Pricing and equity in cross-regional green supply chains

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Highlights

- Macro-economic framework is proposed by broadening the view of a green supply chain.
- Modelling and algorithmic approach are based on user equilibrium model.
- Different carbon emissions regulatory policies' impacts on systematic equity are analysed.
- Price elasticity and carbon emission intensity impact systematic equity.

Abstract

This paper addresses the problem of the firms operating on cross-border or inter-regional platforms that are subject to the enforcement of each local government's carbon emissions regulatory policy, thus causing an imbalance in the sharing of the burden of the greening of the total supply chain. We introduce the concept of equity as the incentive mechanism to coordinate this green supply chain which is a function of the carbon emission permits and the revenue generated by the firms. Due to the complexity and imbalance in the original incentive mechanism to this problem, we provide a new equivalent supply chain network equilibrium model under elastic demand based on user equilibrium theory. We state the user equilibrium conditions and provide the equivalent formulation. We show the trade-offs under various carbon emissions regulatory policies. A product with higher price elasticity and carbon emission intensity not only hampers the firm from gaining a higher revenue, but it also reduces the equity of the system under an invariant emission regulatory policy.

***Keywords*:** Pricing, equity, emission permits allocation, cross-regional green supply chain, cross border

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1. Introduction

Though there is a global call to reduce the greenhouse gas emissions, the equity in the burden-sharing needs to be better addressed. This issue is complex as governments face difficulty in instituting equitable policies simply because one country or regions's proactiveness in its emission mitigation policy may create a free rider effect on another (Aldy et al., 2017). For policy modelling to be equitable, it would require examining the trade-offs stemming from the different stages of economic development of the regions given the emission practices, maturity of production technology and industrial structure, energy efficiency, and level of urbanization (Goulder, 1995; Phylipsen 1998; Liu et al., 2012; Liddle 2014). Such inequity typically affects the large developing countries such as China.

This paper considers what is equitable by studying how the firms and regional governments interact in the emission regulatory policy making in the context of China. We term this as the cross-regional green supply chain (CrGSC), where a set of producers in a supply chain is subject to several local government emissions schemes. Our contribution is to ensure an equitable burden-sharing through coordinating from a central government perspective so that the firms are not burdened by a duplication of the carbon taxes when their supply chain straddles across multiple regions. We note that if the burden-sharing is not properly implemented, producers will have more incentives to cluster their operations within a particular region, leading to a significantly over-industrialised areas such as Baoding in China, which was reported to only have 16 days of "good" air quality in 2014 (Duggan, 2015).

As China emits the most CO_2, the world is monitoring her commitment to the carbon reduction target of 60-65 percent below the 2005 levels by 2030 (Zhao et al., 2017). In response, China launched the National Carbon Emissions Trading Scheme in November 2017 (Xu and Stanway, 2017; Zhu, 2017). This scheme covers emitters from 8 sectors and 15 sub-sectors that are set CO_2 caps based on the respective provincial targets. However, setting the provincial targets and emission caps may create an externality, allowing the firms and local government to be free riders (Green et al., 1976; Groves and Ledyard, 1977; He et al., 2016).

Take the construction supply chain in UK. Due to the national emissions reduction target and climate policy, domestic steel production is reduced, the imports from countries with less stringent climate polices increased (Serrenho et al., 2016), and the contractors replaced the steel and concrete with the Scottish grown timber products. While the domestic steel manufacturer and the local government may have lessened their economic benefits, the overseas steel manufacturer, Scottish timber manufacturer, and their governments reaped more benefits. This form of externality and the inequity will dispel the enthusiasm of some firms and the government to subscribe to such actions, thus rendering the CrGSC unsustainable.

We investigate the effect of several carbon emissions regulatory policies on the coordination of the CrGSC. A carbon emissions regulatory policy includes the subsidy/penalty and the carbon emissions allocation from the local governments. We raise the issue of equity through evaluating the optimal pricing strategies of the firms in the CrGSC system under the various carbon emissions regulatory policies. We provide a more equitable yet holistic response by allowing the local governments to impose a differential carbon emissions regulatory policy but with incentives set centrally, thus removing sub-optimal processes at the local government level.

To achieve this, we call on the equilibrium network theory by transforming the pricing problem of the supply chain network into a commodity assignment problem. The equivalent supply chain network equilibrium model is then constructed along with the UE equilibrium conditions, an elastic market demand.

This paper is organized as follows. Section 2 provides the supporting literature to justify our approach and case. The problem context, market demand, and cost of the firm and the supply chains are analysed in Section 3. This includes the performance of the CrGSC system, the revenue of each firm, and the equity of the CrGSC system based on the modified *Theil* inequity coefficient. Section 4 establishes an equivalent supply chain network equilibrium model by transforming the original multiple Origin-Destination (O-D) ~~O-D~~ pairs problem into a single O-D pair problem, and transforming the elastic-demand problem into a fixed-demand problem with an excess demand variable. Section 5 discusses the sensitivity analyses of the key parameters and managerial insights, Section 6 concludes with some directions for future research.

2. Background

*2.1 **Equity and carbon emissions regulatory policy***

Regulatory methods can be classified as either central planning or market-based (Stewart, 1991). Central planning refers to the environmental protection legislation by the government (Arrow et al., 1996), including the performance and technology-based regulations and standards (Jaffe and Stavins, 1995; Skeete, 2017). Market-based approaches include the economic and fiscal instruments such as pollution tax and emissions trading system (Stavins, 1998), and the subsidies from the government's fiscal policies (Sheu and Chen, 2012). The sustainable supply chain management literature is mainly focused on the operations management and performance problems under the different carbon emissions regulatory policies. Zakeri et al. (2015) presented an analytical supply chain planning model to examine the tactical and operational planning levels of the supply chain under carbon pricing (taxes) and carbon emissions trading. With the carbon tax and cap-and-trade regulations (CTCTR), Zhang and Xu (2013) analyzed the optimal policy of production and carbon trading decisions for a single-period and multi-item newsvendor problem. Manikas and Kroes (2015) then presented a new forward-buying heuristic for a multi-period newsvendor problem with firms that need to purchase emissions allowances via auctions, and Bai and Chen (2016) compared two distributionally robust newsvendor models under the CTCTR. The reviews of Brandenburg et al. (2014), Fahimnia et al. (2015), and Memari (2016) make a rich reading.

Equity is fundamental to the climate change policy research and remains a key tenet in the negotiations for a comperehensive carbon emissions regulatory policy making (Pattanayak and Kumar, 2015). The equity in the climate change negotiation is mainly concerned about outlining the responsibilities for low-carbon development and how to make this more attractive for countries to invest in green technology and eco-industrial solutions, with equality being measured on per capita emissions (Höhne et al., 2014). The 'burden-sharing' problem is difficult to quantify in international climate negotiations, as Méjean et al. (2015) had pointed out that there are two key difficulties in addressing equity: 1) uncertainty over the estimates of policy costs, and 2) the lack of political realism and economic effectiveness of large-scale international transfers. Since no universal consensus best defines equity (Rose et al., 1998), the broader struggles for sustainable development such as international climate policy (Klinsky and Winkler, 2014) are difficult to gain traction. Yet, there are studies that attempt to bridge this gap by operationalizing the inter- and intra-national equity when designing burden-sharing schemes (Cazorla and Toman, 2001; Rao, 2014).

At the inter-regional level, Rose and Zhang (2004) studied alternative allocations of the CO_2 emission permits within the U.S. and found some equity criteria to differ greatly from their application in the international domain. Pan et al. (2014) proposed an allocation scheme based on the cumulative emissions per capita to achieve a globally equitable carbon emissions space. Given the regional imbalance in China's economic development, resource endowment and geographical CO2 emissions space, Chang et al. (2016) proposed an emissions reduction allocation solution by using Shapley's value to estimate the economic welfare effects of inter-regional emissions trading.

2.2 ***Supply chain coordination and network equilibrium***

Supply chain coordination seeks to improve the overall supply chain performance by inducing certain conditions for actors to reach decisions that will benefit the collective whole. This has been a domain of inventory optimization where mechanisms such as quantity discounting provide more predictable inventory levels for the supply chain actors. There is much literature on supply chain coordination and its related methods. The research methods include conceptual analysis (Seuring and Müller, 2008; Kembro et al., 2014), modelling (Stock and Boyer, 2009; Leuschner et al., 2013), simulation (van der Vorst et al., 2013; Ramanathan, 2014), case studies (Oliva and Watson, 2011), mathematical programming and empirics (Petersen et al., 2005; Ramanathan, 2014). Among these alternatives, mathematical programming dominates (see Bernstein and Federgruen, 2005; Yan, 2011; Ghosh and Shah, 2015).

A means of coordination is by the network equilibrium method, which models the O-D ~~origin-destination (O-D)~~ flows (demand) and user-equilibrium route flows for a congested road network (Boyce, 1984, 2013). Network equilibrium has been a primary tool in evaluating proposals and plans for urban road and transit systems (Inoue and Maruyama, 2012). Here, we focus on the network equilibrium with elastic demand given that a real world supply chain is influenced by the retail price and operating cost, and the road network is influenced by the congestion price and the travelling cost.

Liu and Chen (2009) proposed second-best congestion pricing models to evaluate the temporal, spatial, and modal impacts of congestion toll policies for a general traffic network by transforming the elastic-demand problem into a fixed-demand problem with an excess demand variable (Sheffi, 1985). Later, Chen (2013) proposed an equivalent second-best congestion pricing model with User Equilibrium (UE) and System Optimum (SO) conditions and analysed its performance in traffic volume reallocation, traffic mode shifting, and automobile toxic pollutants emission control in urban road systems. According to Nagurney (2006), the “gaming” or competition on a transportation network takes place on paths associated with the O-D node pairs; in a supply chain network, it takes place on the firms (nodes) and trade flows (links). Based on the transportation network equilibrium model with elastic demands of Dafermos and Nagurney (1984), Nagurney et al. (2002) developed an equilibrium model of competitive supply chain networks, representing the optimality conditions of the actors as a finite-dimensional variational inequality (VI) problem. Dong et al. (2004) then extended the model but within the VI formulation by considering stochastic demand with a known probability distribution.

The paper addresses two gaps in the literature. Research-wise, to the best of our knowledge, equity analysis based on the carbon emissions regulatory policy remains un-investigated for the CrGSC system. Thus, we contribute to the modeling, analysis and understanding of the impact between the carbon emissions regulatory policies of local governments and the equity of the CrGCS system. Methodology-wise, we propose a new model for a supply chain network, which can handle demand assignment among the supply chains with commodity pricing of each firm, factoring the potential financial disruption.

3. Model development

3.1 Description of CrGSC

This paper uses the following notations.

Index Sets

E	Set of edges in the supply chain network

I	Set of supply chains in the supply chain network
V	Set of firms in the supply chain network

Variables

x_a	Commodity quantity of edge a
p^j	Price of commodity that firm j supplied to a firm downstream

Costs

$\tilde{C}^j$	Carbon related operating cost of firm j
$\tilde{C}_0^j$	Initial carbon related setup cost of firm j
$\bar{C}^j$	Supply/production/marketing cost of firm j
$\bar{c}^j$	Unit supply/production/marketing cost of firm j
$\hat{C}^j$	Cost of procuring the commodity from an upstream firm by firm j
$\breve{C}^j$	Transportation/transaction cost of firm j
d_a	Unit transportation/transaction cost of edge a
TC^j	Total cost of firm j
ΔC^j	Additional cost to the supply chain due to firm j
Δc^j	Average additional cost of the supply chain caused by firm j
$c_{rs,i}$	Cost of route/supply chain i for the O-D pair rs
u_{rs}	Minimum unit cost of the O-D pair rs

Parameters

a	Label of the edge, $a \in E$
i	Label of the supply chain, $i \in I$
j	Label of the firm, $j \in V$
q	Total demand of the product in the market
e^j	Carbon emission intensity of the commodity that firm j supplied
K^j	Number of free carbon emission permits that firm j gained from the government
Q	Market demand of the CrGSC system
Q^0	Expected demand of the market
p	Retail price in the market
β	Price elasticity of the commodity
f_i^{rs}	Flows in supply chain i for O-D pair rs
$\delta_{a,i}^{rs}$	Chain-edge switch parameter
q^j	Commodity quantity of firm j
γ_j^a	The edge-firm switch parameter

$q^{j'j}$	Commodity flow from firm j' to firm j
g^j	Subsidy/penalty coefficient of carbon emission by local government to firm j
Π^j	Revenue of firm j
q_{rs}	Demand of O-D pair rs
$D_{rs}(\cdot)$	Demand function of O-D pair rs
e_{rs}	Excess demand of flows not accommodated by O-D pair rs
$W_{rs}(\cdot)$	Argument-complementing function of the inverse demand
IE_T	*Theil* inequity coefficient of the CrGSC system

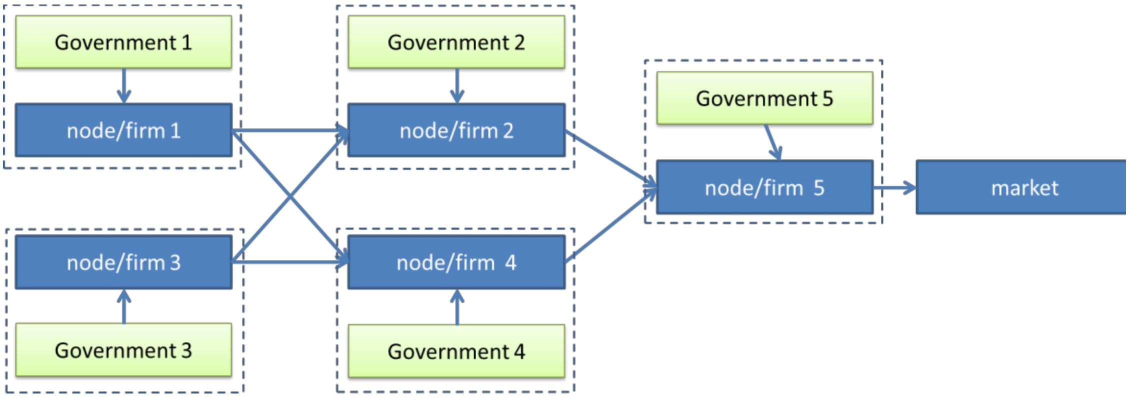

Figure 1: Network structure of CrGSC

Figure 1 shows the supply chain network model comprising 5 firms, including suppliers, manufacturers and retailers, and 5 local governments. We consider one of the firms as the dominant actor in the supply chain, such as Wal-Mart in the retailer supply chain (Pan et al., 2009) and Bao Steel in the steel supply chain (Liu et al., 2017). Here, we consider Firm 5 as dominant, who has the 'power' to decide which supply channel to use and the retail price to set for its products. The edges in the supply chain network denote the transportation/transaction links, the cost related to the transportation/transaction increases as commodity flows on the edge increase. The price of the commodity that the firm supplies to the downstream firm is uniform, which is the normal practice in the industry, and is denoted as p^j, $j=1,2,\cdots,5$. Similar to Nagurney et al. (2002), Dong et al. (2004) and Nagurney et al. (2006), the firms seek to maximize their profits with the price that the consumers are willing to pay for the product being endogenous. Each firm has a different carbon emission intensity e^j per commodity, and the firm gains a free carbon emission permits K^j from its local government. The cost to the firm includes procuring the commodity from an upstream firm, the supply, production and marketing cost, the carbon related operating cost, and the transportation and transaction cost. The carbon related costs refer to the penalty/subsidy incurred due to the difference between the emissions generated and the free carbon emission permits allocated by the government. When the emissions generated is in excess of the free carbon emission permits, the government will impose a penalty on the firm, otherwise the firm will be subsidised.

We assume that the market demand will be fulfilled by minimizing the supply chain cost, while considering a focal firm ~~dominant actor~~ in the supply chain. The cost of each firm changes depending on the quantity of the commodity, while the supply chain cost changes as a result of the commodity flow changes. Based on the UE condition proposed by Wardrop (1952), and similar to Dial (2006), a stable condition is reached only when no unit commodity can reduce its cost by unilaterally changing supply chains, i.e. UE occurs when every commodity goes from its origin to destination via the cheapest supply chain. In this paper, we consider a problem beginning from when a new demand emerges. Then, we show that the focal firm ~~dominant actor~~ can determine which firms should be involved in the network, thus forming a special supply chain for the interaction. The motive for forming a new supply chain is based on cost, which can be extended to any unit of measurement. Cost is merely a generalised commodity quantity of each end-supply and market pair being determined by the assignment of the commodity flow on the network according to the minimum value to each supply chain.

3.2 CrGSC model

3.2.1 Commodity quantity/flow of the firm, edge and supply chain

Suppose the market demand for a commodity is elastic. Then, similar to Qi et al. (2004), Yao et al. (2008) and Yan (2011), the market demand function of the CrGSC system can be set as:

$$Q = Q^0 - \beta p \tag{1}$$

where Q^0 is the initial demand of the market, p is the retail price and β(>0) is the price elasticity, and $p = p^5$ since there is only one focal ~~dominant~~ firm in the supply chain network.

To simplify the analysis, we introduce a virtual firm 0 to denote the suppliers' supplier as illustrated in Sub-Graph B of **Figure 2**. This transforms the multiple O-D pairs problem into a single O-D pair problem. From here on, the analysis and discussions will be based on the single O-D pair problem. For the single O-D pair problem, there are 4 supply chains in the CrGSC network. We denote the commodity flows in supply chain i as f_i^{rs}, where supply chain i serves the O-D pair rs. Then we have following equation.

$$Q = \sum_{rs}\sum_{i} f_i^{rs} \tag{2}$$

where i=1,2,3,4, r=0, and s=6.

In **Figure 2**, a firm could be the upstream/downstream firm of an edge or edges, and an edge could also be a link of a supply chain or supply chains. The commodity flow of the edge is the composite of the commodity flows of each supply chain which can be expressed as:

$$x_a = \sum_{rs} \sum_{i \in I_{rs}} f_i^{rs} \delta_{a,i}^{rs} \tag{3}$$

where $\delta_{a,i}^{rs}$ is the chain-edge switch parameter, and edge a is one of the links of supply chain i in the O-D pair rs, such that $\delta_{a,i}^{rs} = 1$, otherwise $\delta_{a,i}^{rs} = 0$.

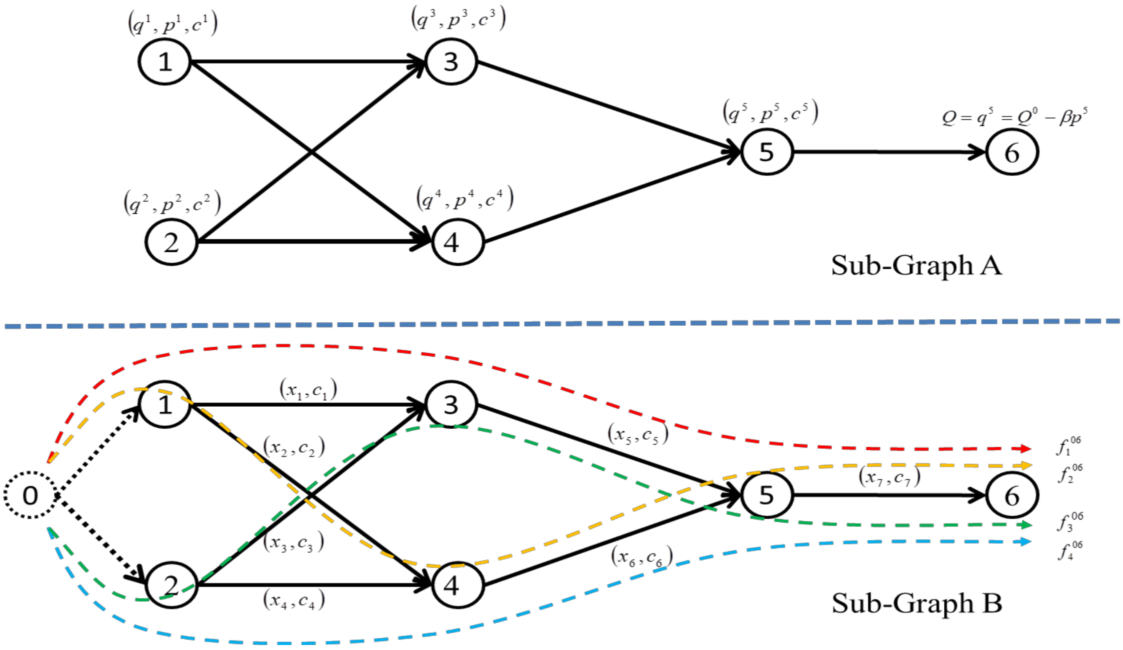

Figure 2: Commodity quantity of the firm, the edge and the supply chain

The commodity quantity of the firm is the composite of the commodity flows when it is linked to either the downstream or upstream firms, depending on the direction of the flow. Here, we have the commodity quantity of the firm composed of the commodity flows to the downstream firms, i.e. outbound flow, denoted as:

$$q^j = \sum_a x_a \gamma_j^a \tag{4}$$

where γ_j^a is the edge-firm switch parameter, and firm j is the upstream firm of edge a, such that $\gamma_j^a = 1$, j=1,2,…,5, else $\gamma_j^a = 0$.

Similarly, the commodity quantity of the firm formed by the inbound flow from the upstream firm is $q^j = \sum_h x_h \rho_h^j$ where ρ_h^j is the firm-edge switch parameter, and firm j is the downstream firm of edge h, such that $\rho_h^j = 1$, otherwise $\rho_h^j = 0$. Given the balance of the inbound and outbound flows of the firm, we have $\sum_a x_a \gamma_j^a = \sum_h x_h \rho_h^j$. Then, the commodity flow from firm j' to firm j can be expressed as:

$$q^{j'j} = x_h \gamma_{j'}^h \rho_h^j \tag{5}$$

such that when $\gamma_{j'}^h = 1$ and $\rho_h^j = 1$ are both satisfied, firm j' is the upstream firm and firm

j is the downstream firm of edge *h*.

3.2.2 Cost to the firm

The total carbon emitted is $e^j q^j$, where q^j is the commodity quantity of firm *j*, while e^j denotes the carbon emission intensity of the commodity. As the number of free carbon emission permits is K^j, the subsidy/penalty from the local government is $g^j\left(K^j - e^j q^j\right)$, with g^j as the subsidy/penalty coefficient. When $K^j - e^j q^j > 0$ holds, i.e. the subsidy scenario, the firm j has a free carbon emission permits of $K^j - e^j q^j$ left, and the local government will subsidise based on this remainder. Otherwise, in the penalty scenario, the firm j needs the additional carbon emission permits of $e^j q^j$-K^j, and the local government will penalise the firm for requiring this extra addition. Then, the carbon related operating cost of firm *j* is:

$$\tilde{C}^j = \tilde{C}_0^j - g^j\left(K^j - e^j q^j\right) \tag{6}$$

where $\tilde{C}^j$ is the carbon related operating cost of firm j, $\tilde{C}_0^j$ is the initial carbon related setup cost no matter how many commodities the firm handles, and $g^j \geq 0$.

The cost related to the transportation/transaction of the edge is borne by the upstream firm. For any firm, the main cost aside from the carbon related operating cost are the supply/production/marketing cost $\overline{C}^j$, the cost of procuring the commodity from the upstream firm $\hat{C}^j$ and the transportation and transaction cost for the downstream firms, which are respectively

$$\begin{aligned} \hat{C}^j &= \sum_{j'} q^{j'j} p^{j'} = \sum_{j'} p^{j'} x_h \gamma_{j'}^h \rho_h^j \\ \overline{C}^j &= \bar{c}^j q^j = \sum_a \bar{c}^j x_a \gamma_j^a = \sum_h \bar{c}^j x_h \rho_h^j \\ \breve{C}^j &= \sum_a d_a x_a \gamma_j^a \end{aligned} \tag{7}$$

where *h* and *a* are the inbound and outbound edges of firm *j* respectively, firm j' is the upstream firm j, $\bar{c}^j$ is the unit supply/production/marketing cost of firm j, and d_a is the unit transportation and transaction cost of edge a.

Based on the 4 types of costs, we introduce and define the additional cost attributed to the supply chain by firm j, i.e. its profit of commodity sales and its carbon related operating cost. The difference includes the supply/production/marketing cost $\overline{C}^j$, the carbon related operating cost $\tilde{C}^j$, the transportation and transaction cost for the downstream firms $\breve{C}^j$ and the revenue Π^j, as illustrated in **Figure 3**.

$$\Delta C^j = p^j q^j - \sum_{j'} p^{j'} x_h \gamma_{j'}^h \rho_h^j + \tilde{C}^j = p^j \sum_a x_a \gamma_j^a - \sum_{j'} p^{j'} x_h \gamma_{j'}^h \rho_h^j + \tilde{C}^j \tag{8}$$

The average additional cost of firm *j* is

$$\Delta c^{j} = \frac{\Delta C^{j}}{q^{j}} = p^{j} - \frac{\sum_{j'} p^{j'} x_{h}\gamma_{j'}^{h}\rho_{h}^{j}}{\sum_{a} x_{a}\gamma_{j}^{a}} + \frac{\tilde{C}^{j}}{\sum_{a} x_{a}\gamma_{j}^{a}} = p^{j} - \frac{\sum_{j'} p^{j'} x_{h}\gamma_{j'}^{h}\rho_{h}^{j}}{\sum_{h} x_{h}\rho_{h}^{j}} + \frac{\tilde{C}^{j}}{\sum_{a} x_{a}\gamma_{j}^{a}} \tag{9}$$

From Eq. (9), the average additional cost of Firm 1 is equal to its selling pricing p^{1}, because the selling price of the virtual firm, i.e. the upstream firm of Firm 1, is zero. When $x_{a} > 0$, there exists a commodity x_{a} in firm j and the cost of procuring that $x_{a} > 0$ is positive, i.e. $\sum_{j'} p^{j'} x_{h}\gamma_{j'}^{h}\rho_{h}^{j} > 0$. Hence, $p^{j} > \Delta c^{j}$.

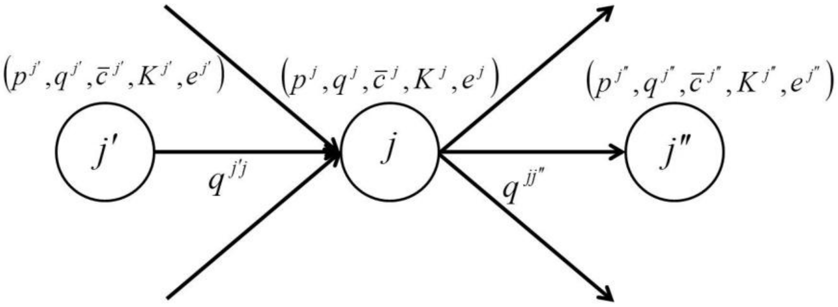

Figure 3: Additional cost attributed to the supply chain by firm j

3.2.3 Performance of CrGSC system

The performance of the CrGSC system includes the revenue and the equity of the local governments' carbon emission permits. The total cost to the firm is thus:

$$\begin{aligned} TC^{j} &= \hat{C}^{j} + \overline{C}^{j} + \widetilde{C}^{j} + \breve{C}^{j} \\ &= \sum_{j'} p^{j'} x_{h}\gamma_{j'}^{h}\rho_{h}^{j} + \sum_{a} \bar{c}^{j} x_{a}\gamma_{j}^{a} + g^{j}\left(K^{j} - e^{j}q^{j}\right) + \widetilde{C}_{0}^{j} + \sum_{a} d_{a}x_{a}\gamma_{j}^{a} \end{aligned} \tag{10}$$

Given the uniform price p^{j} of firm j, the revenue to the firm is

$$\Pi^{j} = p^{j}q^{j} - \sum_{j'} p^{j'} x_{h}\gamma_{j'}^{h}\rho_{h}^{j} - \sum_{a} \bar{c}^{j} x_{a}\gamma_{j}^{a} + g^{j}\left(K^{j} - e^{j}q^{j}\right) - \tilde{C}_{0}^{j} - \sum_{a} d_{a}x_{a}\gamma_{j}^{a} \tag{11}$$

The total revenue of the CrGSC system is then

$$\Pi = \sum_{j} \Pi^{j} \tag{12}$$

Each local government involved in the CrGSC system grants a free carbon emission permits K^{j} to firm j under its supervision, and firm j gains a revenue of Π^{j}, where we account for the different free carbon quota allocations based on the income among the different regions. Similar to Chichilnisky and Heal (1994), the Pareto optimal solution can be found when each region's contribution to solving the climate problem is apportioned to its income. Hence, we consider the income gap when measuring the equity of the CrGSC system. From *Theil*'s entropy measure for the equity of the regional and individual incomes, the level of inequity can be measured, i.e., the greater the value, the less is the equity (Marsh and Schilling, 1994). Hence, given the emissions permit allocation scheme, *Theil's* inequity coefficient of the CrGSC system can be defined as:

$$IE_T = \sum_j \left\{ \frac{\Pi^j - \min\left(\Pi^j\right) + 1}{\sum_j \left(\Pi^j - \min\left(\Pi^j\right) + 1\right)} \left[\log\left(\frac{\Pi^j - \min\left(\Pi^j\right) + 1}{\sum_j \left(\Pi^j - \min\left(\Pi^j\right) + 1\right)} \right) - \log\left(\frac{K^j}{\sum_j K^j} \right) \right] \right\} \tag{13}$$

4. User equilibrium model of the supply chain network with elastic demand

4.1 Formulation of the CrGSC system as a network equilibrium problem

Based on the above analysis, we can transform the supply chain into a directed weighted network $G = \{V, E, W\}$ (Nagurney et al., 2002; Nagurney, 2006), with a given set of firms V, edge E, the weight of the edge W, and the number of firms $|V|$. Each firm *j* in the network is indexed as $j = 1,2,\cdots,6$, where $A = \{a_{j'j}\} \forall j', j = 1,2,\cdots,6$ is the adjacency matrix of size 6×6 with $a_{j'j} = 1$ if there is a directed edge connecting the upstream firm $j' \in V$, else $a_{j'j} = 0$ if there is a directed edge connecting the downstream firm *j* for $j \in V$ ($j' \neq j$). The weight/cost of the edge is denoted as c_a, $\forall a \in A, j \in |V|$.

By introducing the virtual firm, the origin firm is set at 0 and the destination firm is set at 6, thus there is only one O-D pair 0→6 in the CrGSC network. The demand of the O-D pair is the market demand of the CrGSC, which is a function of the retail price. Hence, the demand function associated with O-D pair rs can be represented as

$$q_{rs} = Q = Q^0 - \beta p \tag{14}$$

where Q^0 is the upper bound of the demand in the O-D pair, the price elasticity of the commodity $\beta > 0$ and the final retail price in the market $p = p^5$.

The O-D pair is connected by a set of routes (i.e. supply chains) throughout the network. The commodity flow of the O-D pair is the sum of the flows on all routes in the O-D pair i.e.

$$q_{rs} = \sum_{i \in I_{rs}} f_i^{rs} \tag{15}$$

Here, we take the average additional cost of the firm as the unit cost of its outbound edge, and similar to the analysis of Eq. (4), the cost of the edge can be represented as

$$c_a\left(x_a\right) = \Delta c^j = p^j - \frac{\sum_{j'} p^{j'} x_h \gamma_{j'}^h \rho_h^j}{\sum_a x_a \gamma_j^a} + \frac{\tilde{C}^j}{\sum_a x_a \gamma_j^a} = p^j - \frac{\sum_{j'} p^{j'} x_h \gamma_{j'}^h \rho_h^j}{\sum_h x_h \rho_h^j} + \frac{\tilde{C}^j}{\sum_a x_a \gamma_j^a} \tag{16}$$

Given Eq. (8) and Eq. (9), we have

$$\Delta C^j = \Delta c^j \sum_a x_a \gamma_j^a = \sum_a c_a\left(x_a\right) x_a \gamma_j^a \tag{17}$$

Then the cost of any route is the sum of the cost of the edges comprising this route, i.e.

$$c_{rs,i} = \sum_a c_a\left(x_a\right) \delta_{a,i}^{rs} \tag{18}$$

The edge flow can be expressed as the sum of the route flows traversing this link, which is

$$x_a = \sum_{rs} \sum_{i \in I_{rs}} f_i^{rs} \delta_{a,i}^{rs} \tag{19}$$

Then the basic problem is to find the edge flows given the commodity demand of the O-D ~~origin-destination~~, the cost of the routes and that of each edge. Similar to the traffic assignment or the transportation network equilibrium problem (Sheffi, 1985), we provide the solution by assuming that the commodity flows on the route minimises the cost from origin to destination. This rule of choice implies that, at equilibrium, the edge-route pattern is such that the cost of all the connected used routes of any given O-D pair will be equal, and the cost of all of these used routes will also be less than or equal to the cost of any of the unused routes. At this point, the network is said to be in *user equilibrium*.

From Eq. (18), the unit cost of the edge is the difference between the income generated from the upstream firm selling its commodity and the cost of procuring the commodity. Thus, the minimum unit cost of the route for the O-D pair is equal to the retail price at user equilibrium by applying Eq. (16) and Eq. (18). Here, with the minimum unit cost for the O-D pair as u_{rs}, and the demand function as $D_{rs}(\cdot)$, Eq. (14) can be rewritten as:

$$D_{rs}(u_{rs}) = q_{rs} = Q^0 - \beta u_{rs} \tag{20}$$

where $u_{rs} = \sum_a c_a(x_a)\delta_{a,i}^{rs}$ and $\beta > 0$.

4.2 Equivalent UE minimization model of the CrGSC system network equilibrium problem

In this section, we propose an equivalent UE minimization model for the elastic-demand case based on transforming the supply chain into a directed weighted network. We show that minimizing this program is equivalent to solving the equilibrium equations and that the program has a unique solution (Sheffi, 1985). The model is

$$\min\ Z(\mathbf{x},\mathbf{q}) = \sum_a \int_0^{x_a} c_a(w)dw - \sum_{rs} \int_0^{q_{rs}} D_{rs}^{-1}(w)dw$$

$$s.t. \quad \begin{cases} q_{rs} = \sum_{i \in I_{rs}} f_i^{rs} \\ q_i \geq 0 \\ q_{rs} \geq 0 \end{cases} \tag{21}$$

where $D_{rs}^{-1}(\cdot)$ is the inverse of the demand function associated with O-D pair rs, $(\cdots, q_{rs}, \cdots)$, $x_a = \sum_{rs} \sum_{i \in I_{rs}} f_i^{rs} \delta_{a,i}^{rs}$, $\forall a$, and $D_{rs}(u_{rs}) = q_{rs} = Q^0 - \beta u_{rs}$, $\forall rs$.

The elastic-demand problem can be solved with a more efficient fixed-demand formulation, again through a network representation. In this representation, the variable e denotes the excess demand, that is, commodity flows not accommodated in O-D pair rs as illustrated in **Figure 4**, i.e. $e_{rs} = Q^0 - q_{rs}$. To fix the excess demand e_{rs} into the the equivalent elastic-demand formulation Eq. (21), we denote $W_{rs}(\cdot)$ as the argument-complementing function of the inverse demand, i.e., $W_{rs}(e_{rs}) = D_{rs}^{-1}(q_{rs})$, $\forall r,s$. The interested reader can refer to Sheffi (1985), Ryu et al. (2014), and Kitthamkesorn et al. (2016) for further discussions on the inverse demand function and the associated argument-completing function.

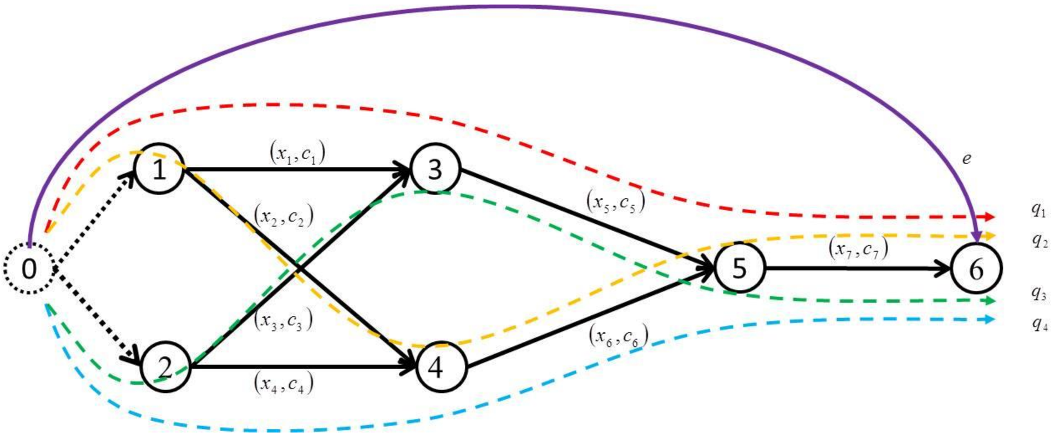

Figure 4: Excess-demand network representation for single O-D pair

We adopt the excess demand formulation. Consider the objective function of the equivalent elastic-demand formulation Eq. (21), where each term in the second sum can be decomposed into two integrals as follows:

$$\sum_{rs}\int_0^{q_{rs}} D_{rs}^{-1}(w)dw = \sum_{rs}\int_0^{Q^0} D_{rs}^{-1}(w)dw - \sum_{rs}\int_{q_{rs}}^{Q^0} D_{rs}^{-1}(w)dw \tag{22}$$

The first term $\sum_{rs}\int_0^{Q^0} D_{rs}^{-1}(w)dw$ on the right-hand-side of Eq. (22) is constant; thus, it can be dropped from the objective function since it will not affect the optimization problem. The second term $-\sum_{rs}\int_{q_{rs}}^{Q^0} D_{rs}^{-1}(w)dw$ represents the excess-demand. Introducing the excess demand variable ($e_{rs} = Q^0 - q_{rs}$), the second term can be re-defined as follows:

$$-\sum_{rs}\int_{q_{rs}}^{Q^0} D_{rs}^{-1}(w)dw = -\sum_{rs}\int_{Q^0-q_{rs}}^{0} D_{rs}^{-1}(Q^0 - v)(-dv) = -\sum_{rs}\int_0^{e_{rs}} W_{rs}(v)dv \tag{23}$$

Similar to Sheffi (1985) and Ryu et al. (2014), the equivalent elastic-demand formulation Eq. (21) can be reformulated as the a fixed-demand problem with an excess demand variable:

$$\min\ Z(\mathbf{x},\mathbf{e}) = \sum_a \int_0^{x_a} c_a(w)dw + \sum_{rs}\int_0^{e_{rs}} W_{rs}(v)dv$$

$$s.t.\quad \begin{cases} Q^0 = e_{rs} + \sum_{i\in I_{rs}} f_i^{rs} \\ f_i^{rs} \geq 0 \\ e_{rs} \geq 0 \end{cases} \tag{24}$$

where $W_{rs}(\cdot)$ is the inverse of the demand function associated with excess demand in the O-D pair rs, $(\cdots,e_{rs},\cdots)$, $x_a = \sum_{rs}\sum_{i\in I_{rs}} f_i^{rs}\delta_{a,i}^{rs}$, $\forall a$, $q_{rs} = \sum_{i\in I_{rs}} f_i^{rs}$ and $D_{rs}(u_{rs}) = q_{rs} = Q^0 - \beta u_{rs}$, $\forall rs$.

To ensure that the UE conditions are met at the point where Eq. (24) is minimized, the first order conditions of the model must be equivalent to the equilibrium conditions. The equilibrium condition stated above is repeated in a network view as the costs on all chosen routes for any O-D pair are equal, and they are also no more than the cost of any unused route, following Wardrop's first principle (Wardrop, 1952). We prescribe an algorithm to solve the model such that the equivalent elastic-demand UE model of Eq. (24) has a unique solution. **Appendix A** presents the analysis of the Equivalent and Uniqueness conditions.

In the above analysis and in **Appendix A**, we do not allow the prices charged by each firm to be unknown. In short, the prices are endogenous variables in the equivalent supply chain network equilibrium model, i.e. the price is endogenous to the model with the commodity quantity of each edge at equilibrium being determined by the equilibrium price vectors, which is also analyzed by Nagurney et al. (2002), Dong et al. (2004), and Nagurney et al. (2006).

The equivalent model is solved by the Frank-Wolfe algorithm (Frank and Wolfe, 1956), which is an efficient algorithm for the traffic assignment problem (LeBlanc et al., 1975; Gutjahr and Dzubur, 2016), similar to the convex minimization problem with linear constraints, such as the one proposed in Eq. (24). By applying this algorithm as shown in **Appendix B.1**, and similar to Tzeng and Chen (1993), we simplify the assignment problem into an 'all-or-nothing assignment' for the edge cost is flow-independent. The algorithm for all-or-nothing assignment can be found in **Appendix B.2.**

5. Simulation

5.1 CrGSC network for simulation study

The iron and steel industry is the world's largest industrial source of CO_2 emissions (Serrenho et al., 2016). In particular, China's steel industry released 1.94 billion tons of CO_2 in 2015 accounting for 16.7% of the global CO_2 emissions (Xu et al., 2017). Similar to the studies on carbon emissions differences between countries (Cantore, 2011; Sauter et al., 2016; Chen et al. 2016), the regional emissions differences in China are attributed mostly to the iron and steel industry (Xu and Lin, 2016) and the metallurgical industry (Lin and Xu, 2018). The central government of China seeks to achieve the emissions reduction target as pledged at the 2015 United Nations Climate Change Conference (Zhao et al., 2017). This requires decomposing the national target into the regions to avoid inequity in the responsibility of sharing the costs of emissions reduction (Hao et al., 2015).

Figure 5 illustrates the cross-regional green supply chain network of the steel industry in China. The iron and steel product manufacturer is located in Guangdong and considered to be the actor that dominates the supply chain. Two iron ore suppliers are located in Inner Mongolia and Sichuan, supplying to two plants located in Jiangsu and Zhejiang respectively. All five firms receive some free carbon emission permits allocated by their local governments respectively. The local governments allocate the amount of free carbon emission permits based on the national target. For simplicity, we provide the setting of the demand as $Q^0 = 15000$ and $\beta = 0.5$. Based on the research of Hasanbeigi et al. (2016)[1] and Li et al. (2018)[2], **Table 1** provides the values of the parameters of the CrGSC system. In **Table 1**, in order to conduct the sensitivity analysis in Section 5.2.2, the carbon emission intensity for each firm is normalised to reflect its own level of output

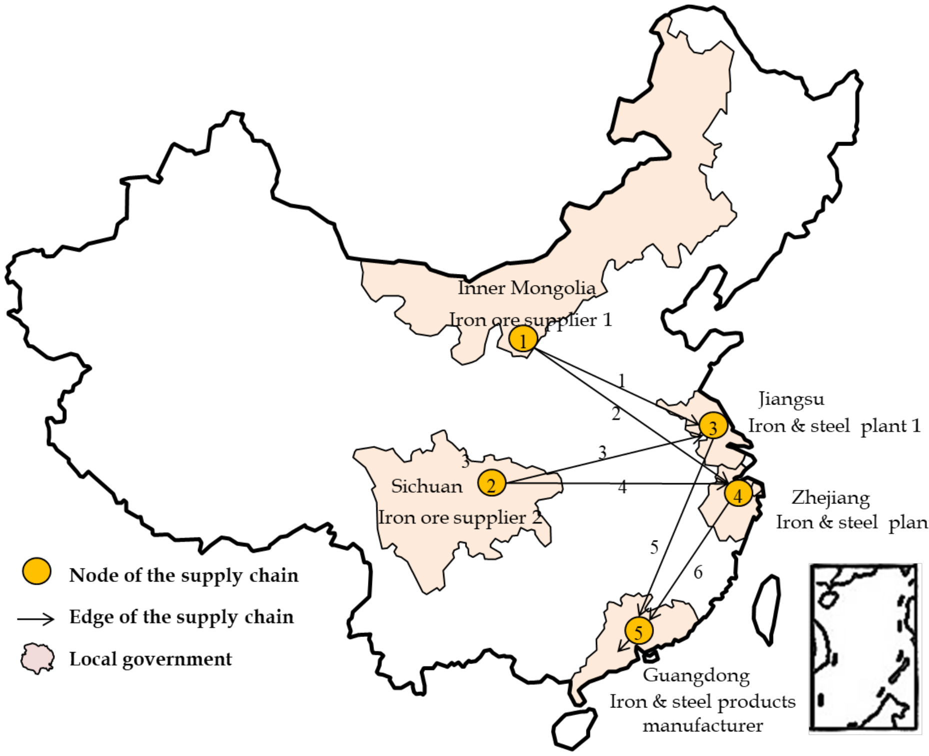

Figure 5: CrGSC network of the steel industry in China

Table 1 Parameters of the firms and edges

<table>
<tr><th>Firm</th><th colspan="2">Supplier 1</th><th>Supplier 2</th><th>Plant 1</th><th>Plant 2</th><th colspan="2">Manufacturer</th></tr>
<tr><td>Carbon emission intensity e^j</td><td colspan="2">20</td><td>25</td><td>1200</td><td>1500</td><td colspan="2">100</td></tr>
<tr><td>Initial carbon related setup cost $\tilde{C}_0^j$</td><td colspan="2">1500</td><td>2000</td><td>4500</td><td>5000</td><td colspan="2">1500</td></tr>
<tr><td>Unit supply/production/marketing cost $\bar{c}^j$</td><td colspan="2">15</td><td>20</td><td>45</td><td>50</td><td colspan="2">10</td></tr>
<tr><td>Edge</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td></tr>
<tr><td>Unit transportation and transaction cost d_a</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>8</td><td>7</td></tr>
</table>

In order to analyse the outcome of the carbon emissions regulatory policies, we first set a baseline condition for the homogenous carbon emission permits and the subsidy/penalty

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[1] For the entire iron and steel production process, the base-case (2010) CO_2 emission intensity was 2148 kg CO_2/tonne crude steel in China, 1708 kg CO_2/tonne crude steel in Germany, 1080 kg CO_2/tonne crude steel in Mexico, and 1736 kg CO_2/tonne crude steel in the U.S. See Hasanbeigi et al. (2016).

[2] The carbon emission factors of pure iron for ICC produced in China are as follows: iron ore (21.69 $kgCO_2e/t$), pig iron (1767.01 $kgCO_2e/t$), crude steel (1889.81 $kgCO_2e/t$), rolled steel (2099.84 $kgCO_2e/t$), and IEP (2099.84 $kgCO_2e/t$). See Li et al. (2018).

coefficient for each firm. We provide 5 cases, in which the free carbon emission permits and subsidy/penalty coefficient are different according to the respective local government's carbon emissions regulations (see **Table 2**). In Cases 1 to 2, the initial allocation of free carbon emission permits is the same as that in Case 0, but their subsidy/penalty coefficients are different. Case 3 provides a setting with a reduction in the allocation of the initial free carbon emission permits to the suppliers and the manufacturer. Contrastingly, Case 4 sets a higher subsidy/penalty coefficients for the plants. Case 5 varies the subsidy/penalty coefficient for the suppliers and the manufacturer across the different carbon emissions regulatory scheme.

Table 2: Parameters of the differential carbon emissions regulatory policies

Case	Carbon emissions regulatory schemes	Government				
		Inner Mongolia (Supplier)	Sichuan (Supplier)	Jiangsu (Plant)	Zhejiang (Plant)	Guangdong (Manufacturer)
Case 0	Subsidy/penalty coefficient g^j	10	10	10	10	10
	Free carbon emission permits $K^j (\times 10^3)$	9000	9000	9000	9000	9000
Case 1	Subsidy/penalty coefficient g^j	10	10	20	20	10
	Free carbon emission permits $K^j (\times 10^3)$	9000	9000	9000	9000	9000
Case 2	Subsidy/penalty coefficient g^j	20	20	10	10	20
	Free carbon emission permits $K^j (\times 10^3)$	9000	9000	9000	9000	9000
Case 3	Subsidy/penalty coefficient g^j	10	10	10	10	10
	Free carbon emission permits $K^j (\times 10^3)$	90	90	9000	9000	900
Case 4	Subsidy/penalty coefficient g^j	10	10	20	20	10
	Free carbon emission permits $K^j (\times 10^3)$	90	90	9000	9000	900
Case 5	Subsidy/penalty coefficient g^j	20	20	10	10	20
	Free carbon emission permits $K^j (\times 10^3)$	90	90	9000	9000	900

5.2 Comparative analysis by carbon emissions regulatory policies

Table 3 shows the base case results. **Table 4** shows the revenue of each firm, commodity quantity, and inequity of the CrGSC system for all of the cases. From **Table 3**, based on Eq. (16) and Eq. (18), the total cost of each supply chain is the same as 1.4132×10^4, and equal that cost obtained by the retail price, which means that the UE condition is satisfied.

Table 3: Base case results

Firm	Supplier 1	Supplier 2	Plant 1	Plant 2	Manufacturer
Commodity price p^j $(\times 10^4)$	0.1460	0.2540	0.4016	0.5484	1.4132
Commodity quantity q^j $(\times 10^4)$	0.8333	0.5961	0.8333	0.5961	1.4293

Revenue Π^j ($\times 10^8$)	0.9292		1.0759	0.4112	0.0407	0.7666
Edge	1	2	3	4	5	6
Commodity quantity x_a ($\times 10^3$)	0.4130	0.3337	0.4203	0.2624	0.8333	0.5961

In **Table 4**, the commodity quantity differs for all 6 cases representing different carbon emissions regulatory policies and their impact on the firms' costs and their final decision. It should noted that in Case 1, plant 2 and the manufacturer exhibit a loss in revenue while minimizing the supply chain cost, i.e. the UE condition is satisfied. For the CrGSC's inequity, Case 2 has the minimum inequity, which is consistent with the market demand being influenced by only the retail price as noted in Eq. (1). By changing the subsidy/penalty scheme (Case 1 and Case 2) and the free carbon emission permits scheme (Case 3) independently, an equity change in the CrGSC system can be found. However, if the change is too great, the inequity will have a sudden surge as in Case 5.

Table 4: Revenue, commodity quantity and inequity of carbon emissions regulatory policies

Case		Case 0	Case 1	Case 2	Case 3	Case 4	Case 5
Revenue of	supplier 1 ($\times 10^8$)	0.9292	0.8522	2.0505	0.0622	0.0891	0.0694
	supplier 2 ($\times 10^8$)	1.0759	1.1473	1.8045	0.0671	0.0922	0.0656
	plant 1 ($\times 10^8$)	0.4112	0.3283	1.8897	0.5756	0.7178	0.5689
	plant 2 ($\times 10^8$)	0.0407	-0.3105	2.0434	0.5400	0.6324	0.5322
	manufacurer ($\times 10^8$)	0.7666	-0.0238	-4.0929	0.8227	0.6084	0.8455
	CrGSC ($\times 10^8$)	3.2236	1.9935	3.6952	2.0676	2.1399	2.0816
CrGSC's	Commodity quantity ($\times 10^4$)	1.2639	1.5128	1.7886	0.63801	0.9346	0.6516
	Inequity E	0.2813	0.3663	0.2233	0.6686	0.3588	0.7010

Next, to investigate further into the impact of the carbon emissions regulatory policies, we conduct sensitivity analyses on the various policies in which the setting of the parameters other than the ones used in the sensitivity analyses is set to be the same as Case 5.

5.3 Sensitivity analyses

5.3.1 Price elasticity coefficient of the market demand β

Insight 1. *Price elasticity coefficient's impact on the price and commodity quantity.*

Figures 6 and **7** show the relationship between price and the commodity quantity across the firms as price elasticity increases. From **Figure 6**, the retail price decreases sharply, while those of the suppliers and plants show very small change as the price elasticity increases. This is so as the manufacturer is the focal firm ~~dominant actor~~ within the CrGSC system. Similar to the comparative analysis in Section 5.2, the change in commodity price for each firm also suggests that results agree with the proposed equivalent supply chain network equilibrium model.

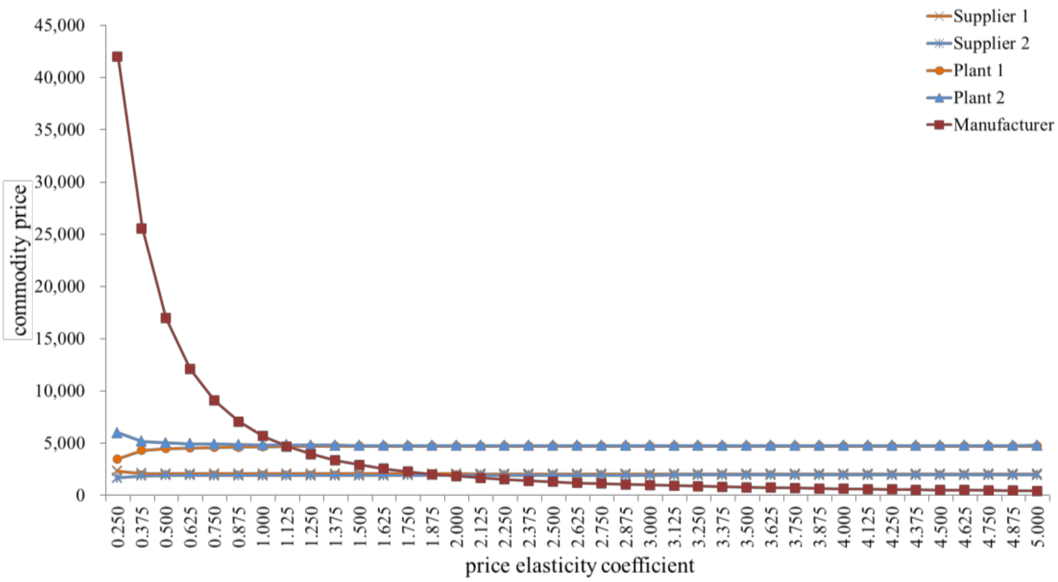

Figure 6: Effect of β on the commodity price of each firm

From **Figure 7**, the commodity quantity of the retailer increases and remains at the initial demand of the market $Q^0 = 15000$ as the price elasticity increases. The commodity quantities of supplier 1 and plant 1 incease at a higher rate than those of supplier 2 and plant 2, which means there is a shift in the commodity quantity among the different supply chains and edges. For example, the flows of edges 3 and 4 increase less than those of edges 1 and 2, as **Figure 8** shows. This commodity quantity shift is similar to the volume shift among the paths of the traffic network (Dial, 2006).

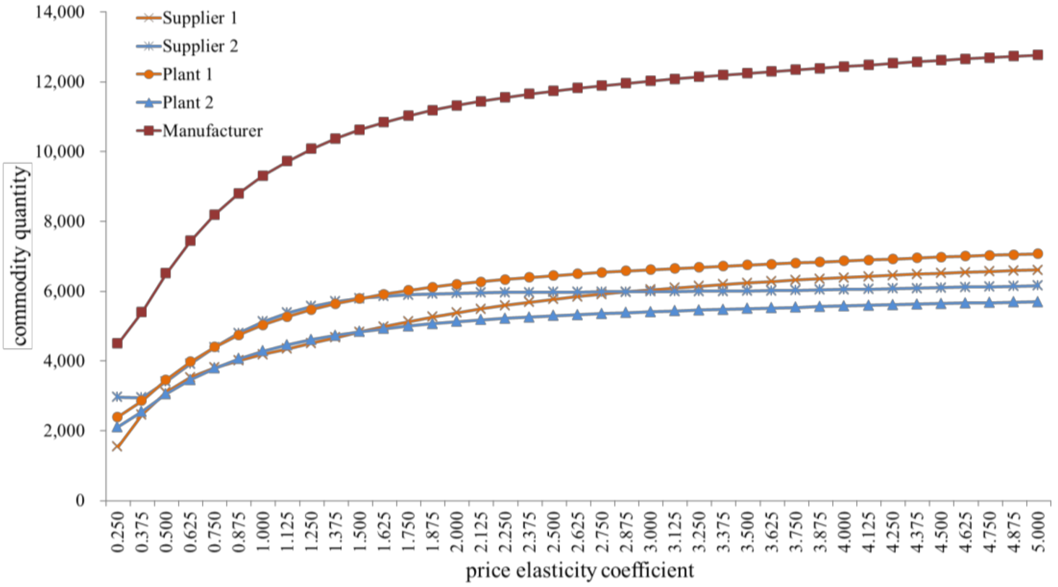

Figure 7: Effect of β on the commodity quantity of each firm

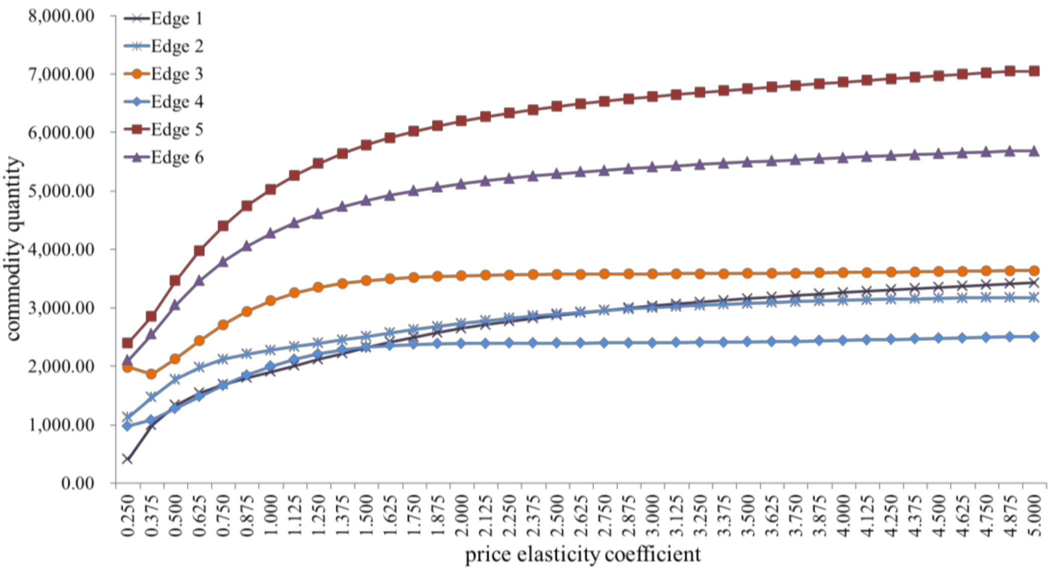

Figure 8: Efect of β on the edge flow

In sum, with the different costs and commodities with different β, the commodity quantity of each firm will be different as a result of the commodity quantity shifting. This will further influence the revenue of each firm and the equity of the carbon emissions regulatory policies set by the different governments, which will be further analysed in **Insight 3**.

Insight 2*. price elasticity coefficient ’s impact on the revenue and carbon emission*.

Figures 9 and **10** show the change in revenue and carbon emissions with the price elasticity coefficient. From **Figure 9**, the revenue of the manufacturer decreases sharply and then tapers off as the price elasticity coefficient increases, whereas both supplier 1 and plant 2 has a gradual decrease until the trends stabilize. Constrastingly, the revenue of suppliers increase with price elasticity. These variation tendencies are consistent with **Insight 1**. From **Figure 10**, the carbon emissions of the manufacturer increase slightly with rising price elasticity coefficient, as its commodity quantity has a small variation change and its carbon emission intensity is also low. It is important to note that when the price elasticity coefficient $\beta > 1$, manufacturer’s revenue is negative in Case 5, and the inequity of the CrGSC system is at its minimum. In short, a low revenue puts the manufacturer in an inferior position but improves the equity of the CrGSC system, when considering the differential carbon emissions regulatory policies.

In conjunction with **Insight 1**, the commodities with different price elasticity, the revenue of the manufacturer will be influenced intensively, and the position of the manufacturer will change from a “free-rider” to a “plant”, and this kind of change will influence the equity of the carbon emissions regulatory policies set by different governments, which will be further analysed in **Insight 3**

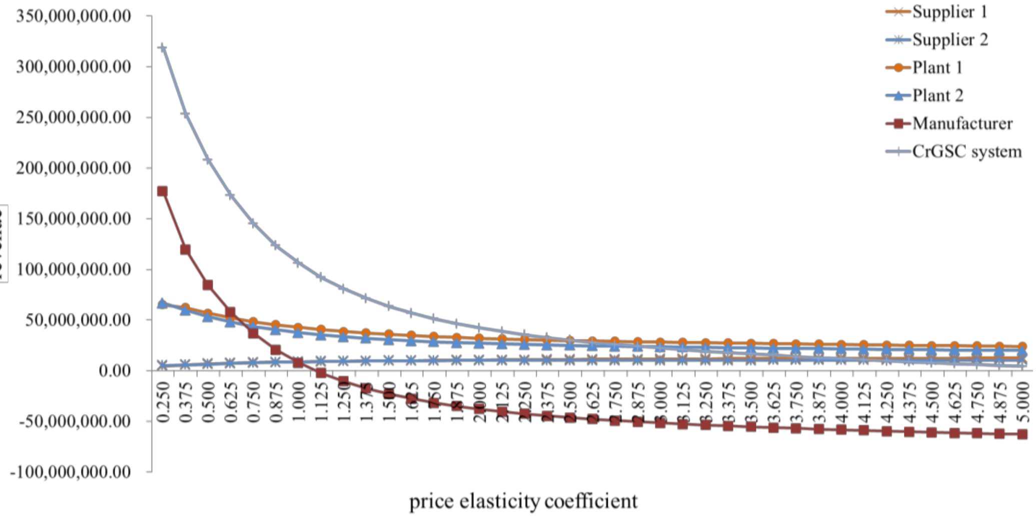

Figure 9: Effect of β on revenue of each firm

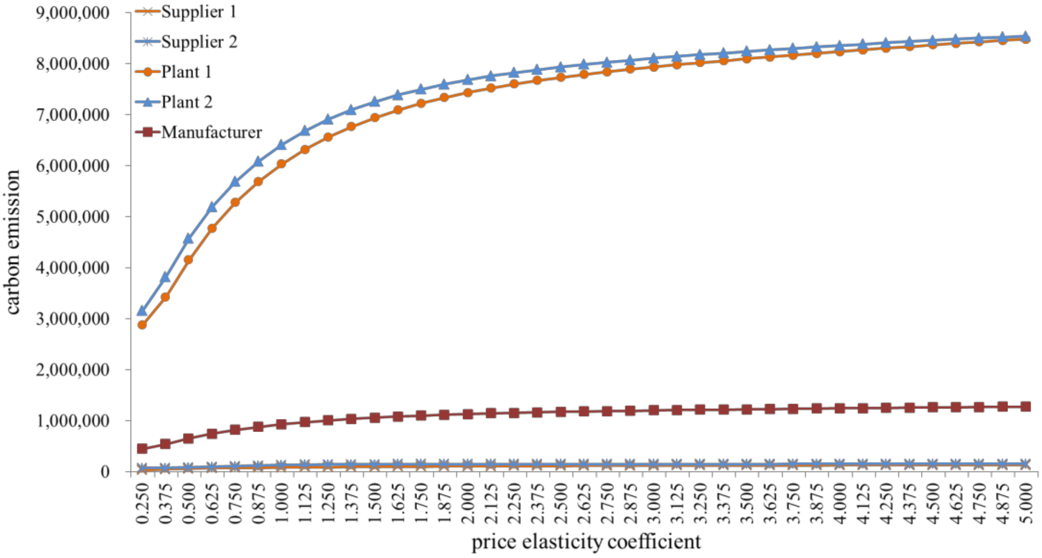

Figure 10: Effect of β on carbon emission of each firm and CrGSC system

Insight 3. *Price elasticity coefficient's impact on the equity of the CrGSC system*.

Figure 11 shows the inequity of the carbon emissions regulatory policy changes according to β. The inequity of Case3, Case 4 and Case 5 declines rapidly and rises steadily with β, while the rest exhibits a fluctuation in the beginning phase and then gently smoothens. It shows that either changing the subsidy/penalty policy or the free carbon emissions regulation policy independently would have the same impact on the equity of the carbon emissions regulatory policy. Comparing the inequity of each case with a different price elasticity coefficient β, it clearly shows that carbon emissions regulatory policy has a higher equity for different price elasticities. For example, the inequity of Case 4 is the lowest when $\beta = 0.625$, whereas the inequity for Case 3 and Case 5 are at the lowest when $\beta = 1$. The difference between the scheme of Case 5 and the other cases are due to stricter regulatory policies (such as lower carbon emission permits ans stricter financial interventions) imposed on the firm with lower emission intensity commodity, where a stricter regulatory policy will lead to better equity.

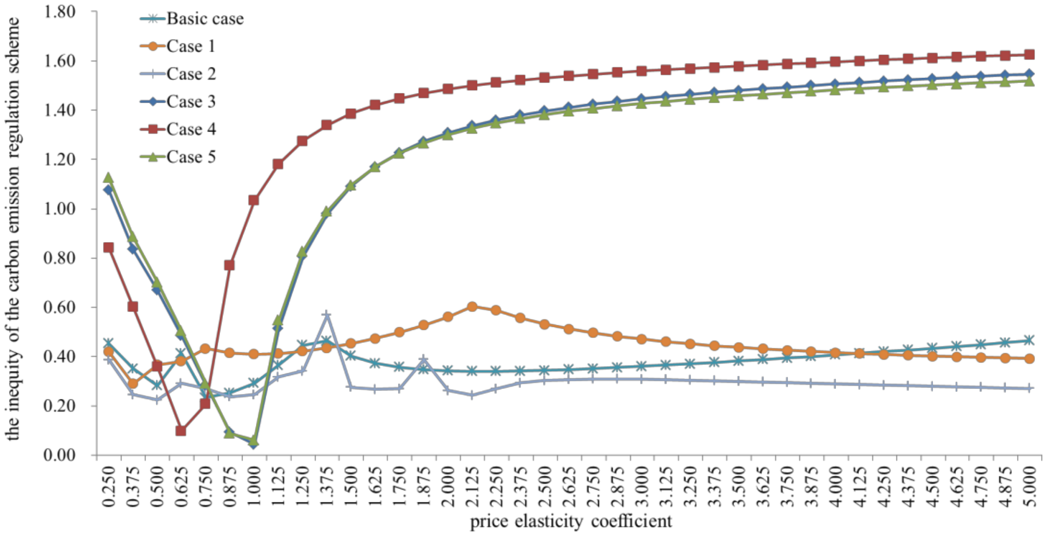

Figure 11: β and equity of the CrGSC system

In summary, for a price sensitive market, the local governments should set carbon emissions regulatory policies for different products jointly. As the manufacturer is the focal firm ~~dominant player~~ in the supply chain network, if the product is less price elastic, a strict policy by the supervising government would help to improve equity.

5.3.2 Carbon emission intensity of the firm (e^j)

Insight 4. *Impact of carbon emission intensity on revenue and equity.*

Figure 12 shows the revenue change with carbon emission intensity for each firm, in which the floating ratio of emission intensity of each firm is between the interval of $\left[0,\ 2\right]$. It is found that the revenue decreases with increasing carbon emission intensity. **Figure 13** shows the effect of the inequity of the carbon emissions regulatory policy with increasing carbon emission intensity of each firm in Case 5. The inequity declines gradually before having a steep surge and sudden fall as a function of increasing carbon emission intensity of the suppliers. The increasing intensity of the plants exhibit an increase, but that of when the manufacture declines. Given the manufacturer's revenue changes in **Figure 12** and the conclusion of **Insight 4**, it is better for the plants to limit their carbon emission~~s~~ intensity. Otherwise, not only will its revenue be negative but also the CrGSC will experience high inequity.

In sum, the firms should keep their carbon emission intensity to within a certain level. By increasing the carbon emission intensity of the firm whose initial carbon emission intensity is low will not help the cause.

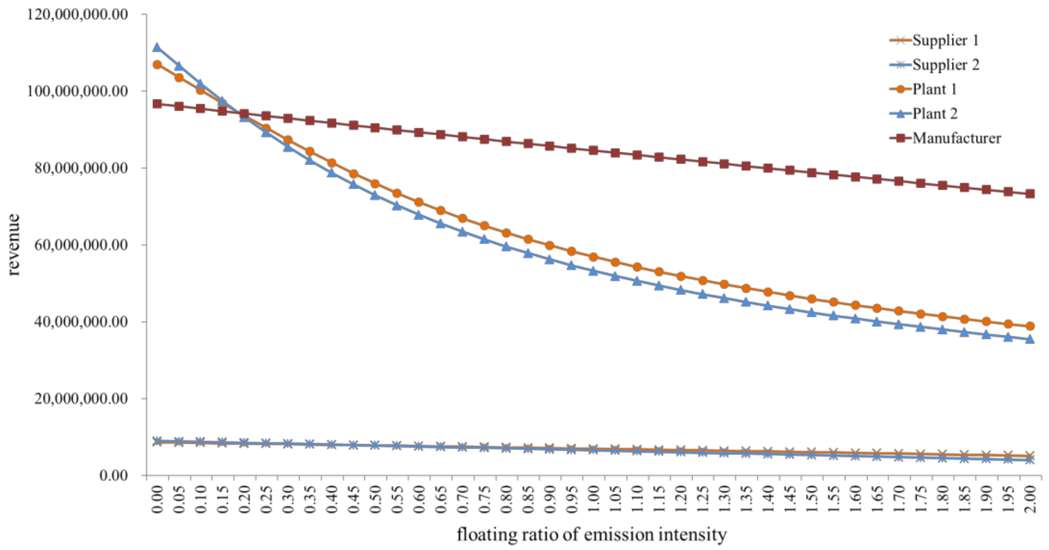

Figure 12: Carbon emission intensity's impact on revenue

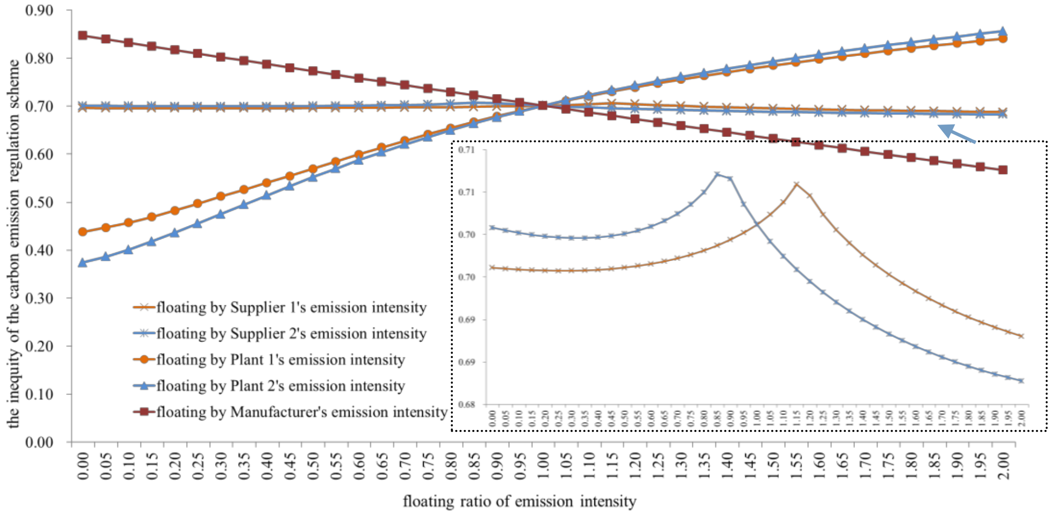

Figure 13: Carbon emission intensity's impact on the equity of CrGSC system

5.3.3 Subsidy/penalty coefficient and the free carbon emission permits (g^j and K^j)

Insight 5*. The carbon emissions regulatory policy's impact on revenue*.

Figures 14 and **15** show that the revenue changes with the subsidy/penalty coefficient and the initial free carbon emission permits respectively. In **Figures 14** and **15**, each firm's revenue is obtained by independently raising the subsidy/penalty coefficient or the free carbon emission permits imposed on it and keeping that of the other firm unchanged. There is a positive correlation between the revenue of each firm and the imposed subsidy/penalty (or the imposed free carbon emission permits). Similar to the comparative analysis in Section 5.1, independently raising the subsidy/penalty coefficient and the free carbon emission permits, can lift the revenue of the firm, supporting the findings of Sheu (2011), Madani and Rasti-Barzoki (2017), and Hafezalkotob (2017).

For the carbon emissions regulatory policy determined by government, i.e. a financial intervention with subsidy/penalty and free carbon emission permits in this paper, intensifying the intervention can lead to increase in the revenues of the stakeholders and help to motivate the enthusiasm of the stakeholders.

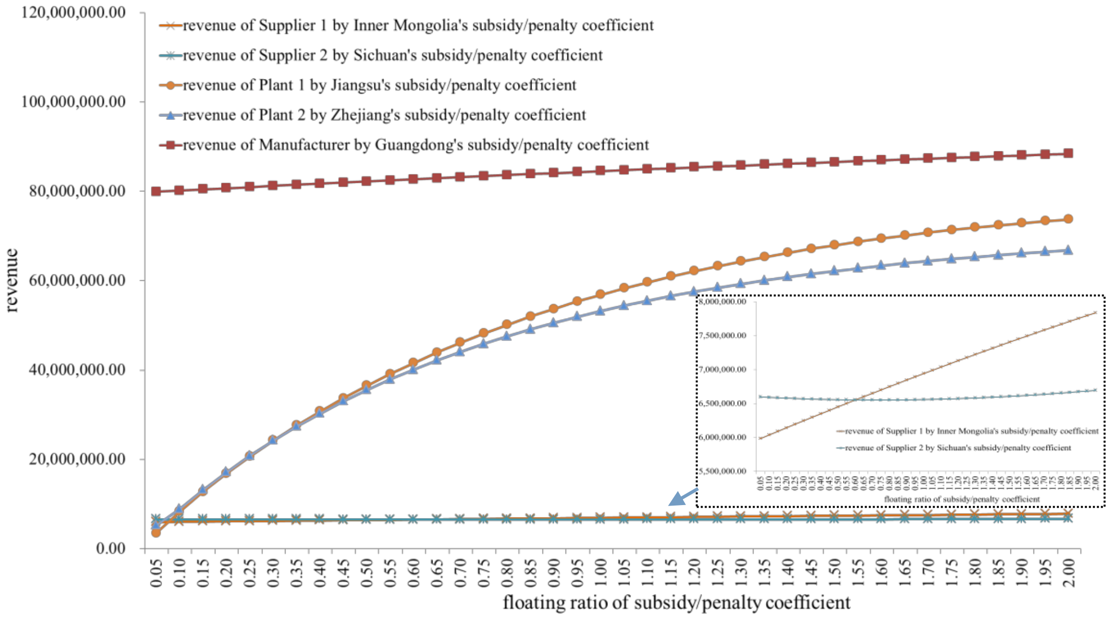

Figure 14: Subsidy/penalty coefficient's impact on revenue of each firm

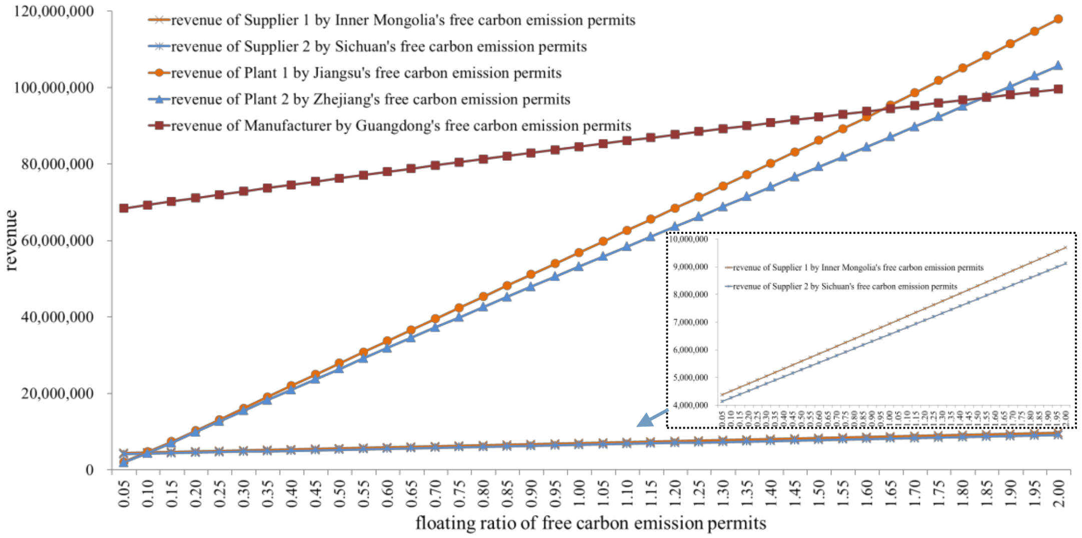

Figure 15: Free carbon emission permits' impact on revenue of each firm

Insight 6. *Carbon emissions regulatory policy's impact on the equity of the CrGSC system.* **Figures 16** and **17** show that the equity of the CrGSC system change with rising subsidy/penalty coefficient and free carbon emission permits of each firm in Case 5 respectively. In **Figure 16**, it is found that the inequity of the CrGSC system decreases with the raising subsidy/penalty coefficient imposed by the plant's supervising government. However, raising the subsidy/penalty coefficient imposed by the manufacturer's supervising government results in an increase in the inequity. Contrastingly, raising the subsidy/penalty coefficient imposed by the supplier's government has a different result, e.g. the inequity increases gradually before exhibitiing a fall for the subsidy/penalty coefficient of Inner

Mongolia and declines gradually before exhibiting an increase for Sichuan, owing to the revenue changes illustrated in **Figure 14**. From **Figure 17**, the inequity firstly increases and then declines with increasing free carbon emission permits of the plants' supervising government. It means that increasing the cap on carbon emission permits granted to the plant has an upper bound limit in terms of the equity of the CrGSC system, and there is also a cost towards improvement where too little may result in a lax regulation on carbon emissions. The inequity declines with increasing free carbon emission permits of the manufacturer's supervising governement. However, raising the cap on carbon emission permits granted to the suppliers results in an increase firstly then a decline in the inequity.

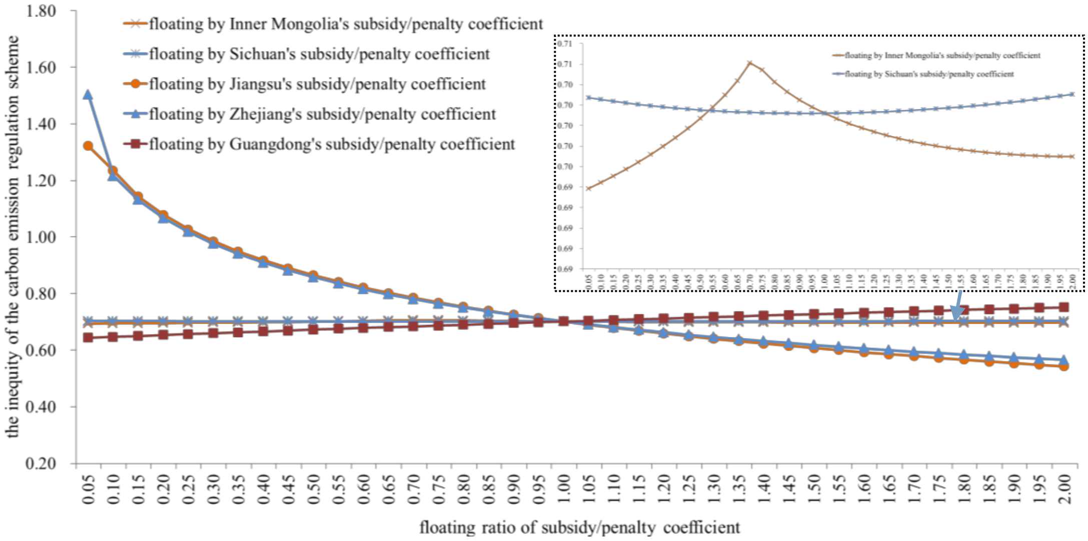

Figure 16: Effect of a subsidy/penalty coefficient on the equity of CrGSC system

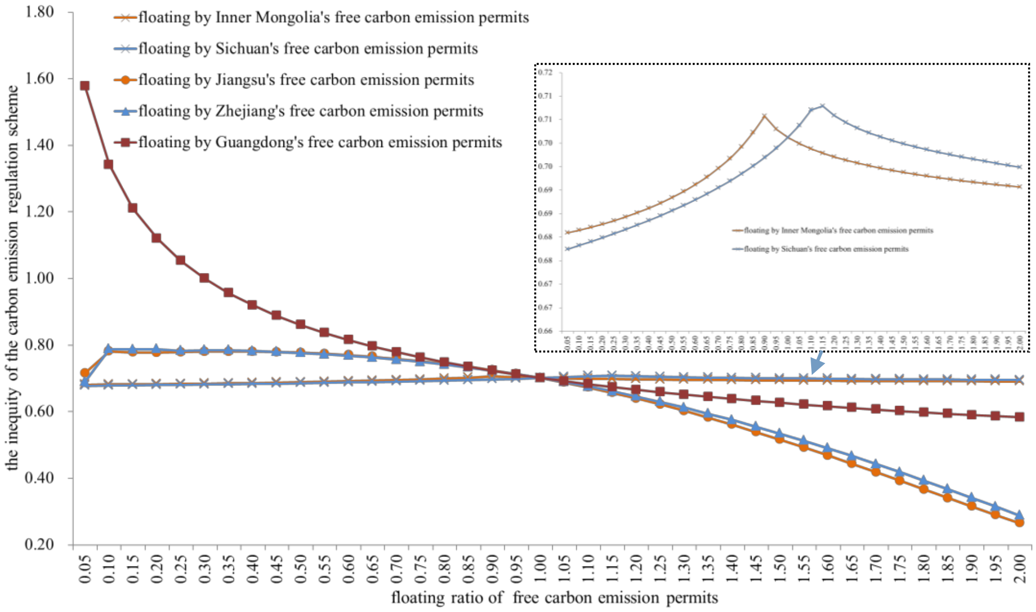

Figure 17: Effect of a free carbon emission permits on the equity of CrGSC system

From **Insight 3** and **Insight 4**, intensifying the subsidy/penalty coefficient or the cap on carbon emission permits can lead to an improvement of the equity in the same way. For improving the equity and reducing the carbon emissions, imposing a stricter carbon emissions regulatory policy on the firm with lower carbon emission intensity is more efficient than that of the firm with higher carbon emission intensity.

5.4 Policy Implications

Our policy implications are derived from two intervention strategies used in evaluating their effectiveness in reducing carbon emissions and inequity of the CrGSC system. First, the 'carrot-and-stick' approach uses subsidy-penalty as a reward-punishment strategy. It is an outcome-based approach as it requires the government to act on its entities performance ex-post. On the other hand, the other intervention strategy uses permits allocation as an ex-ante approach. This is a budgeting approach where permits holders are given an allocation based on an initial audit, which serves as an expectation of the supervising government over its entities output. In the budgeting approach, the entity can either cash in on the difference saved or purchase additional permits based on its need.

Table 5 provides the application of the 2 intervention strategies, including a hybrid strategy across 5 cases. These cases considered the type of intervention strategy imposed on each of the supply chain entities – suppliers, manufacturer and plants. Case 0 is the benchmark case where no intervention strategy is applied, which serves as a point of reference for our policy analyses. Our main finding shows that subsidies and penalties imposed ex-post on suppliers and manufacturer would mean sacrificing some revenue of the manufacturer for the suppliers. Nonetheless, the equity of the entire CrGSC system improves given that the plants do not subject to any intervention policies. Implementation of this 'best-scenario' (Case 2) means that the supervising local government places the burden of fulfilling the greening initiative more on the manufacturer. In the case of our steel supply chain in China, local regional governments can use this strategy to compel the manufacturer to relocate, while still maintaining the revenue of the industry as a whole because of suppliers' revenue improvement. One such situation where it is necessary to do so is in the case of redevelopment or industrial rezoning where manufacturers of final products are encouraged to relocate closer to the plants supplying their semi-finished goods. Future research may consider transportation costs in the relocation decision as part of the intervention strategy on the policy outcomes.

Table 5: The impact of intervention strategies and policy outcomes

ID	Description	Strategy	Policy implications
Case 0	Baseline	-	-
Case 1	Increase subsidy/penalty for plants	Emphasis on 'carrot-and-stick' for plants	The stricter financial intervention strategy imposed on plants would affect its revenue negatively, which would lead to a greater inequity of the CrGSC system. With an emphasis on the financial intervention strategy, the local government can impose higher penalty on plants that do not conform to their green commitment. This strategy can be a method to compel un-abiding plants to relocate due to penalty enforcement outcome.
Case 2	Increase subsidy/penalty for suppliers and manufacturer	Emphasis on 'carrot-and-stick' for suppliers and manufacturer while maintaining status-quo on the plants	The stricter financial intervention strategy imposed on suppliers and manufacturer would result in a revenue reduction for the manufacturer but would increase those of the suppliers. This leads to an overall decline of the inequity of the CrGSC system. This strategy can be a method to compel un-abiding manufacturer to relocate due to the penalty enforcement outcome.
Case 3	Reduce permits for suppliers and manufacturer	Emphasis more on budgeting approach for suppliers while maintaining status-quo on plants and manufacturer	Allocating less carbon emission permits to the suppliers would contribute to revenue reduction for the suppliers. This widens the inequity gap of the CrGSC system. That is, imposing a carbon emission permit strategy for the firms with low level carbon emission intensity will increase the inequity of the CrGSC system.
Case 4	Reduce permits for suppliers and manufacturer but increase subsidy/penalty for plants	Emphasis more on budgeting approach for suppliers but 'carrot-and-stick' approach for plants, while maintaining status-quo on manufacturer	With less carbon emission permits imposed on suppliers, the stricter financial intervention strategy imposed on plants would result in revenue increase for the plants. This widens the inequity of the CrGSC system. However, the equity of the CrGSC system is higher than having a stricter financial intervention strategy imposed on plants (case 3).
Case 5	Reduce permits but increase subsidy/penalty for suppliers and manufacturer	Use a hybrid strategy of 'carrot-and-stick' as well as budgeting approach for suppliers and manufacturer while maintaining status-quo on plants	With less carbon emission permits imposed on suppliers, the stricter financial intervention strategy imposed on suppliers and manufacturer would result in the decline of the revenues of the suppliers. This leads to the increase of the inequity of the CrGSC system. The outcome of the equity of the CrGSC system is worse than that by imposing less carbon emission permits imposed on suppliers. Case 5 is the worst performing case in terms of inequity to the CrGSC system.

Note: We do not consider the cases where budget allocation strategy is used as an intervention mechanism on plants because these plants already exhibit high carbon emission intensity levels.

6. Conclusion

This paper focused on the pricing and equity of the cross-regional green supply chain with constrasting carbon emissions regulatory policies, where the manufacturer dominates the supply chain. Although the demand is expected to be influenced by the retail price, we considered the case where carbon emissions regulatory policies are unique to each local government and the subsidies or penalties are based on whether the initial free carbon emission permits was met. The revenue functions of the firms were formulated by considering governmental intervention and the production of the commodity. Given the complexity of the CrGSC network, we transform the original multiple O-D pairs problem into a single O-D pair problem, and then an equivalent supply chain network equilibrium model with elastic demand based on UE conditions was proposed. Based on the analysis of the *Equivalent conditions* and *Uniqueness conditions*, the optimal solutions for the CrGSC's stakeholders were obtained, i.e. the price and quantity of the commodity. Then, through sensitivity analyses, the effect on the commodity price, commodity quantity, carbon emission and revenue of the firms contrasted by the differential carbon emissions regulatory policies were investigated, as well as the effects of the price elasticity coefficient and the product's carbon emission intensity.

It is observed that a product with a higher price elasticity and carbon emission intensity would limit the firm's revenue growth. From our price elasticity analysis, different products will benefit from different policy schemes. Hence, the carbon emissions regulatory policy could set their policy measures based on the price elasticity and the carbon emission intensity relationship. As the main interventions of the carbon emissions regulation, the subsidy/penalty and the free carbon emission permits have the same impact on the revenue of the firm and the equity of the CrGSC system, which will incentivise the stakeholders to reduce carbon emissions. For the equity of the CrGSC, it is observed that the carbon emissions regulatory policies do not perform well if they are set too strictly.

Similar to Nagurney (2006), the UE conditions are feasible when analysing a complex supply chain network. The network transformation and the excess demand transformation from the original multiple O-D pairs problem into a single O-D pair problem, in conjunction with the demand transformation of the elastic-demand problem into a fixed-demand problem provides an efficient means to analyse the commodity quantity assignment of the complex supply chain network.

While this study has contributed to the green supply chain management literature, the proposed model is restricted to the supply chain network that can produce a single product where the manufacturer dominates the supply chain. It would be interesting to generalize the model to multiple products and different focal firm ~~dominant players~~, so as the competition between the firms ~~players~~. Future studies could look into a different optimization model where the government carbon emissions regulatory policies, i.e. g^j and K^j are taken as decision variables. Then, the results and analyses can support the local government to design its regulation policy. Finally, another means to improve the modeling forefront is to modify the Theil inequity coefficient by considering the differential social and economic restrictions of the regions, then to some extent the "Danish Proposal" as unilaterally protested by many developing countries may be avoided.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (71874158, 71433006, 91746202, 71403245, 71603237), the Zhejiang Provincial Natural Science Foundation of China (LY17G020003, LZ14G020001), and the Key Foundation of Philosophy and Social Science of Zhejiang Province (14NDJC139YB). The authors are grateful to the editors and referees for their valuable comments and suggestions to improve the quality and presentation of the paper.

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Appendices A and B are included as a supplementary file for review.