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Carbon emission transfer strategies in supply chain with lag time of emission reduction technologies and low-carbon preference of consumers

Licheng Sun [a,*], Xiaoxiao Cao [a], Majed Alharthi [b], Jijian Zhang [c], Farhad Taghizadeh-Hesary [d], Muhammad Mohsin [c]

[a] School of Management, Jiangsu University, Zhenjiang, 212013, China
[b] Finance Department College of Business King Abdul-Aziz University, Rabigh, 21911, Saudi Arabia
[c] School of Finance &economics, Jiangsu University, Zhenjiang, 212013, China
[d] School of economics, Tokai University, Tokai, 476-0000, Japan

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ABSTRACT

The construction of a low-carbon supply chain is central for the sustainable development of a country, especially for a large carbon emitter such as China. To better promote supply chain emission reduction, this paper analyzes the carbon emission transfer and emission reduction problem among enterprises within the supply chain, integrating the influence of government emission reduction policies and the low carbon market. Considering the lag time of emission reduction technologies and the low-carbon preferences of consumers, a Stackelberg differential game model (dominated by manufacturers) is constructed under both centralized and decentralized decisions. The results suggest that the lag time of emission reduction technology and the low carbon preference of consumers positively affect the carbon emission transfer level of manufacturers, while not affecting suppliers' undertaking levels. Only when the lag time of emission reduction technology remains within a specific range, will an increase in consumers' low-carbon preferences exert a positive impact on supply chain profits. Notably, under decentralized decision-making, when the emission reduction technology lag time and consumers' low carbon preference remain within a specific range, the carbon emission transfer behavior exerts a positive promoting effect on the emission reduction of the supply chain. This applies when the profit of the supply chain increases and the carbon emission reduction per unit of product decreases. This result provides a new idea for the government to control irrational carbon emission transfer behavior of enterprises. Moreover, considering the lag time of emission reduction technology is also conducive to increasing the acceptability of government carbon quota.

1. Introduction

Since the *Kyoto Protocol* took effect in 2005, governments around the world have actively worked to reduce carbon emissions by various means. However, the total greenhouse gas emission worldwide has not decreased (Micheal, 2019) (Fig. 1). According to the data released by the Global Carbon Project (GCP), in 2018, the total CO_2 emission by energy consumption worldwide increased by 1.7% (about 560 million tons) and reached an all-time high of 33.1 billion tons. To be specific, China's total CO_2 emissions by energy consumption increased by 2.5% (i.e., by about 230 million tons), and reached 9.5 billion tons, which roughly accounts for 28.7% of the global total. Even so, China's total carbon emission is far from reaching its peak. It has been forecast that the peaking year of China's total carbon emission will occur between 2030 and 2040. With this in mind, in 2009, the Chinese government first proposed to "reduce CO_2 emissions per unit of GDP by 40–45% by 2020 on the basis of 2005". Then, in 2015, the Chinese government further proposed to "reduce CO_2 emissions per unit of GDP by 60–65% by 2030 on the basis of 2005". Clearly, for a long time to come, China's total carbon emission will continue to increase, and China will bear increasing pressure to reduce its carbon emissions.

* Corresponding author.
E-mail address: sunsee213@ujs.edu.cn (L. Sun).

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Enterprises, as regional emission reduction subjects, are mostly concerned about their own profits. To reduce emissions, a large amount of human, material, and financial resources have to be exerted, which will reduce their output to a certain extent; consequently, enterprises are not highly motivated to reduce their emissions. To promote the emission reduction of enterprises, governments of various countries have implemented various low-carbon policies. The carbon cap-and-trade mechanism, as one of the common carbon emission reduction policies, imposes carbon quota on enterprises that are dependent on carbon emissions, thus forcing enterprises to engage in emission reduction technology research and development (Yu et al., 2020). At the same time, the energy label, launched by China in 2005, is of great significance for guiding consumers to choose green consumption (which means consumers will choose to buy low-carbon products). Consumers' awareness of the necessity for environmental protection is gradually improving, thus encouraging enterprises to produce and sell low-carbon intensive products (Ji et al., 2017). With regard to this, on the one hand, enterprises actively adopt various measures to reduce their carbon emissions. For instance, IKEA established more rigorous rules for their carbon emissions in 2014, McDonald's used straw less lids as a substitute for plastic straws, and Microsoft and Disney introduced internal taxes. On the other hand, since the enterprise's emission management is a long-term dynamic process, this is subject to a lag effect with regard to the reduction of emissions (Zu et al., 2018). This effect greatly increases the short-term cost of reducing emissions. Therefore, because of the pressure of capital and emission reduction costs, companies often choose to meet the requirements of the government's low-carbon policy and the needs of the low-carbon market through both upstream and downstream cooperation (Kang et al., 2019). Under the current circumstances, carbon emissions transfer has become a new form of cooperation, as well as a form of optimization of the internal quota structure of supply chain enterprises. This is especially the case when insufficient supply quotas affect one side and surplus quotas affect the other side of the supply chain. With regard to carbon emission reduction tasks that are difficult to accomplish, by taking advantage of their dominant position in supply chain, enterprises tend to transfer these tasks to upstream or downstream enterprises via vendor managed inventory (VMI), jointly managed inventory (JMI), transport and processing, as well as manufacturing outsourcing (introduced by HP and Apple). However, in practice, the presence of carbon emission transfer between supply chain enterprises not only makes it difficult to accurately define the carbon emission reduction responsibilities of these enterprises; moreover, should such a transfer become disorganized, the operations of participating enterprises are disturbed, which obstructs the realization of the carbon emission reduction targets of the supply chain as a whole. However, the existing literature rarely addressed the issue of carbon emissions transfer between companies within the supply chain. It is difficult to directly study carbon emissions transfer. Therefore, the purpose of this study is to explore the impact of relevant emission reduction factors on the supply chain carbon emission transfer in the context of known carbon emission transfer. Furthermore, the internal mechanism of the supply chain carbon emission transfer is refined and the influence mechanism of carbon emission transfer in supply chain is extracted. In this way, the carbon emissions transfer structure between supply chain companies can be optimized and the realization of the overall carbon reduction goals of the supply chain can be promoted.

Based on this analysis, enterprises' enthusiasm for emission reduction is influenced by the lag of emission reduction technology and by consumers' low-carbon preference. When consumers' low-carbon preference is too low or when emission reduction technology lags behind for too long, enterprises' enthusiasm for emission reduction will be affected. Therefore, based on the comprehensive consideration of the lag period of emission reduction technology and the influence of consumers' low-carbon preference, this study analyzes carbon emission transfer and other emission reduction decisions of a secondary supply chain. This secondary supply chain is composed of a supplier and a manufacturer under decentralized and centralized decision-making. Among them, it is assumed that the manufacturer's initial carbon quota is insufficient, that the supplier's quota is in surplus, and that the transfer direction of carbon emissions is from the manufacturer to the supplier. The supplier will thus consider undertaking part of the carbon emission transfer as part of the partnership, as shown in Fig. 2.

This study addressed the following questions:(1) What are the optimal carbon emission transfer and other emission reduction decisions for both manufacturers and suppliers under centralized and decentralized decision-making? (2) How will the lag period of emission reduction technology and consumers' low-carbon preference affect manufacturers' carbon emission transfer and suppliers' supply chain undertaking? (3) What is the impact of carbon emission transfer on supply chain emission reduction and supply chain profit? (4) How does the government address the existing

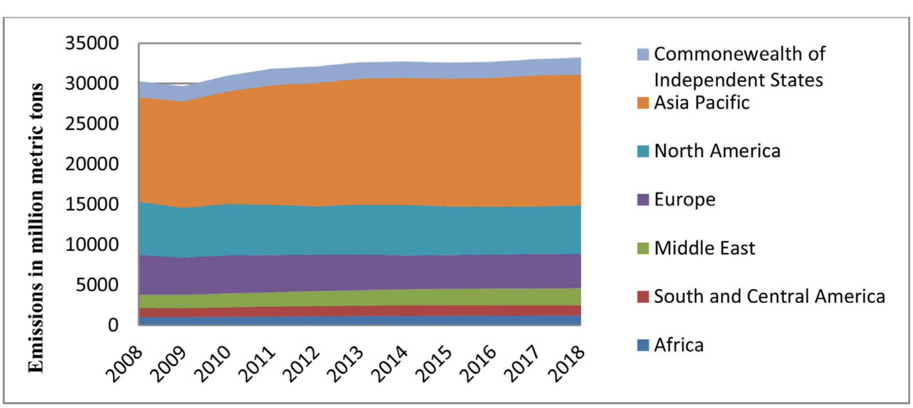

Fig. 1. Global carbon dioxide emissions from 2008 to 2018, by region (In million metric tons of carbon dioxide).

carbon emission transfer behavior?

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature and introduces the main contributions of this study. Section 3 details the basic assumptions and relevant parameters of the developed model. Section 4 constructs a carbon emission transfer model under both decentralized and centralized decision-making and analyzes the results under both conditions. Section 5 uses MATLAB software to simulate and reflect the research results more intuitively. Section 6 summarizes the relevant conclusions and implications.

2. Literature review

This section mainly reviews the literature relevant to this study. Three main literature streams are relevant: (1) supply chain operations under cap-and-trade policy, (2) influencing factors of supply chain emission reduction, and (3) carbon emissions transfer.

2.1. Supply chain operations under the cap-and-trade policy

After the cap-and-trade policy has become an emission reduction policy, many scholars have studied the impact of the cap-and-trade system on supply chain operations. Du et al. (2016a) found that under certain conditions, the cap-and-trade policy can simultaneously constrain the total carbon emissions and promote low-carbon production. Tong et al. (2019) showed that carbon emission caps, carbon trading prices, and consumer preferences for low-carbon products are the key factors affecting the behavior of both retailers and manufacturers. Cao et al. (2017) studied the relationship between manufacturers' carbon emission levels and carbon trading prices. Their results showed that carbon emission reduction levels increase with increasing carbon trading prices. Chen et al., 2016analyzed the optimal decision of storage management and technology investment under the cap-and-trade policy. In addition, Xu et al. (2016a) investigated the joint optimization of production and pricing in the supply chain under cap-and-trade control, and reported that both the production quantity and the optimal total emissions were significantly affected by carbon trading prices. Yang et al. (2018) studied the channel selection and emission reduction decisions of manufacturers when considering carbon emission constraints. The results showed that channel conflicts have eased under the cap-and-trade system, and that retailers can accommodate additional online channels under specific conditions.

The above research shows that the quota and trading system significantly impacts enterprises' carbon emission reduction level, production and pricing, warehouse management, and even channel selection. However, the above literature is based on the premise that supply chain enterprises abide by the cap-and-trade principle, and will consciously purchase permits to emit carbon when the quota is insufficient. However, as rational economic entities, the purchase of carbon quota also increases the cost of emission reduction for enterprises. Du et al. (2016b) also pointed out that from an environmental perspective; most companies did not adopt low-carbon production options because of cost considerations, while consumers' low-carbon preferences forced companies to adopt low-carbon production. Therefore, in the case where one of the companies of the supply chain has insufficient quotas, the other has a surplus of quotas, and thus, the carbon quota market is incomplete. Here, carbon transfer is often a good choice for companies to reduce their emission reduction costs. Existing literature rarely focuses on this level. This paper studies the situation where manufacturers reduce their carbon emissions, while transferring part of their carbon emissions that cannot meet government requirements in the short term to the upstream supply chain.

2.2. Influencing factors of supply chain emission reduction

Existing studies (e.g., Smulders et al. (2014), Yang et al. (2017), Wang et al. (2018), and Napp et al. (2019)) suggested that among factors that influence carbon emissions by enterprises of the supply chain, emission reduction technologies constitute the fundamental driver of long-term economic growth and carbon emission reduction. Consequently, these factors form an important means for the reduction of carbon emissions and the control of climate warming. Therefore, several scholars introduced emission reduction technologies to study low-carbon decisions in the supply chain. For instance, Bai et al. (2019) pointed out that manufacturers' green technology level determines the market demand for supply chain products. By building a bottom-up low-carbon technology evaluation model, Sun et al. (2018) assessed the emission reduction potential of China's oil and gas production industry, and suggested several references for decision makers. Kang et al. (2019) used an evolutionary game model to analyze the influence of a low-carbon technology level on the low-carbon behavior of supply chain enterprises. They proposed several operation strategies for supply chain enterprises under different low-carbon technology levels. Tong et al. (2019) showed that, when consumers are sensitive to carbon emission reduction technologies, more manufacturers will invest in their R&D, and retailers will introduce strategies to promote low-carbon products. Considering that consumers show positive preference for green labels (Grunert et al., 2014; Chen et al., 2018), are willing to purchase green products (Cao et al., 2017), and pay more for low-carbon products (Motoshita et al., 2015; Bull, 2012; Zhang et al., 2011), numerous scholars have probed into the influence of the low-carbon preference of consumers on the supply chain. For

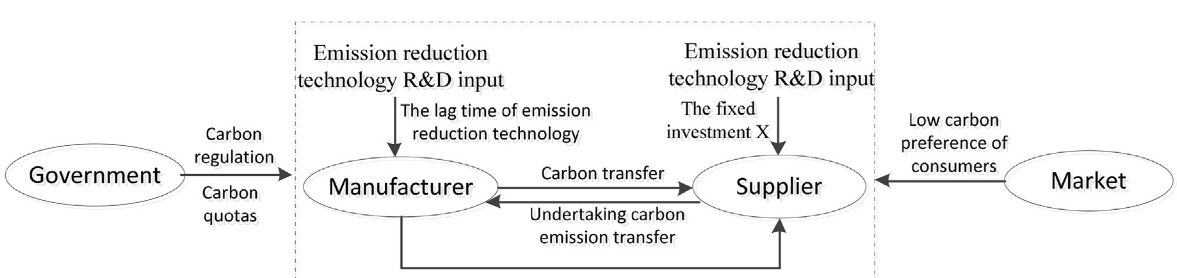

Fig. 2. Manufacturer-supplier carbon emission transfer process.

instance, Nouira et al. (2016) reported that the environmental awareness of consumers urges enterprises to select a site closer to the place of consumption, and choose local suppliers. By building a theoretical model for the low-carbon preference of consumers, Du et al., 2016a, 2016b introduced an optimal production strategy for supply chain enterprises. Zhang et al. (2015) reported that, under low-carbon preference, when manufacturers' profit is positive, retailers' profit will increase. Ji et al. (2017) suggested that manufacturers and retailers only profit from the cap-and-trade system when the low-carbon sensitivity coefficient of consumers exceeds a specific threshold. Xia et al. (2018) indicated that the low-carbon preference of consumers improves enterprise incentive mechanisms, guides supply chain members to invest in emission reduction technologies, and increases social welfare and the profit of supply chain members. Liu (2019) claimed that acquiring the costs of consumer preference information and carbon emission reduction helps retailers to negotiate lower wholesale prices and thus increased revenue.

Existing studies usually separately explored the influence of carbon emission reduction technologies and consumer low-carbon preference on the low-carbon operation of the supply chain, while rarely considering their combined influence. In reality, the emission reduction behavior of supply chain enterprises is affected by both factors. In addition, existing studies rarely focused the influence of the lag phase of emission reduction technology R&D. Tao et al. (2019)suggested that emission reduction technology R&D input constitutes a prerequisite for the development of emission reduction technologies and the enhancement of the cost-effectiveness of emission reduction; however, the emission reduction effect of emission reduction technologies is subject to an inter-phase time lag (Zhao et al., 2016; Zu et al., 2018). Therefore, without considering the influence of the lag phase of emission reduction technologies, it is difficult to extract the emission reduction behavior of supply chain enterprises. Although Zu et al. (2018) considered that the time lag of emission reduction technology will affect the decisions of supply chain entities, the authors merely proposed that the long-term profit of a company should be used to measure the effectiveness of emission reduction; however, the impact of lagging emissions reduction technologies was not considered in their paper. Consequently, based on building a differential game model for the carbon emission transfer in the supply chain that comprehensively considers the influence of both the time lag of emission reduction technologies and the low-carbon preference of consumers, this paper investigates the influencing mechanism of both factors on carbon emission transfer and on other emission reduction decisions in the supply chain.

2.3. Carbon emissions transfer

To date, many studies addressed carbon emission transfer. For instance, Dong et al. (2017), Yang et al. (2014), Wu et al. (2016), and Zhou et al. (2018) mainly focused on carbon emission transfer between countries. These studies suggested that global trade has increased carbon emission transfer (mainly from developed countries to developing countries) and that China has always been a "net carbon exporting country" over the course of global trade. Zhang et al. (2014), Sun et al. (2016), Xie et al. (2017) and Zhou et al. (2018) suggested that carbon emission transfer also exists between the provinces of China due to their unbalanced development, and that there is a trend of carbon emission transfer from the developed East of China to the underdeveloped Center and West of China. Duan et al. (2018) also showed that West China is the controller of most regions in China, and that emission reduction policies adopted in West China exert a fundamental influence on other regions. By measuring inter-industry carbon emission transfer in China and by analyzing its characteristics, Guo et al. (2012), Xu and Zou (2010), Sun et al. (2017), Xu et al. (2017), and Chen et al. (2017) argued that energy-intensive industries constitute the primary contributor of carbon emission transfer. They further indicate that the energy industry sector and the heavy industry sector provide many intermediate products for other industry sectors and initiate a large proportion of carbon emission transfer.

In summary, existing studies on carbon emission transfer mainly focused on different countries, regions, and industries, while neglecting the issue of carbon emission transfer between micro emission reduction subjects in the supply chain. In practice, carbon emission transfer between countries, regions, and industries is inseparable from commodity flow between different emission reduction subjects. In essence, such flow is caused by the circulation of goods between interconnected and interactive micro emission reduction subjects in the supply chain (Sun et al., 2016, 2017). Consequently, without investigating the issue of carbon emission transfer between the subjects of the supply chain, it is difficult to grasp the inner formation mechanism of carbon emission transfer or its influencing factors. Therefore, this paper focuses on studying the carbon emission transfer behavior in the supply chain under the influence of the emission reduction technology lag period and consumers' low carbon preference. Thus, the impact of carbon emission transfer on the existence of supply chain emission reduction is investigated.

Based on the above analysis, this study provides the following contributions: (1) this paper discusses a new cooperation model for emission reduction under the quota and trade system: carbon emission transfer. In doing so, the favorable carbon emission transfer quantity of enterprises is explored without disturbing the market order, which is conducive to optimizing the internal resource structure of supply chain enterprises and compensating for the deficiency caused by incomplete government quota information. (2) A comprehensive analysis is conducted on the impact of technology lag and consumers' low carbon preference on supply chain emission reduction decisions. Previous studies have pointed out that both emission reduction technologies and consumers' low carbon preference are important factors that influence supply chain emission reduction; however, to date, these important factors have not been investigated in combination. In this paper, the lag period of emission reduction technology, which exerts an important influence on emission reduction cost, is selected to expose the influence of emission reduction technology on emission reduction decision of supply chain enterprises.

3. Model assumptions and symbols

Considering that manufacturers are the initiators of the carbon emission transfer, to theoretically realize the carbon emission transfer process as shown in Fig. 1, this paper selects manufacturers as the dominant side of the differential game, and constructs a Stackelberg differential game using both manufacturers and upstream suppliers. To build a differential game model for carbon emission transfer in the supply chain, the following basic assumptions have been made:

(1) In the supply chain, manufacturer M has an initial carbon quota deficit of H, while supplier Shas an initial carbon quota surplus of I. When they maintain a cooperative relationship, $\varepsilon\mathrm{I}$ represents the minimum carbon emission transfer undertaken by supplier S, while $(1-\varepsilon)\mathrm{I}$ represents the carbon

quota disposable by supplier S, written as O for the sake of convenience.

(2) An increase of manufacturers' carbon emission transfer leads to an increase of their emission reduction technology R&D input; the suppliers' emission reduction technology R&D input is the fixed value X. The increase of manufacturers' carbon emission transfer leads to a decrease of the initial carbon quota, in which case, manufacturers are more motivated to invest in emission reduction technologies. The basic assumptions are that the carbon emission transfer level of manufacturer M at time t is $T_M(t)$, the carbon emission transfer undertaking level of supplier S at time t is $T_S(t)$, and the emission reduction technology R&D input of manufacturer M at time t is $R_M(t)$ ($R_M(t) = \varphi T_M(t) + A$). Here, A is a constant and $\varphi > 0$ is the proportion coefficient between manufacturers' emission reduction technology R&D input and carbon emission transfer.

Emission reduction is a dynamic process and the emission reduction per unit of output mainly depends on the efforts of manufacturers and suppliers (Zu et al., 2018; Benchekroun and Martín-Herran, 2016). Based on the Nerlove-Arrow lag model (Chen and Huang, 2018), a differential equation with the time lag of emission reduction technologies can be established to describe the dynamic change of the carbon emission reduction per unit of output, as given below:

$$\dot{E}(t) = \gamma R_M(t-d) + \gamma X - \delta E(t) = \gamma(\varphi T_M(t-d) + A) + \gamma X - \delta E(t) \tag{1}$$

where $E(t)$ representstheemission reduction per unit of output at time t; $E_0 \geq 0$ representsthe initial carbon emission reduction $E(0)$ per unit of output in supply chain; $\gamma \geq 0$ representsthe influence coefficient of manufacturers' and suppliers' emission reduction technology R&D input on the change of emission reduction per unit of output; d representsthe lag time of emission reduction technologies, indicating that input in emission reduction technologies produces an emission reduction effect only after a fixed $(t-d) = 0$ and $X = 0$, which is mainly caused by the aging of emission reduction equipment within the period of time d; $\delta > 0$ represents the attenuation rate of emission reduction per unit of output when R_M, indicating the degeneration of emission reduction technologies.

(3) The market demand $D(t)$ of a product is affected by the low-carbon preference intensity β of consumers, the carbon emission reduction level of supply chain, and suppliers' carbon emission transfer undertaking level $T_S(t)$. In the market, consumers tend to purchase low-carbon products, which indicates their willingness to purchase products with a high emission reduction level per unit of output; the increase of carbon emission transfer undertaking level of suppliers and emission reduction technology R&D input of manufacturers leads to an increase of market demand. The market demand of a product can be expressed as follows (Xu et al., 2016a):

$$D(t) = D_0 + \beta E(t) + \mu T_S(t) \tag{2}$$

where D_0 represents theinitial market demand; μ represents the influence coefficient of suppliers' carbon emission transfer undertaking level on market demand; β represents the low-carbon preference intensity of consumers.

(4) The costs of both manufacturers and suppliers are the increasing functions of emission reduction technology R&D input level and carbon emission transfer undertaking level, respectively. They share the characteristics of convex functions. It can be assumed that they are quadratic functions (Zu et al., 2018), as shown in the following:

$$C_M(t) = \frac{1}{2} m R_M^2(t) = \frac{1}{2} m(\varphi T_M(t) + A)^2 \tag{3}$$

$$C_S(t) = \frac{1}{2} m X^2 + \frac{1}{2} k T_S^2(t) \tag{4}$$

Where m representsthe cost coefficient of manufacturers and suppliers' emission reduction efforts; k representsthe cost coefficient of suppliers' carbon emission transfer undertaking level. This mainly reflects the revenue lost by suppliers from sales of carbon quota due to the carbon emission transfer.

(5) To motivate suppliers to participate in carbon emission transfer, manufacturers share suppliers' R&D costs based on their carbon emission transfer undertaking level, with a sharing coefficient of ϕ.

(6) Manufacturers' and suppliers' discount rates are both $\rho(\rho > 0)$; the supply chain can operate indefinitely, and both manufacturers and suppliers can seek the maximization of economic benefits within an infinite interval. In this study, the objective functions of manufacturer M, supplier S, and the whole supply chain can be expressed as:

$$\max J_M = \int_0^{+\infty} e^{-\rho t}\left\{L_M D(t) - C_M(t) - \phi \frac{1}{2} m X^2 - \theta[H - T_S(t)]\right\} dt \tag{5}$$

$$\max J_S = \int_0^{+\infty} e^{-\rho t}\left\{L_S D(t) + \phi \frac{1}{2} m X^2 - C_S(t) + \theta[I - T_S(t)]\right\} dt \tag{6}$$

$$\max J_{MS} = \int_0^{+\infty} e^{-\rho t}\{(L_M + L_S) D(t) - C_M(t) - C_S(t) + \theta[I - H]\} dt \tag{7}$$

Where $\theta(\theta > 0)$ representsthe average carbon price, stipulated by the government; L_M and L_S represent the marginal profits of manufacturer M and supplier S, respectively.

4. Modeling and analysis

This section studies the carbon emission transfer model of the supply chain under the two scenarios of decentralized and centralized decision-making. The optimal R&D investment level, carbon emission transfer level, carbon emission transfer undertaking level, and unit product emission reduction trajectory of both manufacturers and suppliers are calculated under both models; finally, a comparative analysis is conducted from the perspectives of carbon emission transfer, unit product emission reduction, and supply chain profit. The specific certification process is shown in the appendix.

4.1. Decentralized decision-making

Under decentralized decision-making, both manufacturers and suppliers use the maximization of their own interests as decision criterion. Based on the sharing of suppliers' R&D cost, manufacturers comprehensively consider the initial carbon quota set by the government, the low-carbon preference of consumers, the time lag of emission reduction technologies, and other factors when determining the required emission reduction technology R&D input level and carbon emission transfer level. After manufacturers determined the R&D input level, carbon emission transfer level, and R&D cost sharing coefficient ϕ, suppliers choose their carbon emission transfer undertaking level and R&D input level based on their own willingness. Clearly, this is a manufacturer-dominated Stackelberg differential game (denoted by superscript D). Based on the above game order and the emission reduction sharing coefficient given by manufacturers, manufacturers and suppliers' emission reduction technology R&D input level, carbon emission transfer level, and carbon emission transfer undertaking level can thus be calculated.

Proposition 1. *Under a manufacturer-dominated and supplier-followed decentralized decision-making scenario*:

$$T_M^D(t)=\frac{\gamma\beta L_M}{m\varphi(\delta+\rho)}e^{\delta d}-\frac{A}{\varphi}$$

$$R_M^D(t)=\frac{\gamma\beta L_M}{m(\delta+\rho)}e^{\delta d}$$

$$T_s^D(t)=\frac{\mu L_S-\theta}{k}$$

$$X^D=\frac{\gamma\beta L_S}{m(1-\phi)(\rho+\delta)}$$

$$E^D(t)=E_0e^{-\delta t}+\frac{\gamma^2\beta}{m\delta(\rho+\delta)}\left(L_Me^{\delta d}+\frac{L_S}{1-\phi}\right)\left(1-e^{-\delta t}\right)$$

$$\phi^D=\begin{cases}1-\dfrac{2L_S}{2L_M+L_S}, & \dfrac{L_M}{L_S}>\dfrac{1}{2}\\ 0 & ,0<\dfrac{L_M}{L_S}\le\dfrac{1}{2}\end{cases}$$

(1) The optimal decisions of manufacturers and suppliers are respectively:
(2) The optimal trajectory of carbon emission reduction per unit of output is:
(3) Manufacturers' cost sharing coefficient is:

The above results can be used to obtain the present values of profit of manufacturers, suppliers, and the supply chain:

$$J_M=\begin{cases}\dfrac{L_MD_0+\frac{1}{k}(\mu L_M+\theta)(\mu L_S-\theta)-\theta(H-\varepsilon I)}{\rho}+\dfrac{\beta L_ME_0}{\rho+\delta}+\dfrac{(\gamma\beta L_M)^2}{2\rho m(\rho+\delta)^2}\left(2e^{\delta d}-e^{2\delta d}+1\right)+\dfrac{(\gamma\beta)^2}{2m\rho(\rho+\delta)^2}\left(L_ML_S+\dfrac{L_S^2}{4}\right), & \dfrac{L_M}{L_S}>\dfrac{1}{2}\\ \dfrac{L_MD_0+\frac{1}{k}(\mu L_M+\theta)(\mu L_S-\theta)-\theta(H-\varepsilon I)}{\rho}+\dfrac{\beta L_ME_0}{\rho+\delta}+\dfrac{(\gamma\beta L_M)^2}{2\rho m(\rho+\delta)^2}\left(2e^{\delta d}-e^{2\delta d}\right)+\dfrac{(\gamma\beta)^2L_ML_S}{m\rho(\rho+\delta)^2}, & 0<\dfrac{L_M}{L_S}\le\dfrac{1}{2}\end{cases}$$

$$J_S=\begin{cases}\dfrac{L_SD_0+\theta O}{\rho}+\dfrac{\beta L_SE_0}{\rho+\delta}+\dfrac{(\gamma\beta L_S)^2}{4\rho m(\rho+\delta)^2}+\dfrac{(\gamma\beta)^2L_SL_M\left(2e^{\delta d}+1\right)}{2m\rho(\rho+\delta)^2}+\dfrac{\mu L_S(\mu L_S-\theta)}{\rho k}, & \dfrac{L_M}{L_S}>\dfrac{1}{2}\\ \dfrac{L_SD_0+\theta O}{\rho}+\dfrac{\beta L_SE_0}{\rho+\delta}+\dfrac{(\gamma\beta L_S)^2}{2\rho m(\rho+\delta)^2}+\dfrac{(\gamma\beta)^2L_ML_S}{m\rho(\rho+\delta)^2}e^{\delta d}+\dfrac{\mu L_S(\mu L_S-\theta)}{\rho k}, & 0<\dfrac{L_M}{L_S}\le\dfrac{1}{2}\end{cases}$$

$$J_{MS}=\begin{cases}\dfrac{(L_M+L_S)D_0+\theta(I-H)}{\rho}+\dfrac{(L_M+L_S)\beta E_0}{\rho+\delta}+\dfrac{(\mu L_S-\theta)(\mu L_M+\mu L_S+\theta)}{2\rho k}+\dfrac{(\gamma\beta)^2\left[\left(2L_M^2+2L_SL_M\right)e^{\delta d}-L_M^2e^{2\delta d}+L_M{}^2+2L_SL_M+\frac{3}{4}L_S^2\right]}{2m\rho(\rho+\delta)^2}, & \dfrac{L_M}{L_S}>\dfrac{1}{2}\\ \dfrac{(L_M+L_S)D_0+\theta(I-H)}{\rho}+\dfrac{(L_M+L_S)\beta E_0}{\rho+\delta}+\dfrac{(\mu L_S-\theta)(\mu L_M+\mu L_S+\theta)}{2\rho k}+\dfrac{(\gamma\beta)^2\left[\left(2L_M^2+2L_SL_M\right)e^{\delta d}-L_M{}^2e^{2\delta d}+2L_SL_M+L_S^2\right]}{2m\rho(\rho+\delta)^2}, & 0<\dfrac{L_M}{L_S}\le\dfrac{1}{2}\end{cases}$$

The proof of this Proposition is given in the Appendix.

4.2. Centralized decision-making

Under centralized decision-making, both manufacturers and suppliers reach a steady and binding cooperative agreement prior to cooperation, or realize collaborative emission reduction as advocated by the government. In this case, both manufacturers and suppliers act as a rational community, comprehensively considering the low-carbon preference of consumers and the time lag of emission reduction technologies. They also pursue the maximization of the supply chain profit as policy orientation; in this case, decision variables only include $T_M(t)(R_M(t))$, $T_S(t)$, and X. Superscript C representsthe optimal decision of each side under centralized decision-making.

Proposition 2. *Under centralized decision-making*:

$$T_M^C(t) = \frac{\gamma\beta(L_M + L_S)}{m\varphi(\rho+\delta)}e^{\delta d} - \frac{A}{\varphi}$$

$$R_M^C(t) = \frac{\gamma\beta(L_M + L_S)}{m(\rho+\delta)}e^{\delta d}$$

$$T_s^C(t) = \frac{\mu(L_M + L_S)}{k}$$

$$X^C = \frac{\gamma\beta(L_M + L_S)}{m(\rho+\delta)}$$

$$E^C(t) = E_0e^{-\delta t} + \frac{\gamma^2\beta(L_M + L_S)}{m\delta(\rho+\delta)}\left(e^{\delta d}+1\right)\left(1-e^{-\delta t}\right)$$

$$J_{MS} = \frac{(L_M + L_S)D_0 + \theta(I-H)}{\rho} + \frac{(L_M + L_S)\beta E_0}{\rho+\delta} + \frac{\mu^2(L_M + L_S)^2}{2\rho k} + \frac{(\gamma\beta)^2(L_M + L_S)^2}{2m\rho(\rho+\delta)^2}\left(2e^{\delta d} - e^{2\delta d} + 1\right)$$

(1) The optimal decisions of both manufacturers and suppliers are:
(2) The optimal trajectory of carbon emission reduction per unit of output is:
(3) The present value of the supply chain profit is:

The proof of this Proposition is given in the Appendix.

4.3. Model analysis

Based on the above game equilibrium results of manufacturers and suppliers under decentralized decision-making and centralized decision-making, the following corollaries apply:

Corollary 1. *As indicated in Propositions* 1 *and* 2, *under both decentralized decision-making and centralized decision-making, the lag phase of emission reduction technologies positively affects manufacturers' carbon emission transfer level and R&D input level*; *however, suppliers' carbon emission transfer undertaking level and R&D input level are not affected by the lag phase of emission reduction technologies*.

According to Corollary 1, the R&D input level of manufacturers is affected by the lag time of emission reduction technologies. Consequently, a longer lag time of emission reduction technologies leads to a higher R&D input by manufacturers, which further significantly increases the production cost of manufacturers. Thus, the carbon emissions transferred by manufacturers to suppliers also increase. However, considering the initial carbon quota surplus of suppliers and the low supply chain pressure of reducing carbon emissions, suppliers' carbon emission transfer undertaking level and emission reduction technology R&D level are not affected by the lag time of emission reduction technologies. As indicated in Propositions 1 and 2, suppliers' decisions about undertaking carbon emission transfer depend on their own marginal profit, manufacturers' marginal profit, and the influence of carbon emission transfer on market demand.

Corollary 2. *Similarly*, *as indicated by Propositions* 1 *and* 2, *under two decision scenarios*, *manufacturers' carbon emission transfer level and emission reduction technology R&D level as well as suppliers' emission reduction technology R&D level correlate positively with the low-carbon preference of consumers*; *however*, *suppliers' carbon emission transfer undertaking level is not affected by the low-carbon preference of consumers*.

According to Corollary 2, when consumers prefer low-carbon products, both manufacturers and suppliers will increase their R&D input in carbon emission reduction technologies. Compelled by the pressure of governmental carbon regulation and constrained by the time lag of emission reduction technologies, manufacturers tend to transfer excessive carbon emissions to suppliers with carbon quota surplus. When the low-carbon preference of consumers increases, manufacturers' emission reduction technology R&D input also increases. In this case, manufacturers transfer more carbon emissions to suppliers. However, suppliers' carbon emission transfer undertaking level is not affected by the low-carbon preference of consumers, but rather by the influence coefficient μ of the carbon emission transfer undertaking level on market demand, their own marginal profit L_S, and the cost k of undertaking carbon emission transfer. Thus, when making decisions about whether to accept carbon emission transfer by manufacturers, suppliers mainly start with their own interests.

Corollary 3. *A comparison between Propositions* 1 *and* 2*shows that*, *under centralized decision-making*, *manufacturers' carbon emission transfer level and emission reduction technology R&D level are more likely affected by the lag time of emission reduction technologies and the low-carbon preference of consumers*; *the emission reduction technology R&D level of suppliers is more likely affected by the low-carbon preference of consumers under decentralized decision-making*; *however, suppliers' R&D input level under decentralized decision-making is always lower than under centralized decision-making.*

According to Corollary 3, under centralized decision-making, information is shared within the supply chain, and information spreading is faster under decision-making; therefore, manufacturers are more sensitive and responsive to the lag time of emission reduction technologies and the low-carbon preference of consumers. Under decentralized decision-making, supply chain members make their decisions based on their own interests; therefore, with increasing low-carbon preference of consumers, suppliers' emission reduction technology R&D inputs increase as well. In contrast, under centralized decision-making, supply chain members make their decisions to achieve the maximization of supply chain profit, while emission reduction tasks are mostly undertaken by manufacturers. In this case, the influence of the low-carbon preference of consumers on the emission reduction technology R&D input of suppliers declines.

Corollary 4. *Under centralized decision-making*, *manufacturers' R&D level and carbon emission transfer level are both higher than* *under decentralized decision-making; suppliers' carbon emission transfer undertaking level is higher than under decentralized decision-making.*

According to Corollary 4, due to the sensitivity of manufacturers to the lag time of emission reduction technologies and the low-carbon preference of consumers, both their R&D level and carbon emission transfer level under centralized decision-making are higher than under decentralized decision-making. This suggests that, under centralized decision-making, the carbon emissions transferred by manufacturers to suppliers exceed their carbon quota deficit; furthermore, by increasing carbon emission transfer, manufacturers stimulate suppliers to assume more carbon emission transfer. As indicated by Propositions 1 and 2, suppliers' carbon emission transfer undertaking under centralized decision-making is higher than under decentralized decision-making. In reality, this manifests as a misrepresentation on the part of manufacturers under centralized decision-making, which interferes with suppliers' judgment and causes them to make unexpected decisions.

Corollary 5. *Under decentralized decision-making,* $T_S^D(t)=\frac{\mu L_S-\theta}{k}$, *in which case* $\varepsilon I\le T_S^D(t)\le I$; *thus, when* $\frac{\varepsilon Ik+\theta}{L_S}\le\mu\le\frac{kI+\theta}{L_S}$, *(i.e., when suppliers' carbon emission transfer undertaking behavior exerts a positive influence on market demand), this influencing coefficient is negatively correlated with suppliers' marginal profit, but positively correlated with the average carbon price on the market.*

According to Corollary 5, when suppliers undertake carbon emission transfer from manufacturers, they stimulate an increase of market demand. In essence, undertaking carbon emission transfer by suppliers alleviates the pressure to reduce carbon emissions on manufacturers and motivates manufacturers to invest more energy in emission reduction technology R&D, thus increasing the emission reduction per unit of output. In addition, formula $T_S^D(t)=\frac{\mu L_S-\theta}{k}$ shows that the relationship between the impact coefficient of carbon emission transfer behavior on market demand and the supplier's marginal profit and average carbon trading price contrast with the carbon emission transfer undertaking behavior. This also shows that when the supplier undertakes excessive carbon emission transfer, the manufacturer's enthusiasm for reducing emissions will actually decrease, thus further reducing market demand. The range of influencing coefficient μ suggests that suppliers' carbon emission transfer undertaking behavior exertsa limited influence on market demand. This is because market demand is affected by emission reduction per unit of output, which in turn, is controlled by the lag time of emission reduction technologies and the low-carbon preference of consumers.

Corollary 6. *Under decentralized decision-making, when* $0<d<\frac{1}{\delta}\ln\left(\frac{m\delta(\rho+\delta)E_0}{\gamma^2\beta L_M}-\frac{2L_M+L_S}{2L_M}\right)$ *or* $\beta<\frac{m\delta(\rho+\delta)E_0}{\gamma^2\left(L_Me^{\delta d}+\frac{2L_M+L_S}{2L_M}\right)}$, *the emission reduction per unit of output decreases with time and vice versa. Similarly, under centralized decision-making, when* $0<d<\frac{1}{\delta}\ln\left(\frac{m\delta(\rho+\delta)E_0}{\gamma^2\beta(L_M+L_S)}-1\right)$ *or* $\beta<\frac{m\delta(\rho+\delta)E_0}{\gamma^2(L_M+L_S)(e^{\delta d}+1)}$, *emission reduction per unit of output decreases with time and vice versa.*

Demonstration: Assuming $\frac{\partial E^D(t)}{\partial t}=-\delta E_0e^{-\delta t}+\frac{\gamma^2\beta}{m(\rho+\delta)}\left(L_Me^{\delta d}+\frac{2L_M+L_S}{2}\right)e^{-\delta t}<0$, then $d<\frac{1}{\delta}\ln\left(\frac{m\delta(\rho+\delta)E_0}{\gamma^2\beta L_M}-\frac{2L_M+L_S}{2L_M}\right)$, $\beta<\frac{m\delta(\rho+\delta)E_0}{\gamma^2\left(L_Me^{\delta d}+\frac{2L_M+L_S}{2L_M}\right)}$; similarly, assuming $\frac{\partial E^C(t)}{\partial t}=-\delta E_0e^{-\delta t}+\frac{\gamma^2\beta(L_M+L_S)}{m(\rho+\delta)}(e^{\delta d}+1)e^{-\delta t}$; then, $d<\frac{1}{\delta}\ln\left(\frac{m\delta(\rho+\delta)E_0}{\gamma^2\beta(L_M+L_S)}-1\right)$, $\beta<\frac{m\delta(\rho+\delta)E_0}{\gamma^2(L_M+L_S)(e^{\delta d}+1)}$.

According to Corollary 6, emission reduction per unit of output is affected by the lag time of emission reduction technologies and the low-carbon preference of consumers under both decision scenarios. When the lag time of emission reduction technologies is long and the low-carbon preference of consumers is high, emission reduction per unit of output increases with time. In contrast, when the lag time of emission reduction technologies is short and the low-carbon preference of consumers is small, the emission reduction per unit of output decreases with time. The reason is that in the latter case, the R&D input level of manufacturers declines, and the increase of emission reduction per unit of output induced by the R&D input is less than the attenuation of emission reduction per unit of output; in the former case, manufacturers are compelled to increase their R&D input, which further increases emission reduction per unit of output.

Corollary 7. *Under decentralized decision-making, when* $0<d<\frac{1}{\delta}\ln\left(\frac{L_M+L_S}{L_M}\right)$, *the supply chain profit increases with the lag time of emission reduction technologies; when* $d>\frac{1}{\delta}\ln\left(\frac{L_M+L_S}{L_M}\right)$, *the supply chain profit decreases with the lag time of emission reduction technologies; under centralized decision-making, the supply chain profit continues to decrease with the lag time of emission reduction technologies.*

Demonstration: Assuming $\frac{\partial J_{MS}^D}{\partial d}=\frac{(\gamma\beta)^2[\delta(2L_M^2+2L_SL_M)e^{\delta d}-2\delta L_M^2e^{2\delta d}]}{2m\rho(\rho+\delta)^2}=0$, then $d=\frac{1}{\delta}\ln\frac{L_S+L_M}{L_M}$; when $0<d\le\frac{1}{\delta}\ln\frac{L_S+L_M}{L_M}$ $\frac{\partial J_{MS}^D}{\partial d}>0$, and vice versa. Assuming $\frac{\partial J_{MS}^C}{\partial d}=\frac{\delta(\gamma\beta)^2(L_M+L_S)^2}{m\rho(\rho+\delta)^2}(e^{\delta d}-e^{2\delta d})=0$, then $d=0$, and $\frac{\partial J_{MS}^C}{\partial d}<0$ is always valid; therefore, the demonstration is complete.

According to Corollary 7, under decentralized decision-making, when the lag phase of emission reduction technologies is short, the supply chain profit is directly proportional to the lag time of emission reduction technologies; however, when the lag time is long, the supply chain profit is inversely proportional to the lag time of emission reduction technologies. Under centralized decision-making, the supply chain profit continues to decrease with the lag time of emission reduction technologies. This is mainly because, when the lag phase of emission reduction technologies is short, the R&D input under decentralized decision-making is less than under centralized decision-making (as indicated in Propositions 1 and 2); furthermore, when the lag phase of emission reduction technologies is short and R&D is profitable, suppliers will obtain profit and thus accept more carbon emissions transferred by manufacturers. According to Theorem 5, as a result of the increased market demand, the supply chain profit increases. In contrast, under centralized decision-making, due to their overreaction to the lag time of emission reduction technologies, manufacturers always use a high R&D input level. In this case, the demand increased because the carbon emission transfer undertaking by suppliers is not sufficient to offset the high R&D cost (and the influence of carbon emission transfer on market demand exists within a certain scope); therefore, a longer lag phase leads to less supply chain profit in the short term.

Corollary 8. *Under decentralized decision-making, when* $0\le d<\frac{1}{\delta}\ln\left[\left(1+\frac{L_S}{L_M}\right)+\sqrt{\left(1+\frac{L_S}{L_M}\right)^2+1+2\frac{L_S}{L_M}+\frac{3}{4}\left(\frac{L_S}{L_M}\right)^2}\right]$, *the-supply chain profit increases with increased low-carbon preference of* *consumers; when* $d > \frac{1}{\delta}\ln\left[\left(1+\frac{L_S}{L_M}\right)+\sqrt{\left(1+\frac{L_S}{L_M}\right)^2+1+2\frac{L_S}{L_M}+\frac{3}{4}\left(\frac{L_S}{L_M}\right)^2}\right]$, *the supply chain profit decreases with increased low-carbon preference of consumers. In contrast, under centralized decision-making, when* $0 \le d < \frac{1}{\delta}\ln(1+\sqrt{2})$, *thesupply chain profit is positively correlated with the low-carbon preference of consumers; when* $d > \frac{1}{\delta}\ln(1+\sqrt{2})$, *the supply chain profit is negatively correlated with the low-carbon preference of consumers.*

Demonstration: Assuming $\frac{\partial J_{MS}^D}{\partial \beta} = \frac{(L_M+L_S)E_0}{\rho+\delta} + \frac{\gamma^2\beta\left[(2L_M^2+2L_SL_M)e^{\delta d}-L_M^2e^{2\delta d}+L_M^2+2L_SL_M+\frac{3}{4}L_S^2\right]}{m\rho(\rho+\delta)^2} = 0$, then

$$\beta = -\frac{m\rho(\rho+\delta)(L_M+L_S)E_0}{\gamma^2\left[(2L_M^2+2L_SL_M)e^{\delta d}-{L_M}^2e^{2\delta d}+L_M^2+2L_SL_M+\frac{3}{4}L_S^2\right]}$$

$$= -\frac{m\rho(\rho+\delta)\left(1+\frac{L_S}{L_M}\right)E_0}{L_M\gamma^2\left[\left(2+2\frac{L_S}{L_M}\right)e^{\delta d}-e^{2\delta d}+1+2\frac{L_S}{L_M}+\frac{3}{4}\left(\frac{L_S}{L_M}\right)^2\right]}$$

. Calculation shows that,

when $0 \le d < \frac{1}{\delta}\ln\left[\left(1+\frac{L_S}{L_M}\right)+\sqrt{\left(1+\frac{L_S}{L_M}\right)^2+1+2\frac{L_S}{L_M}+\frac{3}{4}\left(\frac{L_S}{L_M}\right)^2}\right]$, $\frac{\partial J_{MS}^D}{\partial \beta} > 0$; when $d > \frac{1}{\delta}\ln\left[\left(1+\frac{L_S}{L_M}\right)+\sqrt{\left(1+\frac{L_S}{L_M}\right)^2+1+2\frac{L_S}{L_M}+\frac{3}{4}\left(\frac{L_S}{L_M}\right)^2}\right]$, $\frac{\partial J_{MS}^D}{\partial \beta} < 0$.

Assuming $\frac{\partial J_{MS}^C}{\partial \beta} = \frac{(L_M+L_S)E_0}{\rho+\delta} + \frac{\gamma^2\beta(L_M+L_S)^2}{m\rho(\rho+\delta)^2}(2e^{\delta d}-e^{2\delta d}+1)$, calculation shows that, when $0 \le d < \frac{1}{\delta}\ln(1+\sqrt{2})$, $\frac{\partial J_{MS}^C}{\partial \beta} > 0$; when $d > \frac{1}{\delta}\ln(1+\sqrt{2})$, $\frac{\partial J_{MS}^C}{\partial \beta} < 0$; therefore, thedemonstration is complete.

According to Corollary 8, when investigating the influence of the low-carbon preference of consumers on the profit of the supply chain, the lag time of emission reduction technologies must inevitably be considered. Wang et al. (2019) only considered the impact of consumers' low-carbon preference and proposed that the profit of supply chain increases with increasing low-carbon preference of consumers. Similarly, Ji et al. (2017) also pointed out that, under the cap-and-trade system, supply chain enterprises can only be profitable if consumers' low-carbon preference remains within a certain range. In contrast to these studies, this paper points out that the influence of the low-carbon preference of consumers on supply chain profit is affected by the lag time of emission reduction technologies; furthermore, the increase of the low-carbon preference of consumers only exerts a positive influence on the supply chain profit when the lag time of emission reduction technologies remains within a certain range. This is because, when the lag time of emission reduction technologies falls within a certain range, manufacturers actively respond to the demands of both the government and consumers, and thus increase the intensity and pace of emission reduction. In this process, manufacturers bear an increasing emission reduction cost, which further leads to an increase of carbon emission transfer; in contrast, suppliers witness an increase in both marginal profit and carbon emission transfer undertaking; the consumer preference for low-carbon products increases the quantity of manufacturing orders, which further increases supply-chain profit. However, when the lag time of emission reduction technologies exceeds a certain threshold, the increase in the difficulty and cost of emission reduction will slow down the pace of emission reduction by manufacturers and suppliers, and abate their enthusiasm for the reduction of carbon emissions. In this case, manufacturers' carbon emission transfer increases continuously; however, the decrease of suppliers' marginal profit also decreases their carbon emission transfer undertaking. Thus, increasing the low-carbon preference of consumers decreases the sales volume of products with a low emission reduction rate, which eventually results in a decrease of supply chain profit. According to this comparison, under decentralized decision-making, the low-carbon preference of consumers promotes an increase of the supply chain profit within a wide range of the lag time of emission reduction technologies. This indicates that, under decentralized decision-making, the emission reduction system of the supply chain has stronger pressure resistance. In contrast, under centralized decision-making, supply chain subjects have more intense responses due to information sharing; therefore, a longer lag time of emission reduction technologies leads to more R&D input into the supply chain (Corollary 1). However, the embodiment of the emission reduction effect is slow; therefore, in this case, higher low-carbon preference on the part of consumers results in lower supply chain profit.

5. Analysis of examples

To verify the credibility of the above conclusion and the sensitivity of various important parameters, this section performs numerical analyses from three aspects: carbon emission transfer, emission reduction per unit of output, and supply chain profit. Variable assignments in this section are as follows: $\rho = 0.3$, $m = 1$, $k = 0.5$, $\gamma = 0.8$, $\delta = 0.2$, $D_0 = 5$, $\beta = 3$, $\mu = 1.5$, $L_M = 10$, $\Phi = 1.5$, $L_S = 8$, $E_0 = 30$, $A = 15$, $d = 4$, $\theta = 10.00(\text{RMB}/t)$, $\varepsilon = 0.1$, $I = 60(t)$, $H = 50(t)$(Zhou and Ye, 2018; Xu et al., 2016b).

5.1. Analysis of carbon emission transfer

Fig. 3 (a), 3 (b)and 3(c)reflect the influence of lag time and consumer low-carbon preference on manufacturers' carbon emission transfer. According to Fig. 3 (a) and (b), the carbon emission transfer increases with increasing lag time and consumer low-carbon preference. However, observations showed that, a lag time of 0 is also associated with carbon emission transfer by manufacturers, which is mainly the result of the external influence of the low-carbon preference of consumers and governmental regulation. This suggests that manufacturers are willing to decrease and transfer carbon emissions as long as both low-carbon preference and governmental regulation are in place. However, manufacturers want to mitigate their own emissions by shifting carbon, rather than investing a substantial cost for immediately decreasing emissions. When $d < 4$, the carbon emission transfer increases slowly with time; when the lag time increases, carbon emission transfer increases at a faster pace. When the low-carbon preference of consumers is 0, there is no carbon emission transfer by manufacturers.

This suggests that, when consumers have no low-carbon preference and emission reduction technologies have a time lag, manufacturers will have no obvious willingness to reduce carbon emissions. This is true even if governmental regulation is in place, which is mainly due to the low pressure of reducing carbon emissions. With increasing low-carbon preference of consumers, manufacturers' carbon emission transfer increases steadily, and both

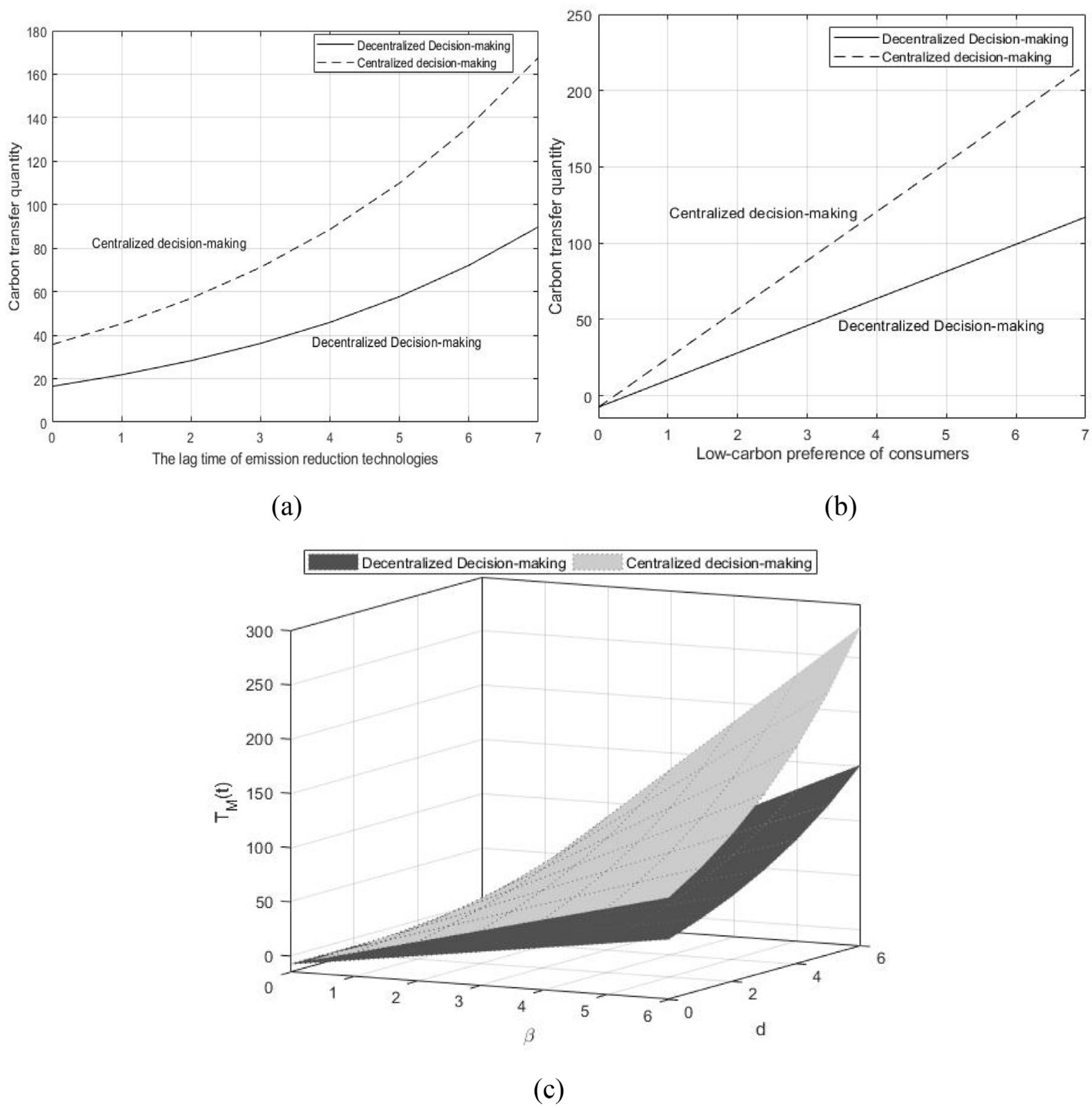

Fig. 3. Influence of lag time and consumer low-carbon preference on carbon emission transfer under different decision-making scenarios.

follow an obvious linear relationship. Compared with the lag time of emission reduction technologies, the low-carbon preference of consumers exerts a more significant influence on carbon emission transfer. According to Fig. 3(c), the increase of the low-carbon preference of consumers causes the lag time to exert a stronger influence on carbon emission transfer and vice versa.

5.2. Analysis on emission reduction per unit of output

Fig. 4 reflects the influence of consumer low-carbon preference and lag time on emission reduction per unit of output. As shown in Fig. 4(a), the emission reduction per unit of output increases with time under two decision scenarios; however, the emission reduction per unit of output under decentralized decision-making is always lower than that under centralized decision-making. Fig. 4(b) shows that the carbon emission reduction per unit of output increases with increasing low-carbon preference of consumers; however, when the low-carbon preference of consumers decreases below 2, the carbon emission reduction per unit of output shows no clear change with time; when the low-carbon preference of consumers increases, carbon emission reduction per unit of output increases at an increasingly higher rate. According to the analysis presented in Section 4.1, when the low-carbon preference of consumers is low, the members of the supply chain (especially manufacturers without information sharing) cannot perceive changes of consumer demand in a timely manner. In this case, insufficient R&D input in emission reduction technologies results in non-significant changes of emission reduction per unit of output. Under centralized decision-making, the carbon emission reduction per unit of output is, to a large extent, affected by the low-carbon preference of consumers. Consequently, under centralized decision-making, due to information sharing between manufacturers and suppliers, manufacturers can timely acquire knowledge about the low-carbon preference of consumers, and thus invest more R&D input in emission reduction technologies.

Fig. 4(c)shows that, under centralized decision-making, emission reduction per unit of output is, to a large extent, affected by the lag time of emission reduction technologies. When $d < 4$, carbon

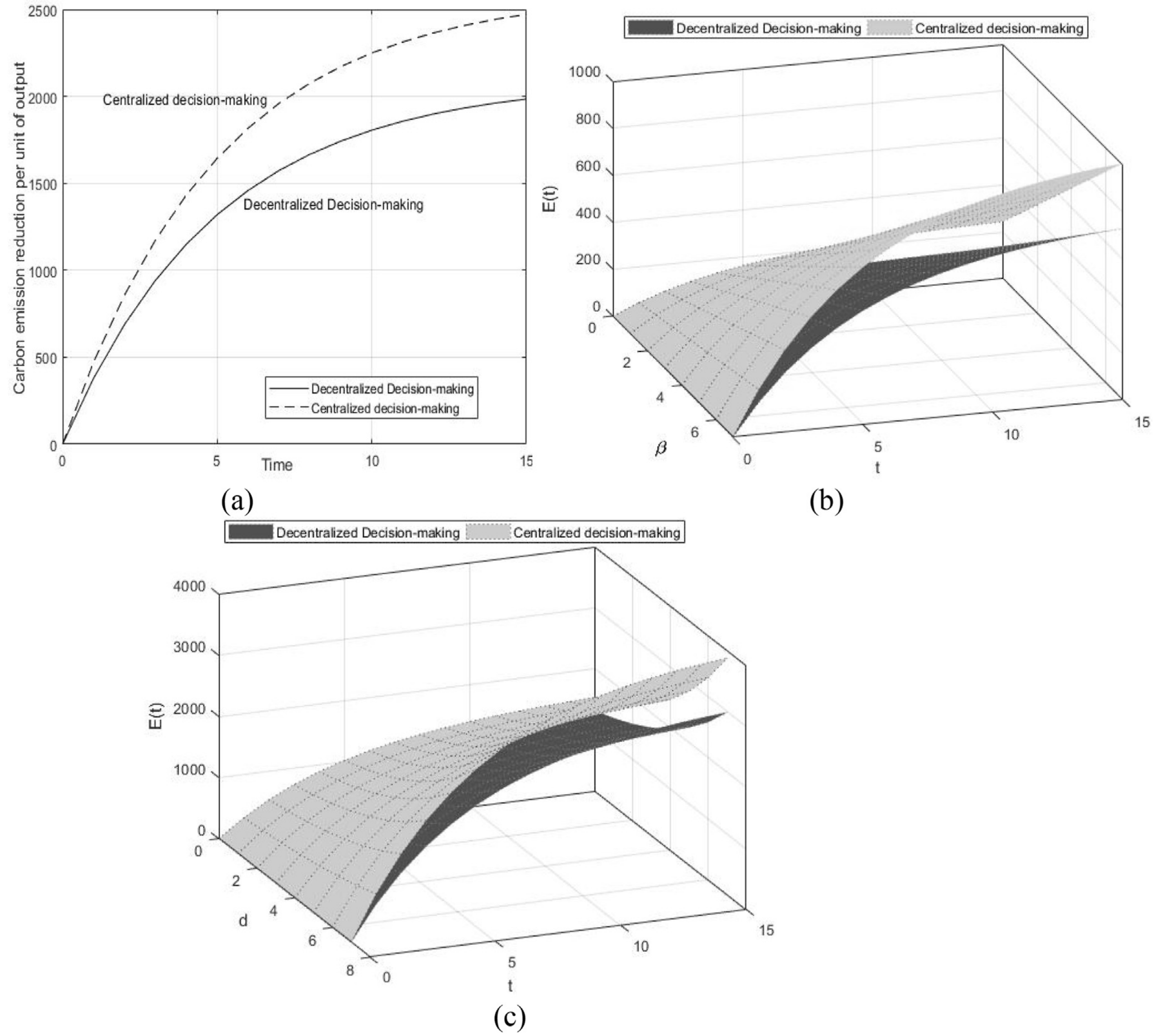

Fig. 4. Influence of lag time and consumer low-carbon preference. on emission reduction per unit of output.

emission reduction per unit of output increases slowly with time; when the lag time increases, carbon emission reduction per unit of output increases at an increased rate. The reason for this is that because of the presence of a lag phase, it takes time for the initial input in emission reduction technology R&D to manifest its effect; moreover, the emission reduction technology R&D input of manufacturers also increases with increasing lag time of emission reduction technologies. A comparison between (b) and (c) indicates that, compared with the lag time, a low-carbon preference of consumers can more significantly promote carbon emission reduction per unit of output.

5.3. Analysis on supply chain profit

Fig.5showsthe influence of lag time and consumer low-carbon preference on the total supply chain profit. As shown in Fig. 5 (a) and (b), when the low-carbon preference of consumers and the lag time of emission reduction technologies are considered separately, supply chain profit is inversely proportional to the lag time of emission reduction technologies, and directly proportional to the low-carbon preference of consumers under all three decision scenarios. When the lag time of emission reduction technologies increases, the R&D input of manufacturers increases as well, thus enabling it to gain short-term payback; therefore, a longer lag phase indicates a lower total supply chain profit. According to Fig. 5(c), (d), and (e), when the lag time is less than 3, the positive influence of the low-carbon preference of consumers outweighs the negative influence of the lag time of emission reduction technologies; moreover, higher consumer low-carbon preference leads to higher supply chain profit. In this case, the profit under centralized decision-making is always higher than under decentralized decision-making. When the lag time exceeds 3, the supply chain profit decreases under both scenarios; when the low-carbon preference of consumers is less than 1.2, compared with decentralized decision-making, centralized decision-making has less R&D input, and higher supply chain profit; however, when the low-carbon preference of consumers exceeds 1.2, the supply chain profit under decentralized decision-making gradually exceeds that under centralized decision-making.

This suggests that, when the lag phase of emission reduction technologies is long, under centralized decision-making, cooperation among supply chain enterprises does not induce an increase of supply chain profit; instead, decentralized decision-making, with the attribute of contractual sharing, seems to be superior in this regard. This conclusion differs from the conclusion drawn by Ye et al. (2018). Existing studies mostly stated that the supply chain profit increases with increasing low-carbon preference of consumers, and that supply chain profit is higher under centralized

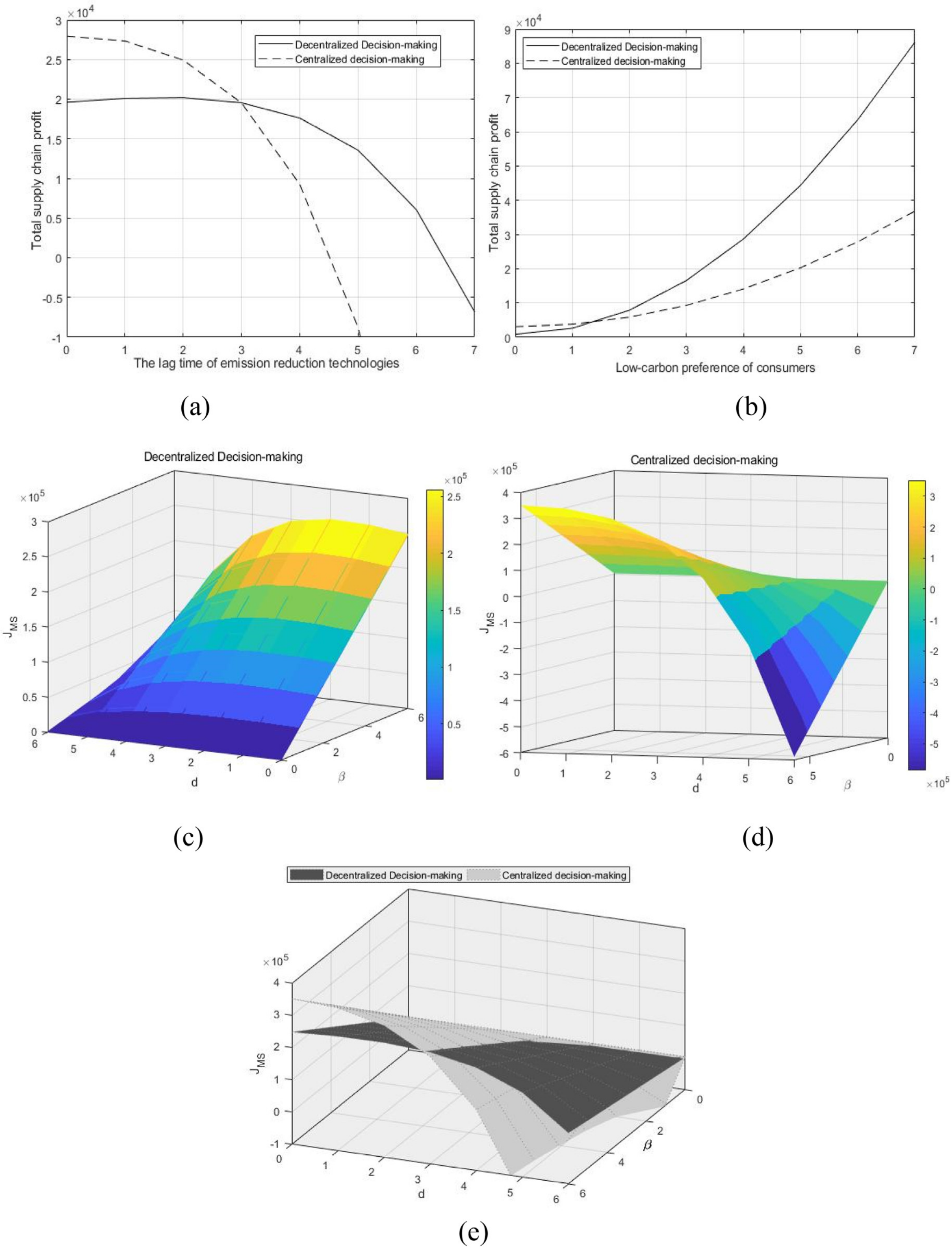

Fig. 5. Influence of lag time and consumer low-carbon preference on total supply chain profit.

decision-making. However, this paper shows that, when the lag time of emission reduction technologies is long, supply chain profit is only higher under centralized decision-making while low-carbon preference remains within a certain range. Therefore, when the lag phase is short, supply chain enterprises tend to select centralized decision-making, or further coordinate contractual sharing to achieve the same effect under centralized decision-making; otherwise, they tend to continue to use current decentralized decision-making.

As indicated in combination with the analysis presented in Section4.2, when the lag time is short, and the low-carbon preference of consumers is high, the Porter hypothesis is verified. The combination of proper governmental regulation and modest encouraging by consumers not only increases supply chain profit, but also continuously increases carbon emission reduction per unit of output, thus creating a win-win scenario in the supply chain. However, when the lag time is long, when considering the total supply chain profit, supply chain enterprises tend to select decentralized decision-making. Then, carbon emission reduction per unit of output is far less than under centralized decision-making and a contradiction is integrated into supply chain goals.

For this reason, the government should further strengthen consumers' low-carbon education, enhance their low-carbon awareness, and intensify the positive influence of the low-carbon preference of consumers on supply chain profit; in contrast, enterprises of the supply chain should improve their technical level as soon as possible, shorten the lag time of emission reduction technologies, and enhance the flexibility of their supply chain; otherwise, the increase of lag time will result in a continuous decline of supply chain profit.

6. Conclusions and managerial insights

6.1. Conclusions

Under the governmental carbon regulation and with the mission of optimizing the structure of carbon emission transfer in supply chain, this paper aims to optimize the structure of carbon emission transfer in supply chain, and promote the construction of a low-carbon supply chain system. Based on previous studies, by building a manufacturer-dominated Stackelberg differential game model, this paper investigated the influencing mechanism of both the time lag of emission reduction technologies and the low-carbon preference of consumers on carbon emission transfer in supply chain, while the previous literature neglects the impact of the limitations of enterprise emission reduction by simply considered the impact of market low-carbon preference and government policies and regulations. We conclude this paper through three perspectives: carbon emission transfer, carbon emission reduction per unit output, and supply chain profit.

(1) Manufacturers' carbon emission transfer is affected by the lag time of emission reduction technologies as well as the consumers' low-carbon preferences, however, this preponement does not happen to suppliers' carbon emission transferring or undertaking. Without considering the new cost-sharing model of supply chain carbon emission transfer, most previous studies have concluded that centralized decision-making outperforms decentralized decision-making. However, in the context of this paper, centralized decision-making without intervention will allocate too much burden of transferring on the shoulders of supplier, resulting in a relaxation and hence slackness of emission control from manufacturer. This is "irrational carbon transfer" and is not conducive to the realization of the overall emission reduction target of the supply chain. In addition, the carbon emission transfer and emission reduction behavior of manufacturers are more likely to be affected by the lag time of emission reduction technologies and the low-carbon preference of consumers under centralized decision-making, while the emission reduction behavior of suppliers is more subject to the low-carbon preference of consumers under decentralized decision-making.

(2) Emission reduction per unit of output is affected by the lag time of emission reduction technologies and the low-carbon preference of consumers in both scenarios of centralized and decentralized decision-making. Emission reduction per unit of output only increases by time when the lag time of emission reduction technologies and the low-carbon preference of consumers exceed certain thresholds. This result indicates that, governmental policies and regulations alone can promote little to emission reduction in the supply chain when these two indicators are relatively low. As we also notice that, this finding is consistent to the arguments of Ji et al. (2017), which means that government policy needs to take other relevant factors into account to ensure it achieve the maximum extent, otherwise it is likely to lose its effectiveness.

(3) When the lag period of emission reduction technology is short under decentralized decision-making, profit from the supply chain is proportional to the lag time of the emission reduction technology; Oppositely, when the lag period is long, their relation is inversely proportional. For centralized decision-making, the profit is decreasing in the lag time of the emission reduction technology. When exploring the impact of consumers' low-carbon preferences on supply chain profits, it is necessary to consider the impact of lagging technologies on the lag. An increase in consumers' low-carbon preferences will positively affect the supply chain profit only when the lag time of mitigation technologies falls within a certain range. This finding extends the research conclusion of Wang et al. (2019) and Ji et al. (2017) who ignored the influence of the lag time of emission reduction technology in their study. This illuminates that supply chain companies and policy makers cannot ignore the impact of lagging emission reduction technology.

Based on the above analysis, when the delay time of emission reduction technology and the low carbon preference of consumers remain within a certain range, the carbon emission reduction per unit of product and the profit of the supply chain can be simultaneously increased. In other words, carbon emission transfer is beneficial to the emission reduction of the supply chain within a certain range. The above conclusion also shows that when only considering the market factor of consumers' low-carbon preference, the behavior of enterprises in the supply chain cannot be accurately extracted, and the influence factors of internal emission reduction should be considered. This is also one of the research significances of this paper.

6.2. Managerial insights

The management significance of this study is presented from two aspects: First, the implications for manufacturers' managers are considered. Secondly, the implications of the research results for policy makers are identified.

The results of this study show that the excessive lag time of emission reduction technology and carbon emission transfer undertaking level will inhibit the enthusiasm of enterprises to engage in emission reduction, while consumers' low carbon preference can increase the enthusiasm of supply chain enterprises to engage in emission reduction. The emission reduction behavior of suppliers is more likely to be influenced by the low carbon preference of consumers under decentralized decision-making. Therefore, for manufacturers, the first step is to use clean production technology to improve their emission reduction capacity and reduce the lag period of emission reduction technology. Secondly, to promote suppliers' emission reduction, it is necessary to constantly pay attention to consumers' low-carbon preference, analyze consumers' low-carbon preference through consumers' purchasing behavior, and provide timely feedback to upstream suppliers.

The carbon emission transfer behavior of the supply chain is essentially caused by an imbalance of internal resources in the supply chain, which in turn is caused by incomplete information when the government conducts quota allocation. Therefore, before quota allocation, the government should first investigate the emission reduction capacity and the lag time of emission reduction technology of the supply chain enterprises, to ensure that the formulated carbon quota is in line with the actual situation of enterprises and thus, more acceptable to enterprises. Second, this paper shows that when consumers' low-carbon preference is too low, enterprises' enthusiasm for emission reduction cannot be mobilized well. Therefore, the government needs to further strengthen consumers' low-carbon education, improve consumers' low-carbon awareness, and strengthen the positive impact of consumers' low-carbon preference on the reduction of supply chain emissions. Third, when the lag time of emission reduction technology is very high, even if consumers' low-carbon preference exists, this preference cannot stimulate manufacturers to reduce emission. Therefore, the government should help relevant enterprises to reduce the lag time of emission reduction technology, i.e., by providing technical assistance and R&D funds. Finally, because of the imperfect carbon trading market and oversupply, when suppliers undertake excessive carbon emissions transfers, manufacturers will be subject to emission reduction inertia, which will affect the emission reduction process of the entire supply chain. Therefore, the government needs to adjust the market carbon trading price to increase the enthusiasm of suppliers to sell excess carbon quotas, thus preventing the occurrence of irrational carbon transfer within the supply chain.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Licheng Sun: Writing - original draft, Supervision, Funding acquisition, Project administration. **Xiaoxiao Cao:** Software. **Majed Alharthi:** Methodology. **Jijian Zhang:** Formal analysis. **Farhad Taghizadeh-Hesary:** Writing - review & editing. **Muhammad Mohsin:** Conceptualization.

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Appendix

Proof of Proposition 1

Under decentralized decision-making, both manufacturers and suppliers use the maximization of their own interests as decision criteria. The Hamilton function is used to solve the optimal control problem (Chen and Huang, 2018). According to the objective functions of manufacturer M and supplier S, the Hamilton functions of both manufacturer and supplier are:

$$H_M = \ell^{-\rho t}\left\{L_M D(t) - C_M(t) - \phi\frac{1}{2}mX^2 - \theta[H - \varepsilon I - T_S(t)]\right\}$$
$$+S(t)[\gamma(\varphi T_M(t-d)+A)+\gamma X - \delta E(t)] \tag{A1}$$

$$H_S = \ell^{-\rho t}\left\{L_S D(t) + \phi\frac{1}{2}mX^2 - C_S(t) + \theta[O - T_S(t)]\right\}$$
$$+S(t)[\gamma(\varphi T_M(t-d)+A)+\gamma X - \delta E(t)] \tag{A2}$$

The necessary condition of manufacturers' optimal control problem is:

$$\frac{\partial H_M}{\partial T_M} = 0 \tag{A3}$$

$$\dot{S}(t) = -\frac{\partial H_M}{\partial E(t)} \tag{A4}$$

Simplifying Formula (A3) yields:

$$\frac{\partial H_M}{\partial T_M} = -e^{-\rho t} m\varphi(\varphi T_M(t)+A) + \gamma\varphi S(t)\frac{\partial T_M(t-d)}{\partial T_M(t)} = 0 \tag{A5}$$

Assuming $\frac{\partial T_M(t-d)}{\partial T_M(t)} = G(t)$, then $G(t) = \Phi(t-d,t) = e^{\delta d}$ (Chen and Huang, 2018; Basin et al., 2006).

After substitution,

$$T_M(t) = \frac{\gamma S(t)}{m\varphi}e^{\delta d+\rho t} - \frac{A}{\varphi} \tag{A6}$$

Simplifying Formula (A4) yields:

$$\dot{S}(t) = -\frac{\partial H_M}{\partial E(t)} = \delta S(t) - \beta L_M e^{-\rho t} \tag{A7}$$

Solving this differential equation yields:

$$S(t) = \frac{\beta L_M}{\delta+\rho}e^{-\rho t} + ce^{\delta t} \tag{A8}$$

Substituting this into Formula (A6) yields manufacturer's optimal carbon emission transfer under decentralized decision-making:

$$T_M^D(t) = \frac{\gamma\beta L_M}{m\varphi(\delta+\rho)}e^{\delta d} + \frac{\gamma}{m\varphi}ce^{\delta d+\rho t+\delta t} - \frac{A}{\varphi} \tag{A9}$$

Manufacturers' emission reduction efforts and carbon emission transfer level are limited, and cannot infinitely increase with the passage of time; therefore, $c = 0$. In this case, manufacturers' optimal carbon emission transfer level is:

$$T_M^D(t) = \frac{\gamma\beta L_M}{m\varphi(\delta+\rho)}e^{\delta d} - \frac{A}{\varphi} \tag{A10}$$

Then, manufacturers' optimal emission reduction technology R&D input is:

$$R_M^D(t) = \frac{\gamma\beta L_M}{m(\delta+\rho)}e^{\delta d} \tag{A11}$$

To solve the optimal behavior of the supplier, it is necessary to take the partial derivative of the supplier's objective function with respect toT_S and X.

$$\frac{\partial H_S}{\partial T_S} = e^{-\rho t}[L_S\mu - kT_s(t) - \theta] = 0 \tag{A12}$$

$$\frac{\partial H_S}{\partial X} = e^{-\rho t}(\phi-1)mX + \gamma S(t) = 0 \tag{A13}$$

The solution of $S(t)$ is the same as above, and can be written as below.

$$S(t) = \frac{\beta L_S}{\delta + \rho} e^{-\rho t} + c e^{\delta t} \tag{A14}$$

Substituting this into Formula (A13) yields,

$$T_S^D(t) = \frac{\mu L_S - \theta}{k} \tag{A15}$$

$$X^D = \frac{\gamma \beta L_S}{m(1-\phi)(\rho+\delta)} \tag{A16}$$

Substituting Formulas (A10) and (A16) into the differential equation of the carbon emission reduction per unit of output, we have

$$\dot{E}(t) = \gamma R_M(t-d) + \gamma X - \delta E(t) = \gamma(\varphi T_M(t-d) + A) + \gamma X - \delta E(t) \tag{A17}$$

By solving this differential equation, we obtain the carbon emission reduction per unit of output:

$$E^D(t) = E_0 e^{-\delta t} + \frac{\gamma^2 \beta}{m\delta(\rho+\delta)} \left(L_M e^{\delta d} + \frac{L_S}{1-\phi} \right) \left(1 - e^{-\delta t}\right) \tag{A18}$$

Substituting the above conclusion into manufacturers' present value of profit yields:

$$J_M = \frac{L_M[D_0 + \mu T_S(t)] + C_M(t) + \phi \frac{1}{2} m X^2 + \theta[H - \varepsilon I - T_S(t)]}{\rho} + \frac{\beta L_M E_0}{\rho + \delta} + \frac{\gamma \beta L_M (R_M(t) + X)}{\rho(\rho+\delta)} \tag{A19}$$

To identify the optimal cost-sharing ratio of manufacturers, the following assumption is made:

$$\frac{\partial J_M}{\partial \phi} = -\frac{(\gamma\beta)^2 L_M L_S}{m\rho(\rho+\delta)^2(1-\phi)^2} - \frac{(\gamma \beta L_S)^2 \left[(1-\phi)^2 + 2(1-\phi)\phi\right]}{2m\rho(\rho+\delta)^2(1-\phi)^4} = 0 \tag{A20}$$

Simplifying the above formula yields:

$$\phi^D = \begin{cases} 1 - \dfrac{2L_S}{2L_M + L_S}, & \dfrac{L_M}{L_S} > \dfrac{1}{2} \\ 0, & 0 < \dfrac{L_M}{L_S} \le \dfrac{1}{2} \end{cases} \tag{A21}$$

Proof of Proposition 2

Under centralized decision-making, both manufacturers and suppliers use the maximization of supply chain benefits as the decision criterion. According to the objective functions of the whole supply chain,

$$\max J_{MS} = \int_0^\infty \ell^{-\rho t}\{(L_M + L_S)D(t) - C_M(t) - C_S(t) + \theta(I - H)\}dt = \int_0^\infty \ell^{-\rho t}\Big\{ \times (L_M + L_S)(D_0 + \beta E(t) + \mu T_S(t)) - \frac{1}{2}m(\varphi T_M(t) + A)^2 - \frac{1}{2}mX^2 - \frac{1}{2}kT_S^2(t) + \theta[I - H]\Big\}dt \tag{A22}$$

The established Hamilton equation is:

$$H_{MS} = \ell^{-\rho t}\Big\{(L_M + L_S) \times (D_0 + \beta E(t) + \mu T_S(t)) - \frac{1}{2}m(\varphi T_M(t) + A)^2 - \frac{1}{2}mX^2 - \frac{1}{2}kT_S^2(t) + \theta(I - H)\Big\} + S(t)[\gamma(\varphi T_M(t-d) + A) + \gamma X - \delta E(t)] \tag{A23}$$

If T_M is required, take the partial derivative of the supply chain's objective function ∂H_{MS} with respect to T_M. Assume $\frac{\partial H_{MS}}{\partial T_M} = 0$.

$$\frac{\partial H_{MS}}{\partial T_M} = -e^{-\rho t} m\varphi(\varphi T_M(t) + A) + \gamma\varphi S(t)\frac{\partial T_M(t-d)}{\partial T_M(t)} = 0 \tag{A24}$$

The above indicates that $\frac{\partial T_M(t-d)}{\partial T_M(t)} = e^{\delta d}$, then $T_M(t) = \frac{\gamma S(t) e^{\delta d + \rho t}}{m\varphi} - \frac{A}{\varphi}$.

The solution of $S(t)$ here is similar to that under decentralized decision-making, so

$$S(t) = \frac{\beta}{\rho + \delta}(L_M + L_S)\ell^{-\rho t} + c e^{\delta t} \tag{A25}$$

Substituting this into Formula (A24) yields manufacturer's optimal carbon emission transfer under centralized decision-making:

$$T_M^C(t) = \frac{\gamma\beta(L_M + L_S)}{m\varphi(\rho+\delta)} e^{\delta d} - \frac{A}{\varphi} \tag{A26}$$

Manufacturers' optimal emission reduction technology R&D input is:

$$R_M^C(t) = \frac{\gamma\beta(L_M + L_S)}{m(\rho+\delta)} e^{\delta d} \tag{A27}$$

When determining the suppliers' carbon emission transfer undertaking level and emission reduction technology R&D input, assume

$$\frac{\partial H_{MS}}{\partial T_S} = e^{-\rho t}[(L_M + L_S)\mu - kT_S(t)] = 0 \tag{A28}$$

$$\frac{\partial H_{MS}}{\partial X} = -e^{-\rho t} m X + \gamma S(t) = 0 \tag{A29}$$

Solving the above formula yields:

$$T_S^C(t) = \frac{\mu(L_M + L_S)}{k} \tag{A30}$$

$$X^C = \frac{\gamma\beta(L_M + L_S)}{m(\rho+\delta)} \tag{A31}$$

Substituting Formulas (A26) and (A31) into Formula (A17) yields the carbon emission reduction per unit of output:

$$E^C(t) = E_0 e^{-\delta t} + \frac{\gamma^2\beta(L_M + L_S)}{m\delta(\rho+\delta)}\left(e^{\delta d} + 1\right)\left(1 - e^{-\delta t}\right) \tag{A32}$$

Substituting the above results into the objective function of the supply chain, the present value of the profit of the supply chain can be obtained:

$$J_{MS}=\frac{(L_M+L_S)D_0+\theta(I-H)}{\rho}+\frac{(L_M+L_S)\beta E_0}{\rho+\delta}+\frac{\mu^2(L_M+L_S)^2}{2\rho k}+\frac{(\gamma\beta)^2(L_M+L_S)^2}{2m\rho(\rho+\delta)^2}\left(2e^{\delta d}-e^{2\delta d}+1\right) \quad (A33)$$

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