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Research article

# Carbon reduction decisions under progressive carbon tax regulations: A new dual-channel supply chain network equilibrium model

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ABSTRACT

Since the production process in manufacturing industry is one of the main sources of carbon emissions, most governments have enacted relevant carbon policies to encourage manufacturers to invest in green production technology and reduce carbon emissions. However, the effectiveness of the carbon policy deserves further investigation because the manufacturers focus more on economic profits in actual operations. For this purpose, this paper proposes a dual-channel supply chain network (DCSCN) equilibrium model based on variational inequality theory to examine progressive carbon tax mechanism design of the government and its impacts on the production/pricing and abatement level decisions of the manufacturers in the DCSCN. In addition, this paper also examines the influences of the online channel introduction on supply chain network equilibrium decisions, carbon emissions and profits. We employ the modified projection and contraction algorithm to obtain the numerical solutions for several examples, and analyze the impacts of the key parameters on the equilibrium decisions and derive several managerial insights. The results show that if the government sets the high-level carbon tax and the cut-off value in progressive carbon tax policy appropriately, it can induce the manufacturers to improve abatement level actively; meanwhile the profit maximization goal of the manufacturer and the whole DCSCN can be consistent with the government's low-carbon emission target. Moreover, the introduction of online channel may depress the economic activities and lead to profit loss for the supply chain network but contributes to reducing the carbon emissions under progressive carbon tax policy. The conclusions may be useful for reference in the study of the low-carbon supply chain and the design of carbon emission reduction policy for government.



## 1. Introduction

With the frequent occurrence of extreme weather, and the worsening ecological environment, the reduction of *carbon dioxide ($CO_2$) emissions* has become one of the world's hot topics. Several countries have devoted much effort to curbing *carbon emission* and clearly setting the national level goals. For example, China, the biggest carbon emitter around the world currently, accounting for 27.8% of the world's total $CO_2$ emissions (BP, 2019; Zhang et al., 2020), has committed to reducing the intensity of carbon dioxide emissions per unit of GDP in 2030 by 60%–65% compared with the level of 2005 (Zhang et al., 2020), and to increase the share of non-fossil fuels in primary energy consumption to approximately 15% by 2020 (Wang et al., 2016).

However, in the current economic situation, it is not easy for these countries to achieve carbon reduction target only by traditional command and control measures (Dong et al., 2017). Efficient regulations are a pre-requisite for restricting the firms' carbon emission behaviors (Kannan et al., 2012). The low-carbon policies in a carbon tax, cap-and-trade, and low-carbon offset are promulgated and implemented by the governments in practice. Among these policies, a carbon tax is one of the important policy options, i.e., the tax is imposed on a firm for each unit of product that emits $CO_2$. Economists and international organizations have long advocated it because it is easier and can bring more massive carbon emission reduction with a less negative impact on economic

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**Nomenclature**

*Basic parameters*

| | |
|---|---|
| $o$ | The manufacturer, $o = 1, 2, \cdots, M$. |
| $i$ | The retailer, $i = 1, 2, \cdots, N$. |
| $j$ | The demand market, $j = 1, 2, \cdots, K$. |
| $a$ | The basic market capacity. |
| $\omega$ | Consumer's preference for online channel, $\omega \in (0, 1)$. |
| $\theta$ | Consumer's sensitivity to product abatement level, $\theta \in (0, 1)$. |
| $\beta_r$ | The raw material conversion rate. |
| $\beta_0$ | The carbon emission of unit regular product. |
| $B_o$ | The cutoff value used to define the carbon tax bracket. |
| $t_0$,$t_1$ | The high-level carbon tax and the low-level carbon tax. |
| $\eta_o$ | A scaling parameter for green technology investment |
| $m_{xy}$ | The elastic coefficient of the market demand affected by the product price of its own channel ($m_{xy} > 0, x = 1, 2; y = 1, 2$). |
| $n_z$ | The elastic coefficient of the market demand affected by the product price of its competitive channel, $m_{xy} > n_z > 0$, $z = 1, 2$. |

*Decision variables*

| | |
|---|---|
| $q_o^r$ | The raw materials amount used by manufacturer, $\boldsymbol{q}^r = (q_o^r)_{M\times 1} \in R_+^M$. |
| $q_{oi}^p$ | The products transaction amount from manufacturer to retailer in offline channel, $\boldsymbol{Q}^1 = (q_{oi}^p)_{MN\times 1} \in R_+^{MN}$. |
| $q_{ij}^p$ | The products transaction amount from retailer to demand market in offline channel, $\boldsymbol{Q}^2 = (q_{ij}^p)_{NK\times 1} \in R_+^{NK}$. |
| $q_{oj}^e$ | The products transaction amount from manufacturer to demand market in online channel, $\boldsymbol{Q}^3 = (q_{oj}^e)_{MK\times 1} \in R_+^{MK}$. |
| $\rho_j^p$ | The price of unit product paid by consumers in offline channel. |
| $\rho_j^e$ | The price of unit product paid by consumers in online channel. |
| $\alpha_o$ | The product abatement level, $\alpha_o \in [0, 1]$,$\boldsymbol{\alpha} = (\alpha_o)_{M\times 1}$. $\alpha_o = 0$ denotes the product is a regular product, while $\alpha_o = 1$ denotes the product is a completely zero-carbon-emission product. |
| $\varepsilon_0^o$ | a manufacturer's carbon emission below the cut-off value, $\boldsymbol{\varepsilon}_0 = (\varepsilon_0^o)_{o\times 1}$. |
| $\varepsilon_1^o$ | a manufacturer's carbon emission exceeding the cut-off value, $\boldsymbol{\varepsilon}_1 = (\varepsilon_1^o)_{o\times 1}$. |

*Endogenous price variables*

| | |
|---|---|
| $\rho_{oi}^p$ | The transaction price between manufacturer and retailer. |
| $\rho_{oj}^e$ | The transaction price between manufacturer and demand market. |
| $\rho_{ij}^p$ | The transaction price between retailer and demand market. |

*Functions*

| | |
|---|---|
| $f_o(q_o^r)$ | The raw material cost function. |
| $f_o^M = f_o^M(\beta_r, \alpha_o, \boldsymbol{q}^r)$ | The production cost function. |
| $C_{\alpha_o}(\alpha_o)$ | The green technology investment |
| $c_{oi}^M = c_{oi}^M(q_{oi}^p)$ | The transaction cost between manufacturer and retailer borne by manufacturer. |
| $c_{oj}^x = c_{oj}^x(q_{oj}^e)$ | The transaction cost between manufacturer and demand market, $x = M$ denotes the cost borne by manufacturer, while $x = K$ denotes the cost borne by consumer. |
| $c_{ij}^x = c_{ij}^x(q_{ij}^p)$ | The transaction cost between retailer and demand market. $x = N$ denotes the cost borne by retailer, while $x = J$ denotes the cost borne by consumer. |
| $c_i = c_i(\sum_o q_{oi}^p)$ | the retailer's exhibition cost function for the products in offline store. |
| $d_j^p = d_j^p(\rho_j^p, \rho_j^e, \boldsymbol{\alpha}; \omega)$ | The demand function of offline channel at demand market |
| $d_j^e = d_j^e(\rho_j^p, \rho_j^e, \boldsymbol{\alpha}; \omega)$ | The demand function of online channel at demand market |
| $\pi_x$ | The member's profit. $x = o$ represents manufacturer, and $x = i$ represents retailer. |

Note that the variables with "*" in the following indicate the corresponding decision variables' equilibrium values.

growth (Dong et al., 2017). Just more recently, a new form of carbon tax, namely progressive carbon tax, has been put forward by scholars and recommended for governments to avoid the inequalities caused by a traditional carbon tax (Chiroleu-Assouline et al., 2014; Fremstad, 2019). In a progressive carbon tax mechanism, the carbon tax rate is not constant but stepwise, i.e., when the total carbon emission exceeds a certain threshold, the carbon tax rate will increase (Yu et al., 2019). In this paper, we will also take progressive carbon tax as the carbon regulation policy.

The implementation of carbon emission regulations will urge manufacturers to explore green technologies (e.g. sustainable design and sustainable manufacturing) and improve the carbon abatement levels of the products. Abatement level refers to the percentage that carbon emission abatement for each product with green technology adoption accounts for that without green technology (Yang et al., 2017). In this context, more and more low-carbon products are emerging in the market. In addition, consumers have been shown to have a higher preference for low-carbon products compared with regular products (Kotchen, 2005; Li et al., 2017). From this perspective, the manufacturers' revenues may improve with green technologies adoption. But in the meantime, the manufacturers will also unavoidably face high green investment (Liu et al., 2012; Ji et al., 2017). Whether the increased revenue can compensate for the additional green investment is the focus of attention for the manufacturers. (Wang et al., 2016). They should carefully figure out this problem by taking the government's carbon policies and green investment into account.

The advent of e-commerce has greatly changed the buying habit of consumers and the marketing fashion of enterprises. Some manufacturers, such as IBM, Cisco, Nike (Cai et al. 2009), Haier, and other enterprises, have designed their online channel to meet consumers' needs via the internet and the traditional channel. Hence, the opening-up of the online marketing channel makes the traditional supply chain become a dual-channel supply chain. In reality, the dual-channel supply chain is usually a complex network with multiple tiers, including the manufacturer tier, retailer tier, and demand market tier. The decision-makers in each tier engage in the same businesses. Specifically, the manufacturers produce homogeneous products and sell them to the consumers via dual-channels. The retailers distribute the manufacturers' products and the consumers choose one channel to purchase products. Non-cooperative competitions exist among the same tier members, while transactions occur between different tiers (Nagurney et al., 2002; Nagurney and Toyasaki, 2005; Zhang et al., 2020). How to describe the interaction relations among decision-makers and obtain the dual-channel supply chain network (DCSCN) equilibrium conditions under carbon tax regulation is of great theoretical and practical significance.

In view of the aforementioned analysis of realistic background, the objective of this paper is to investigate the DCSCN equilibrium problem under progressive carbon tax policy issued by the government based on variational inequality theory. The existence and uniqueness of the equilibrium solutions are proved. Combined with numerical examples, we focus on analyzing the impacts of the progressive carbon tax policy on the product abatement level's decision rules, production and transaction volumes, as well as members' profits. We also compare the influences of two different consumers' online transaction costs on DCSCN equilibrium, and provide comparisons between the DCSCN and traditional supply chain network (SCN). More precisely, it mainly covers the following four aspects: (1) whether the progressive carbon tax mechanism is effective in the DCSCN and how to design an appropriate progressive carbon tax mechanism for the government; (2) whether there exist some conditions that the economic benefit goal is consistent with low-carbon emission goal in the DCSCN. (3) how the consumers' online transaction cost influences the equilibrium decisions, carbon emissions and profits in the DCSCN under progressive carbon tax mechanism. (4) compared to traditional SCN, whether the introduction of the online channel can reduce carbon emissions and improve members' economic benefits. Based on numerical experiments analysis, several managerial insights are provided for decision-makers and policy-makers when dealing with progressive carbon tax policy and green production.

This paper makes contributions in the following four folds:

(1) To the best of our knowledge, this is the first paper that studies the abatement level and production/pricing decisions in a DCSCN with carbon tax regulations, especially the progressive carbon tax policy. Hence, this paper builds connections between the DCSCN literature and the emerging sustainable supply chain literature with abatement level decisions.
(2) This paper utilizes variational inequality theory to characterize the equilibrium decisions in a dual-channel supply chain with network structure, which is very different from the majority of existing literature that applies Stackelberg game into a dyadic dual-channel supply chain. The variational inequality theory provides an opportunity for us to analyze the impacts of progressive carbon tax policy on the abatement level and production/pricing decisions in a complex DCSCN with multiple competitive manufacturers, multiple competitive retailers and multiple demand markets.
(3) By the theoretical derivation and comprehensive numerical analysis, we find both the high-level carbon tax and the cut-off value in the progressive carbon tax policy have great impacts on the manufacturer's production, abatement level decisions and carbon emissions. By contrast, the low-level carbon tax is indecisive. The conclusion is significantly different from Yu et al. (2019) due to the differences of manufacturers' low-carbon behavior, network structure and competition pattern between these two papers. Moreover, on condition that the high-level carbon tax and the cut-off value are set appropriately, the economic benefit goals of the manufacturer and the whole DCSCN are consistent with low-carbon emission goal of the government.
(4) We also find that the introduction of online channel may depress the economic activities and lead to profit loss for the SCN but contributes to reducing the carbon emissions under progressive carbon tax policy, which is greatly different from the prevailing conclusion that online channel certainly benefits the entire system in a dyadic supply chain. In addition, the comparison of the abatement levels between two cases of high and low consumers' online transaction costs mainly depends on the cutoff value.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 introduces the methodology and states model assumptions, based on which the DCSCN equilibrium model utilizing variational inequalities is presented. Section 4 describes and analyzes the results of numerical examples, as well as gives some discussions and policy suggestions. Section 5 concludes with a summary and presents limitations of this research. The proof of the existence and uniqueness of the equilibrium solutions are provided in the Appendix.

## 2. Literature review

The study is closely related to three growing streams of literature: the manufacturer's green technology innovation under carbon emission regulations, SCN equilibrium under carbon emission regulations, and production/pricing decisions and coordination mechanism in dual-channel supply chains. We will review them subsequently. Also, the research gaps of the existing literature are pointed out.

### 2.1. The manufacturer's green technology innovation under carbon emission regulations

Due to the significance of green development, countries and governments have adopted diverse regulations to encourage enterprises to reduce carbon emissions. Therefore, enterprises should response positively, such as investments in green technology (Krass et al., 2013; Gong and Zhou, 2013; Wang et al., 2016). Meanwhile, with the rise of consumers' environmental awareness, product abatement level as an important factor for enterprises to enhance competitiveness and profits has been recognized by academia as well as industry (Subramanian et al., 2007; Liu et al., 2012; Xu et al., 2017; Peng et al.,2020). Up to now, scholars have constructed various supply chain models to examine the abatement level decisions according to different carbon emission regulations (Ji et al., 2017; Yang et al., 2017; Yang and Chen, 2018; Yu and Cao, 2019; Zhang et al., 2020). For example, Yang and Chen (2018) propose four-stage Stackelberg models to study the roles of *RS* (revenue sharing) and *CS* (cost sharing) offered by a dominant retailer on a manufacturer's carbon emission abatement effort and both parties' profitability with carbon tax policy and consumer environmental consciousness. Yu and Cao (2019) investigate the impacts of different information sharing formats on carbon emissions abatement decisions in a supply chain with one manufacturer and two competing retailers under cap-and-trade regulation. Zhang et al. (2020) investigate the equilibrium strategies considering abatement decision and manufacturer encroachment in a dual-channel supply chain. Although the above papers have studied the enterprises' abatement level decisions (or green technology investment) under different carbon emission regulations in depth, they are all limited to the cases of monopoly, duopoly and dyadic (dual-channel) supply chain. In reality, supply chain could be viewed as a complex network which consists of multiple competitive manufacturers and multiple competitive retailers. Therefore, it is crucial to consider carbon abatement problems from the perspective of SCN.

### 2.2. Supply chain network equilibrium under carbon emission regulations

Nagurney et al. (2002) first establish a SCN model and make great contribution to the development and application of SCN theory, and now it has been widely applied in various fields (Nagurney and Yu, 2012; Nagurney et al., 2013; Nagurney et al., 2015; Nagurney et al., 2017). With the increasingly serious environmental problems, consideration of SCN equilibrium under carbon regulation policies is worthwhile and deserves further analyses (Tao et al., 2015). Several papers have carried out researches on this issue. For instance, Allevi et al. (2018) establish a closed-loop supply chain network model and assume manufacturers are subject to the EU-ETS (a form of cap-and-trade) and a carbon tax is imposed on truck transport. Yu et al. (2019) compare the impacts of different carbon tax policies (flat emission tax rate and progressive carbon tax) on the economic benefit and environmental performance of a multi-tier SCN with firms competing in an oligopolistic manner and product heterogeneity. They find that the low-cost progressive carbon tax policies can be as effective as the high flat emission tax rate in carbon emission reduction under some conditions. Inspired by this paper, we also take progressive carbon tax as the main carbon emission regulations. He et al. (2019) propose a SCN model considering the manufacturers are constrained by a stringent carbon policy with mandatory cap, and examine how operational decision modes (centralized/decentralized manufacturing and cap sharing/non-sharing among the manufacturers) influence the profitability and carbon emission of the system. However, the above studies mainly examine how the enterprises passively adjust their production and pricing strategies to cope with the government's carbon emission regulations, rarely mention enterprises' active carbon reduction behaviors, such as the adoption of green production technology to improve the product abatement level. Saberi et al. (2018) is the first to investigate the abatement level decisions in a multi-period competitive SCN, in which firms (manufacturers, retailers, and carriers) try to maximize the net present value of their investment in eco-friendly technology. The demand functions at the markets depend not only on the price but also on the retailers' energy ratings. The conclusions show that sustainability and abatement level should be viewed holistically.

### 2.3. Production/pricing decisions and coordination mechanism in dual-channel supply chains

As electronic commerce rapidly develops, scholars have paid great attention to the research on the dual-channel supply chain (Lu and Liu, 2015; He et al., 2020; Yan et al., 2020; Wang et al., 2021). Once a manufacturer opens up a direct online channel, it becomes not only a supplier, but also a direct competitor to the retailer (Liu et al., 2020). Then a question arises on how to eliminate the obvious but unavoidable channel conflict and improve dual-channel supply chain performance. On this basis, several scholars focus on enterprises' production/pricing strategies and channel coordination in a dual-channel environment (Jafari et al., 2016; Jamali and Rasti-Barzoki, 2018; Liu et al., 2020; Ryan et al., 2013; Xiao and Shi, 2016; Tang et al., 2018; Wu et al., 2020; Shi et al., 2020). For example, Xiao and Shi (2016) believe that coordination of the dual-channel supply chain can alleviate the retailer's complaint of insufficient supply. Jafari et al. (2016) evaluate the impacts of different power structures between two competing retailers on the direct channel price, the retail channel price, the production quantities and three parties' profits. However, there has been limited research on the effects of government intervention in a dual-channel supply chain (Ghosh et al., 2020; Ji et al., 2017; Xu et al., 2018). Ghosh et al. (2020) analyze a two-echelon dual-channel supply chain model considering governments' mandatory cap-and-trade regulation and consumers' low carbon preferences. Xu et al. (2018) indicate that the government can realize carbon emission reduction and coordinated development between the economy and environment efficiently by adopting cap-and-trade regulation in a dyadic dual-channel supply chain. As for the DCSCN, Nagurney et al. (2005) study the equilibrium problem of multi-tier business-to-business DCSCN with supply-side risk and demand-side risk based on variational inequality theory. Yu et al. (2015) propose a supply chain system model with online and offline selling channels and obtain the SCN equilibrium using the finite-dimensional variational inequality method. Zhang et al. (2020) investigate the DCSCN problem with the consideration that both manufacturers and retailers provide services to the consumers in the demand markets and find that the service levels in dual channels are positively correlated with their respective transaction volumes.

### 2.4. Research gaps

Table 1 compares the differences between our model and the existing closely related models mentioned above from three dimensions: carbon policy, supply chain structure and abatement level decisions/green technology investment. In summary, the limitations of previous literature are listed in the following four aspects: (1) Almost all the existing literature examining green technology investment/abatement level decision takes a monopoly manufacturer, a competitive duopoly market or dyadic (dual-channel) supply chain as research objects except Saberi et al. (2018) for a SCN. However, their research overlooks government's carbon emission regulations and do not introduce online sales channel. (2) All the literature exploring the impacts of government's carbon emission regulations on a SCN does not regard the abatement level/green technology investment as the manufacturers' decision variables. (3) The existing literature on DCSCN not only does not consider the impacts of carbon emission regulations, but also fails to take sustainable production into account. (4) None of the literature considers progressive carbon tax policy in a SCN except Yu et al. (2019).

## 3. Methods

### 3.1. Research method

Nash equilibrium theory is one of the most important scientific advances in the 20th century (Nash, 1950), which has also had a huge impact on supply chain management field for many years (Nagurney et al., 2002). For a complex SCN with manufacturer layer, retailer layer and demand market layer, in ideal conditions, in each layer all the mutual competitive members form Nash equilibrium state in the process of production and transaction, which can be referred as SCN equilibrium (Nagurney et al., 2002). Due to the complexity of SCN, it is a challenging work to derive the SCN equilibrium states. Several scholars have focused on this issue, and currently one of the mainstream methods is to transform the profit maximization problem into a variational inequality problem (Nagurney et al., 2002). In particular, based on variational inequality theory, we can obtain the optimal condition in each layer respectively, and then variational inequalities in all the layers are added up to derive Nash equilibrium condition for the whole SCN.

Variational inequality is the extension and development of the classical variational problem, which is widely used in economic field, operations management problems and urban traffic network modeling. There are several algorithms for solving variational inequality problem, among which the modified projection algorithm

**Table 1**
Comparisons between the established model and the previous closely relative models.

| Author | Carbon Policy | Supply chain structure | | Abatement level/ Green technology investment |
|---|---|---|---|---|
| | | dual-channel | network | |
| Krass et al. (2013) | flat carbon emission tax | | | √ |
| | cap-and-trade | | | √ |
| Subramanian et al. (2007); Gong and Zhou (2013); Xu et al. (2017) | | | | |
| Ren et al. (2015) | Mandatory carbon emission constraint | | | √ |
| Liu et al. (2012) | | | | √ |
| Wang et al. (2016) | Mandatory carbon emission constraint, flat carbon emission tax | | | √ |
| Yang et al. (2017), Yang and Chen (2018) | flat carbon emission tax | | | √ |
| Yu and Cao (2019) | cap-and-trade | | | √ |
| Peng et al. (2020) | | | | √ |
| Ji et al. (2017), Zhou and Ye (2018) | | √ | | √ |
| Xu et al. (2018) | cap-and-trade | √ | | √ |
| Zhang et al, (2020) | | √ | | √ |
| Nagurney et al. (2005), Yu et al. (2015) | | √ | √ | |
| Tao et al. (2015) | Mandatory carbon emission constraint | | √ | |
| Nagurney et al. (2015) | flat carbon emission tax | | √ | |
| Allevi et al. (2018) | flat carbon emission tax, cap-and-trade | | √ | √ |
| Saberi et al. (2018) | | | √ | √ |
| Yu et al. (2019) | flat/progressive carbon emission taxes | | √ | |
| He et al., (2019) | Mandatory carbon emission constraint | | √ | |
| Ghosh et al. (2020) | cap-and-trade | √ | | √ |
| Ji et al. (2017) | cap-and-trade | √ | | √ |
| Xu et al. (2018) | cap-and-trade | √ | | √ |
| Zhang et al. (2020) | | √ | √ | |
| This paper | progressive carbon taxes | √ | √ | √ |

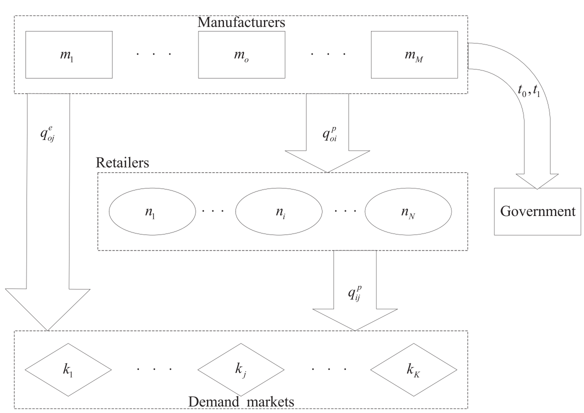


**Fig. 1.** The dual-channel supply chain network structure with progressive carbon tax policy.

is a common one (Korpelevich, 1976). The main idea of the algorithm is as follows: for the current decision point, it moves one step in the modified gradient direction based on projection operators and gets a new feasible point, and then calculates the distance between these two points. If the distance is less than the threshold value, the new point is regarded as the equilibrium solution; otherwise, it will implement the next iteration.

### 3.2. Conditional assumptions

The DCSCN in this paper comprises $M$ manufacturers, $N$ retailers, and $K$ demand markets. Its network structure is as depicted in Fig. 1. Specifically, we consider the manufacturers use raw materials purchased from external suppliers to produce new products. The retailers wholesale the products from the manufacturers and then sell them in the demand markets; simultaneously, the manufacturers also directly sell the products to the consumers via online channel. Note that the manufacturers, the retailers and the demand markets are located at the top tier, the middle tier and the bottom tier in the network, respectively. The links denote the product transactions between the members in different tiers, such as manufacturer $o$ and retailer $i$, retailer $i$ and demand market $j$, and manufacturer $o$ and demand market $j$. Following the classical studies on SCN equilibrium problem by Nagurney and Zhao (1993); Nagurney et al. (2002), we also assume the same type of members such as all manufacturers or all retailers compete in a non-cooperative Nash game.

Moreover, the government, as the advocator of sustainable development, promotes the manufacturers to invest in green technology and reduce carbon emissions by adopting progressive carbon tax policy. Then we propose a DCSCN equilibrium model to examine how the government designs the progressive carbon tax policy and its impacts on the network members' equilibrium decisions, profits and carbon emissions.

Before we establish the DCSCN model, we present the following assumptions.

- Consistent with the existing research, the manufacturers produce homogeneous/substitutable products with certain abatement levels to reduce their emissions (Yang, et al., 2017; Yang and Chen, 2018). The higher product abatement level is, the lower carbon emissions it generates, and more investment is needed. In practice, energy efficiency labeling and carbon labeling are normally used to reflect products' abatement level (Xu et al., 2017).

- The consumers have different purchasing experiences and shopping habits, thus have different preferences for the two marketing channels (Chiang et al., 2003). Generally, it is assumed that these preferences will not change for a certain period.
- Each manufacturer emits carbon dioxide in the production process, and the government adopts a progressive carbon tax mechanism for each manufacturer. Similar to Yu and Cao (2019), it is assumed that the emission tax function is a piecewise function of his total emission. In this paper, we only consider the case of a two-stage carbon tax, i.e., there exists one cutoff value$B_o$. If the manufacturer's carbon total emission is below $B_o$, he will incur a lower unit carbon tax $t_0$; otherwise, he has to pay for a higher unit carbon tax $t_1$ for the excess part.
- Based on related studies (Giri et al., 2017; Wu et al., 2020), we assume that there is a linear relationship between market demand and product price and abatement level, which can be expressed as $d_j^p(\rho_j^p,\rho_j^e,\boldsymbol{\alpha};\omega)=(1-\omega)a-m_{11}\rho_j^p-m_{21}\rho_z^p|_{z\neq j}+n_1\sum_{j=1}^K\rho_j^e+\theta\frac{1}{M}\sum_{o=1}^M\alpha_o$ and $d_j^e(\rho_j^p,\rho_j^e,\boldsymbol{\alpha};\omega)=\omega a-m_{12}\rho_j^e-m_{22}\rho_z^e|_{z\neq j}+n_2\sum_{j=1}^K\rho_j^p+\theta\frac{1}{M}\sum_{o=1}^M\alpha_o$, in which $d_j^p$ and $d_j^e$ are the product market demand through the offline channel and the online channel at demand market$j$, respectively. In particular, the product demand of offline channel is not only affected by the product price in the local market and competitive market through offline channel, but also affected by the product prices of online channels; similarly, the product demand of online channel is not only affected by the product price in the local market and competitive market through online channel, but also affected by the product prices of offline channels. In other words, the demand in one channel will decrease (increase) with the increase of its own channel (the other channel)'s prices. Moreover, the demands in both channels increase with the product abatement level due to consumer environmental consciousness.
- Each manufacturer makes a one-action green technology investment to decide the product abatement level. Following Ji et al. (2017); Wang et al. (2016), the investment cost function is a quadratic function of the abatement level for capturing the characteristic of diminishing margin return on this type of expenditure, i.e.,$C_{\alpha_o}=\eta_o\alpha_o^2/2$.
- All the cost functions in the model are convex and twice differentiable (Nagurney et al., 2002; Hammond and Beullens, 2007).

### 3.3. Model formulation and solution

This section describes the optimal behaviors of manufacturer tier, retailer tier, and demand market tier. The optimal conditions in each layer are derived by variational inequality theory, respectively, then the equilibrium condition of the whole DCSCN is obtained. Finally, the recovery method of endogenous prices is given.

#### 3.3.1. The optimal behavior and equilibrium conditions of manufacturers

According to the previous description, the manufacturer decides the number of products made from raw materials, the abatement level of products, and the transaction amount through offline channel and online channel based on government's progressive carbon tax, respectively. The products are sold to retailers and consumers simultaneously at different prices. The profit that the manufacturer $o$ seeks to maximize can be expressed as

$$\max\pi_o=\sum_{i=1}^N\rho_{oi}^pq_{oi}^p+\sum_{j=1}^K\rho_{oj}^eq_{oj}^e-f_o(q_o^r)-f_o^M-\sum_{i=1}^Nc_{oi}^M-\sum_{j=1}^Kc_{oj}^M-t_0\varepsilon_0^o-t_1\varepsilon_1^o-0.5\eta_o\alpha_o^2 \tag{1}$$

$$s.t.\ \ \beta_rq_o^r\geq\sum_{i=1}^Nq_{oi}^p+\sum_{j=1}^Kq_{oj}^e \tag{2}$$

$$\varepsilon_0^o\leq B_o \tag{3}$$

$$\beta_0(1-\alpha_o)\left(\sum_{i=1}^Nq_{oi}^p+\sum_{j=1}^Kq_{oj}^e\right)\leq\varepsilon_1^o+\varepsilon_0^o \tag{4}$$

The revenue of manufacturer $o$ comprises product sales revenue $\sum_{i=1}^N\rho_{oi}^pq_{oi}^p+\sum_{j=1}^K\rho_{oj}^eq_{oj}^e$ through two channels, while the costs comprise raw material procurement cost $f_m(q_o^r)$, production cost $f_o^M$, transaction costs $\sum_{i=1}^Nc_{oi}^M+\sum_{j=1}^Kc_{oj}^M$, carbon taxes $t_0\varepsilon_0^o$ and $t_1\varepsilon_1^o$, and the green technology investment cost $\eta_o\alpha_o^2/2$. Then Eq. (1) results from the difference between the sum of revenue and costs listed above. Eq. (2) can be called flow balance constraint. Eq. (3) illustrates the relation of the carbon emission with lower carbon tax and the cutoff value. Eq. (4) can be called carbon emission balance constraint. All of the decision variables of the manufacturers are non-negative.

We assume $\lambda_o^1$, $\lambda_o^2$ and $\lambda_o^3$ are the Lagrange multiplier of constraint (2), constraint (3) and constraint (4) respectively, and $\boldsymbol{\lambda}^1\in R_+^M$, $\boldsymbol{\lambda}^2\in R_+^M$ and $\boldsymbol{\lambda}^3\in R^M$ are column vectors with the elements of manufacturers' Lagrange multipliers $\lambda_o^1$, $\lambda_o^2$ and $\lambda_o^3$ respectively. Since the manufacturers compete in a Nash non-cooperative fashion, then the optimal conditions of all manufacturers can be described as the following variational inequalities: determining $(\boldsymbol{q}^{r*},\boldsymbol{Q}^{1*},\boldsymbol{Q}^{2*},\boldsymbol{\alpha}^*,\boldsymbol{\varepsilon}_0^*,\boldsymbol{\varepsilon}_1^*,\boldsymbol{\lambda}^{1*},\boldsymbol{\lambda}^{2*},\boldsymbol{\lambda}^{3*})\in\Omega^M$, such that

$$\begin{aligned}
&\sum_{o=1}^M\left[\frac{\partial f_o^{M*}}{\partial q_o^r}+\frac{\partial f_o(q_o^{r*})}{\partial q_o^r}-\beta_r\lambda_o^{1*}\right]\times[q_o^r-q_o^{r*}]\\
&+\sum_{o=1}^M\sum_{i=1}^N\left[\frac{\partial c_{oi}^{M*}}{\partial q_{oi}^p}+\lambda_o^{1*}-\rho_{oi}^{p*}+\lambda_o^{3*}\beta_0(1-\alpha_o^*)\right]\times\left[q_{oi}^p-q_{oi}^{p*}\right]\\
&+\sum_{o=1}^M\sum_{j=1}^K\left[\frac{\partial c_{oj}^{M*}}{\partial q_{oj}^e}+\lambda_o^{1*}-\rho_{oj}^{e*}+\lambda_o^{3*}\beta_0(1-\alpha_o^*)\right]\times\left[q_{oj}^e-q_{oj}^{e*}\right]\\
&+\sum_{o=1}^M\left[\frac{\partial f_o^{M*}}{\partial\alpha_o}+\eta_o\alpha_o^*-\lambda_o^{3*}\beta_0\left(\sum_{i=1}^Nq_{oi}^{p*}+\sum_{j=1}^Kq_{oj}^{e*}\right)\right]\times[\alpha_o-\alpha_o^*]\\
&+\sum_{o=1}^M\left[t_0+\lambda_o^{2*}-\lambda_o^{3*}\right]\times\left[\varepsilon_o^0-\varepsilon_o^{0*}\right]\\
&+\sum_{o=1}^M\left[t_1-\lambda_o^{3*}\right]\times\left[\varepsilon_o^1-\varepsilon_o^{1*}\right]\\
&+\sum_{o=1}^M\left[\beta_rq_o^{r*}-\sum_{i=1}^Nq_{oi}^{p*}-\sum_{j=1}^Kq_{oj}^{e*}\right]\times\left[\lambda_o^1-\lambda_o^{1*}\right]\\
&+\sum_{o=1}^M\left[B_o-\varepsilon_o^0\right]\times\left[\lambda_o^2-\lambda_o^{2*}\right]\\
&+\sum_{o=1}^M\left[\varepsilon_o^0+\varepsilon_o^{1*}-\beta_0(1-\alpha_o^*)\left(\sum_{i=1}^Nq_{oi}^{p*}+\sum_{j=1}^Kq_{oj}^{e*}\right)\right]\\
&\times\left[\lambda_o^3-\lambda_o^{3*}\right]\geq0
\end{aligned} \tag{5}$$

$$\forall(\boldsymbol{q}^r,\boldsymbol{Q}^1,\boldsymbol{Q}^2,\boldsymbol{\alpha},\boldsymbol{\varepsilon}_0,\boldsymbol{\varepsilon}_1,\boldsymbol{\lambda}^1,\boldsymbol{\lambda}^2,\boldsymbol{\lambda}^3)\in\Omega^M,\ \text{where}\ \Omega^M=R_+^{M+MN+MK+5M}\times R^M$$

According to the equivalence relation of the complementary problem and variational inequality, from the 2nd and 3rd term of Eq. (5), we can know that $\rho_{oi}^{p*} = \frac{\partial c_{oi}^M}{\partial q_{oi}^p} + \lambda_o^{1*} + \lambda_o^{3*}\beta_0(1-\alpha_o^*)$ and $\rho_{oj}^{e*} = \frac{\partial c_{oj}^M}{\partial q_{oj}^p} + \lambda_o^{1*} + \lambda_o^{3*}\beta_0(1-\alpha_o^*)$ in the equilibrium state of manufacturers. We can find $\rho_{oi}^{p*}$ and $\rho_{oj}^{e*}$ decrease in $\alpha_o^*$, which seems paradoxical and counterintuitive. The reason can be explained as follows: from the 4th term of Eq. (5), when $\alpha_o^* > 0$, we have $\alpha_o^* = \frac{1}{\eta_o}(\lambda_o^{3*}\beta_0(\sum_{i=1}^N q_{oi}^{p*} + \sum_{j=1}^K q_{oj}^{e*}) - \frac{\partial f_o^{M*}}{\partial \alpha_o})$. Since $\lambda_o^{3*} \geq 0$, $\beta_0$ and $\eta_o$ are constant, $\alpha_o^*$ and $\sum_{i=1}^N q_{oi}^{p*} + \sum_{j=1}^K q_{oj}^{e*}$ are of positive correlation. According to the demand function, the transaction price and amount are negatively correlated. Therefore, $\rho_{oi}^{p*}$ and $\alpha_o^*$ have a negative correlation, which means when $\alpha_o^*$ increases, the demand will increase, and then the price will decrease.

According to the 8th term of Eq. (5), $B_o = \varepsilon_0^{0*}$ when $\lambda_o^{2*} > 0$; according to 6th term of Eq.(5), $t_1 = \lambda_o^{3*}$ when $\varepsilon_o^{1*} > 0$; according to 5th term of Eq. (5), $t_0 + \lambda_o^{2*} = \lambda_o^{3*}$ when $\varepsilon_o^{0*} > 0$. Therefore, if $t_0 + \lambda_o^{2*} = \lambda_o^{3*}$ holds, as long as the increment of $t_0$ is equal to the decrement of $\lambda_o^{2*}$, the change of $t_0$ does not affect the equilibrium state (It is clear that the value of the Lagrange multiplier $\lambda_o^{2*}$ does not influence the decision variables when $\lambda_o^{2*} > 0$ satisfies).

*3.3.2. The optimal behaviors and equilibrium conditions of retailers*

In the offline channel, the retailers decide the number of products purchased from each manufacturer, and the amount sold to consumers in the demand markets. The profit maximization problem of retailer $i$ can be formulated as

$$\max \pi_i = \sum_{j=1}^K \rho_{ij}^p q_{ij}^p - \sum_{o=1}^M \rho_{oi}^p q_{oi}^p - \sum_{j=1}^K c_{ij}^N - c_i \tag{6}$$

$$s.t. \quad \sum_{o=1}^M q_{oi}^p \geq \sum_{j=1}^K q_{ij}^p \tag{7}$$

The profit of retailer $i$ comprises four parts: product sales revenue $\sum_{j=1}^K \rho_{ij}^p q_{ij}^p$, purchase cost $\sum_{o=1}^M \rho_{oi}^p q_{oi}^p$ from manufacturers, transaction costs $\sum_{j=1}^K c_{ij}^N + \sum_{o=1}^M c_{oi}^N$, and the exhibition cost in offline store $c_i$. We assume $\gamma_i^1$ is the Lagrange multipliers of constraint (7), while $\boldsymbol{\gamma}^1 \in R_+^N$ is a column vector with the elements of all retailers' Lagrange multipliers. Since the retailers compete in a Nash non-cooperative fashion, then the optimal conditions of all retailers can be described as the following variational inequalities: determining $(\boldsymbol{Q}^{1*}, \boldsymbol{Q}^{3*}, \boldsymbol{\gamma}^{1*}) \in \Omega^N$, such that

$$\begin{aligned} &+ \sum_{o=1}^M \sum_{i=1}^N \left[ \frac{\partial c_i^*}{\partial q_{oi}^p} + \rho_{oi}^{p*} - \gamma_i^{1*} \right] \times \left[ q_{oi}^p - q_{oi}^{p*} \right] \\ &+ \sum_{i=1}^N \sum_{j=1}^K \left[ \frac{\partial c_{ij}^{N*}}{\partial q_{ij}^p} - \rho_{ij}^{p*} + \gamma_i^{1*} \right] \times \left[ q_{ij}^p - q_{ij}^{p*} \right] \\ &+ \sum_{i=1}^N \left[ \sum_{o=1}^M q_{oi}^p - \sum_{j=1}^K q_{ij}^p \right] \times \left[ \gamma_i^1 - \gamma_i^{1*} \right] \geq 0 \end{aligned} \tag{8}$$

$\forall(\boldsymbol{Q}^1, \boldsymbol{Q}^3, \boldsymbol{\gamma}^1) \in \Omega^N$, where $\Omega^N = R_+^{MN+NK+N}$

Similar as the analysis of manufacturer tier, according to the equivalence relationship of complementary problem and variational inequality, in equilibrium state, from the 1st term of Eq. (8), we have $\gamma_i^{1*} = \frac{\partial c_i^*}{\partial q_{oi}^p} + \frac{\partial c_{oi}^{N*}}{\partial q_{oi}^p} + \rho_{oi}^{p*}$; from the 2nd term of Eq.(8), we have $\rho_{ij}^{p*} = \frac{\partial c_{ij}^{N*}}{\partial q_{ij}^p} + \gamma_i^{1*} = \frac{\partial c_{ij}^{N*}}{\partial q_{ij}^p} + \frac{\partial c_i^*}{\partial q_{oi}^p} + \frac{\partial c_{oi}^{N*}}{\partial q_{oi}^p} + \rho_{oi}^{p*}$, which means the transaction price between retailer $i$ and demand market $j$ is related to the price between the retailer and each manufacturer $o$. When $\rho_{oi}^{p*}$ increases, $\rho_{ij}^{p*}$ also increase, and $\rho_{oi}^{p*}$ is a part of $\rho_{ij}^{p*}$, which implies that the transaction price of the previous stage will transmit to the next stage.

*3.3.3. Consumers' optimal behaviors and equilibrium conditions in demand markets*

Consumers of the demand markets buy products based on the product prices offered by the manufacturers and retailers. The product prices of the two channels at demand market $j$ should satisfy the following complementary relationships (Hammond and Beullens, 2007; Yu et al., 2015).

$$\rho_{oj}^{e*} + c_{oj}^K(q_{oj}^{e*}) \begin{cases} = \rho_j^{e*}, q_{oj}^{e*} > 0 \\ \geq \rho_j^{e*}, q_{oj}^{e*} = 0 \end{cases} \tag{9}$$

$$\rho_{ij}^{p*} + c_{ij}^K(q_{ij}^{p*}) \begin{cases} = \rho_j^{p*}, q_{ij}^{p*} > 0 \\ \geq \rho_j^{p*}, q_{ij}^{p*} = 0 \end{cases} \tag{10}$$

Conditions (9) state that, in equilibrium state for the online channel, if the consumers at demand market $j$ buy the product from manufacturer $o$, then the sum of the price charged by the manufacturer and the transaction cost borne by the consumers will be no more than the price that the consumers are willing to pay. A similar explanation can be given for conditions (10) in the offline transaction between retailer $i$ and demand market $j$. At the same time, the relationship between supply and demand in the demand market must be satisfied.

$$d_j^e(\rho_j^{p*}, \rho_j^{e*}, \boldsymbol{\alpha}^*; \omega) \begin{cases} = \sum_{o=1}^M q_{oj}^{e*}, \rho_j^{e*} > 0 \\ \leq \sum_{o=1}^M q_{oj}^{e*}, \rho_j^{e*} = 0 \end{cases} \tag{11}$$

$$d_j^p(\rho_j^{p*}, \rho_j^{e*}, \boldsymbol{\alpha}^*; \omega) \begin{cases} = \sum_{i=1}^N q_{ij}^{p*}, \rho_j^{p*} > 0 \\ \leq \sum_{i=1}^N q_{ij}^{p*}, \rho_j^{p*} = 0 \end{cases} \tag{12}$$

Conditions (11) imply that in the online channel, if the equilibrium price the consumers are willing to pay for the product at demand market $j$ is positive, then the quantities purchased from all the manufacturers in the online channel will be exactly equal to the demand at this demand market. A similar explanation can be given for conditions (12) in the offline transaction for demand market $j$. Conditions (9)-(12) are derived based on the spatial price equilibrium conditions (Nagurney et al., 2002; Hammond and Beullens, 2007).

In equilibrium state, conditions (9)-(12) must hold for all the demand markets, then the optimal conditions of demand markets can be described as the following variational inequalities: determining $(\boldsymbol{Q}^{3*}, \boldsymbol{Q}^{2*}, \boldsymbol{\rho}^{p*}, \boldsymbol{\rho}^{e*}) \in \Omega^K$, such that

$$\begin{aligned} &\sum_{o=1}^M \sum_{j=1}^K \left[ \rho_{oj}^{e*} + c_{oj}^K(q_{oj}^{e*}) - \rho_j^{e*} \right] \times \left[ q_{oj}^e - q_{oj}^{e*} \right] \\ &+ \sum_{i=1}^N \sum_{j=1}^K \left[ \rho_{ij}^{p*} + c_{ij}^K(q_{ij}^{p*}) - \rho_j^{p*} \right] \times \left[ q_{ij}^p - q_{ij}^{p*} \right] \\ &+ \sum_{j=1}^K \left[ \sum_{o=1}^M q_{oj}^{e*} - d_j^e(\rho_j^{p*}, \rho_j^{e*}, \boldsymbol{\alpha}^*; \omega) \right] \times \left[ \rho_j^e - \rho_j^{e*} \right] \\ &+ \sum_{j=1}^K \left[ \sum_{i=1}^N q_{ij}^{p*} - d_j^p(\rho_j^{p*}, \rho_j^{e*}, \boldsymbol{\alpha}^*; \omega) \right] \times \left[ \rho_j^p - \rho_j^{p*} \right] \geq 0 \end{aligned} \tag{13}$$

$\forall(\boldsymbol{Q}^3, \boldsymbol{Q}^2, \boldsymbol{\rho}^p, \boldsymbol{\rho}^e) \in \Omega^K$, where $\Omega^K = R_+^{NK+MK+2K}$

*3.3.4. Equilibrium condition of the whole dual-channel supply chain network model*

It is necessary to determine the Nash equilibrium condition of the whole DCSCN comprised of manufacturers, retailers, and demand markets. In particular, the product amount purchased by retailers and consumers in the demand markets must be equal to the amount of these products sold by manufacturers in two channels, respectively; similarly, the product amount purchased by consumers through offline channel must be equal to the amount of these products sold by retailers. Variational inequalities (5), (8), and (13) describe the equilibrium conditions of manufacturers, retailers, and demand markets, respectively. Therefore, the equilibrium prices and transaction amount patterns in the DCSCN must satisfy the sum of variational inequalities (5), (8), and (13).

**Definition 1.** (Equilibrium). The equilibrium state for the DCSCN with progressive carbon tax policy and product abatement level is that the trading flows between different tiers coincide and satisfy the sum of variational inequalities (5), (8), and (13).

We eliminate the endogenous price variables of inter-layer transactions and then obtain the Nash equilibrium condition of the entire DCSCN.

**Theorem 1.** (Variational inequalities formulation of the DCSCN with progressive carbon tax policy and product abatement level). According to Definition 1, the equilibrium state of the DCSCN with progressive carbon tax policy and product abatement level is consistent with the solution of the following variational inequalities: find $(\boldsymbol{q}^{r*}, \boldsymbol{Q}^{1*}, \boldsymbol{Q}^{2*}, \boldsymbol{Q}^{3*}, \boldsymbol{\alpha}^*, \boldsymbol{\varepsilon}_0^*, \boldsymbol{\varepsilon}_1^*, \boldsymbol{\rho}^{p*}, \boldsymbol{\rho}^{e*}, \boldsymbol{\lambda}^{1*}, \boldsymbol{\lambda}^{2*}, \boldsymbol{\lambda}^{3*}, \boldsymbol{\gamma}^{1*}) \in \Omega$, such that

$$
\begin{aligned}
&\sum_{o=1}^{M}\left[\frac{\partial f_o^{M*}}{\partial q_o^r}+\frac{\partial f_o(q_o^{r*})}{\partial q_o^r}-\beta_r\lambda_o^{1*}\right]\times[q_o^r-q_o^{r*}]\\
&+\sum_{o=1}^{M}\sum_{i=1}^{N}\left[\frac{\partial c_{oi}^{M*}}{\partial q_{oi}^p}+\lambda_o^{1*}+\lambda_o^{3*}\beta_0(1-\alpha_o^*)+\frac{\partial c_i^*}{\partial q_{oi}^p}+\frac{\partial c_{oi}^{N*}}{\partial q_{oi}^p}-\gamma_i^{1*}\right]\\
&\times\left[q_{oi}^p-q_{oi}^{p*}\right]\\
&+\sum_{i=1}^{N}\sum_{j=1}^{K}\left[\frac{\partial c_{ij}^{N*}}{\partial q_{ij}^p}+\gamma_i^{1*}+c_{ij}^K(q_{ij}^{p*})-\rho_j^{p*}\right]\times\left[q_{ij}^p-q_{ij}^{p*}\right]\\
&+\sum_{o=1}^{M}\sum_{j=1}^{K}\left[\frac{\partial c_{oi}^{M*}}{\partial q_{oj}^e}+\lambda_o^{1*}+\lambda_o^{3*}\beta_0(1-\alpha_o^*)+c_{oj}^K(q_{oj}^{e*})-\rho_j^{e*}\right]\times\left[q_{oj}^e-q_{oj}^{e*}\right]\\
&+\sum_{o=1}^{M}\left[\frac{\partial f_o^{M*}}{\partial \alpha_o}+\eta_o\alpha_o^*-\lambda_o^{3*}\beta_0\left(\sum_{i=1}^{N}q_{oi}^{p*}+\sum_{j=1}^{K}q_{oj}^{e*}\right)\right]\times[\alpha_o-\alpha_o^*]\\
&+\sum_{o=1}^{M}\left[t_0+\lambda_o^{2*}-\lambda_o^{3*}\right]\times\left[\varepsilon_o^0-\varepsilon_o^{0*}\right]\\
&+\sum_{o=1}^{M}\left[t_1-\lambda_o^{3*}\right]\times\left[\varepsilon_o^1-\varepsilon_o^{1*}\right]\\
&+\sum_{i=1}^{N}\left[\sum_{i=1}^{N}q_{ij}^{p*}-d_j^p(\rho_j^{p*},\rho_j^{e*},\boldsymbol{\alpha}^*;\omega)\right]\times\left[\rho_j^p-\rho_j^{p*}\right]\\
&+\sum_{j=1}^{K}\left[\sum_{o=1}^{M}q_{oj}^{e*}-d_j^e(\rho_j^{p*},\rho_j^{e*},\boldsymbol{\alpha}^*;\omega)\right]\times\left[\rho_j^e-\rho_j^{e*}\right]\\
&+\sum_{o=1}^{M}\left[\beta_r q_o^{r*}-\sum_{i=1}^{N}q_{oi}^{p*}-\sum_{j=1}^{K}q_{oj}^{e*}\right]\times\left[\lambda_o^1-\lambda_o^{1*}\right]\\
&+\sum_{o=1}^{M}\left[B_o-\varepsilon_o^{0*}\right]\times\left[\lambda_o^2-\lambda_o^{2*}\right]\\
&+\sum_{o=1}^{M}\left[\varepsilon_o^0+\varepsilon_o^{1*}-\beta_0(1-\alpha_o^*)\left(\sum_{i=1}^{N}q_{oi}^{p*}+\sum_{j=1}^{K}q_{oj}^{e*}\right)\right]\times\left[\lambda_o^3-\lambda_o^{3*}\right]\\
&+\sum_{i=1}^{N}\left[\sum_{o=1}^{M}q_{oi}^{p*}-\sum_{j=1}^{K}q_{ij}^{p*}\right]\times\left[\gamma_i^1-\gamma_i^{1*}\right]\geq 0
\end{aligned}
\tag{14}
$$

$\forall(\boldsymbol{q}^r, \boldsymbol{Q}^1, \boldsymbol{Q}^2, \boldsymbol{Q}^3, \boldsymbol{\alpha}, \boldsymbol{\varepsilon}_0, \boldsymbol{\varepsilon}_1, \boldsymbol{\rho}^p, \boldsymbol{\rho}^e, \boldsymbol{\lambda}^1, \boldsymbol{\lambda}^2, \boldsymbol{\lambda}^3, \boldsymbol{\gamma}^1) \in \Omega$, where $\Omega = \Omega^M \times \Omega^N \times \Omega^K$, and the multiplication sign represents the Cartesian product.

From Eq. (14), we can know that both decision variables such as $\boldsymbol{q}^r, \boldsymbol{Q}^1, \boldsymbol{Q}^2, \boldsymbol{Q}^3, \boldsymbol{\alpha}, \boldsymbol{\varepsilon}_0, \boldsymbol{\varepsilon}_1$ and the corresponding Lagrange multipliers$\boldsymbol{\lambda}^1, \boldsymbol{\lambda}^2, \boldsymbol{\lambda}^3, \boldsymbol{\gamma}^1$can be derived. Their optimal values are $\boldsymbol{q}^{r*}, \boldsymbol{Q}^{1*}, \boldsymbol{Q}^{2*}, \boldsymbol{Q}^{3*}, \boldsymbol{\alpha}^*, \boldsymbol{\varepsilon}_0{}^*, \boldsymbol{\varepsilon}_1{}^*$ and $\boldsymbol{\lambda}^{1*}, \boldsymbol{\lambda}^{2*}, \boldsymbol{\lambda}^{3*}, \boldsymbol{\gamma}^{1*}$, respectively. Thus, by the above steps we transform the profit maximization problem with constraints and complementarity problem into a variational inequality problem. The optimal decisions of variational inequality (14) correspond to the solutions of primary profit maximization problem and complementary problem. Then we can get the optimal solutions by related solving algorithms.

***Proof*** **See** Nagurney et al. (2002). □

According to the standard form (See Nagurney and Zhao, 1993), the variational inequalities can be rewritten as: find $X^* \in \Omega$, such that

$$
\langle F(X^*), X^*-X\rangle \geq 0, \quad \forall X \in \Omega \tag{15}
$$

where $X \equiv (\boldsymbol{q}^r, \boldsymbol{Q}^1, \boldsymbol{Q}^2, \boldsymbol{Q}^3, \boldsymbol{\alpha}, \boldsymbol{\varepsilon}_0, \boldsymbol{\varepsilon}_1, \boldsymbol{\rho}^p, \boldsymbol{\rho}^e, \boldsymbol{\lambda}^1, \boldsymbol{\lambda}^2, \boldsymbol{\lambda}^3, \boldsymbol{\gamma}^1)$ with $X \in \Omega$, and $F(X) \equiv [F_1(X), F_2(X), F_3(X), F_4(X), F_5(X), F_6(X), F_7(X), F_8(X), F_9(X), F_{10}(X), F_{11}(X), F_{12}(X), F_{13}(X)]$, with

$$
\begin{aligned}
F_1(X) &= \frac{\partial f_o^{M*}}{\partial q_o^r}+\frac{\partial f_o(q^{r*})}{\partial q_o^r}-\beta_r\lambda_o^{1*},\ F_2(X)=\frac{\partial c_{oi}^{M*}}{\partial q_{oi}^p}\\
&+\lambda_o^{1*}+\lambda_o^{3*}\beta_0(1-\alpha_o^*)+\frac{\partial c_i^*}{\partial q_{oi}^p}+\frac{\partial c_{oi}^{N*}}{\partial q_{oi}^p}-\gamma_i^{1*},
\end{aligned}
$$

$$
\begin{aligned}
F_3(X) &= \frac{\partial c_{ij}^{N*}}{\partial q_{ij}^p}+\gamma_i^{1*}+c_{ij}^K(q_{ij}^{p*})-\rho_j^{p*},\ F_4(X)=\frac{\partial c_{oi}^{M*}}{\partial q_{oj}^e}\\
&+\lambda_o^{1*}+\lambda_o^{3*}\beta_0(1-\alpha_o^*)+c_{oj}^K(q_{oj}^{e*})-\rho_j^{e*},
\end{aligned}
$$

$$
\begin{aligned}
F_5(X) &= \frac{\partial f_o^{M*}}{\partial \alpha_o}+\eta_o\alpha_o^*-\lambda_o^{3*}\beta_0\left(\sum_{i=1}^{N}q_{oi}^{p*}+\sum_{j=1}^{K}q_{oj}^{e*}\right),\\
&F_6(X)=t_0+\lambda_o^{2*}-\lambda_o^{3*},\ F_7(X)=t_1-\lambda_o^{3*},
\end{aligned}
$$

$$
\begin{aligned}
F_8(X) &= \left[\sum_{i=1}^{N}q_{ij}^{p*}-d_j^p(\rho_j^{p*},\rho_j^{e*},\boldsymbol{\alpha}^*;\omega)\right],\\
&F_9(X)=\sum_{o=1}^{M}q_{oj}^{e*}-d_j^e(\rho_j^{p*},\rho_j^{e*},\boldsymbol{\alpha}^*;\omega),\\
&F_{10}(X)=\beta_r q_o^{r*}-\sum_{i=1}^{N}q_{oi}^{p*}-\sum_{j=1}^{K}q_{oj}^{e*},\ F_{11}(X)=B_o-\varepsilon_o^{0*},\\
&F_{12}(X)=\varepsilon_o^{0*}+\varepsilon_o^{1*}-\beta_0(1-\alpha_o^*)\left(\sum_{i=1}^{N}q_{oi}^{p*}+\sum_{j=1}^{K}q_{oj}^{e*}\right),\\
&F_{13}(X)=\sum_{o=1}^{M}q_{oi}^{p*}-\sum_{j=1}^{K}q_{ij}^{p*}
\end{aligned}
$$

The qualitative properties are given in the Appendix at the end of this paper.

*3.3.5. Transaction price*

The transaction prices including $\rho_{oi}^p$, $\rho_{oj}^e$ and $\rho_{ij}^p$ are endogenous variables decided by cost functions (mainly the transaction costs).

According to the 2nd term and 3rd term of Eq. (5), when the transactions of manufacturer tier reach equilibrium, $\rho_{oj}^e$ and $\rho_{oj}^e$ can be retrieved by the following equations.

$$
\rho_{oi}^{p*}=\frac{\partial c_{oi}^{M*}}{\partial q_{oi}^p}+\lambda_o^{1*}+\lambda_o^{3*}\beta_0(1-\alpha_o^*) \tag{16}
$$

**Table 2**
The parameter values in numerical experiments.

| parameter | value |
|---|---|
| $\beta_r$ | 0.95 |
| $\eta_o$ | 1.5 |
| $a$ | 200 |
| $\beta_0$ | 0.4 |
| $\omega$ | 0.25 |

$$\rho_{oj}^{e*} = \frac{\partial c_{oj}^{M*}}{\partial q_{oj}^{e}} + \lambda_o^{1*} + \lambda_o^{3*}\beta_0(1-\alpha_o^*) \tag{17}$$

At the same time, according to the 2nd term of Eq. (8), in equilibrium state of retailer tier, $\rho_{ij}^{p*}$ can be retrieved as:

$$\rho_{ij}^{p*} = \frac{\partial c_{ij}^{N*}}{\partial q_{ij}^{p}} + \gamma_i^{1*} \tag{18}$$

Thus, by the above steps, the endogenous prices can be obtained by using the equivalence between complementary problem and variational inequality. Specifically, Eq. (16) can be explained as follows: according to the 2nd term of Eq. (5), $q_{oi}^{p*}$ and $\frac{\partial c_{oi}^{M*}}{\partial q_{oi}^{p}} + \lambda_o^{1*} - \rho_{oi}^{p*} + \lambda_o^{3*}\beta_0(1-\alpha_o^*)$ form complementary relation. Thus, if $q_{oi}^{p*} > 0$, then $\frac{\partial c_{oi}^{M*}}{\partial q_{oi}^{p}} + \lambda_o^{1*} - \rho_{oi}^{p*} + \lambda_o^{3*}\beta_0(1-\alpha_o^*) = 0$, which means the transaction occurs; in contrast, if $q_{oi}^{p*} = 0$, then $\frac{\partial c_{oi}^{M*}}{\partial q_{oi}^{p}} + \lambda_o^{1*} - \rho_{oi}^{p*} + \lambda_o^{3*}\beta_0(1-\alpha_o^*) > 0$, which implies the transaction does not occur. Eqs. (17) and (18) can be explained in the same way.

## 4. Results and discussions

The model in this paper belongs to the nonlinear optimization problem with the feasible region of convex sets, and we describe the conditions of this optimization problem by variational inequality (15). Since the common methods are not able to solve the problem of a variational inequality, we choose the modified projection algorithm to obtain the approximate solutions. As mentioned in Section 3.1, the modified projection algorithm program is designed simply with fixed steps, modified gradient direction and can simultaneously obtain the decision variables and Lagrange multipliers corresponding to the constraints (Korpelevich, 1976; Nagurney and Toyasaki, 2005; Hammond and Beullens, 2007).

Similar as the study of Hammond and Beullens (2007), the numerical experiments in this paper are based on a DCSCN including two manufacturers ($M = 2$), two retailers ($N = 2$) and two demand markets ($K = 2$), and the data of the parameters described in previous sections are given in Table 2.

There are 32 decision variables (including Lagrange multipliers) in our model. The algorithm is implemented in Matlab, in which the iteration step is set to be 0.01, and both the initial error and the values of decision vectors are equal to 1. The stop criterion of iteration is $10^{-8}$. Similar to Nagurney and Toyasaki. (2005); Hammond and Beullens (2007), the transaction cost functions, and other functions are listed as follows for $i = 1, 2$; $o = 1, 2$ and $j = 1, 2$.

$$f_o(q_o^r) = 2(q_o^r)^2 + q_o^r + 1,\ f_o^M = f_o^M(\alpha_o, \beta_r, \boldsymbol{q}^r) = 2(\beta_r q_o^r)^2 + (1+0.05\alpha_o)\beta_r q_o^r q_{3-o}^r + 2q_o^r,$$

$$c_{oi}^M = 2(q_{oi}^p)^2 + 3.5q_{oi}^p,\ c_{oj}^M = 2.5(q_{oj}^e)^2 + 3.5q_{oj}^e,\ c_{ij}^N = (q_{ij}^p)^2 + 2q_{ij}^p,$$

$$c_{ij}^K = q_{ij}^p + 0.5,\ c_i = 0.5(q_{1i}^p + q_{2i}^p)^2,$$

**Table 3**
The impacts of $t_1$ on the dual-channel supply chain network equilibrium.

| Variables | | $t_1 = 0.5$ | $t_1 = 0.7$ | $t_1 = 0.9$ | $t_1 = 1.1$ | $t_1 = 1.3$ | $t_1 = 1.5$ |
|---|---|---|---|---|---|---|---|
| $q_o^{r*}$ | $\bar{c}_{oj}^K$ | 5.424 | 5.419 | 5.432 | 5.45 | 5.452 | 5.452 |
| | $\underline{c}_{oj}^K$ | 5.46 | 5.456 | 5.469 | 5.487 | 5.49 | 5.49 |
| $q_{oi}^{p*}, q_{ij}^{p*}$ | $\bar{c}_{oj}^K$ | 2.171 | 2.17 | 2.168 | 2.165 | 2.165 | 2.165 |
| | $\underline{c}_{oj}^K$ | 2.137 | 2.135 | 2.132 | 2.13 | 2.13 | 2.13 |
| $q_{oj}^{e*}$ | $\bar{c}_{oj}^K$ | 0.405 | 0.404 | 0.413 | 0.423 | 0.425 | 0.425 |
| | $\underline{c}_{oj}^K$ | 0.457 | 0.456 | 0.465 | 0.476 | 0.478 | 0.478 |
| $\alpha_o^*$ | $\bar{c}_{oj}^K$ | 0 | 0.031 | 0.304 | 0.578 | 0.614 | 0.614 |
| | $\underline{c}_{oj}^K$ | 0 | 0.025 | 0.3 | 0.576 | 0.617 | 0.617 |
| $\varepsilon_0^{o*}$ | $\bar{c}_{oj}^K$ | 0.648 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| | $\underline{c}_{oj}^K$ | 0.646 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| $\varepsilon_1^{o*}$ | $\bar{c}_{oj}^K$ | 1.413 | 1.195 | 0.637 | 0.074 | 0 | 0 |
| | $\underline{c}_{oj}^K$ | 1.429 | 1.221 | 0.655 | 0.085 | 0 | 0 |
| $\varepsilon_0^{o*} +$ | $\bar{c}_{oj}^K$ | 2.061 | 1.995 | 1.437 | 0.874 | 0.8 | 0.8 |
| $\varepsilon_1^{o*}$ | $\underline{c}_{oj}^K$ | 2.075 | 2.021 | 1.455 | 0.885 | 0.8 | 0.8 |
| $\rho_{oi}^{p*}$ | $\bar{c}_{oj}^K$ | 64.412 | 64.44 | 64.606 | 64.767 | 64.788 | 64.788 |
| | $\underline{c}_{oj}^K$ | 64.604 | 64.628 | 64.798 | 64.963 | 64.987 | 64.987 |
| $\rho_{oj}^{e*}$ | $\bar{c}_{oj}^K$ | 57.751 | 57.782 | 58.003 | 58.222 | 58.250 | 58.250 |
| | $\underline{c}_{oj}^K$ | 58.339 | 58.365 | 58.595 | 58.824 | 58.857 | 58.857 |
| $\rho_{ij}^{p*}$ | $\bar{c}_{oj}^K$ | 75.098 | 75.119 | 75.274 | 75.428 | 75.448 | 75.448 |
| | $\underline{c}_{oj}^K$ | 75.152 | 75.169 | 75.327 | 75.483 | 75.506 | 75.506 |
| $\pi_o$ | $\bar{c}_{oj}^K$ | 131.602 | 131.522 | 132.168 | 132.885 | 132.984 | 132.984 |
| | $\underline{c}_{oj}^K$ | 132.746 | 132.646 | 133.32 | 134.068 | 134.185 | 134.185 |
| $\pi_i$ | $\bar{c}_{oj}^K$ | 18.859 | 18.829 | 18.785 | 18.755 | 18.752 | 18.752 |
| | $\underline{c}_{oj}^K$ | 18.266 | 18.238 | 18.186 | 18.148 | 18.143 | 18.143 |
| Total | $\bar{c}_{oj}^K$ | 150.461 | 150.352 | 150.953 | 151.64 | 151.736 | 151.736 |
| profit | $\underline{c}_{oj}^K$ | 151.012 | 150.885 | 151.506 | 152.216 | 152.328 | 152.328 |

$$d_j^p = (1-\omega)a - 1.3\rho_j^p - 0.8\rho_{3-j}^p + 0.15(\rho_1^e + \rho_2^e) + 0.45(\alpha_1 + \alpha_2),$$

$$d_j^e = \omega a - 0.8\rho_j^e - 0.3\rho_{3-j}^e + 0.1\left(\rho_1^p + \rho_2^p\right) + 0.45(\alpha_1 + \alpha_2).$$

Moreover, because the consumers may need to pay the freight fee for delivery when they purchase products in online channel, for the transaction cost $c_{oj}^K$ borne by the consumers, we consider two cases: if the freight fee is relatively expensive (cheap), $c_{oj}^K$ may be higher (lower) than $c_{ij}^K$ in the retail channel. In the following examples we set $\bar{c}_{oj}^K = 1.5q_{oj}^e + 0.5$ and $\underline{c}_{oj}^K = 0.5q_{oj}^e + 0.2$ for the consumers' high transaction cost and low transaction cost in online channel, respectively.

Two-stage progressive carbon tax policy comprises three parameters: the high-level carbon tax $t_1$, the low-level carbon tax $t_0$ and the cutoff value $B_o$. We will investigate their impacts on DCSCN equilibrium subsequently.

### 4.1. Numerical Example 1

In Numerical Example 1, we assume the parameters $t_0 = 0.5$ and $B_o = 0.8$, and then analyze the impact of $t_1$ on the equilibrium states of the DCSCN. Let $t_1$ increase with the step of 0.2. The results of the main decision variables and profits of the manufacturer $o$ and retailer$i$ are shown in Table 3.

Table 3 shows that, for both $\bar{c}_{oj}^K$ and $\bar{c}_{oj}^K$, in the process of $t_1$ growing, the decision variables of production quantity and online transaction volume $q_o^{r*}$,$q_{oj}^{e*}$, the manufacturer's profit and the total profit of the DCSCN decline at the beginning, then increase steadily, in the end, stay the same. The offline transaction volume $q_{oi}^{p*}$ and the retailer's profit decrease monotonically. As for the environmental performance, the abatement level $\alpha_o^*$ is zero when $t_0 = t_1 = 0.5$ in a flat carbon tax case, and then becomes positive and increases rapidly from 0.0311 to 0.6139 as $t_1$ increases from 0.7 to 1.3; when $t_1 > 1.3$, $\alpha_o^*$ keeps stable. The carbon emission shows a decreasing trend in the process of carbon tax $t_1$ increasing. Specifically, in the flat carbon tax case $t_0 = t_1 = 0.5$, the total emission $\varepsilon_0^{o*} + \varepsilon_1^{o*}$ is the most and exceeds the cutoff value $B_o$ by a wide margin. With $t_1$ increasing further, $\varepsilon_1^{o*}$ decreases gradually till zero, so the total carbon emission also decreases. At the points $t_1 = 1.3$ and $t_1 = 1.5$, the total emission is exactly equal to $B_o$ with all the other variables and profits keeping constant.

The above changing tendencies of decision variables can be explained as follows: provided that the cut-off value $B_o$ is given, when the high-level tax $t_1$ is relatively low ($t_1 \in [0.5, 0.7]$), the manufacturer has little motivation to invest in green technology owing to relatively lower tax burden. He responses to progressive carbon tax policy by decreasing the total production quantity and transaction volumes in both channels, but still emits much more carbon footprints than the cut-off value. As $t_1$ increases step by step ($t_1 \geq 0.9$), the manufacturer is forced to control the carbon emission to avoid heavy tax burden. Specifically, he may have to adopt at least one of the following two strategies to make the carbon emissions no more than $B_o$ or at least close to $B_o$: one is to further cut down the total production/transaction volume and the other is to raise the product abatement level by investing in green technology. Due to the fact that the former strategy will lead to a marked drop in sales revenue, especially when $t_1$ is relatively higher, the manufacturer prefers to take the latter strategy, i.e., improves the product abatement level significantly and increases the total production/transaction volume moderately (recall that the market demands in dual channels are increasing in the abatement level due to consumer environmental consciousness) to partly offset the increased expenses of green technology investment. In this way the carbon emissions can be reduced steadily. For more analysis, the manufacturer could raise total transaction volume via the two channels in the DCSCN. Although he gives priority to increasing the offline transaction volume rather than the online counterpart because of lower transaction cost in offline channel ($c_{oi}^M(q_{oi}^p) < c_{oj}^M(q_{oj}^e)$) and the retailer certainly hopes the manufacturer to do so, it decreases instead while the transaction volume in online channel increases. It can be attributed to the characteristics of the two sales channels and Nash equilibrium in the DCSCN as well. In the offline channel, the manufacturer and the retailer mutually interact and their decisions influence each other, besides that, it is the retailer who transacts with the consumers in the demand markets for the products. By contrast, in the online channel, there is no retailer and the manufacturer can sell the products directly in the demand markets. So it is more flexible for the manufacturer to adjust transaction volume decisions in online channel than in offline channel. Then given that the competition relation between the two channels, the increase of transaction volume in the online channel leads to a slightly decrease of transaction volume in the offline channel. Since $t_1$ exceeds a certain threshold (between 1.1 and 1.3 in this example), it will be uneconomical for the manufacturer to emit any more carbon footprint than $B_o$ due to high carbon tax. In other words, he will adjust the production quantity and the abatement level spontaneously to ensure that the carbon emission is exactly equal to $B_o$ and then keep them unchanged even if $t_1$ continues to increase.

The numerical results also reveal that a relatively lower high-level carbon tax ($t_1 \in [0.5, 0.7]$ in Numerical Example 1) not only fails to make the manufacturer reduce the carbon emission and improve environmental performance obviously, but also damages the economic benefits of the manufacturer, the retailer and the whole DCSCN. Specifically, in this example the worst case comes for the manufacturer, the retailer and the whole DCSCN at $t_1 = 0.7$, and compared to the case $t_1 = 0.5$, the carbon emission reduction is very limited. In contrast, when $t_1$ increases to a reasonable region ($t_1 \in [0.9, 1.3]$), it can not only induce the manufacturer to raise the abatement level and then reduce carbon emission, but also realize the significant improvement of his own economic benefit. Although it still has a negative impact on the retailer due to the decrease of the transaction volume in the offline channel, fortunately, the total DCSCN profit also improves with $t_1$ increasing. In other words, a reasonable high-level carbon tax can make the whole DCSCN reach a better equilibrium state. The phenomenon differs from the related conclusions in the cases of monopoly, duopoly, and dyadic supply chain, which can be explained by the characteristic of Nash equilibrium in a dual-channel supply chain with network structure. So, an increased profit-sharing mechanism could be effectively utilized to achieve win-win situation between the manufacturer and the retailer. When $t_1$ goes beyond the reasonable region, as mentioned above, all the decision variables maintain constant, so the profits of the manufacturer, the retailer and the whole DCSCN also remain the same.

Based on the above discussion, we can draw the conclusion that the government should choose a reasonable (median) high-level carbon tax in the progressive carbon tax mechanism. Too low high-level carbon tax makes both the environmental performance and economic benefits of the manufacturer, the retailer and the whole DCSCN unsatisfactory, while too high high-level carbon tax is unnecessary and worthless. In this example, the government may set the high-level carbon tax $t_1 = 1.3$, at this point, the carbon emission is the minimum and the manufacturer's profit and the total DCSCN profit arrive at the maximum.

Comparisons between the equilibrium states with $\bar{c}_{oj}^K$ and $\underline{c}_{oj}^K$ show that lower online transaction cost will attract more consumers to purchase products via e-commerce, and then induce the manufacturer to raise the online transaction volume and total production quantity, while reduce the transaction volume in offline channel. The boost of online channel for the case $\underline{c}_{oj}^K$ will certainly harm the retailer, but enhance the manufacturer's profit instead due to higher transaction prices and higher total transaction volumes. The total profit of DCSCN also improves. Compared to the case $\bar{c}_{oj}^K$, the product abatement level and the carbon emission in the case of $\underline{c}_{oj}^K$ is lower and higher, respectively. The reason lies in that since the manufacturer can earn more sales revenue for the case $\underline{c}_{oj}^K$, he does not mind paying the government more tax for higher carbon emission.

### 4.2. Numerical Example 2

We set the parameters $t_1 = 1.1$ and $B_o = 0.8$, and then examine the influence of $t_0$ on the DCSCN equilibrium states. Let $t_0$ increase with the step of 0.2. The results of the main variables and profits of manufacturer $o$ and retailer $i$ are given in Table 4.

From Table 4 we can find that all the variables, carbon emissions and the retailer's profit maintain constant values as $t_0$ increases from 0 to 1. The manufacturer's profit and the total DCSCN profit uniformly decrease by $0.2 \times B_0 = 0.2 \times 0.8 = 0.16$ respectively when $t_0$ increases by 0.2. In other words, no matter how the government varies the low-level carbon tax $t_0$, it has no effect on the manufacturer's abatement level decision and production scheme at all. The result can be explained as follows: based on the analysis in Section 3.3,1, when $B_o = \varepsilon_0^{o*}$, the change of $t_0$ does not affect the equilibrium state. For the cost function forms and the parameter values in this example, because the cut-off value $B_o = 0.8$ is below the carbon emission under regular production scheme (flat carbon emission tax case), it is impossible for the manufacturer to emit less carbon footprints than $B_o$, and then $\varepsilon_0^{o*}$ must be equal to $B_o$. On the contrary, if $B_o$ is set to be higher than the carbon emission under regular production scheme, the progressive carbon tax mechanism and its low-level carbon tax will also become invalid.

The finding is very different from that without green technology investment decision under oligopolistic competition in Yu et al. (2019). Their results show that the relatively lower emis-

**Table 4**
The impacts of $t_0$ on the dual-channel supply chain network equilibrium.

| Variables | | $t_0 = 0.0$ | $t_0 = 0.2$ | $t_0 = 0.4$ | $t_0 = 0.6$ | $t_0 = 0.8$ | $t_0 = 1.0$ |
|---|---|---|---|---|---|---|---|
| $q_o^{r*}$ | $\bar{c}_{oj}^K$ | 5.45 | 5.45 | 5.45 | 5.45 | 5.45 | 5.45 |
| | $\underline{c}_{oj}^K$ | 5.487 | 5.487 | 5.487 | 5.487 | 5.487 | 5.487 |
| $q_{oi}^{p*}, q_{ij}^{p*}$ | $\bar{c}_{oj}^K$ | 2.165 | 2.165 | 2.165 | 2.165 | 2.165 | 2.165 |
| | $\underline{c}_{oj}^K$ | 2.13 | 2.13 | 2.13 | 2.13 | 2.13 | 2.13 |
| $q_{oj}^{e*}$ | $\bar{c}_{oj}^K$ | 0.423 | 0.423 | 0.423 | 0.423 | 0.423 | 0.423 |
| | $\underline{c}_{oj}^K$ | 0.476 | 0.476 | 0.476 | 0.476 | 0.476 | 0.476 |
| $\alpha_o^*$ | $\bar{c}_{oj}^K$ | 0.578 | 0.578 | 0.578 | 0.578 | 0.578 | 0.578 |
| | $\underline{c}_{oj}^K$ | 0.576 | 0.576 | 0.576 | 0.576 | 0.576 | 0.576 |
| $\varepsilon_0^{o*}$ | $\bar{c}_{oj}^K$ | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| | $\underline{c}_{oj}^K$ | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| $\varepsilon_1^{o*}$ | $\bar{c}_{oj}^K$ | 0.074 | 0.074 | 0.074 | 0.074 | 0.074 | 0.074 |
| | $\underline{c}_{oj}^K$ | 0.085 | 0.085 | 0.085 | 0.085 | 0.085 | 0.085 |
| $\varepsilon_0^{o*} +$ | $\bar{c}_{oj}^K$ | 0.874 | 0.874 | 0.874 | 0.874 | 0.874 | 0.874 |
| $\varepsilon_1^{o*}$ | $\underline{c}_{oj}^K$ | 0.885 | 0.885 | 0.885 | 0.885 | 0.885 | 0.885 |
| $\pi_o$ | $\bar{c}_{oj}^K$ | 133.285 | 133.125 | 132.965 | 132.805 | 132.645 | 132.485 |
| | $\underline{c}_{oj}^K$ | 134.468 | 134.308 | 134.148 | 133.988 | 133.828 | 133.668 |
| $\pi_i$ | $\bar{c}_{oj}^K$ | 18.755 | 18.755 | 18.755 | 18.755 | 18.755 | 18.755 |
| | $\underline{c}_{oj}^K$ | 18.148 | 18.148 | 18.148 | 18.148 | 18.148 | 18.148 |
| Total | $\bar{c}_{oj}^K$ | 152.04 | 151.88 | 151.72 | 151.56 | 151.4 | 151.24 |
| profit | $\underline{c}_{oj}^K$ | 152.616 | 152.456 | 152.296 | 152.136 | 151.976 | 151.816 |

sion tax rates of the low tax brackets can motivate the manufacturers to decrease the production quantity and reduce the total carbon footprints. Thus, the discrepancies in terms of manufacturer's green behavior, network structure, competition pattern may jointly lead to the different effects of the low-level carbon tax in the progressive carbon emission policy.

### *4.3. Numerical Example 3*

In Numerical Example 3 we set $t_1 = 1.1, t_0 = 0.5$, and then discuss $B_o$ on the equilibrium states of the DCSCN. Let $B_o$ increase with the interval of 0.2. We also add the key column $B_o = 0.9$ to present the changing trends of decision variables and profits more clearly. The computational results are shown in Table 5.

For both $\bar{c}_{oj}^K$ and $\underline{c}_{oj}^K$, in the left two columns of Table 5 ($B_o = 0.6 \text{and} B_o = 0.8$), the total carbon emission is higher than $B_o$, and all the price variables and transaction volumes remain the same. The manufacturer's profit becomes larger due to the decrease of carbon tax paid to the government. Specifically, when $B_o$ increases from 0.6 to 0.8, the carbon tax that the manufacturer can reduce is $0.2 \times (t_1 - t_0) = 0.2 \times (1.1 - 0.5) = 0.12$, and the revenue coming from product transactions does not change. Thus, the manufacturer's profit at $B_o = 0.8$ is 0.12 higher than that at $B_o = 0.6$. The retailer's profit remains the same due to the unchanged transaction volume in offline channel. The right five columns ($B_o \geq 0.9$) appear differently from the left two columns, where the carbon emission is exactly equal to $B_o$. The manufacturer will gradually reduce the amount of raw materials used in production $q_o^{r*}$, the transaction amount in online channel $q_{oj}^{e*}$ and the product abatement level $\alpha_o^*$, but increase the transaction amount in offline channel $q_{oi}^{p*}(q_{ij}^{p*})$ slightly. The maximum profits of both the manufacturer and the total channel profit appear at $B_o = 0.9$. As $B_o$ increases further, these two profits decrease step by step; on the contrary, the retailer's profit improves due to the increase of the transaction amount.

The above results reveal that when the cut-off value $B_o$ is very low ($B_o = 0.6 \text{and} B_o = 0.8$in this example), it will be uneconomical for the manufacturer to reduce the carbon emission to no more than $B_o$ by the two strategies presented in Numerical Example 1, even if they contribute to reducing the tax liabilities. In particular, the first strategy of cutting down the total production quantities and transaction volumes will lead to a sharp drop-off of his sales revenue, while the second strategy of raising the product abatement level will increase his production cost dramatically from the current levels 0.578 and 0.576 owing to the characteristic of the diminishing margin return of the abatement investment function. As a matter of fact, when $B_o = 0.6$ and $B_o = 0.8$, the carbon emissions have been greatly reduced from 2.061 and 2.075 under a flat carbon tax rate to 0.874 and 0.885 under progressive carbon tax for the two cases $\bar{c}_{oj}^K$ and $\underline{c}_{oj}^K$ respectively.

When $B_o$ continues to increase, the tax policy becomes milder and milder, i.e., the manufacturer is eligible to emit more carbon footprints at a low-level carbon tax $t_0$. Once $B_0$ increases to the level ($B_o = 0.9$ in this example) that allows the manufacturer to reach an acceptable production/transaction volume and sales revenue, he will adjust his production scheme and the abatement level to ensure that the carbon emission is exactly equal to $B_o$ and avoid paying more tax. After this, as $B_0$ increase further, the manufacturer will decrease the production quantity slightly, reduce the abatement level significantly and still keep the carbon emission equal to $B_0$. The result seems counter-intuitive. One may think that a higher cut-off value $B_0$ allows the manufacturer to raise production and then certainly increases his sales revenue. But in our model, since the carbon emission is jointly determined by the production quantity and abatement level, there is a coupling relationship between these two decision variables. Thus, in the process of $B_0$ increasing, by weighing pros and cons, reducing the abatement level substantially to save the green technology investment expenditure to a large extent is a more profitable strategy for the manufacturer than increasing both production/transaction volume and the abatement level. Then according to the monotone increasing relation between the market demands and abatement level, the total market demand and the manufacturer's production quantity also decrease a little. In addition, as mentioned before, due to the mutual restriction between the manufacturer and the retailer in the offline channel, it is not easy for the manufacturer to adjust the transaction volume by a wide margin in this channel. Thus, he decreases the transaction volume dramatically in the online channel, but increases the transaction volume in the offline channel a little instead due to the competition relation between the two channels. However, this strategy of the manufacturer is against the government's goals of boosting the economic activities and realizing low-carbon development in the DCSCN.

Based on the above analysis, the government should carefully set the cut-off value in progressive carbon tax mechanism with the consideration of the manufacturer's production quantity, product abatement level and the corresponding carbon emission under the flat carbon tax policy. Neither too high nor too low cut-off value will be effective to encourage the manufacturer to raise the abatement level and reduce carbon emission. Too low cut-off value cannot restrict the manufacturer to emitting the carbon footprints no more than it, while too high cut-off value not only leads to lower product abatement level, but also results in the shrinkage of the economic activities in the DCSCN. Therefore, the government should choose a reasonable (median) cut-off value. In particular, it could be set at the point that $\varepsilon_1^{o*}$ is just equal to zero (it is between 0.8 and 0.9 for both $\bar{c}_{oj}^K$ and $\underline{c}_{oj}^K$ in this example). Under this circumstance, the economy benefits of the manufacturer and the whole DCSCN can be maximized simultaneously, besides that, the carbon emission is well controlled.

Table 5 also shows how the consumers' online transaction cost influences the DCSCN with the increase of $B_o$. By comparing the equilibrium states with $\bar{c}_{oj}^K$ and $\underline{c}_{oj}^K$ under different $B_o$, we can obtain similar results as those in numerical example 1 except the abatement level $\alpha_o^*$. Particularly, in the left two columns where the carbon emission is higher than $B_o(\varepsilon_1^{o*} > 0)$, $\alpha_o^*$ for the case $\bar{c}_{oj}^K$ is higher than that for the case $\underline{c}_{oj}^K$; but in the right five columns

**Table 5**
The impacts of $B_o$ on the dual-channel supply chain network equilibrium.

| Variables | | $B_o = 0.6$ | $B_o = 0.8$ | $B_o = 0.9$ | $B_o = 1.0$ | $B_o = 1.2$ | $B_o = 1.4$ | $B_o = 1.6$ |
|---|---|---|---|---|---|---|---|---|
| $q_o^{r*}$ | $\bar{c}_{oj}^K$ | 5.450 | 5.450 | 5.449 | 5.445 | 5.439 | 5.433 | 5.428 |
| | $\underline{c}_{oj}^K$ | 5.487 | 5.487 | 5.486 | 5.483 | 5.476 | 5.470 | 5.465 |
| $q_{oi}^{p*}, q_{ij}^{p*}$ | $\bar{c}_{oj}^K$ | 2.165 | 2.165 | 2.165 | 2.166 | 2.166 | 2.167 | 2.168 |
| | $\underline{c}_{oj}^K$ | 2.130 | 2.130 | 2.130 | 2.130 | 2.131 | 2.132 | 2.133 |
| $q_{oj}^{e*}$ | $\bar{c}_{oj}^K$ | 0.423 | 0.423 | 0.423 | 0.421 | 0.417 | 0.414 | 0.410 |
| | $\underline{c}_{oj}^K$ | 0.476 | 0.476 | 0.476 | 0.474 | 0.47 | 0.466 | 0.463 |
| $\alpha_o^*$ | $\bar{c}_{oj}^K$ | 0.578 | 0.578 | 0.565 | 0.517 | 0.419 | 0.322 | 0.224 |
| | $\underline{c}_{oj}^K$ | 0.576 | 0.576 | 0.568 | 0.52 | 0.423 | 0.327 | 0.230 |
| $\varepsilon_0^{o*}$ | $\bar{c}_{oj}^K$ | 0.6 | 0.8 | 0.9 | 1 | 1.2 | 1.4 | 1.6 |
| | $\underline{c}_{oj}^K$ | 0.6 | 0.8 | 0.9 | 1 | 1.2 | 1.4 | 1.6 |
| $\varepsilon_1^{o*}$ | $\bar{c}_{oj}^K$ | 0.274 | 0.074 | 0 | 0 | 0 | 0 | 0 |
| | $\underline{c}_{oj}^K$ | 0.285 | 0.085 | 0 | 0 | 0 | 0 | 0 |
| $\varepsilon_0^{o*} +$ | $\bar{c}_{oj}^K$ | 0.874 | 0.874 | 0.9 | 1 | 1.2 | 1.4 | 1.6 |
| $\varepsilon_1^{o*}$ | $\underline{c}_{oj}^K$ | 0.885 | 0.885 | 0.9 | 1 | 1.2 | 1.4 | 1.6 |
| $\pi_o$ | $\bar{c}_{oj}^K$ | 132.765 | 132.885 | 132.909 | 132.829 | 132.655 | 132.46 | 132.245 |
| | $\underline{c}_{oj}^K$ | 133.948 | 134.068 | 134.106 | 134.023 | 133.842 | 133.64 | 133.42 |
| $\pi_i$ | $\bar{c}_{oj}^K$ | 18.755 | 18.755 | 18.756 | 18.760 | 18.770 | 18.783 | 18.796 |
| | $\underline{c}_{oj}^K$ | 18.148 | 18.148 | 18.149 | 18.155 | 18.168 | 18.182 | 18.198 |
| Total | $\bar{c}_{oj}^K$ | 151.520 | 151.640 | 151.665 | 151.589 | 151.425 | 151.243 | 151.041 |
| profit | $\underline{c}_{oj}^K$ | 152.096 | 152.216 | 152.255 | 152.178 | 152.01 | 151.822 | 151.618 |

**Table 6**
The impacts of $t_1$ on the traditional supply chain network equilibrium.

| Variables | $t_1 = 0.5$ | $t_1 = 0.7$ | $t_1 = 0.9$ | $t_1 = 1.1$ | $t_1 = 1.3$ | $t_1 = 1.5$ |
|---|---|---|---|---|---|---|
| $q_o^{r*}$ | 6.251 | 6.246 | 6.242 | 6.244 | 6.246 | 6.246 |
| $q_{oi}^{p*}, q_{ij}^{p*}$ | 2.969 | 2.967 | 2.965 | 2.966 | 2.967 | 2.967 |
| $\alpha_o^*$ | 0 | 0 | 0.189 | 0.505 | 0.663 | 0.663 |
| $\varepsilon_0^{o*}$ | 0.503 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| $\varepsilon_1^{o*}$ | 1.872 | 1.573 | 1.123 | 0.374 | 0 | 0 |
| $\varepsilon_0^{o*} + \varepsilon_1^{o*}$ | 2.376 | 2.373 | 1.923 | 1.174 | 0.8 | 0.8 |
| $\pi_o$ | 133.94 | 133.845 | 133.839 | 133.9 | 133.934 | 133.934 |
| $\pi_i$ | 35.269 | 35.203 | 35.167 | 35.184 | 35.208 | 35.208 |
| Total profit | 169.209 | 169.048 | 169.006 | 169.084 | 169.142 | 169.142 |

where the carbon emission is exactly equal to $B_o$ ($\varepsilon_1^{o*} = 0$), the $\alpha_o^*$ relation between the two cases is the opposite. The comparison results can be interpreted as follows: when it is not economical for the manufacturer to control the carbon emission no more than $B_o$, compared to the case $\bar{c}_{oj}^K$, the manufacturer will pay more attention to sales revenue but less attention to the product abatement level in the case of $\underline{c}_{oj}^K$, even if this leads to more carbon emission and more tax liabilities. In contrast, when the manufacturer in both cases $\bar{c}_{oj}^K$ and $\underline{c}_{oj}^K$ is willing to limit his carbon tax emission at the level of $B_o$, compared to the case $\bar{c}_{oj}^K$, he has to set higher product abatement level in the case of $\underline{c}_{oj}^K$ due to higher production quantity.

### *4.4. Numerical example 4*

Finally, as a supplement, we will examine how the manufacturer responds to the government's progressive carbon tax policy in a traditional SCN, and then focus on whether the introduction of online channel contributes to improving the economic profit and enhancing the environmental performance or not. To facilitate comparisons, all the parameters and functions are exactly the same as those in Numerical Example 1 except that there is no cost associated with online channel. Tables 6 and 7 show the impacts of high-level carbon tax $t_1$ (with the same parameters $t_0 = 0.5, B_o = 0.8$ as Numerical Example 1) and low-level carbon tax $t_0$ (with the same parameters $t_1 = 1.1, B_o = 0.8$ as Numerical Example 2) on the equilibrium states of transaction volumes, the abatement level, carbon emission and profits in the traditional SCN respectively. Table 8 provides the trends of main variables and profits in the traditional SCN in the process of the cut-off value $B_o$ increasing, with the identical parameters $t_0 = 0.5, t_0 = 1.1$ as Numerical Example 3.

We can find from Table 6 to 8 that the manufacturer will take similar adjustment strategies in the traditional SCN as in the DC-SCN when the three parameters of progressive carbon tax policy change respectively. In detail, 1) when the high-level carbon tax $t_1$ increases, if $t_1$ is at a relatively lower level now ($t_1 \leq 0.9$ in the example), the manufacturer prefers to cut down the production quantity rather than significantly improve the abatement level $\alpha_o^*$ to reduce the carbon tax liabilities, which makes $\alpha_o^*$ relatively low (0 and 0.189); but if $t_1$ exceeds the threshold ($t_0 > 0.9$ in this example), although the manufacturer increases his production quantity slightly, he raises $\alpha_o^*$ by a large margin simultaneously. Consequently, the carbon emission can be effectively controlled; 2) the low-level carbon tax $t_0$ has no effect on the transaction volumes, abatement levels and carbon emission in the traditional SCN; 3) when the cut-off value $B_o$ increases, if the current value of $B_o$ is no more than a certain threshold (between 0.6 and 1.0 in this example), it cannot influence the manufacturer's production quantity and abatement level decisions. So the carbon emission also remains the same which is higher than $B_o$. On the contrary, if the current value of $B_o$ surpasses the threshold (1.2, 1.4 and 1.6 in this example), i.e., the tax policy is relatively milder, the manufacturer reduces green technology investment and the abatement level gradually. In addition, he also decreases the production quantity a little. The resulting carbon emission is exactly equal to $B_o$.

By comparing the data in Table 6 (Table 8) with that in Table 3 (Table 5), we find that under the cost structure in our examples, the manufacturer's introducing online channel unexpect-

**Table 7**
The impacts of $t_0$ on the traditional supply chain network equilibrium.

| Variables | $t_0 = 0.5$ | $t_0 = 0.6$ | $t_0 = 0.7$ | $t_0 = 0.8$ | $t_0 = 0.9$ | $t_0 = 1.0$ |
|---|---|---|---|---|---|---|
| $q_o^{r*}$ | 6.244 | 6.244 | 6.244 | 6.244 | 6.244 | 6.244 |
| $q_{oi}^{p*}, q_{ij}^{p*}$ | 2.966 | 2.966 | 2.966 | 2.966 | 2.966 | 2.966 |
| $\alpha_o^*$ | 0.505 | 0.505 | 0.505 | 0.505 | 0.505 | 0.505 |
| $\varepsilon_0^{o*}$ | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| $\varepsilon_1^{o*}$ | 0.374 | 0.374 | 0.374 | 0.374 | 0.374 | 0.374 |
| $\varepsilon_0^{o*} + \varepsilon_1^{o*}$ | 1.174 | 1.174 | 1.174 | 1.174 | 1.174 | 1.174 |
| $\pi_o$ | 133.9 | 133.83 | 133.74 | 133.66 | 133.58 | 133.5 |
| $\pi_i$ | 35.184 | 35.184 | 35.184 | 35.184 | 35.184 | 35.184 |
| Total profit | 169.084 | 169.004 | 168.924 | 168.844 | 168.764 | 168.684 |

**Table 8**
The impacts of $B_o$ on traditional supply chain network equilibrium.

| Variables | $B_o = 0.6$ | $B_o = 0.8$ | $B_o = 0.9$ | $B_o = 1.0$ | $B_o = 1.2$ | $B_o = 1.4$ | $B_o = 1.6$ |
|---|---|---|---|---|---|---|---|
| $q_o^{r*}$ | 6.244 | 6.244 | 6.244 | 6.244 | 6.244 | 6.243 | 6.242 |
| $q_{oi}^{p*}, q_{ij}^{p*}$ | 2.966 | 2.966 | 2.966 | 2.966 | 2.966 | 2.965 | 2.964 |
| $\alpha_o^*$ | 0.505 | 0.505 | 0.505 | 0.505 | 0.494 | 0.410 | 0.326 |
| $\varepsilon_0^{o*}$ | 0.6 | 0.8 | 0.9 | 1 | 1.2 | 1.4 | 1.6 |
| $\varepsilon_1^{o*}$ | 0.573 | 0.373 | 0.274 | 0.173 | 0 | 0 | 0 |
| $\varepsilon_0^{o*} + \varepsilon_1^{o*}$ | 1.173 | 1.173 | 1.173 | 1.173 | 1.2 | 1.4 | 1.6 |
| $\pi_o$ | 133.780 | 133.90 | 133.96 | 134.02 | 134.135 | 134.204 | 134.252 |
| $\pi_i$ | 35.184 | 35.184 | 35.184 | 35.184 | 35.183 | 35.175 | 35.169 |
| Total profit | 168.964 | 169.084 | 169.144 | 169.204 | 169.318 | 169.379 | 169.421 |

edly depresses the production and transaction activities in the network. Specifically, there is a sharp drop-off in the transaction volume between the manufacturer and the retailer in the offline channel but a small increase in the online channel. The manufacturer benefits very little but both the retailer and the whole SCN are seriously victimized. In other words, from the perspective of economic development, the introduction of online channel leads to a worse equilibrium state for a traditional SCN. The result is significantly different from the prevailing conclusion that online channel benefits the entire system in a dyadic supply chain. Under this circumstance, an increased profit-sharing mechanism is not effective in achieving win-win situation any more. Thus, a novel and effective coordination contract needs to be put forward for the DCSCN to increase the total network profit and meanwhile realize Pareto improvement for both the manufacturer and the retailer.

As for the product abatement level $\alpha_o^*$ and carbon emission $\varepsilon_0^{o*} + \varepsilon_1^{o*}$, when $t_1(B_o)$ is below a certain threshold, the manufacturer in both DCSCN and traditional SCN emit more footprints than $B_o$. At this time, provided $t_1(B_o)$ is given, the manufacturer chooses a higher $\alpha_o^*$ in the DCSCN than that in the traditional SCN; in contrast, if $t_1(B_o)$ is above the certain threshold, the manufacturer in both DCSCN and traditional SCN emit carbon footprints exactly equal to $B_o$. In view of the fact that in our examples, the manufacturer makes more products in the traditional SCN than that in the DCSCN, he has to reach a higher $\alpha_o^*$ in the traditional SCN to reduce carbon emission of each product. Comparisons of the total carbon emissions between DCSCN and traditional SCN show that for any given $t_1(B_o)$, the carbon emission in the DCSCN will never be higher than that in the traditional SCN. Therefore, the introduction of online channel benefits the SCN in terms of sustainable development.

## 5. Conclusions

In the context of low-carbon and sustainable development and dual-channel marketing strategy, the government usually guides the manufacturers to improve product abatement level and reduce carbon emissions by promulgating carbon emission regulations in the DCSCN with multiple manufacturers, multiple retailers and multiple demand markets. This paper develops a DCSCN model under progressive carbon tax policy based on variational inequality theory and proves the existence and uniqueness of the equilibrium solutions. The modified project algorithm is utilized to obtain the numerical solutions. Then we focus on analyzing the impacts of progressive carbon tax mechanism on equilibrium decisions and profits of manufacturers, retailers and the whole DCSCN, based on which give some managerial insights and policy implications.

First, in the progressive carbon tax mechanism, both the high-level carbon tax and the cut-off value have great impacts on the equilibrium states, profits and carbon emissions in the DCSCN. However, their influence mechanisms on the DCSCN are different, and the manufacturer will take different measures to response to the changing of these two parameters, respectively. Specifically, in order to ensure that the carbon emission is no more than the cut-off value, when the high-level carbon tax increases, the manufacturer improves the abatement level significantly and increases the production quantity moderately; in contrast, when the cut-off value increases, the manufacturer reduces the abatement level dramatically and decreases the production quantity slightly. Compared to the above two parameters, the low-level carbon tax is indecisive.

From the perspective of the government, it should set both the high-level carbon tax and the cut-off value in reasonable (median) regions. Under this circumstance, the progressive carbon tax mechanism is not only effective in promoting the manufacturers to improve product abatement levels actively and reduce carbon emissions, but also realizes that the economic benefit goals of the manufacturer and the whole DCSCN are consistent with the low-carbon emission goal of the government. Furthermore, on conditions that these two parameters take specific values, the goals of profit maximization of the manufacturer and the whole DCSCN, and the carbon emission minimization may be realized simultaneously.

Second, the consumers' online transaction cost will influence the abatement levels, carbon emissions and profits in the DCSCN in a certain extent. A lower online transaction cost for the consumers will certainly benefit the manufacturer and the whole DCSCN but harm the retailer. The relation of the abatement levels between two cases of high and low consumers' online transaction cost mainly depends on the cutoff value. Specifically, when the cut-off value is relatively low, it is not economical for the manufacturer to limit the carbon emissions no more than the cut-off value in both cases; under this circumstance, the manufacturer will set a higher abatement level in the case of high consumer's online transaction cost. In contrast, when the cut-off value exceeds a certain threshold, the manufacturer in both cases controls the carbon emissions at the level of the cut-off value; under this condition, the manufacturer will set a higher abatement level in the case of low consumers' online transaction cost.

Third, the manufacturer's introducing online channel may depress the production and economic activities in the SCN. The relation of the abatement levels between DCSCN and traditional SCN hinges upon the cut-off value. In most cases, the abatement level in the DCSCN is higher than that in the traditional SCN. Moreover, the carbon emission in the DCSCN will never be more than that in the traditional SCN.

The research in this paper can be further expanded in the following two aspects. The first possible direction is to design effective coordination contracts for the DCSCN. As one of the conclusions in this paper shows, under certain conditions, the designed progressive carbon tax policy can realize the goals of profit maximization for the manufacturers and the whole DCSCN, as well as the carbon emission minimization, but the retailers may suffer losses. Thus, how to achieve a win-win situation in a DCSCN by effective supply chain contracts (such as revenue-sharing contract, quantity-discount contract and two-part tariff contract) is a crucial question worthy of exploration. In addition, a novel and effective coordination contract needs also to be put forward to increase the total DCSCN profit and meanwhile realize Pareto improvement for both the manufacturer and the retailer compared to traditional SCN. The second possible direction is to extend the established DCSCN model into a multi-period setting and investigate the influence of progressive carbon tax on dynamic production/pricing and abatement level decisions of the multi-period DCSCN.

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We declare that there is no conflict of interests regarding the publication of this article.

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## Appendix

Let $\Omega^r = \{(\boldsymbol{q}^r, \boldsymbol{Q}^1, \boldsymbol{Q}^2, \boldsymbol{Q}^3, \boldsymbol{\alpha}, \boldsymbol{\varepsilon}_0, \boldsymbol{\varepsilon}_1, \boldsymbol{\rho}^p, \boldsymbol{\rho}^e, \boldsymbol{\lambda}^1, \boldsymbol{\lambda}^2, \boldsymbol{\lambda}^3, \boldsymbol{\gamma}^1) | 0 \le \boldsymbol{q}^r \le r_1; 0 \le \boldsymbol{Q}^1 \le r_2; 0 \le \boldsymbol{Q}^2 \le r_3; 0 \le \boldsymbol{Q}^3 \le r_4; 0 \le \boldsymbol{\alpha} \le r_5; 0 \le \boldsymbol{\varepsilon}_0 \le r_6; 0 \le \boldsymbol{\varepsilon}_1 \le r_7; 0 \le \boldsymbol{\rho}^p \le r_8; 0 \le \boldsymbol{\rho}^e \le r_9; 0 \le \boldsymbol{\lambda}^1 \le r_{10}; 0 \le \boldsymbol{\lambda}^2 \le r_{11}; 0 \le \boldsymbol{\lambda}^3 \le r_{12}; 0 \le \boldsymbol{\gamma}^1 \le r_{13}\}$.

Where $0 \le \boldsymbol{q}^r \le r_1$ means that $0 \le q_o^r \le r_1$, $\forall o$, and the other notations can be explained in the same way. $r = (r_1, r_2, r_3, r_4, r_5, r_6, r_7, r_8, r_9, r_{10}, r_{11}, r_{12}, r_{13}) \ge 0$, and $K_r = \Omega \cap \Omega^r$.

Based on the assumptions above, $K_r$ is a bounded, closed, convex set, and in our model, we can guarantee the continuity of function $F(X)$. According to the variational inequality theory, we have the solution $(\boldsymbol{q}^{r*}, \boldsymbol{Q}^{1*}, \boldsymbol{Q}^{2*}, \boldsymbol{Q}^{3*}, \boldsymbol{\alpha}^*, \boldsymbol{\varepsilon}_0^*, \boldsymbol{\varepsilon}_1^*, \boldsymbol{\rho}^{p*}, \boldsymbol{\rho}^{e*}, \boldsymbol{\lambda}^{1*}, \boldsymbol{\lambda}^{2*}, \boldsymbol{\lambda}^{3*}, \boldsymbol{\gamma}^{1*}) \in K_r$, such that

$$
\begin{aligned}
&\sum_{o=1}^{M}\left[\frac{\partial f_o^{M*}}{\partial q_o^r} + \frac{\partial f_o(q_o^{r*})}{\partial q_o^r} - \beta_r\lambda_o^{1*}\right] \times [q_o^r - q_o^{r*}] \\
&+ \sum_{o=1}^{M}\sum_{i=1}^{N}\left[\frac{\partial c_{oi}^{M*}}{\partial q_{oi}^p} + \lambda_o^{1*} + t_c\beta_0(1-\alpha_o^*) + \frac{\partial c_i^*}{\partial q_{oi}^p} + \frac{\partial c_{oi}^{N*}}{\partial q_{oi}^p} - \gamma_i^{1*}\right] \\
&\times\left[q_{oi}^p - q_{oi}^{p*}\right] \\
&+ \sum_{i=1}^{N}\sum_{j=1}^{K}\left[\frac{\partial c_{ij}^{N*}}{\partial q_{ij}^p} + \gamma_i^{1*} + c_{ij}^K(q_{ij}^{p*}) - \rho_j^{p*}\right] \times \left[q_{ij}^p - q_{ij}^{p*}\right] \\
&+ \sum_{o=1}^{M}\sum_{j=1}^{K}\left[\frac{\partial c_{oi}^{M*}}{\partial q_{oj}^e} + \lambda_o^{1*} + t_c\beta_0(1-\alpha_o^*) + c_{oj}^K(q_{oj}^{e*}) - \rho_j^{e*}\right] \\
&\times\left[q_{oj}^e - q_{oj}^{e*}\right] \\
&+ \sum_{o=1}^{M}\left[\frac{\partial f_o^{M*}}{\partial \alpha_o} + \eta_o\alpha_o^* - t_c\beta_0\left(\sum_{i=1}^{N} q_{oi}^{p*} + \sum_{j=1}^{K} q_{oj}^{e*}\right)\right] \times [\alpha_o - \alpha_o^*] \\
&+ \sum_{o=1}^{M}\left[t_0 + \lambda_o^{3*} - \lambda_o^{2*}\right] \times \left[\varepsilon_o^0 - \varepsilon_o^{0*}\right] + \sum_{o=1}^{M}\left[t_1 - \lambda_o^{2*}\right] \times \left[\varepsilon_o^1 - \varepsilon_o^{1*}\right] \\
&+ \sum_{i=1}^{N}\left[\sum_{i=1}^{N} q_{ij}^{p*} - d_j^p(\rho_j^{p*}, \rho_j^{e*}, \boldsymbol{\alpha}^*; \omega)\right] \times \left[\rho_j^p - \rho_j^{p*}\right] \\
&+ \sum_{j=1}^{K}\left[\sum_{o=1}^{M} q_{oj}^{e*} - d_j^e(\rho_j^{p*}, \rho_j^{e*}, \boldsymbol{\alpha}^*; \omega)\right] \times \left[\rho_j^e - \rho_j^{e*}\right] \\
&+ \sum_{o=1}^{M}\left[\beta_r q_o^{r*} - \sum_{i=1}^{N} q_{oi}^p - \sum_{j=1}^{K} q_{oj}^e\right] \times \left[\lambda_o^1 - \lambda_o^{1*}\right] \\
&+ \sum_{o=1}^{M}\left[B_o - \varepsilon_o^0\right] \times \left[\lambda_o^2 - \lambda_o^{2*}\right] \\
&+ \sum_{o=1}^{M}\left[\varepsilon_o^0 + \varepsilon_o^{1*} - \beta_0(1-\alpha_o^*)\left(\sum_{i=1}^{N} q_{oi}^{p*} + \sum_{j=1}^{K} q_{oj}^{e*}\right)\right] \times \left[\lambda_o^3 - \lambda_o^{3*}\right] \\
&+ \sum_{i=1}^{N}\left[\sum_{o=1}^{M} q_{oi}^p - \sum_{j=1}^{K} q_{ij}^p\right] \times \left[\gamma_i^1 - \gamma_i^{1*}\right] \ge 0
\end{aligned}
\tag{19}
$$

$\forall(\boldsymbol{q}^r, \boldsymbol{Q}^1, \boldsymbol{Q}^2, \boldsymbol{Q}^3, \boldsymbol{\alpha}, \boldsymbol{\varepsilon}_0, \boldsymbol{\varepsilon}_1, \boldsymbol{\rho}^p, \boldsymbol{\rho}^e, \boldsymbol{\lambda}^1, \boldsymbol{\lambda}^2, \boldsymbol{\lambda}^3, \boldsymbol{\gamma}^1) \in K_r$.

**Theorem 2.** Since $K_r$ is compact and $F(X)$ is continuous, variational inequality (19) admits a solution $(\boldsymbol{q}^{r*}, \boldsymbol{Q}^{1*}, \boldsymbol{Q}^{2*}, \boldsymbol{Q}^{3*}, \boldsymbol{\alpha}^*, \boldsymbol{\varepsilon}_0^*, \boldsymbol{\varepsilon}_1^*, \boldsymbol{\rho}^{p*}, \boldsymbol{\rho}^{e*}, \boldsymbol{\lambda}^{1*}, \boldsymbol{\lambda}^{2*}, \boldsymbol{\lambda}^{3*}, \boldsymbol{\gamma}^{1*}) \in K_r$, if and only if there exists $r_i > 0$, $i = 1, 2, \cdots, 13$, and satisfy $0 \le \boldsymbol{q}^r \le r_1$, $0 \le \boldsymbol{Q}^1 \le r_2$, $0 \le \boldsymbol{Q}^2 \le r_3$, $0 \le \boldsymbol{Q}^3 \le r_4$,$0 \le \boldsymbol{\alpha} \le r_5$, $0 \le \boldsymbol{\varepsilon}_0 \le r_6$, $0 \le \boldsymbol{\varepsilon}_1 \le r_7$, $0 \le \boldsymbol{\rho}^p \le r_8$, $0 \le \boldsymbol{\rho}^e \le r_9$, $0 \le \boldsymbol{\lambda}^1 \le r_{10}$, $0 \le \boldsymbol{\lambda}^2 \le r_{11}$, $0 \le \boldsymbol{\lambda}^3 \le r_{12}$, $0 \le \boldsymbol{\gamma}^1 \le r_{13}$.

From Theorem 2, whether there is a solution to the variational inequality (14) can be converted to the condition that the solution to the variational inequality (19) should exist.

**Theorem 3.** (Existence). Suppose that there exist positive constants $A_i$, $i = 1, 2, 3$, and $A_3 > 0$, such that

$F_1(X) \ge A_3$, $\forall \boldsymbol{q}^r \ge A_2$; $F_2(X) \ge A_3$, $\forall \boldsymbol{Q}^1 \ge A_2$; $F_3(X) \ge A_3$, $\forall \boldsymbol{Q}^2 \ge A_2$; $F_4(X) \ge A_3$, $\forall \boldsymbol{Q}^3 \ge A_2$; $F_5(X) \ge A_3$, $\forall \boldsymbol{\alpha} \ge A_2$; $F_6(X) \ge A_3$,

$\forall \boldsymbol{\varepsilon}_0 \geq A_2$; $F_7(X) \geq A_3$, $\forall \boldsymbol{\varepsilon}_1 \geq A_2$; $d_j^p(\rho_j^{p*}, \rho_j^{e*}, \boldsymbol{\alpha}^*; \tau) \leq A_2$, $\forall \rho_j^p > A_1$; $d_j^e(\rho_j^{p*}, \rho_j^{e*}, \boldsymbol{\alpha}^*; \tau) \leq A_2$, $\forall \rho_j^e > A_1$.

Then variational inequality (19) admits at least one solution *(see* Nagurney and Zhao, 1993).

**Theorem 4.** (Monotonicity and strict monotonicity). Let $x^1$, $x^2 \in K_r$, $\nabla F(x)$ is the vector function with the gradients of variational inequality (19), according to the assumptions of convex, we have $F(x^1) \geq F(x^2) + [\nabla F(x^2)]^T(x^1 - x^2)$, $F(x^2) \geq F(x^1) + [\nabla F(x^1)]^T(x^2 - x^1)$, then $[\nabla F(x^1) - \nabla F(x^2)]^T(x^1 - x^2) \geq 0$, when the strict inequality is established, the function $F(x)$ is strict monotonic.

**Theorem 5.** (Uniqueness). Under the conditions of Theorem 3, there must be a unique pattern of the dual-channel supply chain network. That is, if the variational inequality (19) admits a solution, that should be the only solution.

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