + \frac{[1-(c_m+c_s)(1-\theta)]^2}{4(2-\theta)^2} - \frac{\varepsilon\{2a[1-(c_m+c_s+a\varepsilon)(1-\theta)](1-\theta)-a^2\varepsilon(1-\theta)^2\}}{4(2-\theta)^2}$  and  $\Pi_{S2}^{R-H} = \frac{(2+\theta)[1-(c_m+c_s+a\varepsilon)(1-\theta)]^2}{4(2-\theta)(2-\theta^2)}$ . The consumer surplus and carbon emissions are  $CS^{R-H} = \frac{[1-(c_m+c_s+a\varepsilon)(1-\theta)]^2\{20+\theta[8-19\theta-\theta^2(4-5\theta)]\}}{8(2-\theta)^2(2-\theta^2)^2}$  and  $E^{R-H} = \frac{a[1-(c_m+c_s+a\varepsilon)(1-\theta)][6+\theta(1-3\theta)]}{2(2-\theta)(2-\theta^2)}$ . Hence, the total social welfare is

$$W^{R-H} = 2K\varepsilon + \frac{[1-(c_m+c_s+a\varepsilon)(1-\theta)]^2\{76+\theta[24-69\theta-\theta^2(12-17\theta)]\}}{8(2-\theta)^2(2-\theta^2)^2} - \frac{a\eta[1-(c_m+c_s+a\varepsilon)(1-\theta)][6+\theta(1-3\theta)]}{2(-2+\theta)(-2+\theta^2)}.$$

**Corollary 4.9.** For  $i = 1, 2$ , the followings hold: (i)  $p_i^{R-D} \geq p_2^{R-H} > p_1^{R-H} \geq p_i^{R-C}$ ; (ii)  $q_1^{R-H} \geq q_i^{R-C} \geq q_i^{R-D} \geq q_2^{R-H}$ ; (iii)  $\omega_i^{R-D} \geq \omega_2^{R-H}$ .

Corollary 4.9 compares the sales and wholesaler prices and the market demands of the C-C, D-D, and C-D structures under cap-and-trade regulation. From Corollary 4.9, we observe that for the three structures under cap-and-trade regulation, the relationships of the sales and wholesale prices and the market demand are similar to those of the three structures in the absence of cap-and-trade regulation. This phenomenon occurs imply that the implementation of cap-and-trade regulation does not change the operational decisions for the three structures.

**Corollary 4.10.**  $E^{R-C} \geq E^{R-H} \geq E^{R-D}$ .

Corollary 4.10 shows that under cap-and-trade regulation, the carbon emissions of the C-C structure are higher than or equal to those of the C-C structure while the latter are higher than the carbon emissions of the D-D structure. This finding means that the degree of cooperation play a key role in comparing the carbon emissions of the three structure under cap-and-trade regulation.

### 5. IMPACTS OF CAP-AND-TRADE REGULATION

This section examines the impacts of cap-and-trade regulation on the sale price, market demand, economy (include enterprise profits and consumer surplus), environment (*i.e.*, carbon emission) and total social welfare. The following propositions illustrate the impacts of cap-and-trade regulation on the C-C, D-D, and C-D structures, respectively.

#### 5.1. Impacts for the C-C structure

**Proposition 5.1.** For  $i = 1, 2$ , the followings hold:  $p_i^{R-C} > p_i^{N-C}$  and  $q_i^{R-C} \leq q_i^{N-C}$ .

Proposition 5.1 indicates that for the C-C structure, the unit price of the supply chain  $i$  under cap-and-trade regulation is higher than that in the absence of cap-and-trade regulation. The opposite occurs for the market demand. The main realistic reasons regarding these findings are (i) when cap-and-trade regulation is imposed on the supply chain, the manufacturer produces the low-carbon product. In reality, the sales price of the low-carbon product is higher than that of those regular product; (ii) for the product, the market demand decreases with the sales price.

**Proposition 5.2.** (i) If  $K > \hat{K}_{\Pi i}^C$ ,  $\Pi_i^{R-C} > \Pi_i^{N-C}$  holds; otherwise,  $\Pi_i^{R-C} \leq \Pi_i^{N-C}$  holds, where  $\hat{K}_{\Pi i}^C = \frac{2a[1-(c_m+c_s)(1-\theta)](1-\theta)+a^2\varepsilon(1-\theta)^2}{(2-\theta)^2}$ ,  $i = 1, 2$ .  
 (ii)  $E^{R-C} \leq E^{N-C}$ .

- (iii)  $CS^{R-C} \leq CS^{N-C}$ .
- (iv) If  $K > \hat{K}_W^C$ ,  $W^{R-C} > W^{N-C}$  holds; otherwise,  $W^{R-C} \leq W^{N-C}$  holds, where  $\hat{K}_W^C = \frac{6a[1-(c_m+c_s)(1-\theta)](1-\theta)-a^2[2\eta(2-\theta)+3\varepsilon(1-\theta)](1-\theta)}{2(2-\theta)^2}$ .

Proposition 5.2(i) shows the impacts of cap-and-trade regulation on the total profit of the supply chain  $i$  for the C-C structure. From Proposition 5.2(i), we observe that when the carbon emissions cap is relatively large, the supply chain gains higher profit under cap-and-trade regulation than in the absence of cap-and-trade regulation. The main reasons are that when for a large carbon cap, the supply chain sells excess carbon emission permits to gain some revenue. Propositions 5.2(ii) and 5.2(iii) compare the carbon emissions and consumer surplus under cap-and-trade regulation with those in the absence of carbon regulation. The corresponding findings occur because the implement of cap-and-trade regulation improve the environmental performance of the supply chain. Proposition 5.2(iv) shows the impact of cap-and-trade regulation on the social welfare for the C-C structure. From Proposition 5.2(iv), we observe that when the carbon cap is relatively large, the supply chain has higher social welfare. The main reasons are that when a large carbon cap is allocated, the supply chain not only gains higher profit but also reduce carbon emissions. In this scenario, the improvement of the economic and environmental performances increases the social welfare of the supply chain.

### 5.2. Impacts for the D-D structure

**Proposition 5.3.** For  $i = 1, 2$ , the followings hold:  $\omega_i^{R-D} \leq \omega_i^{N-D}$ ,  $p_i^{R-D} > p_i^{N-D}$ , and  $q_i^{R-D} \leq q_i^{N-D}$ .

Proposition 5.3 indicates that, for the D-D structure, the wholesale price and market demand of the supplier  $i$  under cap-and-trade regulation are lower than or equal to those in the absence of carbon cap-and-trade regulation. The opposite occurs for the sales price. The main realistic reasons regarding these findings are (i) in the competitive market, the supplier as the leader always decreases the wholesale price such that the regulated manufacturer orders more products and the competitiveness of the supply chain is improved; (ii) In reality, the sales price of the low-carbon product is higher than that of those regular product while an increase in the sales price leads to a reduction in the market demand.

- Proposition 5.4.** (i) For the supplier,  $\Pi_{Si}^{R-D} \leq \Pi_{Si}^{N-D}$  holds. For the manufacturer, if  $K > \hat{K}_{\Pi Mi}^D$ ,  $\Pi_{Mi}^{R-D} > \Pi_{Mi}^{N-D}$  holds; otherwise,  $\Pi_{Mi}^{R-D} \leq \Pi_{Mi}^{N-D}$  holds, where  $\hat{K}_{\Pi Mi}^D = \frac{a[2-(2c_m+2c_s+a\varepsilon)(1-\theta)](1-\theta)(2-\theta^2)^2}{(2-\theta)^2(4-\theta-2\theta^2)^2}$ ,  $i = 1, 2$ .
- (ii)  $E^{R-D} \leq E^{N-D}$ .
  - (iii)  $CS^{R-D} \leq CS^{N-D}$ .
  - (iv) If  $K > \hat{K}_W^D$ ,  $W^{R-D} > W^{N-D}$  holds; otherwise,  $W^{R-D} \leq W^{N-D}$  holds, where  $\hat{K}_W^D = \frac{a(1-\theta)(2-\theta^2)\{[2-(2c_m+2c_s+a\varepsilon)(1-\theta)](14-5\theta^2)-2a\eta(2-\theta)(4-\theta-2\theta^2)\}}{2(2-\theta)^2(4-\theta-2\theta^2)^2}$ .

Proposition 5.4(i) shows that for the D-D structure, the profit of the supplier under cap-and-trade regulation is always lower than that in the absence of cap-and-trade regulation. When the carbon emissions cap is higher than the threshold, the profit of the manufacturer is higher than that in the absence of cap-and-trade regulation. The main realistic reasons are that the supplier is not regulated by carbon regulation and the regulated manufacturer benefits from the implementation of cap-and-trade regulation. Propositions 5.4(ii) and 5.4(iii) compare the carbon emissions and consumer surplus under cap-and-trade regulation with those in the absence of carbon regulation. The corresponding findings are similar to those of the C-C structure. Proposition 5.4(iv) presents a threshold to show that when the carbon cap is higher than the threshold, the supply chain has higher social welfare.

### 5.3. Impacts for the C-D structure

**Proposition 5.5.** (i)  $\omega_2^{R-H} \leq \omega_2^{N-H}$ ,  $p_1^{R-H} > p_1^{N-H}$ ,  $p_2^{R-H} > p_2^{N-H}$ ; (ii)  $q_1^{R-H} \leq q_1^{N-H}$ ,  $q_2^{R-H} \leq q_2^{N-H}$ .

Proposition 5.5 indicates that, for the C-D structure, the wholesale price and market demand of each supply chain under cap-and-trade regulation are lower than or equal to those in the absence of carbon cap-and-trade regulation. The opposite occurs for the sales prices of two supply chains. Proposition 5.5 can provide insights for business industry for the C-D structure to make pricing and production decisions.

**Proposition 5.6.** (i) For supply chain 1, if  $K > \hat{K}_{\Pi 1}^H$ ,  $\Pi_1^{R-H} > \Pi_1^{N-H}$  holds; otherwise,  $\Pi_1^{R-H} \leq \Pi_1^{N-H}$  holds, where  $\hat{K}_{\Pi 1}^H = \frac{a[2-(2c_m+2c_s+a\varepsilon)(1-\theta)](1-\theta)(4+\theta-2\theta^2)^2}{4(2-\theta)^2(2-\theta^2)^2}$ . For supplier 2,  $\Pi_{S2}^{R-H} \leq \Pi_{S2}^{N-H}$  holds. For manufacturer 2, if  $K > \hat{K}_{\Pi M2}^H$ ,  $\Pi_{M2}^{R-H} > \Pi_{M2}^{N-H}$  holds; otherwise,  $\Pi_{M2}^{R-H} \leq \Pi_{M2}^{N-H}$  holds, where

$$\hat{K}_{\Pi M2}^H = \frac{2a[1-(c_m+c_s)(1-\theta)](1-\theta)+a^2\varepsilon(1-\theta)^2}{4(2-\theta)^2}$$

- (ii)  $E^{R-H} \leq E^{N-H}$ .
- (iii)  $CS^{R-H} \leq CS^{N-H}$ .
- (iv) If  $K > \hat{K}_W^H$ ,  $W^{R-H} > W^{N-H}$  holds; otherwise,  $W^{R-H} \leq W^{N-H}$  holds, where

$$\hat{K}_W^H = \frac{a(1-\theta)}{16(2-\theta)^2(2-\theta^2)^2} \left\{ \begin{array}{l} [2-(2c_m+2c_s+a\varepsilon)(1-\theta)][76+24\theta-\theta^2(69+12\theta-17\theta^2)] \\ -4a\eta(2-\theta)(2-\theta^2)(6+\theta-3\theta^2) \end{array} \right\}$$

Proposition 5.6(i) shows that for the C-D structure, when the carbon cap is relatively large, the implementation of cap-and-trade regulation leads to the increase in the profit of supply chain 1. The profit of the supplier 2 under cap-and-trade regulation is always lower than or equal to that in the absence of cap-and-trade regulation. For the manufacturer 2, a relatively large value of carbon cap will be conducive to gain higher profit. Propositions 5.6(ii) and 5.6(iii) show that the carbon emissions and consumer surplus under cap-and-trade regulation are always lower than or equal to those in the absence of carbon regulation. This finding is consistent with those of the C-C and D-D structures. Proposition 5.6(iv) shows that when the carbon cap is higher than the threshold, the supply chain has higher welfare because a large carbon cap yields the improvement of the economic and environmental performances of the supply chain.

### 5.4. Managerial implications

The above mentioned theoretical results for the C-C, D-D, and C-D structures yield the following main managerial implications:

- (i) It is necessary for the government agent to impose cap-and-trade regulation on the competitive supply chains. Moreover, for the regulated member under each structure, a relatively large carbon cap should be allocated such that the carbon emissions are lowered and social welfare is improved.
- (ii) When cap-and-trade regulation is implemented, the managers who have environmental friendly preference should choose the D-D structure to operations because the environmental performance of the supply chain is improved. When cap-and-trade regulation is not implemented, the managers should choose C-C structure to operation because the economic performance of the supply chain is improved.
- (iii) For the C-C structure under cap-and-trade regulation, if the carbon cap is relatively large, the managers of the supply chains can increase the sales prices to gain higher profit and lower carbon emissions comparing with the structure in the absence of carbon regulation.
- (iv) For the D-D structure under cap-and-trade regulation, the suppliers gain lower profits comparing with those in the absence of carbon regulations. In this scenario, the managers of the suppliers may increase their wholesale prices. Moreover, if the carbon cap is relatively large, the managers of the manufacturers can increase sales prices to gain higher profit and lower carbon emissions.
- (v) For the C-D structure under cap-and-trade regulation, a relatively large carbon cap will be beneficial to the improvement profits of the supply chain 1 and the manufacturer 2 in the supply chain 2. Their managers

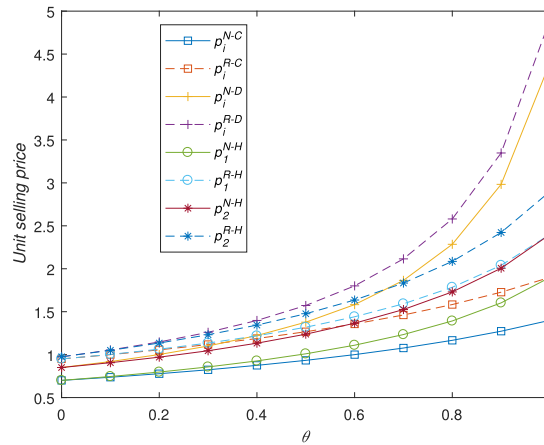


FIGURE 1. The impact of cap-and-trade regulation on unit selling price.

can increase the corresponding sales prices. However, comparing with the C-D structure in the absence of cap-and-trade regulation, the supplier in the supply chain as the leader gains lower profit. In this scenario, the supplier may increase the wholesale price.

### 6. NUMERICAL STUDY

In this section, we use a numerical example to illustrate the impacts of carbon cap-and-trade regulation on two competing supply chains. The parameters of the example are set as follows:  $c_m = 0.2$ ,  $c_s = 0.2$ ,  $a = 0.5$ ,  $\varepsilon = 1$  and  $\eta = 0.1$ .

Figure 1 shows the impact of cap-and-trade regulation on unit selling price. It can be found that the unit selling prices under cap-and-trade regulation are higher than those in the absence of cap-and-trade regulation, respectively, *i.e.*,  $p_i^{R-C} > p_i^{N-C}$ ,  $p_i^{R-D} > p_i^{N-D}$ ,  $p_1^{R-H} > p_1^{N-H}$  and  $p_2^{R-H} > p_2^{N-H}$ , which verify Propositions 5.1, 5.3 and 5.5(i). Also, the unit selling prices increase as the competition degree  $\theta$  increase.

In addition, from Figure 1, we obtain the relationship of the unit selling price in the absence of cap-and-trade regulation is  $p_i^{N-D} \geq p_2^{N-H} > p_1^{N-H} \geq p_i^{N-C}$ . Also, the relationship of unit selling price under cap-and-trade regulation is  $p_i^{R-D} \geq p_2^{R-H} > p_1^{R-H} \geq p_i^{R-C}$ . These findings verify Corollaries 4.4(i) and 4.9(i).

Figure 2 shows the impact of cap-and-trade regulation on market demand. It can be found that the market demands under cap-and-trade regulation are not higher than ones in the absence of carbon cap-and-trade regulation, respectively, *i.e.*,  $q_i^{R-C} \leq q_i^{N-C}$ ,  $q_i^{R-D} \leq q_i^{N-D}$ ,  $q_1^{R-H} \leq q_1^{N-H}$  and  $q_2^{R-H} \leq q_2^{N-H}$ , which verify Propositions 5.1, 5.3, and 5.5(ii). Also, the market demands increase as the competition degree  $\theta$  increase. Specifically, when  $\theta = 1$ , we have  $q_i^{R-C} = q_i^{N-C} = q_i^{R-D} = q_i^{N-D}$ ,  $q_1^{R-H} = q_1^{N-H}$  and  $q_2^{R-H} = q_2^{N-H}$ .

From Figure 2, we obtain the relationship of market demand in the absence of cap-and-trade regulation is  $q_1^{N-H} \geq q_i^{N-C} \geq q_i^{N-D} \geq q_2^{N-H}$ . Also, the relationship of market demand under cap-and-trade regulation is  $q_1^{R-H} \geq q_i^{R-C} \geq q_i^{R-D} \geq q_2^{R-H}$ . These findings verify Corollaries 4.4(ii) and 4.9(ii).

Figure 3 shows the impact of cap-and-trade regulation on wholesale price for D-D structure and C-D structure. It can be found that the wholesale prices for the two structures under cap-and-trade regulation are not higher than those in the absence of carbon cap-and-trade regulation, respectively, *i.e.*,  $\omega_i^{R-D} \leq \omega_i^{N-D}$  and  $\omega_2^{R-H} \leq \omega_2^{N-H}$ , which verify Propositions 5.1, 5.3, and 5.5(i). Also, the wholesale prices increase as the competition degree  $\theta$  increase. Specifically, when  $\theta = 1$ , we have  $\omega_i^{R-D} = \omega_i^{N-D}$  and  $\omega_2^{R-H} = \omega_2^{N-H}$ .

From Figure 3, we also obtain the relationship of wholesale price in the absence of cap-and-trade regulation is  $\omega_i^{N-D} \geq \omega_2^{N-H}$ . The relationship of wholesale price under cap-and-trade regulation is  $\omega_i^{R-D} \geq \omega_2^{R-H}$ . These findings verify Corollaries 4.4(iii) and 4.9(iii).

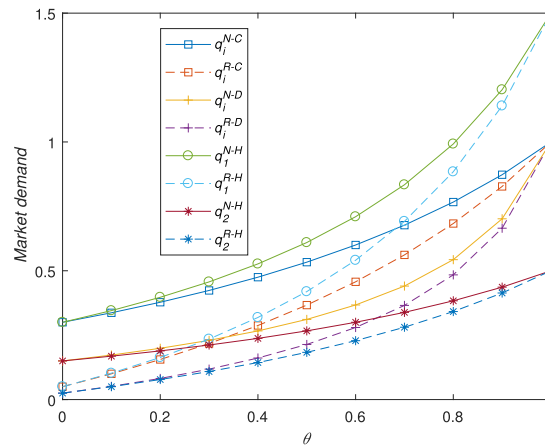


FIGURE 2. The impact of cap-and-trade regulation on market demand.

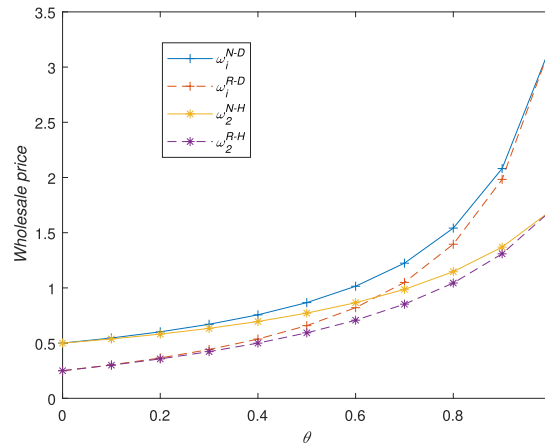


FIGURE 3. The impact of cap-and-trade regulation on wholesale price.

When  $\theta = 0.5$ , the impact of cap-and-trade regulation on profit for C-C structure is shown in Figure 4. The threshold of carbon cap  $K$  is  $\hat{K}_{\Pi i}^C = 0.150$ . It is worth noting that, when  $K > 0.150$ , the implementation of cap-and-trade regulation leads to the increase in the profit of supply chain  $i$  for C-C structure; otherwise, when  $K < 0.150$ , the implementation of cap-and-trade regulation leads to a decrease in the profit of supply chain  $i$  for C-C structure. This finding verifies Proposition 5.2(i).

When  $\theta = 0.5$ , the impact of cap-and-trade regulation on profit for D-D structure is shown in Figure 5. For the supplier, it can be seen that the profit of the supplier under cap-and-trade regulation is always lower than that in the absence of cap-and-trade regulation. For the manufacturer, the threshold of carbon cap  $K$  is  $\hat{K}_{\Pi M i}^D = 0.051$ . It is worth noting that, when  $K > 0.051$ , the implementation of cap-and-trade regulation leads to the increase in the profit of manufacturer  $i$  for D-D structure; otherwise, when  $K < 0.051$ , the implementation of cap-and-trade regulation leads to a decrease in the profit of manufacturer  $i$  for D-D structure. These findings verify Proposition 5.4(i).

When  $\theta = 0.5$ , the impact of cap-and-trade regulation on profit for C-D structure is shown in Figure 6. The comparison between  $\Pi_{S_2}^{R-H}$  and  $\Pi_{S_2}^{N-H}$  shows that, the profit of supplier 2 under cap-and-trade regulation

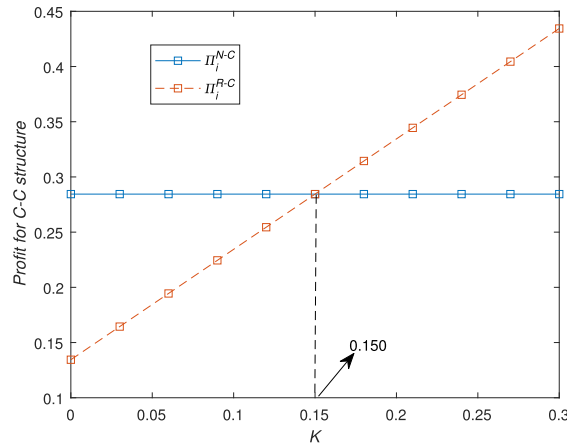


FIGURE 4. The impact of cap-and-trade regulation on profit for C-C structure.

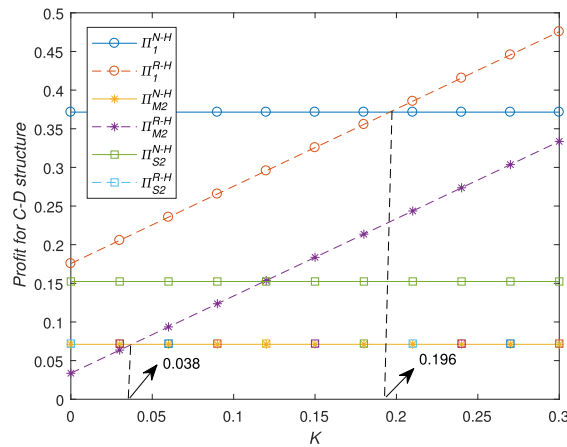


FIGURE 5. The impact of cap-and-trade regulation on profit for D-D structure.

is always lower than that in the absence of cap-and-trade regulation. For supply chain 1, the threshold of carbon cap  $K$  is  $\hat{K}_{\Pi 1}^H = 0.196$ . It is worth noting that, when  $K > 0.196$ , the implementation of cap-and-trade regulation leads to the increase in the profit of supply chain 1 for C-D structure; otherwise, when  $K < 0.196$ , the implementation of cap-and-trade regulation leads to a decrease in the profit of supply chain 1 for C-D structure. For manufacturer 2, the threshold of carbon cap  $K$  is  $\hat{K}_{\Pi M2}^H = 0.038$ . It is worth noting that, when  $K > 0.038$ , the implementation of cap-and-trade regulation leads to the increase in the profit of manufacturer 2 for C-D structure; otherwise, when  $K < 0.038$ , the implementation of cap-and-trade regulation leads to a decrease in the profit of manufacturer 2 for C-D structure. These findings verify Proposition 5.6(i).

Figure 7 shows the impact of cap-and-trade regulation on carbon emission. It can be found that the carbon emissions under cap-and-trade regulation are not higher than ones in the absence of carbon cap-and-trade regulation, respectively, *i.e.*,  $E^{R-C} \leq E^{N-C}$ ,  $E^{R-D} \leq E^{N-D}$  and  $E^{R-H} \leq E^{N-H}$ , which verify Propositions 5.2(ii), 5.4(ii) and 5.6(ii). Also, the carbon emissions increase as the competition degree  $\theta$  increase. Specifically, when  $\theta = 1$ , we have  $E^{R-C} = E^{N-C} = E^{R-D} = E^{N-D} = E^{R-H} = E^{N-H} = \frac{2\alpha}{2-\theta} = 1$ .

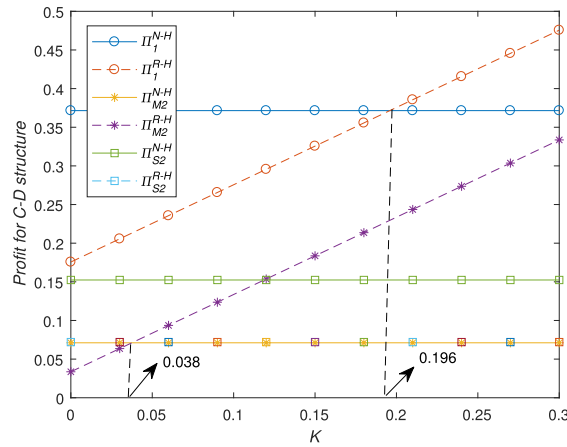


FIGURE 6. The impact of cap-and-trade regulation on profit for C-D structure.

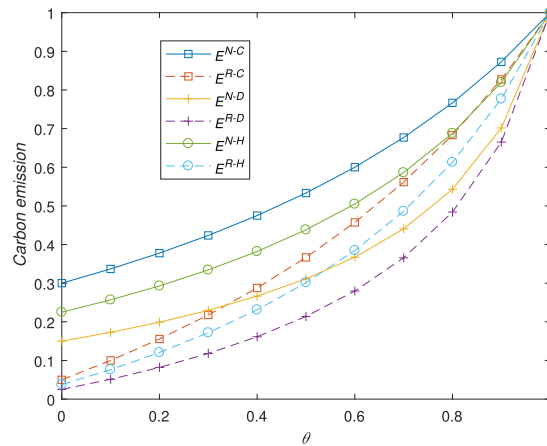


FIGURE 7. The impact of cap-and-trade regulation on carbon emission.

From Figure 7, we also obtain the relationship of carbon emission in the absence of cap-and-trade regulation is  $E^{N-C} \geq E^{N-H} \geq E^{N-D}$ . Also, the relationship of carbon emission under cap-and-trade regulation is  $E^{R-C} \geq E^{R-H} \geq E^{R-D}$ . These findings verify Corollaries 4.5 and 4.10.

Figure 8 shows the impact of cap-and-trade regulation on consumer surplus. It can be found that the consumer surpluses under cap-and-trade regulation are not higher than ones in the absence of carbon cap-and-trade regulation, respectively, *i.e.*,  $CS^{R-C} \leq CS^{N-C}$ ,  $CS^{R-D} \leq CS^{N-D}$  and  $CS^{R-H} \leq CS^{N-H}$ , which are already stated in Propositions 5.2(iii), 5.4(iii) and 5.6(iii). Also, the consumer surpluses increase as the competition degree  $\theta$  increase. Specifically, when  $\theta = 1$ , we have  $CS^{R-C} = CS^{N-C} = CS^{R-D} = CS^{N-D}$  and  $CS^{R-H} = CS^{N-H}$ .

When  $\theta = 0.5$ , the impact of cap-and-trade regulation on social welfare is shown in Figure 9. The thresholds of carbon cap  $K$  are  $\hat{K}_W^C = 0.217$  (for the C-C structure),  $\hat{K}_W^D = 0.181$  (for the D-D structure) and  $\hat{K}_W^H = 0.208$  (for the C-D structure). It is worth noting that, when the carbon cap  $K$  is higher than the threshold, the implementation of cap-and-trade regulation leads to the increase in social welfare; otherwise, when the carbon

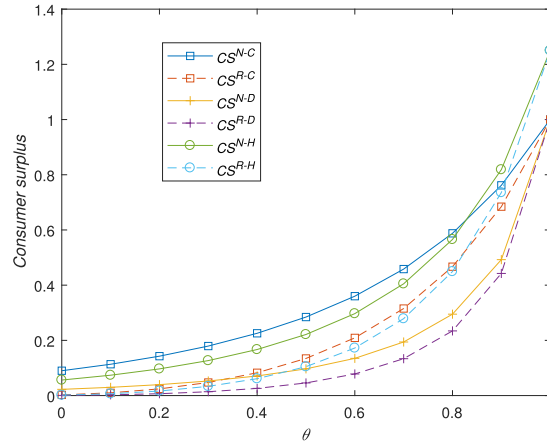


FIGURE 8. The impact of cap-and-trade regulation on consumer surplus.

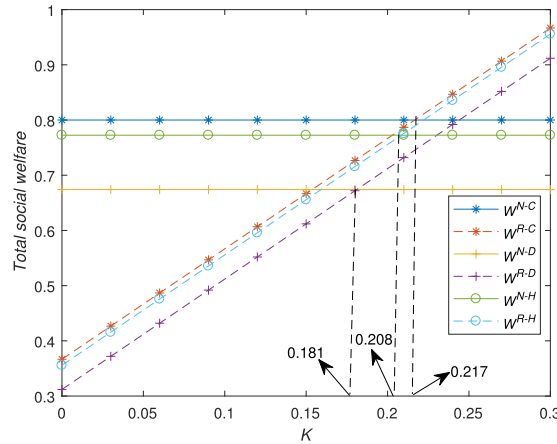


FIGURE 9. The impact of cap-and-trade regulation on social welfare.

cap  $K$  is less than the threshold, the implementation of cap-and-trade regulation leads to a decrease in the social welfare. These findings verify Proposition 5.6(iv).

### 7. CONCLUSIONS

To reduce carbon emissions, many countries and regions have implemented regulations such as cap-and-trade. In a horizontally competitive market, modern business competition channels are no longer limited to enterprises, but competition between the entire supply chain. These real cases motivate us to study the impacts of cap-and-trade regulation on two competing supply chains. In this paper, we consider two cases: (1) in the absence of cap-and-trade regulation and (2) in the presence of cap-and-trade regulation. First, we analyze the optimal pricing decisions of two competing supply chains for the two cases, and then explore the impacts of cap-and-trade regulation on the sale price, market demand, profits, the environment, consumer surplus, and social welfare. By comparing the results of the two cases, the main management insights and the corresponding practical implications are as follows:

- (i) The sales prices under cap-and-trade regulation are higher than those in the absence of cap-and-trade regulation. This can provide insights for business industry to make pricing decisions. The market demand under cap-and-trade regulation are less than those in the absence of cap-and-trade regulation. This can provide insights for business industry to make production decisions.
- (ii) For of the supplier, the profit under cap-and-trade regulation is always lower than that in the absence of cap-and-trade regulation. Therefore, the implementation of carbon cap-and-trade regulation is not good for the supplier, for example Contemporary Amperex Technology Co., Limited (CATL), who is the main battery supplier of Tesla. Hence, the management implication for the supplier, such as CATL, is that it is not wise to participate in carbon trading unless the government or manufacturers, such as Tesla, subsidizes him.
- For the manufacturer, when the carbon cap is relatively high, the implementation of cap-and-trade regulation leads to the increase in the profit of manufacturer; otherwise, the implementation of cap-and-trade regulation leads to a decrease in the profit of manufacturer. Hence, the management implication for the manufacturers, such as such as Tesla and BYD, is they can judge whether the implementation of cap-and-trade regulation is beneficial to them according to the carbon cap, so as to decide whether to join the carbon trading scheme.
- (iii) The carbon cap-and-trade regulation leads to the reduction of carbon emission. In other words, the implementation of carbon cap-and-trade regulation is always good for the environment. The management implication is that the government can effectively use the carbon cap-and-trade regulation to supervise the carbon emission of enterprises, and finally achieve the goal of carbon emission reduction.
- Moreover, the consumer surplus under cap-and-trade regulation is less than that in the absence of cap-and-trade regulation for the three structures. This is because, in order to reduce carbon emissions, consumers also need to sacrifice part of their profits to contribute to protecting the environment.
- (iv) The impact of cap-and-trade regulation on the social welfare depends on the carbon cap. When the carbon cap is high enough, the implementation of cap-and-trade regulation leads to the increase in social welfare; otherwise, the implementation of cap-and-trade regulation leads to a decrease in the social welfare. This can provide a reference for carbon regulation makers to set policy indicators from the perspective of total social welfare.

This paper has some limitations. For example, this paper is based on the assumption of complete information and demand determination. If asymmetric information or market demand is taken into account, the problem will be more complicated. Our study can be extended in several directions. First, this paper is based on the assumption of complete information and demand determination. Future research could explore this problem based on asymmetric information or uncertain market demand. Second, in our study, the carbon reduction investment is not considered. It would be valuable to extend the current work to a complex scenario where the carbon reduction investment is to be optimized.

#### APPENDIX A. PROOF OF PROPOSITION 4.1

Substituting  $q_i = 1 - p_i + \theta p_j$  into equation (2), we have  $\max_{p_i} \Pi_i^{N-C} = (p_i - c_m - c_s) \cdot (1 - p_i + \theta p_j)$  where  $j = 3 - i$  and  $i = 1, 2$ . Taking the second partial derivative of  $\Pi_i^{N-C}$  with  $p_i$ , we have  $\frac{\partial^2 \Pi_i^{N-C}}{\partial p_i^2} = -2 < 0$ . It is obvious that  $\Pi_i^{N-C}$  is a concave function of  $p_i$ . Taking the first-order derivative and solving the joint equations for  $i = 1, 2$ , it follows  $p_i^{N-C} = \frac{1+c_m+c_s}{2-\theta}$ .

#### APPENDIX B. PROOF OF PROPOSITION 4.2

Firstly, substituting  $q_i = 1 - p_i + \theta p_j$  into equation (4), we have  $\max_{p_i} \Pi_{Mi}^{N-D} = (p_i - \omega_i - c_s)(1 - p_i + \theta p_j)$  where  $j = 3 - i$  and  $i = 1, 2$ . Taking the second partial derivative of  $\Pi_{Mi}^{N-D}$  with  $p_i$ , we have  $\frac{\partial^2 \Pi_{Mi}^{N-D}}{\partial p_i^2} = -2 < 0$ . It is obvious that  $\Pi_{Mi}^{N-D}$  is a concave function of  $p_i$ . Taking the first-order derivative and solving the joint equations

for  $i = 1, 2$ , it follows  $p_i^{N-D} = \frac{2+\theta+c_m(2+\theta)+2\omega_i+\theta\omega_j}{4-\theta^2}$ . Substituting optimal price  $p_i^{N-D}$  into the equation (1) yields  $q_i^{N-D} = \frac{2-c_m(2-\theta-\theta^2)-2\omega_i+\theta(1+\theta\omega_i+\omega_j)}{4-\theta^2}$ . Substituting optimal price  $p_i^{N-D}$  and  $q_i^{N-D}$  into the equation (3) yields  $\max_{\omega_i} \Pi_{S_i}^{N-D} = \frac{(c_s-\omega_i)[2+c_m(-2+\theta+\theta^2)-2\omega_i+\theta(1+\theta\omega_i+\omega_j)]}{-4+\theta^2}$ .

Taking the second partial derivative of  $\Pi_{S_i}^{N-D}$  with  $\omega_i$ , we have  $\frac{\partial^2 \Pi_{S_i}^{N-D}}{\partial \omega_i^2} = -\frac{2(2-\theta^2)}{4-\theta^2} < 0$ . It is obvious that  $\Pi_{S_i}^{N-D}$  is a concave function of  $\omega_i$ . Taking the first-order derivative and solving the joint equations for  $i = 1, 2$ , it follows  $\omega_i^{N-D} = \frac{2+(1+c_m)\theta+(c_s-c_m)(2-\theta^2)}{4-\theta-2\theta^2}$ .

### APPENDIX C. PROOF OF PROPOSITION 4.3

Firstly, substituting  $q_i = 1 - p_i + \theta p_j$  into equations (5) and (7), we have  $\max_{p_1} \Pi_1^{N-H} = (p_1 - c_m - c_s)(1 - p_1 + \theta p_2)$  and  $\max_{p_2} \Pi_{M_2}^{N-H} = (p_2 - \omega_2 - c_s)(1 - p_2 + \theta p_1)$  where  $j = 3 - i$  and  $i = 1, 2$ . Taking the second partial derivative of  $\Pi_1^{N-H}$  and  $\Pi_{M_2}^{N-H}$  with  $p_1$  and  $p_2$ , respectively, we have  $\frac{\partial^2 \Pi_1^{N-H}}{\partial p_1^2} = -2 < 0$  and  $\frac{\partial^2 \Pi_{M_2}^{N-H}}{\partial p_2^2} = -2 < 0$ . It is obvious that  $\Pi_1^{N-H}$  is a concave function of  $p_1$ , and  $\Pi_{M_2}^{N-H}$  is a concave function of  $p_2$ . Taking the first-order derivative and solving the joint equations, we have  $p_1^{N-H} = \frac{2+2c_s+\theta+c_m(2+\theta)+\theta\omega_2}{4-\theta^2}$  and  $p_2^{N-H} = \frac{2+\theta+c_s\theta+c_m(2+\theta)+2\omega_2}{4-\theta^2}$ . Substituting optimal price  $p_i^{N-D}$  into the equation (6) yields

$$\max_{\omega_2} \Pi_{S_2}^{N-H} = \frac{(\omega_2 - c_s)[2 + \theta + c_s\theta - c_m(2 - \theta - \theta^2) - (2 - \theta^2)\omega_2]}{4 - \theta^2}.$$

Taking the second partial derivative of  $\Pi_{S_2}^{N-H}$  with  $\omega_2$ , we have  $\frac{\partial^2 \Pi_{S_2}^{N-H}}{\partial \omega_2^2} = -\frac{2(2-\theta^2)}{4-\theta^2} < 0$ . It is obvious that  $\Pi_{S_2}^{N-H}$  is a concave function of  $\omega_2$ . Taking the first-order derivative and solving the joint equations, it follows  $\omega_2^{N-H} = \frac{(2+\theta)+c_s(2+\theta-\theta^2)-c_m(2-\theta-\theta^2)}{2(2-\theta^2)}$ .

### APPENDIX D. PROOF OF COROLLARY 4.4

- (i) Comparing the unit selling prices in the absence of cap-and-trade regulation for the three 2-chain structures, we have  $p_i^{N-D} - p_2^{N-H} = \frac{\theta(3-\theta^2)[1-(c_m+c_s)(1-\theta)]}{(2-\theta)(2-\theta^2)(4-\theta-2\theta^2)} \geq 0$ ,  $p_2^{N-H} - p_1^{N-H} = \frac{1-(c_m+c_s)(1-\theta)}{2(2-\theta^2)} > 0$ , and  $p_1^{N-H} - p_i^{N-C} = \frac{\theta[1-(c_m+c_s)(1-\theta)]}{2(2-\theta)(2-\theta^2)} \geq 0$ .
- (ii) Comparing the market demands in the absence of cap-and-trade regulation for the three 2-chain structures, we have  $q_1^{N-H} - q_i^{N-C} = \frac{\theta[1-(c_m+c_s)(1-\theta)]}{2(2-\theta)(2-\theta^2)} \geq 0$ ,  $q_i^{N-C} - q_i^{N-D} = \frac{[1-(c_m+c_s)(1-\theta)](2-\theta-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)} \geq 0$ , and  $q_i^{N-D} - q_2^{N-H} = \frac{\theta[1-(c_m+c_s)(1-\theta)]}{2(2-\theta)(4-\theta-2\theta^2)} \geq 0$ .
- (iii) Comparing the wholesale prices in the absence of cap-and-trade regulation for the D-D and C-D structures, we have  $\omega_i^{N-D} - \omega_2^{N-H} = \frac{\theta(2+\theta)[1-(c_m+c_s)(1-\theta)]}{2(2-\theta^2)(4-\theta-2\theta^2)} \geq 0$ .

### APPENDIX E. PROOF OF COROLLARY 4.5

Comparing the carbon emissions in the absence of cap-and-trade regulation for the three 2-chain structures, we have  $E^{N-C} - E^{N-H} = \frac{a[1-(c_m+c_s)(1-\theta)](2-\theta-\theta^2)}{2(2-\theta)(2-\theta^2)} \geq 0$  and  $E^{N-H} - E^{N-D} = \frac{a[1-(c_m+c_s)(1-\theta)](1-\theta)(2+\theta)[4+\theta(1-2\theta)]}{2(2-\theta)(2-\theta^2)(4-\theta-2\theta^2)} \geq 0$ .

### APPENDIX F. PROOF OF PROPOSITION 4.6

The proof of Proposition 4.6 is similar to Proposition 4.1.

APPENDIX G. PROOF OF PROPOSITION 4.7

The proof of Proposition 4.7 is similar to Proposition 4.2.

APPENDIX H. PROOF OF PROPOSITION 4.8

The proof of Proposition 4.8 is similar to Proposition 4.3.

APPENDIX I. PROOF OF COROLLARY 4.9

- (i) Comparing the unit selling prices considering carbon cap-and-trade regulation for the three 2-chain structures, we have  $p_i^{R-D} - p_2^{R-H} = \frac{\theta(3-\theta^2)[1-(c_m+c_s+a\varepsilon)(1-\theta)]}{(2-\theta)(2-\theta^2)(4-\theta-2\theta^2)} \geq 0$ ,  $p_2^{R-H} - p_1^{R-H} = \frac{1-(c_m+c_s+a\varepsilon)(1-\theta)}{2(2-\theta^2)} > 0$ , and  $p_1^{R-H} - p_i^{R-C} = \frac{\theta[1-(c_m+c_s+a\varepsilon)(1-\theta)]}{2(2-\theta)(2-\theta^2)} \geq 0$ .
- (ii) Comparing the market demands considering carbon cap-and-trade regulation for the three 2-chain structures, we have  $q_1^{R-H} - q_i^{R-C} = \frac{\theta[1-(c_m+c_s+a\varepsilon)(1-\theta)]}{2(2-\theta)(2-\theta^2)} \geq 0$ ,  $q_i^{R-C} - q_i^{R-D} = \frac{[1-(c_m+c_s+a\varepsilon)(1-\theta)](2-\theta-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)} \geq 0$ , and  $q_i^{R-D} - q_2^{R-H} = \frac{\theta[1-(c_m+c_s+a\varepsilon)(1-\theta)]}{2(2-\theta)(4-\theta-2\theta^2)} \geq 0$ .
- (iii) Comparing the wholesale prices considering carbon cap-and-trade regulation for the D-D and C-D structures, we have

$$\omega_i^{R-D} - \omega_2^{R-H} = \frac{\theta(2+\theta)[1-(c_m+c_s+a\varepsilon)(1-\theta)]}{2(2-\theta^2)(4-\theta-2\theta^2)} \geq 0.$$

APPENDIX J. PROOF OF COROLLARY 4.10

Comparing the carbon emissions considering carbon cap-and-trade regulation for the three 2-chain structures, we have

$$E^{R-C} - E^{R-H} = \frac{a[1-(c_m+c_s+a\varepsilon)(1-\theta)](2-\theta-\theta^2)}{2(2-\theta)(2-\theta^2)} \geq 0$$

and  $E^{R-H} - E^{R-D} = \frac{a[1-(c_m+c_s+a\varepsilon)(1-\theta)](1-\theta)(2+\theta)[4+\theta(1-2\theta)]}{2(2-\theta)(2-\theta^2)(4-\theta-2\theta^2)} \geq 0.$

APPENDIX K. PROOF OF PROPOSITION 5.1

- (i) Comparing the price of the supply chain  $i$  for the C-C Structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have  $p_i^{R-C} - p_i^{N-C} = \frac{1+c_m+c_s+a\varepsilon}{2-\theta} - \frac{1+c_m+c_s}{2-\theta} = \frac{a\varepsilon}{2-\theta} > 0$ .
- (ii) Comparing the market demand of supply chain  $i$  for the C-C structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have  $q_i^{R-C} - q_i^{N-C} = \frac{1-c_m-c_s-a\varepsilon+(c_m+c_s+a\varepsilon)\theta}{2-\theta} - \frac{1-c_m-c_s+(c_m+c_s)\theta}{2-\theta} = -\frac{a\varepsilon(1-\theta)}{2-\theta} \leq 0$ .

APPENDIX L. PROOF OF PROPOSITION 5.2

- (i) Comparing the profit of supply chain  $i$  for the C-C structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} \Pi_i^{R-C} - \Pi_i^{N-C} &= K\varepsilon + \frac{[1-c_m-c_s-a\varepsilon+(c_m+c_s+a\varepsilon)\theta]^2}{(2-\theta)^2} - \frac{[1-c_m(1-\theta)-c_s(1-\theta)]^2}{(2-\theta)^2} \\ &= \frac{\varepsilon \left\{ K(2-\theta)^2 - 2a[1-(c_m+c_s)(1-\theta)](1-\theta) + a^2\varepsilon(1-\theta)^2 \right\}}{(2-\theta)^2}. \end{aligned}$$

Hence, we obtain  $\Pi_i^{R-C} - \Pi_i^{N-C} > 0$  when  $K > \frac{2a[1-(c_m+c_s)(1-\theta)](1-\theta)+a^2\varepsilon(1-\theta)^2}{(2-\theta)^2}$ .

- (ii) Comparing the carbon emission for the C-C structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$E^{R-C} - E^{N-C} = \frac{2a[1-(c_m+c_s+a\varepsilon)(1-\theta)]}{2-\theta} - \frac{2a[1-c_m(1-\theta)-c_s(1-\theta)]}{2-\theta} = -\frac{2a^2\varepsilon(1-\theta)}{2-\theta} \leq 0.$$

- (iii) Comparing the consumer surplus for the C-C structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$CS^{R-C} - CS^{N-C} = -\frac{a\varepsilon[2-2c_m(1-\theta)-2c_s(1-\theta)-a\varepsilon(1-\theta)](1-\theta)}{(2-\theta)^2} \leq 0.$$

- (iv) Comparing the social welfare for the C-C structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$W^{R-C} - W^{N-C} = \frac{\varepsilon\left\{2K(2-\theta)^2 - 6a[1-(c_m+c_s)(1-\theta)](1-\theta) + a^2[2\eta(2-\theta) + 3\varepsilon(1-\theta)](1-\theta)\right\}}{(2-\theta)^2}.$$

Hence, we obtain  $W^{R-C} - W^{N-C} > 0$  when

$$K > \frac{6a[1-(c_m+c_s)(1-\theta)](1-\theta) - a^2[2\eta(2-\theta) + 3\varepsilon(1-\theta)](1-\theta)}{2(2-\theta)^2}.$$

### APPENDIX M. PROOF OF PROPOSITION 5.3

- (i) Comparing the wholesale price of the supplier in the supply chain  $i$  for the D-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} \omega_i^{R-D} - \omega_i^{N-D} &= \frac{[1-a\varepsilon(1-\theta)](2+\theta) + c_s(2-\theta^2) - c_m(2-\theta-\theta^2)}{4-\theta-2\theta^2} \\ &\quad - \frac{2+\theta+c_s(2-\theta^2) - c_m(2-\theta-\theta^2)}{4-\theta-2\theta^2} = -\frac{a\varepsilon(2-\theta-\theta^2)}{4-\theta-2\theta^2} \leq 0. \end{aligned}$$

Comparing the unit selling price of manufacturer in the supply chain  $i$  for the D-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} p_i^{R-D} - p_i^{N-D} &= \frac{2(3+c_m+c_s+a\varepsilon) - (2+c_m+c_s+a\varepsilon)\theta^2}{(2-\theta)(4-\theta-2\theta^2)} - \frac{2(3+c_m+c_s) - (2+c_m+c_s)\theta^2}{(2-\theta)(4-\theta-2\theta^2)} \\ &= \frac{a\varepsilon(2-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)} > 0. \end{aligned}$$

- (ii) Comparing the market demand of supply chain  $i$  for the D-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} q_i^{R-D} - q_i^{N-D} &= \frac{[1-c_m-c_s-a\varepsilon+(c_m+c_s+a\varepsilon)\theta](2-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)} - \frac{[1-c_m-c_s+(c_m+c_s)\theta](2-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)} \\ &= -\frac{a\varepsilon(1-\theta)(2-\theta^2)}{(2-\theta)(4-\theta-2\theta^2)} \leq 0. \end{aligned}$$

APPENDIX N. PROOF OF PROPOSITION 5.4

- (i) Comparing the profit of manufacturer in the supply chain  $i$  for the D-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} \Pi_{Mi}^{R-D} - \Pi_{Mi}^{N-D} &= K\varepsilon + \frac{[1 - c_m - c_s - a\varepsilon + (c_m + c_s + a\varepsilon)\theta]^2(2 - \theta^2)^2}{(2 - \theta)^2(4 - \theta - 2\theta^2)^2} \\ &\quad - \frac{[1 - c_m - c_s + (c_m + c_s)\theta]^2(2 - \theta^2)^2}{(2 - \theta)^2(4 - \theta - 2\theta^2)^2} \\ &= \varepsilon \left( K - \frac{a[2 - (2c_m + 2c_s + a\varepsilon)(1 - \theta)](1 - \theta)(-2 + \theta^2)^2}{(2 - \theta)^2(4 - \theta - 2\theta^2)^2} \right). \end{aligned}$$

Hence, we obtain  $\Pi_{Mi}^{R-D} > \Pi_{Mi}^{N-D}$  when  $K > \frac{a[2 - (2c_m + 2c_s + a\varepsilon)(1 - \theta)](1 - \theta)(2 - \theta^2)^2}{(2 - \theta)^2(4 - \theta - 2\theta^2)^2}$ .

Comparing the profit of supplier  $i$  for the D-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} \Pi_{Si}^{R-D} - \Pi_{Si}^{N-D} &= \frac{[1 - c_m - c_s - a\varepsilon + (c_m + c_s + a\varepsilon)\theta]^2(2 + \theta)(2 - \theta^2)}{(2 - \theta)(4 - \theta - 2\theta^2)^2} \\ &\quad - \frac{[1 - c_m - c_s + (c_m + c_s)\theta]^2(2 + \theta)(2 - \theta^2)}{(2 - \theta)(4 - \theta - 2\theta^2)^2} \\ &= - \frac{a\varepsilon[2 - (2c_m + 2c_s + a\varepsilon)(1 - \theta)](1 - \theta)(2 + \theta)(2 - \theta^2)}{(2 - \theta)(4 - \theta - 2\theta^2)^2} \leq 0. \end{aligned}$$

- (ii) Comparing the carbon emission for the D-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} E^{R-D} - E^{N-D} &= \frac{2a[1 - c_m(1 - \theta) - c_s(1 - \theta) - a\varepsilon(1 - \theta)](2 - \theta^2)}{(2 - \theta)(4 - \theta - 2\theta^2)} \\ &\quad - \frac{2a[1 - c_m(1 - \theta) - c_s(1 - \theta)](2 - \theta^2)}{(2 - \theta)(4 - \theta - 2\theta^2)} = - \frac{2a^2\varepsilon(1 - \theta)(2 - \theta^2)}{(2 - \theta)(4 - \theta - 2\theta^2)} \leq 0. \end{aligned}$$

- (iii) Comparing the consumer surplus for the D-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$CS^{R-D} - CS^{N-D} = - \frac{a\varepsilon[2 - (2c_m + 2c_s + a\varepsilon)(1 - \theta)](1 - \theta)(2 - \theta^2)^2}{(2 - \theta)^2(4 - \theta - 2\theta^2)^2} \leq 0.$$

- (iv) Comparing the social welfare for the D-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$W^{R-D} - W^{N-D} = \frac{\varepsilon \left( \frac{2K(2 - \theta)^2(4 - \theta - 2\theta^2)^2 + a[(2c_m + 2c_s + a\varepsilon)(1 - \theta) - 2](1 - \theta)(2 - \theta^2)}{(14 - 5\theta^2) + a^2(1 - \theta)(2 - \theta^2)2\eta(2 - \theta)(4 - \theta - 2\theta^2)} \right)}{(2 - \theta)^2(4 - \theta - 2\theta^2)^2}.$$

Hence, we obtain  $\Pi_{Mi}^{R-D} > \Pi_{Mi}^{N-D}$  when

$$K > \frac{a(1 - \theta)[2 - (2c_m + 2c_s + a\varepsilon)(1 - \theta)](2 - \theta^2)(14 - 5\theta^2) - a(2 - \theta^2)2\eta(2 - \theta)(4 - \theta - 2\theta^2)}{2(2 - \theta)^2(4 - \theta - 2\theta^2)^2}.$$

APPENDIX O. PROOF OF PROPOSITION 5.5

- (i) Comparing the wholesale price of the supplier 2 for the C-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} \omega_2^{R-H} - \omega_2^{N-H} &= \frac{[1 - a\varepsilon(1 - \theta)](2 + \theta) + c_s(2 + \theta - \theta^2) - c_m(2 - \theta - \theta^2)}{2(2 - \theta^2)} \\ &\quad - \frac{(2 + \theta) + c_s(2 + \theta - \theta^2) - c_m(2 - \theta - \theta^2)}{2(2 - \theta^2)} = -\frac{a\varepsilon(2 + \theta - \theta^2)}{2(2 - \theta^2)} \leq 0. \end{aligned}$$

Comparing the unit selling price of manufacturer 1 for the C-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} p_1^{R-H} - p_1^{N-H} &= \frac{4(1 + c_m + c_s + a\varepsilon) + (1 - c_m - c_s - a\varepsilon)\theta - (2 + c_m + c_s + a\varepsilon)\theta^2}{2(2 - \theta)(2 - \theta^2)} \\ &\quad - \frac{4(1 + c_m + c_s) + (1 - c_m - c_s)\theta - (2 + c_m + c_s)\theta^2}{2(2 - \theta)(2 - \theta^2)} = \frac{a\varepsilon(4 - \theta - \theta^2)}{2(2 - \theta)(2 - \theta^2)} > 0. \end{aligned}$$

Comparing the unit selling price of manufacturer 2 for the C-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} p_2^{R-H} - p_2^{N-H} &= \frac{3 + c_m + c_s + a\varepsilon + (c_m + c_s + a\varepsilon)\theta - (1 + c_m + c_s + a\varepsilon)\theta^2}{2(2 - \theta)(2 - \theta^2)} \\ &\quad - \frac{3 + c_m + c_s + (c_m + c_s)\theta - (1 + c_m + c_s)\theta^2}{(2 - \theta)(2 - \theta^2)} = \frac{a\varepsilon(1 + \theta - \theta^2)}{(2 - \theta)(2 - \theta^2)} > 0. \end{aligned}$$

- (ii) Comparing the market demand of supply chain 1 for the C-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} q_1^{R-H} - q_1^{N-H} &= \frac{(1 - c_m(1 - \theta) - c_s(1 - \theta) - a\varepsilon(1 - \theta))(4 + \theta - 2\theta^2)}{2(2 - \theta)(2 - \theta^2)} \\ &\quad - \frac{[1 - c_m(1 - \theta) - c_s(1 - \theta)](4 + \theta - 2\theta^2)}{2(2 - \theta)(2 - \theta^2)} = -\frac{1}{2}a\varepsilon\left(2 - \frac{1}{2 - \theta} - \frac{1}{2 - \theta^2}\right) \leq 0. \end{aligned}$$

Comparing the market demand of supply chain 2 for the C-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$q_2^{R-H} - q_2^{N-H} = \frac{1 - c_m(1 - \theta) - c_s(1 - \theta) - a\varepsilon(1 - \theta)}{2(2 - \theta)} - \frac{1 - c_m(1 - \theta) - c_s(1 - \theta)}{2(2 - \theta)} = -\frac{a\varepsilon(1 - \theta)}{2(2 - \theta)} \leq 0.$$

APPENDIX P. PROOF OF PROPOSITION 5.6

- (i) Comparing the profit of supply chain 1 for the C-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} \Pi_1^{R-H} - \Pi_1^{N-H} &= K\varepsilon + \frac{[1 - c_m(1 - \theta) - c_s(1 - \theta) - a\varepsilon(1 - \theta)]^2(4 + \theta - 2\theta^2)^2}{4(2 - \theta)^2(2 - \theta^2)^2} \\ &\quad - \frac{[1 - c_m(1 - \theta) - c_s(1 - \theta)]^2(4 + \theta - 2\theta^2)^2}{4(2 - \theta)^2(2 - \theta^2)^2} \end{aligned}$$

$$= K\varepsilon - \frac{a\varepsilon[2 - (2c_m + 2c_s + a\varepsilon)(1 - \theta)](1 - \theta)(4 + \theta - 2\theta^2)^2}{4(2 - \theta)^2(2 - \theta^2)^2}.$$

Hence, we obtain  $\Pi_1^{R-H} > \Pi_1^{N-H}$  when

$$K > \frac{a[2 - (2c_m + 2c_s + a\varepsilon)(1 - \theta)](1 - \theta)(4 + \theta - 2\theta^2)^2}{4(2 - \theta)^2(2 - \theta^2)^2}.$$

Comparing the profit of manufacturer 2 for the C-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} \Pi_{M2}^{R-H} - \Pi_{M2}^{N-H} &= \varepsilon K - \frac{\varepsilon\{2a[1 - c_m(1 - \theta) - c_s(1 - \theta) - a\varepsilon(1 - \theta)](1 - \theta) - a^2\varepsilon(1 - \theta)^2\}}{4(2 - \theta)^2} \\ &\quad + \frac{[1 - c_m(1 - \theta) - c_s(1 - \theta)]^2}{4(2 - \theta)^2} - \frac{[1 - c_m(1 - \theta) - c_s(1 - \theta)]^2}{4(2 - \theta)^2} \\ &= \frac{\varepsilon\{4K(2 - \theta)^2 - 2a[1 - (c_m + c_s)(1 - \theta)](1 - \theta) + a^2\varepsilon(1 - \theta)^2\}}{4(2 - \theta)^2}. \end{aligned}$$

Hence, we can obtain  $\Pi_{M2}^{R-H} > \Pi_{M2}^{N-H}$  when  $K > \frac{2a[1 - (c_m + c_s)(1 - \theta)](1 - \theta) + a^2\varepsilon(1 - \theta)^2}{4(2 - \theta)^2}$ .

Comparing the profit of supplier 2 for the C-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} \Pi_{S2}^{R-H} - \Pi_{S2}^{N-H} &= \frac{(2 + \theta)[1 - c_m(1 - \theta) - c_s(1 - \theta) - a\varepsilon(1 - \theta)]^2}{4(2 - \theta)(2 - \theta^2)} - \frac{(2 + \theta)[1 - c_m(1 - \theta) - c_s(1 - \theta)]^2}{4(2 - \theta)(2 - \theta^2)} \\ &= -\frac{a\varepsilon[2 - (2c_m + 2c_s + a\varepsilon)(1 - \theta)](1 - \theta)(2 + \theta)(2 - \theta^2)}{(2 - \theta)(4 - \theta - 2\theta^2)^2} \leq 0. \end{aligned}$$

(ii) Comparing the carbon emission for the C-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$\begin{aligned} E^{R-H} - E^{N-H} &= \frac{a[1 - c_m(1 - \theta) - c_s(1 - \theta) - a\varepsilon(1 - \theta)][6 + \theta(1 - 3\theta)]}{2(2 - \theta)(2 - \theta^2)} \\ &\quad - \frac{a[1 - c_m(1 - \theta) - c_s(1 - \theta)][6 + \theta(1 - 3\theta)]}{2(2 - \theta)(2 - \theta^2)} = -\frac{a^2\varepsilon\{6 - \theta[5 + (4 - 3\theta)\theta]\}}{2(2 - \theta)(2 - \theta^2)} \leq 0. \end{aligned}$$

(iii) Comparing the consumer surplus for the C-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$CS^{R-H} - CS^{N-H} = -\frac{a\varepsilon[2 - (2c_m + 2c_s + a\varepsilon)(1 - \theta)](1 - \theta)\{20 + \theta[8 - 19\theta - \theta^2(4 - 5\theta)]\}}{8(2 - \theta)^2(2 - \theta^2)^2} \leq 0.$$

(iv) Comparing the social welfare for the C-D structure under cap-and-trade regulation with that in the absence of cap-and-trade regulation, we have

$$W^{R-H} - W^{N-H} = \frac{\varepsilon\left(\begin{aligned} &16K(2 - \theta)^2(2 - \theta^2)^2 + a[(2c_m + 2c_s + a\varepsilon)(1 - \theta) - 2] \\ &\cdot(1 - \theta)\{76 + \theta[24 - 69\theta - \theta^2(12 - 17\theta)]\} \\ &+ a^2(1 - \theta)4\eta(2 - \theta)(2 - \theta^2)[6 + \theta(1 - 3\theta)] \end{aligned}\right)}{8(2 - \theta)^2(2 - \theta^2)^2}.$$

Hence, we obtain  $W^{R-H} > W^{N-H}$  when

$$K > \frac{\left( \begin{array}{l} a[2 - (2c_m + 2c_s + a\varepsilon)(1 - \theta)](1 - \theta)\{76 + \theta[24 - 69\theta - \theta^2(12 - 17\theta)]\} \\ -a^2(1 - \theta)4\eta(2 - \theta)(2 - \theta^2)[6 + \theta(1 - 3\theta)] \end{array} \right)}{16(2 - \theta)^2(2 - \theta^2)^2}.$$

#### Acknowledgements

The authors are grateful to the editor and the two anonymous reviewers who provided valuable suggestions to improve the quality of this paper significantly. This work was supported by the Jiangsu University Philosophy and Social Science Research Project, China (Grant No. 2021SJA1410); National Natural Science Foundation of China (Grant No. 72271141); Youth Innovation Science and Technology Support Program of Shandong Province Higher Education, China (Grant No. 2021RW024); and Changshu Philosophy Society Application Research Project, China (Grant No. Cs202367).

#### REFERENCES

- [1] Q. Bai, Y. Gong, M. Jin and X. Xu, Effects of carbon emission reduction on supply chain coordination with vendor-managed deteriorating product inventory. *Int. J. Prod. Econ.* **208** (2019) 83–99.
- [2] Q. Bai, J. Xu, Y. Gong and S.S. Chauhan, Robust decisions for regulated sustainable manufacturing with partial demand information: mandatory emission capacity versus emission tax. *Eur. J. Oper. Res.* **298** (2022) 874–893.
- [3] H. Barman, M. Pervin and S.K. Roy, Impacts of green and preservation technology investments on a sustainable EPQ model during COVID-19 pandemic. *RAIRO-Oper. Res.* **56** (2022) 2245–2275.
- [4] Y. Cai, T. Choi, L. Feng and Y. Li, Producer's choice of design-for-environment under environmental taxation. *Eur. J. Oper. Res.* **297** (2021) 532–544.
- [5] Y. Chen, B. Li, G. Zhang and Q. Bai, Quantity and collection decisions of the remanufacturing enterprise under both the take-back and carbon emission capacity regulations. *Transp. Res. E-Log.* **141** (2020) 102032.
- [6] D. Chen, C. Tian, Z. Chen and D. Zhang, Competition among supply chains: the choice of financing strategy. *Oper. Res. Int. J.* **22** (2022) 977–1000.
- [7] C. Dong, B. Shen, P. Chow, L. Yang and C.T. Ng, Sustainability investment under cap-and-trade regulation. *Ann. Oper. Res.* **240** (2016) 509–531.
- [8] Y.Y. Fan, M. Wang and L.D. Zhao, Production-inventory and emission reduction investment decision under carbon cap-and-trade policy. *RAIRO-Oper. Res.* **52** (2018) 1043–1067.
- [9] H. Feng, Y. Zeng, X. Cai, Q. Qian and Y. Zhou, Altruistic profit allocation rules for joint replenishment with carbon cap-and-trade policy. *Eur. J. Oper. Res.* **290** (2021) 956–967.
- [10] Z. Guan, X. Zhang, M. Zhou and Y. Dan, Demand information sharing in competing supply chains with manufacturer-provided service. *Int. J. Prod. Econ.* **220** (2020) 107450.
- [11] R. Guchhait and B. Sarkar, Economic and environmental assessment of an unreliable supply chain management. *RAIRO-Oper. Res.* **55** (2021) 3153–3170.
- [12] A.Y. Ha, Q. Tian and S. Tong, Information sharing in competing supply chains with production cost reduction. *Manuf. Serv. Oper. Manag.* **19** (2017) 246–262.
- [13] A. Hafezalkotob, Modelling intervention policies of government in price-energy saving competition of green supply chains. *Comput. Ind. Eng.* **119** (2018) 247–261.
- [14] K. Halat and A. Hafezalkotob, Modeling carbon regulation policies in inventory decisions of a multi-stage green supply chain: a game theory approach. *Comput. Ind. Eng.* **128** (2019) 807–830.
- [15] X. Hu, Z. Yang, J. Sun and Y. Zhang, Carbon tax or cap-and-trade: which is more viable for Chinese remanufacturing industry? *J. Clean. Prod.* **243** (2020) 118606.
- [16] M. Jamali and M. Rasti-Barzoki, A game theoretic approach for green and non-green product pricing in chain-to-chain competitive sustainable and regular dual-channel supply chains. *J. Clean. Prod.* **170** (2018) 1029–1043.
- [17] X. Li and Y. Li, Chain-to-chain competition on product sustainability. *J. Clean. Prod.* **112** (2016) 2058–2065.
- [18] J. Li, S. Yang, V. Shi and S. Zhai, Partial vertical centralization in competing supply chains. *Int. J. Prod. Econ.* **224** (2020) 107565.
- [19] H. Liu, X. Kou, G. Xu, X. Qiu and H. Liu, Which emission reduction mode is the best under the carbon cap-and-trade mechanism? *J. Clean. Prod.* **314** (2021) 128053.
- [20] R. Sadeghi, A.A. Taleizadeh, F.T.S. Chan and J. Heydari, Coordinating and pricing decisions in two competitive reverse supply chains with different channel structures. *Int. J. Prod. Res.* **57** (2019) 2601–2625.
- [21] B. Sarkar, W. Ahmed and N. Kim, Joint effects of variable carbon emission cost and multi-delay-in-payments under single-setup-multiple-delivery policy in a global sustainable supply chain. *J. Clean. Prod.* **185** (2018) 421–445.
- [22] H. Sun and J. Yang, Optimal decisions for competitive manufacturers under carbon tax and cap-and-trade policies. *Comput. Ind. Eng.* **156** (2021) 107244.

- [23] A.A. Taleizadeh and R. Sadeghi, Pricing strategies in the competitive reverse supply chains with traditional and e-channels: a game theoretic approach. *Int. J. Prod. Econ.* **215** (2019) 48–60.
- [24] F. Tao, Y. Xie, Y. Wang, F. Lai and K.K. Lai, Contract strategies in competitive supply chains subject to inventory inaccuracy. *Ann. Oper. Res.* **309** (2021) 641–661.
- [25] J. Wang, Q. Wan and M. Yu, Green supply chain network design considering chain-to-chain competition on price and carbon emission. *Comput. Ind. Eng.* **145** (2020) 106503.
- [26] X. Xu, X. Xu and P. He, Joint production and pricing decisions for multiple products with cap-and-trade and carbon tax regulations. *J. Clean. Prod.* **112** (2016) 4093–4106.
- [27] X. Xu, W. Zhang, P. He and X. Xu, Production and pricing problems in make-to-order supply chain with cap-and-trade regulation. *Omega* **66** (2017) 248–257.
- [28] H. Xu, X. Liu, H. Huang, Y. Zhou and Y. Wei, Innovation information sharing between two competitive supply chains. *Int. T. Oper. Res.* **29** (2022) 471–495.
- [29] H. Yang, J. Luo and H. Wang, The role of revenue sharing and first-mover advantage in emission abatement with carbon tax and consumer environmental awareness. *Int. J. Prod. Econ.* **193** (2017) 691–702.
- [30] Y.H. Zhang and Y. Wang, The impact of government incentive on the two competing supply chains under the perspective of corporation social responsibility: a case study of photovoltaic industry. *J. Clean. Prod.* **154** (2017) 102–113.
- [31] W. Zhang, G. Li and F. Guo, Does carbon emissions trading promote green technology innovation in China? *Appl. Energy.* **315** (2022) 119012.
- [32] J. Zhou, D. Wu and W. Chen, Cap and trade versus carbon tax: an analysis based on a CGE model. *Comput. Econ.* **59** (2022) 853–885.
- [33] X. Zhu, M. Ren, G. Wu, J. Pei and P.M. Pardalos, Promoting new energy vehicles consumption: the effect of implementing carbon regulation on automobile industry in China. *Comput. Ind. Eng.* **135** (2019) 211–226.
- [34] X. Zhu, R. Chiong, M. Wang, K. Liu and M. Ren, Is carbon regulation better than cash subsidy? The case of new energy vehicles. *Transp. Res. A-pol.* **146** (2021) 170–192.



**Please help to maintain this journal in open access!**

This journal is currently published in open access under the Subscribe to Open model (S2O). We are thankful to our subscribers and supporters for making it possible to publish this journal in open access in the current year, free of charge for authors and readers.

Check with your library that it subscribes to the journal, or consider making a personal donation to the S2O programme by contacting [subscribers@edpsciences.org](mailto:subscribers@edpsciences.org).

More information, including a list of supporters and financial transparency reports, is available at <https://edpsciences.org/en/subscribe-to-open-s2o>.