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Manufacturers' emission reduction investment strategy under carbon cap-and-trade policy and uncertain low-carbon preferences

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Chunqiu Xu
College of Tourism and Service Management, Nankai University, Tianjin, China
Fengzhi Liu
College of Economic and Social Development, Nankai University, Tianjin, China
Yanjie Zhou
School of Management, Zhengzhou University, Zhengzhou, China
Runliang Dou
College of Management and Economics, Tianjin University, Tianjin, China
Xuehao Feng
Ocean College, Zhejiang University, Jinan, China, and
Bo Shen
Energy Analysis and Environmental Impacts Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA

Abstract

Purpose – This paper aims to find optimal emission reduction investment strategies for the manufacturer and examine the effects of carbon cap-and-trade policy and uncertain low-carbon preferences on emission reduction investment strategies.

Design/methodology/approach – This paper studied a supply chain consisting of one manufacturer and one retailer, in which the manufacturer is responsible for emission reduction investment. The manufacturer has two emission reduction investment strategies: (1) invest in traditional emission reduction technologies only in the production process and (2) increase investment in smart supply chain technologies in the use process. Then, three different Stackelberg game models are developed to explore the benefits of the manufacturer in different cases. Finally, this paper coordinates between the manufacturer and the retailer by developing a revenue-sharing contract.

Findings – The manufacturer's optimal emission reduction strategy is dynamic. When consumers' low-carbon preferences are low and the government implements a carbon cap-and-trade policy, the manufacturer can obtain the highest profit by increasing the emission reduction investment in the use process. The carbon cap-and-trade policy can encourage the manufacturer to reduce emissions only when the initial carbon emission is low. The emission reduction, order quantity and the manufacturer's profit increase with the consumers' low-carbon preferences. And the manufacturer can adjust the emission reduction investment according to the emission reduction cost coefficient in two processes.

Originality/value – This paper considers the investment of emission reduction technologies in different processes and provides theoretical guidance for manufacturers to make a low-carbon transformation. Furthermore, the paper provides suggestions for governments to effectively implement carbon cap-and-trade policy.

Keywords Supply chain, Emission reduction, Low-carbon preferences, Carbon cap-and-trade policy, Stackelberg game

Paper type Research paper

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1. Introduction

Global warming has raised a series of environmental and health issues. One of the effective solutions to this problem is to reduce carbon emissions (Chen *et al.*, 2019; Tiwari *et al.*, 2021; Luo *et al.*, 2022). The Paris Agreement adopted in 2015 proposed that global greenhouse gas emissions should reach a peak and achieve net-zero emissions as soon as possible, establishing the general direction of low-carbon development (Kern and Rogge, 2016). Countries around the world are actively making efforts to reduce carbon emissions. In response to global climate change, China has taken the initiative to propose a dual carbon policy of Carbon Peaking and Carbon Neutrality. To achieve these goals, the manufacturing industry, which is a major carbon producer, will have to undergo a low-carbon transformation.

One of the issues for manufacturers in low-carbon transformation is the choice of emission-reduction technologies. Traditional emission reduction technologies focus on reducing emissions in the production process by improving equipment. However, in many industries, carbon emissions occur not only in the production process, but also in the use process. *Annual Report on Energy-Saving and New Energy Vehicle in China 2021* reported that in 2020, carbon emissions of automobiles in the use process were 720 million tons, accounting for more than 90% of the total carbon emissions. According to McKinsey, the entire value chain of the oil and gas industry (from extraction, transportation, storage and end-use) generates significant emissions. Emissions from the production process account for 20%, and emissions from the use process account for 80%. The urgency of reducing emissions in the use process requires manufacturers to speed up technological updating. However, the improvement of the original equipment alone cannot mitigate the emission reduction of the use process.

In recent years, the rapid development of smart supply chain has provided more technical support for enterprises to make decisions. Smart supply chain technologies include digital twin technology, the Internet of things and blockchain technology, which have been applied to various industries, such as agriculture (Liu *et al.*, 2022a) and pharmaceutical supply chain (Chen *et al.*, 2023). Using digital technologies can also assist enterprises in coping with supply chain disruptions (Ning *et al.*, 2023). More importantly, the emergence of smart supply chain technology induces significant transformations in logistics and transportation (Chung, 2021; Liu *et al.*, 2021a). For example, the implementation of intelligent logistics transformation realizes the efficient distribution of goods (Liu *et al.*, 2022b), which can effectively reduce carbon emissions in the transportation process. Many automobile enterprises are also constantly updating technology. BYD (Build Your Dreams: an automotive manufacturer) has introduced high-safety blade batteries, high-performance silicon carbide chips and high-efficiency DM-i super hybrid systems to accelerate the electrification of private vehicles. Toyota is also increasing investment in electrification technology. On December 2, 2021, Toyota announced that new vehicles sold in Western Europe would emit zero carbon dioxide by 2035. Compared to traditional emission reduction technologies, smart supply chain technologies can minimize carbon emissions in the use process.

On the other hand, investing in smart supply chain technologies inevitably brings increased costs (Zhang *et al.*, 2022; Liu *et al.*, 2023). And enterprises are also facing many uncertainties in the low-carbon transformation (Lee *et al.*, 2020). While smart supply chain technologies are widely considered to reduce cost, anticipate demand, reduce waste, etc. (Li, 2020), few scholars have focused on the role of smart supply chain technologies in promoting sustainability. Therefore, this paper takes a manufacturer's perspective and explores the feasibility of investing in smart supply chain technologies to reduce carbon emissions. Previous studies examining low-carbon supply chains have only considered emission reduction in the production process (Ma *et al.*, 2021; Khan and Dong, 2017). On this basis, we divide emission reduction into two processes (production process and use process) and propose two emission reduction investment strategies: the manufacturer only invests in equipment used in the production process (as in the Case I analysis); the other is that the manufacturer increases the smart supply chain technologies investment in the use process based on Case I (as in the Case II analysis).

To incentivize manufacturers to undergo low-carbon transformation, several countries have implemented the carbon cap-and-trade policy. The carbon cap-and-trade mechanism, considered a market mechanism to control carbon emissions, is an important policy tool for achieving emission reduction targets (Chai *et al.*, 2018). More than 30 countries and regions have established carbon emission trading systems by the end of 2020. Scholars have hotly debated the policy's effectiveness (Fan *et al.*, 2023; Yang *et al.*, 2021). Unlike the above literature, this paper focuses on the incentive effect of the policy under different emission reduction processes. Considering the practical application of the carbon cap-and-trade policy, we introduce it to Case II and analyze the impact of this policy on investment strategy selection (as in the Case III analysis).

In addition, the consumer market environment is also changing. Consumers are paying more attention to the carbon footprint of products (Wang *et al.*, 2021). Consumer low-carbon preferences are also an essential factor in influencing product demand. Previous literature examining low-carbon supply chains has considered consumer low-carbon preferences, whereas most of them quantified consumers' low-carbon preferences' as a certain constant (Liu *et al.*, 2012; Tong *et al.*, 2019). However, in reality, consumers' low-carbon preferences for different products in different industries are varied. Enterprises cannot obtain information about consumers' actual preferences for products. Considering the reality of the situation, this paper examines the impact of consumers' low-carbon preferences on manufacturers' investment selection and innovatively quantifies it as an uncertain factor.

Based on the above descriptions and reality, we mainly focus on manufacturers' emissions reduction investment decisions under the carbon cap-and-trade policy and uncertain low-carbon preferences. These observations motivate us to examine the following research questions:

(1) How do consumers' uncertain low-carbon preferences affect equilibrium solutions?

(2) Which investment strategy is more profitable for the manufacturer?

(3) Can the carbon cap-and-trade policy encourage the manufacturer to increase emission reduction investment and improve emission reduction levels simultaneously?

This paper constructed Stackelberg game models in three cases to answer the above questions and obtained some interesting conclusions. Firstly, emission reduction, order quantity and retailer profit increase with consumers' low-carbon preferences. Improving the emission reduction is conducive to the manufacturer expanding production scale and improving the environment. However, under the carbon cap-and-trade policy, the manufacturer's profit increases first and then decreases in low-carbon preferences. Secondly, the manufacturer does not have an absolutely optimal emission reduction strategy. The manufacturer's optimal emission reduction strategy changes with consumers' low-carbon preferences. When consumers' low-carbon preferences are low, the manufacturer's profit is the largest in Case III. However, with the improvement of consumers' low-carbon preferences, the manufacturer can obtain the highest profit in Case II. Under any conditions, Case I is not the optimal choice for the manufacturer. Finally, the initial carbon emission and carbon emission quota also affect the manufacturer's decision-making and the effect of policies. When the manufacturer's initial carbon emission is low, the carbon cap-and-trade policy can encourage the manufacturer to reduce emissions. However, if the initial carbon emission is large, the manufacturer will not profit from the carbon trading market.

This study contributes to the literature mainly in two aspects. On the one hand, we take emission reduction as a decision variable and classify investment strategies into two types:

one is adopted in the production process; another is for the use process. Based on these two types, we classify them into three cases. In Case I, the manufacturer invests only in the production process. In Case II, the manufacturer increases the emission reduction investment in the use process. In Case III, the carbon cap-and-trade policy is introduced, closer to reality than in previous studies. On the other hand, consumers may have different characteristics when buying low-carbon products, and consumption environments are dynamic. The low-carbon preferences of consumers are not always a constant value. Thus, we describe consumers' low-carbon preferences as uncertain.

The remainder of this paper is organized as follows. Section 2 provides a literature review and highlights the innovations of this paper. Section 3 is mainly the description of the problems and the basic assumptions that are involved in the models. Section 4 shows the establishment and solution of the models in different situations. Section 5 gives the analytical analysis, comparing the equilibrium solution and profit under different cases. Section 6 provides a numerical analysis. Section 7 discusses the profit changes of manufacturers who choose to cooperate with retailers. Section 8 puts forward management recommendations and conclusions. Proofs are provided in Appendix.

2. Literature review

The related studies of this paper are divided into three categories: emission reduction investment, consumers' low-carbon preferences and carbon cap-and-trade policy. In Section 2.4, we find the research gaps by sorting out relevant literature and point out the innovations of this paper.

2.1 Emission reduction investment

This study first contributes to the vast literature on emission reduction investment. Bui *et al.* (2021) recommended that manufacturers should conduct effective green product development to minimize the negative impact of the supply chain on the environment. Therefore, manufacturers' investment in reducing emissions is an important aspect. The existing literature mainly studied the relationship between investment in emission reduction and the benefits obtained by the manufacturers from an operational perspective. Tong *et al.* (2019) explored emission reduction in retailer-led supply chains and pointed out that manufacturers should invest in emissions reduction and retailers should promote low-carbon products for long-term profits. Kumar and Sun (2019) took the data of a mail leasing company as an example to analyze the low carbon technological transformation, which provided some references for the manufacturers to use green technology. Considering a capital-constrained manufacturer, Qin *et al.* (2020) found that when the efficiency of a manufacturer's carbon emission reduction was high, mixed financing could encourage the manufacturer to reduce carbon emissions. Sustainable supply chain finance is also an essential part of the supply chain, which helps enterprises solve funding problems in the reform process (Tseng *et al.*, 2021). Peng *et al.* (2020) compared the impact of the two option contracts on emission reduction. They found that the manufacturer under the bidirectional option had the highest carbon emission reduction, but the manufacturer was more profitable under the unidirectional option.

Other literature has also studied the influence of manufacturers' emission reduction on their decisions from other aspects, e.g. supply chain coordination (Fallahpour *et al.*, 2021; Liu *et al.*, 2021b), supplier selection (Lou *et al.*, 2020), technical effects (Beltagui *et al.*, 2020). But few works were conducted on emission reduction investment in different processes. Although Yang *et al.* (2020) further analyzed the emission reduction during the use process, they did not consider the emission reduction as a decision variable. This paper takes the emission reduction of different processes as the decision variable and focuses on the emission reduction investment of manufacturers in different processes.

2.2 Consumers' low-carbon preferences

Our study also complements the stream of literature on consumers' low-carbon preferences. Consumer demand is the primary driving force for production. Usually, consumers have different preferences for different products, which affects manufacturers' production decisions. Consumers' choice behavior affects the operation of the entire supply chain. McCollum *et al.* (2018) and Zhang *et al.* (2021) found that improving consumers' low-carbon awareness was conducive to reducing carbon emissions and the effectiveness of channel members. However, Fan *et al.* (2019) found that moderate consumer low-carbon preferences were beneficial in the dynamic Stackelberg game, whereas excessive consumer low-carbon preferences are not conducive to decision-makers. Zhang *et al.* (2015) analyzed the impact of consumers' environmental awareness on the prices of different products and the profits of supply chain members. In addition, Liu *et al.* (2012) set consumers' low-carbon preferences as an uncertain factor. They used a two-stage Stackelberg game model to analyze the impact of competition (products, retailers) and consumer environmental awareness on critical members of the supply chain.

When considering consumers' low-carbon preferences, most literature (McCollum *et al.*, 2018; Fan *et al.*, 2019; Zhang *et al.*, 2021; Gao and Souza, 2022; Xu *et al.*, 2023) assumed it follows a fixed value. However, little literature (Liu *et al.*, 2012; Zhang *et al.*, 2015) discussed ordering low-carbon products under random low-carbon preferences. This paper adopts the newsboy model and consumers' random low-carbon preferences are the main reason for random demand. We mainly study the impact of random low-carbon preferences on emission reduction and order quantity.

2.3 Carbon cap-and-trade policy

Our work is closely related to the carbon cap-and-trade policy. Many scholars analyzed whether the carbon cap-and-trade policy could incentivize manufacturers to reduce emissions. Some work showed that the carbon cap-and-trade policy could encourage enterprises to reduce emissions by improving their equipment (Hasan *et al.*, 2021; Pathak *et al.*, 2020). Sun *et al.* (2020) demonstrated that when the lag time of emission reduction technology and consumers' low-carbon preferences exceeded certain thresholds, policies and regulations could promote emission reduction in the supply chain. This means that other relevant factors should also be considered to ensure the maximal efficiency of government policy. Otherwise, it may lose its effectiveness to some degree. Ghosh *et al.* (2020) analyzed the influence of the carbon cap-and-trade policy on channel selection and pointed out that it was profitable to introduce a dual-channel strategy when the initial emission of products was low. An *et al.* (2021) found that green credit financing could be used to make green investments and achieve sustainable development under relatively strict carbon emission policies.

The above literature analyzes the impact of the carbon cap-and-trade policy from the manufacturer's perspective, but Mishra *et al.* (2020) considered the cap-and-trade strategy of the retailer. Retailers can reduce carbon emissions by buying, selling, or transferring extra emission credit. Under uncertain demand, Cohen *et al.* (2016) analyzed the impact of policy-making on manufacturers' low-carbon production by introducing government subsidies for consumers. To motivate individuals to reduce emissions, the government has also established a public emission reduction project to encourage individuals to sell credits on the carbon trading market (Han *et al.*, 2022).

However, the above literature only considered the impact of the carbon cap-and-trade policy on the emission reduction in the production process and did not take the use process into account. This paper focuses on the importance of emission reduction in the use process and considers emission reduction in the use process into the carbon cap-and-trade mechanism. We concretely analyze the effect of this policy on emission reduction in the use process.

2.4 Literature summary

The above literature is from the viewpoint of manufacturers' emission reduction strategy, carbon cap-and-trade policy and the impact of consumer low-carbon preferences, whereas few literature considers the interaction between the three aspects. Different from previous literature, this paper mainly studies emission reduction investment strategies based on consumers' low carbon preference and the carbon cap-and-trade policy. On the one hand, this paper regards consumers' low-carbon preference as a random factor, and the uncertain demand is mainly caused by the randomness of consumers' low-carbon preference. On the other hand, the emission reduction process is subdivided into the production process and use process and the emission reduction of different processes is taken as the decision variable. In addition, this paper takes the emission reduction of the production process and use process into the carbon cap-and-trade policy and provides suggestions for the government to implement the emission reduction policy better. The comparison between previous studies and this paper is shown in Table 1.

3. Problem descriptions and model assumptions

3.1 Problem description

This paper studies a supply chain consisting of a manufacturer and a retailer. The manufacturer invests in emission reduction technologies to produce low-carbon products, which are distributed to the retailer at wholesale price $w_i (i = 1, 2)$. The retailer then sells products to consumers at a retail price $p_i (i = 1, 2)$. To explore the manufacturers' emission reduction strategies, we explore the emission reduction behaviors of the manufacturer in three cases. Case I is that the manufacturer only makes an emission reduction investment in the production process. Products under this strategy are denoted as product 1. Case II is that the manufacturer increases the emission reduction investment in the use process based on Case I. Products under this strategy are denoted as product 2. Product 1 and product 2 are in the same category. The main difference is emission reduction. The emission reduction of product 2 is higher than that of product 1. Finally, to further analyze the impact of the carbon cap-and-trade policy on manufacturers' emission reduction decisions, Case III considers the carbon cap-and-trade policy based on Case II. In the following sections, we use subscripts

Table 1. Comparison between previous studies with this paper

Literature	Consumers' low-carbon awareness		Carbon cap-and-trade policy	Emission reduction process		Coordinated contract
	Certain	Uncertain		Production process	Use process	
Liu *et al.* (2012)	√	–	–	√	–	√
Zhang *et al.* (2015)	–	√	–	–	–	√
Cohen *et al.* (2016)	√	–	√	√	–	–
McCollum *et al.* (2018)	√	–	√	√	–	–
Tong *et al.* (2019)	√	–	√	√	–	–
Kuiti *et al.* (2020)	√	–	√	√	–	√
Sun *et al.* (2020)	√	–	√	√	–	–
Yang *et al.* (2020)	√	–	√	√	√	–
Hasan *et al.* (2021)	√	–	√	–	√	–
Liu *et al.* (2021b)	√	–	–	√	–	√
This study		√	√		√	√

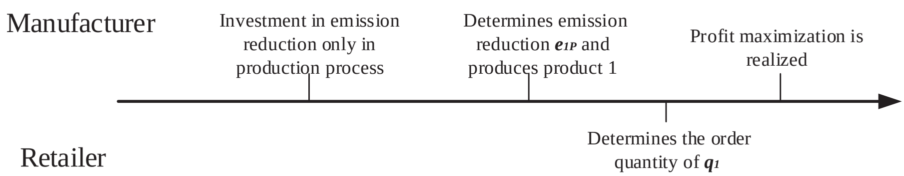
Note(s): √ denotes that the content is covered; – denotes that the content is uncovered
Source(s): Author's own creation/work

1 and 2 to indicate the two kinds of products; P and U respect the production and use processes, respectively. The three cases are as follows:

Case I: We take Case I as the benchmark and only consider the emission reduction in the production process. In Case I, the manufacturer first decides on the emission reduction e_{1P}. For example, Gree upgraded its air conditioning technology in 2021 and introduced a "zero carbon source" system, reducing air conditioning carbon emissions by 85.7%. Then, the retailer orders a certain amount of products q_1 from the manufacturer according to consumer demand for the product d_1 and sells them to consumers at a price p_1. The decision process is shown in Figure 1.

Case II: The manufacturer makes emission reduction investments in the production and use processes. Therefore, product 2 includes emission reduction investment in two processes. Firstly, the manufacturer decides on the emission reduction e_{2P} and e_{2U} respectively. e_{2P} represents the emission reduction in the production process, e_{2U} represents the emission reduction in the use process. Then, the retailer orders q_2 from the manufacturer according to consumer demands for the product d_2. Finally, the retailer sells the products to consumers at a price p_2. The decision process is shown in Figure 2.

Case III: The carbon cap-and-trade policy is introduced into the model, and the decision process is shown in Figure 3. In order to encourage the manufacturer to reduce carbon emissions, the government provides the manufacturer with some carbon quotas for free. If the carbon quota is not used up, the manufacturer can sell them in the market.



Source(s): Author's own creation/work

Figure 1. The events' sequence for Case I

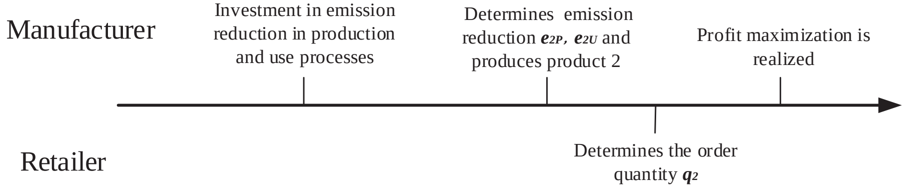


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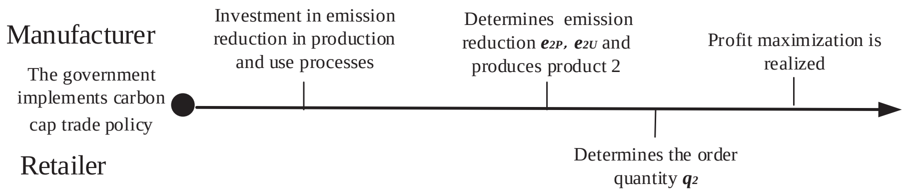
Figure 2. The events' sequence for Case II



Source(s): Author's own creation/work

Figure 3. The events' sequence for Case III

The manufacturer must buy them from the market if the carbon quotas are insufficient. The price of carbon quotas in the market is p_e. This changes the cost and profit of the supply chain stakeholders and finally affects the manufacturer's choice of investment strategy.

The three cases are progressive relationships. Case II adds emission reduction in the use process based on Case I. By comparing Case I with Case II, the manufacturer's optimal investment strategy for emission reduction can be analyzed. Case III adds the carbon cap-and-trade policy based on Case II, and the main purpose is to study the incentive effect of the carbon cap-and-trade policy on manufacturers' emission reduction. In Section 5, we provide a detailed comparative analysis of the equilibrium results in the three cases, which can help the manufacturer make optimal investment decisions when faced with different scenarios.

3.2 Model assumptions

Before introducing the details of the game models, the models' assumptions are presented as follows.

Assumption 1. Consumers have a preference for low-carbon products. The low-carbon preferences of the consumer can vary significantly across industries, regions, consumer groups and time. Therefore, referencing literature by Zhang *et al.* (2015), we assume that the consumer's low-carbon preferences τ is an uncertain factor that follows a uniform distribution $[0, 2t]$. The expected value is $E(\tau) = t$. t represents the expected value of consumer low-carbon preferences. Its probability density is $f(\tau)$.

Assumption 2. The cost of producing one product includes product cost c and the emission reduction cost. To simplify the calculation, we assume $c = 0$. Even if $c \neq 0$, it will hardly affect the results of this paper. Referencing literature by Fan *et al.* (2023), the emission reduction cost is a quadratic function. $\frac{1}{2}h(e_{1P})^2$ represents the emission reduction cost of product 1, h is the cost coefficient for reducing unit carbon emissions in the production process. $\frac{1}{2}h(e_{2P})^2 + \frac{1}{2}k(e_{2U})^2$ represents the emission reduction cost of product 2, k is the cost coefficient of using smart technology for emission reduction in the use process. The cost coefficients of emission reduction technologies vary across different processes in different industries. In Section 5, we analyze the impact of the size relationship of the cost coefficients on the decision.

Assumption 3. Without losing generality, we assume $w_i < p_i$. w_i is the unit wholesale price of the product i. p_i denotes the unit retail price of product i. Combined with the research focus of this paper, we assume that the unit wholesale price and the unit retail price are exogenous. Consumers are more sensitive to emission reduction than prices.

Assumption 4. Considering the importance of the use process, in order to encourage the manufacturer to increase the emission reduction investment of the use process, we include the emission reduction in the use process into the carbon cap-and-trade policy. The government gives the manufacturer a certain carbon quota for free. If the initial carbon emission per unit product is λ and the emission reduction per unit product is e_i, the manufacturer's amount of carbon quota needs to buy or sell $(\lambda q_2 - e_{2P}q_2 - e_{2U}q_2) - E_g$.

For ease of exposition, we incorporate superscripts into the three scenarios. I, II and III represent Case I, Case II and Case III, respectively. The model parameters and decision variables are presented in Table 2.

4. Model establishment and solution

In this section, we first consider emission reduction investment in the production process as Case I in Section 4.1. Then, we explore that the manufacturer increases emission reduction investment in the use process as in Case II in Section 4.2. Finally, to analyze the impact of carbon cap-and-trade policy on emission reduction decisions, we further add carbon cap-and-trade policy to the model as Case III in Section 4.3.

4.1 Case I

4.1.1 Optimal behaviors of the retailer. In Case I, the manufacturer only invests in emission reduction in the production process and produces product 1. The demand function of product 1 is as follows:

$$d_1 = a - bp_1 + \tau e_{1P} \tag{1}$$

Where a is initial market potential, $b > 0$ measures the sensitivity of the market price to demand. For ease of calculation, let $u_1 = a - bp_1$, which is the deterministic demand affected only by price.

	Descriptions
Index	
i	Subscripts, representing the index of product i, $i = 1,2$
M	Subscripts, representing the manufacturer
R	Subscripts, representing the retailer
P	Subscripts, representing the production process
U	Subscripts, representing the use process
Parameters	
a	Initial market potential
b	Price elasticity of demand
c	The unit production cost of product
d_i	Market demand of product i
E_g	Free government carbon emission allowances
h	Manufacturer's cost parameter of emission reduction in the production process
t	The expected value of consumer low-carbon preferences
k	Manufacturer's cost parameter of emission reduction in the use process
p_e	The unit market price of voluntary emission reduction
p_i	Retail price per unit of product i
s_i	The unit out-of-stock cost of product i
v_i	The unit recycling price of product i at the end of the sale period
w_i	Manufacturer's wholesale price of the product i
τ	Consumer low-carbon preferences
λ	The unit initial carbon emissions of a product
Decision variables	
e_{ip}	The emission reduction in the production process of product i
e_{iu}	The emission reduction in the use process of product i
q_i	Order quantity of product i for the retailer

Source(s): Author's own creation/work

Table 2.
Symbols in this paper

The profit function faced by the retailer is defined as:

$$\pi_r(q_1)^I = p_1(d_1 \wedge q_1) + v_1(q_1 - d_1)^+ - s_1(d_1 - q_1)^+ - w_1 q_1 \tag{2}$$

where $x \wedge y = \min\{x, y\}$, $(x-y)^+ = \max(x-y, 0)$, then $x \wedge y = x - (x-y)^+$. Let $d_1 = q_1 = a - bp_1 + \tau e_{1P}$, we can get the auxiliary variable $z_1 = (q_1 - u_1)/e_{1P}$.

Given e_{1P}, the optimization problem faced by the retailer is defined as:

$$\text{Maximize}\, E(\pi_r)^I = p_1 q_1 + (v_1 - p_1)\int_0^{z_1}(q_1 - d_1)f(\tau)d\tau - s_1\int_{z_1}^{2t}(d_1 - q_1)f(\tau)d\tau - w_1 q_1 \tag{3}$$

By solving the above objective Eq. (3), we can obtain the optimal q_1, which is represented by e_{1P}.

$$q_1 = \frac{2te_{1P}(p_1 + s_1 - w_1)}{p_1 + s_1 - v_1} + u_1 \tag{4}$$

To simplify the calculation, let $A_1 = p_1 + s_1 - v_1$, $B_1 = p_1 + s_1 - w_1$.

4.1.2 Optimal behaviors of the manufacturer. And the optimization problem faced by the manufacturer is defined as:

$$E(\pi_m)^I = w_1 q_1 - \frac{1}{2}h(e_{1P})^2 \tag{5}$$

Then, substituting Eq. (4) into Eq. (5), the manufacturer's profit function is given by:

$$E(\pi_m)^I = w_1\left[\frac{2te_{1P}(w_1 - p_1)}{v_1 - p_1 + s_1} + u_1\right] - \frac{1}{2}h(e_{1P})^2 \tag{6}$$

By adopting the backward induction method, the optimal emission reduction of product 1 is given by:

$$e_{1P}^{I*} = \frac{2tw_1 B_1}{hA_1} \tag{7}$$

After replacing e_{1P}, the order quantity of the retailer is given by:

$$q_1^{I*} = \frac{4t^2 B_1^2}{hA_1^2} + u_1 \tag{8}$$

The proof of these results is shown in Appendix 1. Substituting Eqs. (7) and (8) into Eqs. (3) and (5), we can get the optimal profits π_m^{I*} and π_r^{I*}, respectively. π_m^{I*} and π_r^{I*} are given respectively by:

$$\pi_m^{I*} = w_1 q_1^{I*} - \frac{1}{2}h\left(e_{1P}^{I*}\right)^2 \tag{9}$$

$$\pi_r^{I*} = p_1\left(d_1 \wedge q_1^{I*}\right) + v_1\left(q_1^{I*} - d_1\right)^+ - s_1\left(d_1 - q_1^{I*}\right)^+ - w_1 q_1^{I*}. \tag{10}$$

4.2 Case II

The manufacturer increases emission reduction investment in the use process to meet more market demand. If creating low-carbon products is profitable for the manufacturer, the manufacturer will consider producing low-carbon products to reduce emissions. Otherwise, the manufacturer will not make an effort to reduce emissions. Hence, studying the feasibility of emission reduction investment is necessary from the manufacturer's perspective.

4.2.1 Optimal behaviors of the retailer. In Case II, the manufacturer produces product 2 with higher emission reduction. The total emission reduction of product 2 is $e_{2P} + e_{2U}$. Due to the different consumer low-carbon preferences, the market demands of product 2 are also different. The demand functions of product 2 are defined as follows:

$$d_2 = a - bp_2 + \tau(e_{2P} + e_{2U}) \tag{11}$$

For ease of calculation, let $u_2 = a - bp_2$. u_2 represents the deterministic demand of product 2 that is only affected by prices.

The profit function of the retailer is defined as:

$$\pi_r(q_2)^{II} = p_2(d_2 \wedge q_2) + v_2(q_2 - d_2)^+ - s_2(d_2 - q_2)^+ - w_2 q_2 \tag{12}$$

Given the emission reduction e_{2P} and e_{2U}, the optimization problem faced by the retailer is defined as:

$$E(\pi_r)^{II} = p_2 q_2 + (v_2 - p_2)\int_0^{z_2}(q_2 - d_2)f(\tau)d\tau - s_2\int_{z_2}^{2t}(d_2 - q_2)f(\tau)d\tau - w_2 q_2 \tag{13}$$

Here, $z_2 = \frac{q_2 - u_2}{e_{2P} + e_{2U}}$.

Proposition 1. The optimal order quantities of product 2 can be obtained, which is represented by e_{2P} and e_{2U}:

$$q_2 = \frac{2t(p_2 + s_2 - w_2)(e_{2P} + e_{2U})}{p_2 + s_2 - v_2} + u_2 \tag{14}$$

Proof. See Appendix 2.

The retailer's order quantities increase in t. To simplify the calculation, let $A_2 = p_2 + s_2 - v_2$, $B_2 = p_2 + s_2 - w_2$.

4.2.2 Optimal behaviors of the manufacturer. Then the optimization problem faced by the manufacturer is defined as:

$$E(\pi_m)^{II} = w_2 q_2 - \frac{1}{2}h(e_{2P})^2 - \frac{1}{2}k(e_{2U})^2 \tag{15}$$

After replacing q_2 and adopting the backward induction method, the optimal emission reduction of product 2 in two processes are given respectively by:

$$e_{2P}^{II*} = \frac{2tw_2B_2}{hA_2}, e_{2U}^{II*} = \frac{2tw_2B_2}{kA_2} \tag{16}$$

After replacing e_{2P} and e_{2U}, the order quantity of the retailer is given by:

$$q_2^{II*} = \frac{4w_2t^2B_2^2(k+h)}{khA_2^2} + u_2 \tag{17}$$

Further, substituting Eqs. (16) and (17) into Eqs. (13) and (15), respectively, π_m^{II*} and π_r^{II*} are given respectively by:

$$\pi_m^{II*} = w_2 q_2 - \frac{1}{2} h\left(e_{2P}^{II*}\right)^2 - \frac{1}{2} k\left(e_{2U}^{II*}\right)^2 \tag{18}$$

$$\pi_r^{II*} = p_2\left(d_2 \wedge q_2^{II*}\right) + v_2\left(q_2^{II*} - d_2\right)^+ - s_2\left(d_2 - q_2^{II*}\right)^+ - w_2 q_2^{II*}. \tag{19}$$

4.3 Case III

The government gives the manufacturer a free carbon quota to encourage the manufacturer to reduce emissions. This section introduces the carbon cap-and-trade policy and analyzes the incentive effect on the manufacturers' emission reduction.

4.3.1 Optimal behaviors of the retailer. Referencing Case II, the expected profit faced by the retailer in Case III does not change. Given the emission reduction e_{2P} and e_{2U}, the optimization problem faced by the retailer is defined as:

$$E(\pi_r)^{III} = p_2 q_2 + (v_2 - p_2)\int_0^{z_2} (q_2 - d_2) f(\tau) d\tau - s_2 \int_{z_2}^{2t} (d_2 - q_2) f(\tau) d\tau - w_2 q_2 \tag{20}$$

The optimal quantities of product 2 can be obtained, which is represented by e_{2P} and e_{2U}:

$$q_2 = \frac{2t(p_2 + s_2 - w_2)(e_{2P} + e_{2U})}{p_2 + s_2 - v_2} + u_2 \tag{21}$$

4.3.2 Optimal behaviors of the manufacturer. The optimization problem faced by the manufacturer is defined as:

$$E(\pi_m)^{III} = w_2 q_2 - \frac{1}{2} h(e_{2P})^2 - \frac{1}{2} k(e_{2U})^2 - p_e(\lambda q_2 - E_g - (e_{2P} + e_{2U}) q_2) \tag{22}$$

After replacing q_2 and adopting the backward induction method, the optimal emission reduction of product 2 in two processes are given respectively by:

$$e_{2P}^{III*} = \frac{2t(w_2 - \lambda p_e)B_2 + p_e u_2 A_2}{hA_2 - 4p_e t B_2}, e_{2U}^{III*} = \frac{2t(w_2 - \lambda p_e)B_2 + p_e u_2 A_2}{kA_2 - 4p_e t B_2} \tag{23}$$

After replacing e_{2P} and e_{2U}, the order quantity of the retailer is given by:

$$q_2^{III*} = \frac{\left[4t^2 B_2^2 (w_2 - \lambda p_e) + 2A_2 u_2 t B_2 p_e\right](kA_2 + hA_2 - 8p_e t B_2)}{A_2(hA_2 - 4p_e t B_2)(kA_2 - 4p_e t B_2)} + u_2 \tag{24}$$

Further, substituting Eqs. (23) and (24) into Eqs. (13) and (22), respectively, π_m^{III*} and π_r^{III*} are given respectively by:

$$\pi_m^{III*} = w_2 q_2 - \frac{1}{2} h\left(e_{2P}^{III*}\right)^2 - \frac{1}{2} k\left(e_{2U}^{III*}\right)^2 \tag{25}$$

$$\pi_r^{III*} = p_2\left(d_2 \wedge q_2^{III*}\right) + v_2\left(q_2^{III*} - d_2\right)^+ - s_2\left(d_2 - q_2^{III*}\right)^+ - w_2 q_2^{III*} \tag{26}$$

5. Analysis and discussion

The previous section carried out modeling solutions and obtained the optimal solutions in three cases. This section compares the optimal solutions under the three cases to provide more references for manufacturers' decision-making.

5.1 Comparison of Case I and Case II

In Case I and II, the carbon cap-and-trade policy is omitted. We first compare the optimal emission reduction of Case I and Case II and analyze the allocation of emission reduction investment in different processes by the manufacturer. Then, the order quantities of Case I and Case II are compared and analyzed. Proposition 2 and proposition 3 show the results of the analysis.

Proposition 2. The following two equations always hold.

(i). When $\frac{B_1 w_1}{A_1} > \frac{B_2 w_2}{A_2}$, $e_{1P}^{I*} < e_{2P}^{II*}$; otherwise, $e_{1P}^{I*} > e_{2P}^{II*}$.

(ii). When $h < k$, $e_{2P}^{II*} > e_{2U}^{II*}$; otherwise, $e_{2P}^{II*} < e_{2U}^{II*}$.

Proof. See Appendix 3.

Proposition 2 (i) shows that the emission reduction of the production process in Case II is higher than in Case I under this condition. When the manufacturer increases the emission reduction investment in the use process, it may impact the emission reduction in the production process. Therefore, in Case II, we also take the emission reduction of the production process as the decision variable and give the above conditions through analysis. The level of emission reduction is related to the product price. The manufacturer can adjust the emission reduction of the production process according to the price comparison of the two products.

Proposition 2 (ii) shows that the emission reduction of the use process is more than that of the production process under $k > h$. The cost coefficient of emission reduction in different processes affects the cost of emission reduction investment. The larger the emission reduction cost coefficient, the higher the emission reduction investment cost. Thus, the manufacturer can adjust the emission reduction investment in different processes according to the emission reduction cost coefficient in the two processes.

Proposition 3. The ordering quantities in two cases have the following relationship:

$$\text{When } u_2 - u_1 < \frac{4B_1^2 t^2 w_1}{hA_1^2} - \frac{4(k+h)B_2^2 t^2 w_2}{hkA_2^2},\ q_1^{I*} > q_2^{II*};\ \text{otherwise},\ q_1^{I*} < q_2^{II*}.$$

By comparison, we find a certain relationship between the order quantity and the determined demand for the two products. When the deterministic demand difference between product 1 and product 2 is small, the retailer should reduce the order quantity of product 2 and order more of product 1. This is because the ordering cost of product 1 is lower, and the retailer faces fewer sales risks. On the contrary, if the deterministic demand for product 1 is less, the retailer should reduce the order quantity of product 1. And consumers' low-carbon preferences will affect the size of the threshold. With the increase in consumers' low-carbon preferences, the threshold gradually increases. The retailer will adjust the order quantity of the two products according to consumer preferences. For the retailer, before ordering products, he/she should fully investigate the market demand and grasp consumers' preferences for different products to reduce unnecessary costs.

5.2 Comparison of Case II and Case III

In this section, we analyze the carbon cap-and-trade policy's effect on the manufacturer's optimal behaviors. The comparison of equilibrium solutions in Case II and Case III is shown in proposition 4.

Proposition 4. Comparing the emission reduction of product 2 in Case II and Case III, the following two equations always hold.

(i). When $u_2 > \frac{2tB_2}{A_2} - \frac{8t^2B_2^2w_2}{hA_2^2}$, $e_{2P}^{III*} > e_{2P}^{II*}$; otherwise, $e_{2P}^{III*} < e_{2P}^{II*}$.

(ii). When $k > h$, $e_{2P}^{III*} > e_{2U}^{III*}$; otherwise, $e_{2P}^{III*} < e_{2U}^{III*}$.

Proof. See Appendix 4.

After implementing the carbon cap-and-trade policy, the emission reduction of product 2 in different processes has changed. Proposition 4 (i) shows that when the deterministic demand of product 2 is larger, the emission reduction of the production process is higher under the carbon cap-and-trade policy. When emission reduction is increased by more than a certain amount, the manufacturer can earn extra profit in the carbon market. Thus, under the carbon cap-and-trade policy, the manufacturer should adjust emission reduction investments for different processes to gain extra profits.

The conclusion of proposition 4 (ii) is consistent with proposition 2 (ii). The two processes' emission reduction is mainly related to the emission reduction cost coefficient.

5.3 The impact of consumers' low-carbon preferences

This section analyzes the impact of consumers' low-carbon preferences on emission reduction and order quantities in different cases and provides references for supply chain members' decision-making.

Proposition 5. In Case I, the retailer's optimal order quantity and the emission reduction increase with the consumers' average low-carbon preferences *t:*

Where $\frac{\partial q_1^{I*}}{\partial t} = \frac{8B_1^2w_1}{hA_1^2} > 0$; $\frac{\partial e_1^{I*}}{\partial t} = \frac{2B_1w_1}{hA_1} > 0$.

Proposition 5 shows that the improvement of consumers' low-carbon preferences benefits expanding production and improving the environment. With the increase in low-carbon preferences, the retailer increases the order quantity of product 1, which also reflects the gradual expansion of market demand for product 1. Although the emission reduction of product 1 is small, some consumers prefer product 1. Because product 1 has a price advantage over product 2 with higher emission reduction.

The emission reduction of product 1 also increases with consumers' low-carbon preferences. The increase in consumers' low-carbon preferences means that they pay more attention to the emission reduction of products and prefer low-carbon products. The manufacturer's production goal is mainly to meet the needs of consumers. When the demand of consumers changes, the manufacturer should also adjust the emission reduction investment strategy in time.

Proposition 6. In Case II, the order quantity of product 2 also increases with the consumers' average low-carbon preferences *t*. The emission reduction of product 2 in the two production processes increases with *t* and consistent with the results of Case I.

Where $\frac{\partial q_2^{II*}}{\partial t} = \frac{8(h+k)B_2^2w_2}{hkA_2^2} > 0$; $\frac{\partial e_{2P}^{II*}}{\partial t} = \frac{2B_2w_2}{hA_2} > 0$; $\frac{\partial e_{2U}^{II*}}{\partial t} = \frac{2B_2w_2}{kA_2} > 0$.

From the above analysis, we can find that the order quantities and emission reduction of the two products are positively correlated with the average low-carbon preferences *t* in Case I or Case II.

One managerial application of Proposition 6 is that both the manufacturer and the retailer should pay attention to consumer preferences. Before making decisions, they first investigate the market information and formulate reasonable emission reduction strategies according to the low carbon preferences of consumers. Only by grasping the market trend accurately can the manufacturer and the retailer make profits for a long time.

Proposition 7. In Case I and Case II, the manufacturer's profit increases with the consumers' average low-carbon preferences *t:*

$$\frac{\partial \pi_m^{I*}}{\partial t} > 0; \ \frac{\partial \pi_m^{II*}}{\partial t} > 0.$$

According to proposition 7, the manufacturer's profit increases with consumers' low-carbon preferences. Whether the manufacturer increases its emission reduction investment or not, the manufacturer can benefit from the improvement of low-carbon preferences awareness. When t increases, consumers pay more and more attention to the emission reduction of products and take the emission reduction as the standard of purchase decision. Therefore, the manufacturer producing low-carbon products will gain more market share, and the higher the low-carbon level of products, the market demand will increase with t. For the manufacturer, the degree of consumer preferences for products is also an essential factor that needs to be considered. In the sales stage, the manufacturer should constantly publicize the advantages of low-carbon products and improve consumers' low-carbon preferences to stimulate consumer demand.

The profit function of the retailer is relatively complex, and we cannot give intuitive analysis results. Therefore, in the following section, we use numerical analysis to discuss.

6. Numerical analysis

In this section, we give serval groups of numerical analysis to explore the theoretical. Firstly, we analyze the impact of consumers' average low-carbon preferences on channel performance. Secondly, we analyze the impact of unit initial carbon emission on channel performance. Then, we analyze the impact of carbon trading quotas on channel performance and explore different factors' impact on decision-making. Finally, we give some management suggestions from different perspectives.

Following the literature (Zhang *et al.*, 2015; Kuiti *et al.*, 2020), the parameters setting used in the following experiments show in Table 3. To satisfy $c + he_i^2 < w_i < p_i, i = 1, 2$, we set $t \in [0, 1]$. To simplify the calculation, we assume $c = 0$, $b = 1$.

6.1 The impact of consumers' average low-carbon preferences on channel performance

Figure 4 shows the impact of consumers' uncertain low-carbon preferences on the emission reduction of product 1 and product 2. As consumers' low-carbon preferences increase, the emission reduction of product 1 and product 2 increases.

As can be seen from Figure 4a, regardless of the value of the consumer's low-carbon preferences, the emission reduction in the production process is the highest in Case III and the

Parameters	Value	Parameters	Value	Parameters	Value
a	12	p_e	0.4	v_1	1.5
k	3	p_1	8	v_2	2
h	2	p_2	10	w_1	4
s_1	0.5	λ	4.8	w_2	5
s_2	1	Eg	20	b	1

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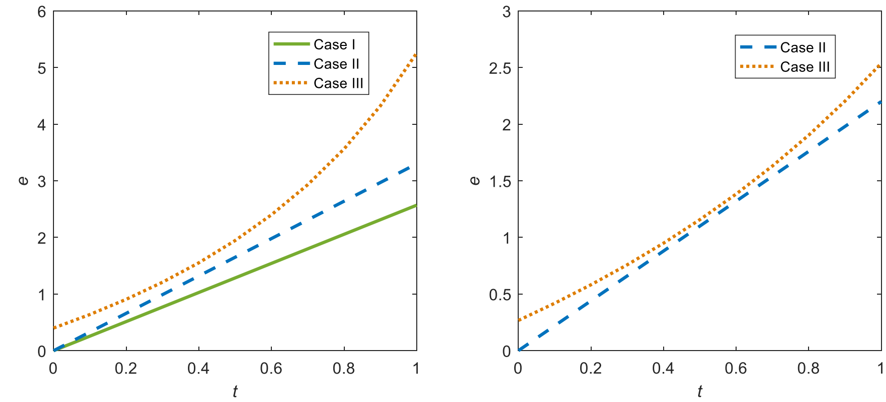
Table 3. Parameter setting



In the production process
(a)

In the use process
(b)

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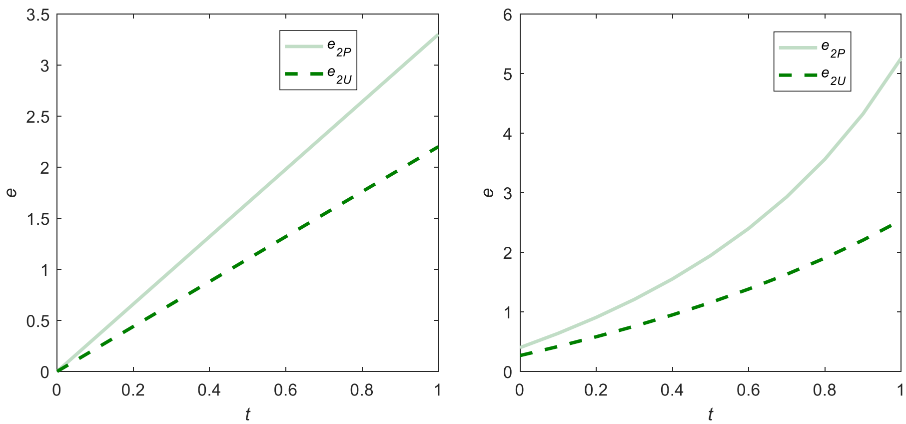
Figure 4.
Emission reduction with *t* in different processes

lowest in Case I. In Figure 4b, regardless of the value of the consumer's low-carbon preferences, the emission reduction in the use process is the highest in Case III and the lowest in Case II. When the use process is included in the carbon cap-and-trade policy, the emission reduction of the production process also increases correspondingly, enhancing the effect of the policy.

In Figure 5, we compare the emission reduction of product 2 in different processes. In Case II and Case III, when $h < k$, the emission reduction of product 2 in the production process is higher than that in the use process. This is mainly because of cost. The result is consistent with Proposition 2 and Proposition 4.

Figure 6 presents the influence of consumers' uncertain low-carbon preferences on the order quantities of products 1 and 2. Figure 6a shows the change in the order quantities of



Case II (h = 2, k =3)
(a)

Case III (h = 2, k =3)
(b)

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Figure 5.
Comparison of the emission reduction in Case II and Case III

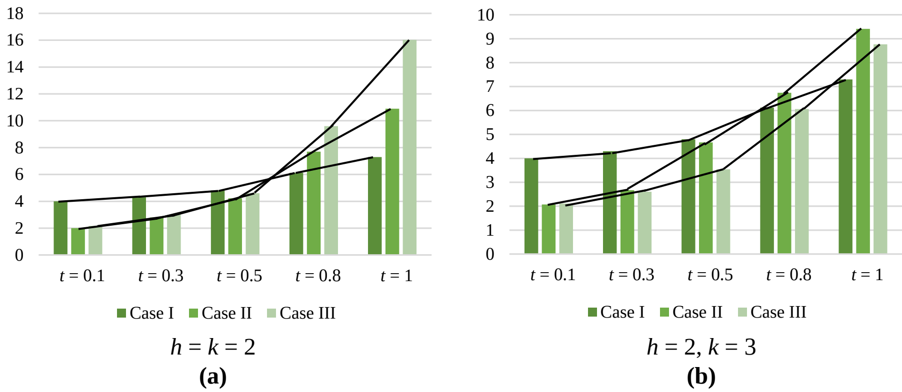

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Figure 6.
Order quantity with t in different cases

different products under the three cases when $h = k$. Figure 6b shows the order quantities of different products change when $h < k$.

From Figure 6, we can find that the order quantities of the two types of products are increasing with consumers' low-carbon preferences. In Figure 6a, the order quantities of product 2 in Case III increase the fastest, while that of product 1 increase the slowest. In Figure 6b, when k increases, the order quantities of product 2 decrease gradually. Furthermore, the order quantities of product 2 in Case II increase the fastest. Product 2 has a tremendous competitive advantage in quality. With the increase in consumers' low-carbon preferences, consumers have become more favored by product 2. Product 2 seizes more market share of product 1, and the demand for product 1 gradually declines.

At last, when the government intervenes in the market, the market also begins to fluctuate. While implementing the carbon cap-and-trade policy, the government also raises consumers' environmental awareness. Consumers' demand for low-quality products gradually declines, which results in product 1 having the least order quantities in Case I. This is why the order quantities of product 1 are slowly more minor than that of product 2 in Case II and Case III.

Consumers' differentiated low-carbon preferences influence manufacturers' investment decisions to reduce emissions. In Figure 7a, we analyze the manufacturer's profit changes in three cases. After comparison, it is found that the optimal emission reduction strategy of the manufacturer is dynamic, which is mainly affected by consumers' low-carbon preferences.

In Figure 7a, as consumers' low-carbon preferences increase, the manufacturer's profit in Case I and Case II increases. However, in Case III, the manufacturer's profit increases first and then decreases. When consumers' low-carbon preferences are low, the manufacturer will make more profits by increasing emission reduction investment and participating in the carbon trading market. However, the manufacturer's profit in Case II is lower than in Case I. This is because when consumers' low-carbon preferences are low, the order quantities of product 2 are less than that of product 1, and the market demand for product 2 is small. However, with the increase in consumers' low-carbon preferences, the order quantities of product 2 gradually expand, and the manufacturer obtains more economies of scale. Therefore, the manufacturer's profit in Case II is higher than in Case I. In Case III, the decline in manufacturers' profit is mainly due to the sharp increase in emission reduction costs. With the increase in low-carbon preferences, the manufacturer's emission reduction in the two processes is also gradually improved, but the manufacturer has to pay more emission reduction costs. The rapid increase in cost reduces the manufacturer's profit.

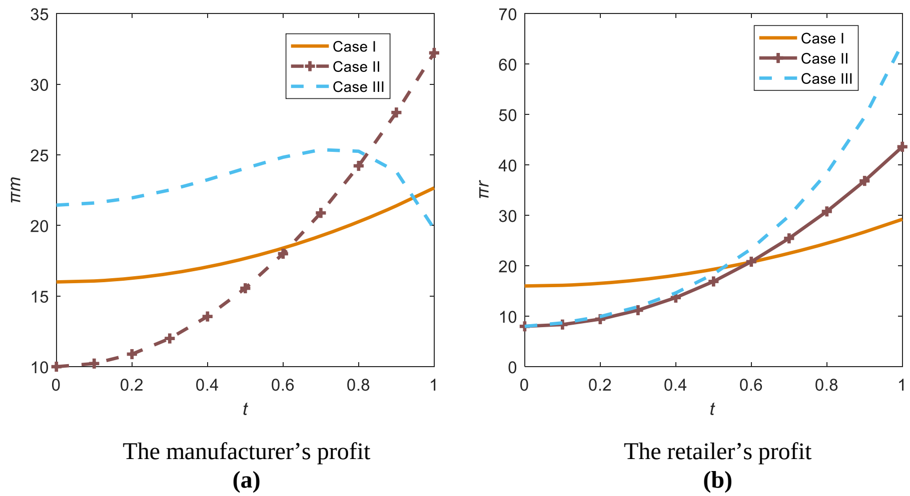

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Figure 7.
The manufacturer's profit and retailer's profit in Case I-III with *t*

As shown in Figure 7b, as consumers' low-carbon preferences increase, the retailers' profit also increases under different cases. The comparison indicates that the retailer in Case III has the highest profit, and the retailer in Case I has the lowest profit. Moreover, the retailer's profit is higher than that of the manufacturer in different cases. After the manufacturer increases investment in emission reduction, the retailers' profit gradually increases. It shows that the retailer enjoys the benefits of emission reduction investment for free, which may reduce the efficiency of cooperation between the two parties.

Figure 8 compares the supply chain profits, which is the sum of the manufacturer's profit and the retailer's profit. As shown in Figure 8, Case III has the highest total supply chain

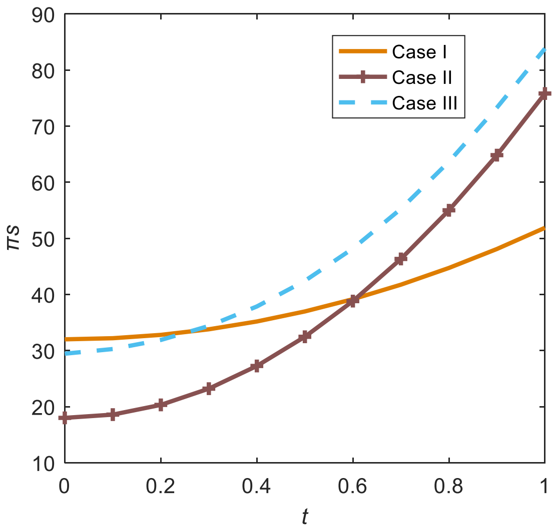

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Figure 8.
Comparison of the supply chain profit among various cases

profits, while Case I has the lowest supply chain profits. At the same time, as consumers' low-carbon preferences increase, the supply chain profit will increase accordingly.

Part of the reason for the above phenomenon is the role of the retailer. In Case II and Case III, the retailer's profit also increases after the manufacturer reduces emissions. The retailer enjoys the benefits of emission reduction for free. This means free-riding behavior, which has a counterproductive effect on the manufacturers' emission reduction incentives. From the entire supply chain perspective, the retailer and the manufacturer should establish emission reduction cooperation and achieve a win-win goal through a particular contract. In Section 7, we use revenue-sharing contracts to coordinate the profit of the manufacturer and the retailer.

When consumers' low-carbon preferences are relatively low, consumers have less demand for low-carbon products. The manufacturer faces more significant risks and costs in increasing emission reduction investment. The government's emission reduction policies cannot be effective. However, as consumers' low-carbon preferences gradually increases, consumers prefer green products. The promotional costs and inventory costs to be paid by the manufacturer are reduced. And the carbon cap-and-trade policy plays a better incentive role at this time. Moreover, when consumers' preference for low-carbon is high, the profit of the supply chain is the maximum in Case III. This also reflects the importance of taking emissions reduction in the use process into account in the carbon cap-and-trade policy, which benefits society.

Consumers can influence the whole supply chain at the end of the supply chain. Both manufacturers and government departments must consider consumers' behaviors when making production plans or policies. Therefore, it is of practical significance to study consumers' uncertain low-carbon preferences.

6.2 The impact of unit initial carbon emissions of product on channel performance

Whether an enterprise participates in the carbon trading market also needs to consider its carbon emissions. If the initial carbon emissions are too high for emission control manufacturers, they have to pay higher costs to offset the environmental damage when conducting carbon trading. If the initial carbon emissions are low, the remaining carbon emission allowances can be sold after emission reduction. Enterprises can achieve the dual goals of maximizing profits and protecting the environment by investing in emission reduction.

To ensure $c + he_i^2 < w_i < p_i, i = 1, 2$, we take $t = 0.5$ and discuss the impact of initial carbon emissions on implementing the carbon cap-and-trade policy.

As shown in Figure 9, when $\lambda < 8$, the manufacturer has the highest profit in Case III; when $\lambda > 8$, the manufacturer's profit in Case II is higher than in Case III. The manufacturer's profit gradually decreases in initial carbon emissions. When the manufacturer's initial carbon emissions are high, joining the carbon trading market is not wise. Because the manufacturer is more likely to face an increase in carbon trading costs. On the contrary, if the initial carbon emission is low, the manufacturer will easily meet the carbon emission standards set by the government and make more profits in carbon trading.

6.3 The impact of carbon trading quotas on channel performance

As shown in Figure 10, the government's free carbon emission allowances also impact the manufacturers' profit. With the government's free carbon emission allowances increasing, the manufacturer's profit in Case III also increases. In Figure 10a, when the government grants fewer carbon emission allowances, the manufacturer's profit in Case I is the highest. When the government gives more carbon emission allowances, the manufacturer's profit in Case III is the highest. In Figure 10b, when consumers have higher low-carbon preferences, no matter how much carbon emission allowances the government grants, the manufacturer's profit is always the highest in Case II and the lowest in Case III.

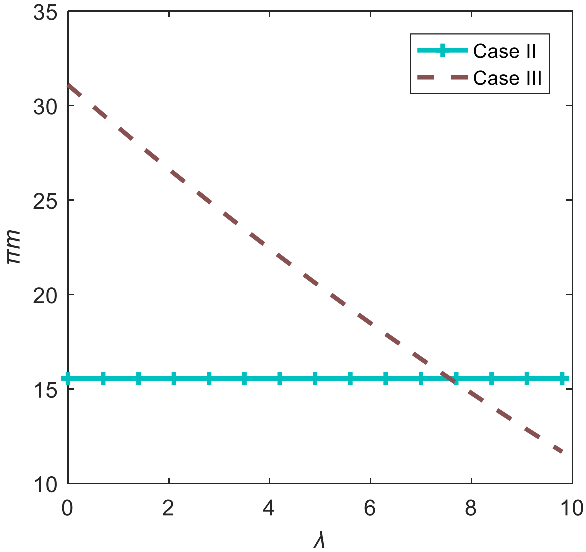

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Figure 9.
The manufacturer's profit varies with the initial carbon emissions in Case II and Case III

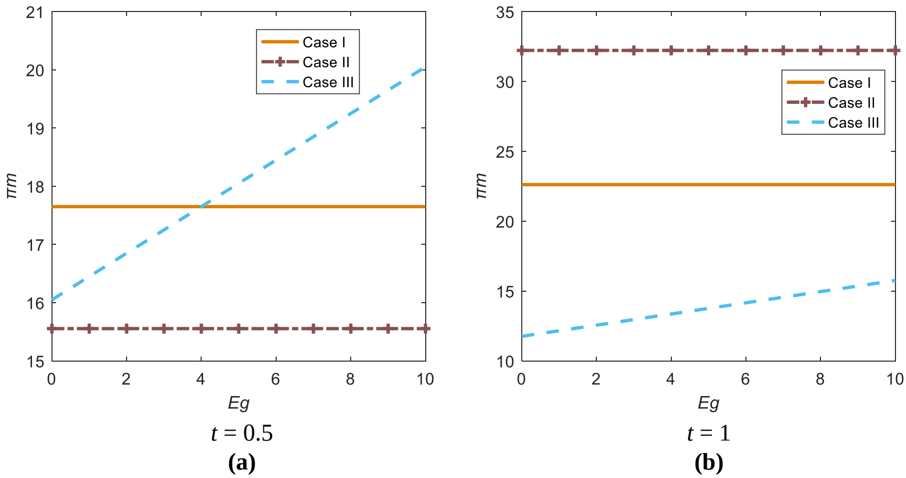

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Figure 10.
Comparison of the manufacturer's profit among various cases

From Figure 10, we can find that when consumers have high low-carbon preferences, the government cannot encourage the manufacturer to participate in the carbon trading market, no matter how many carbon emission allowances the government grants to the manufacturer. However, when consumers' low-carbon preferences are small, as the carbon emission allowances granted by the government increase, the manufacturer can obtain more profits by participating in the carbon trading market. At this time, implementing the carbon cap-and-trade policy can play a more effective role. Therefore, the government should grant reasonable carbon emission allowances at a suitable period. When the carbon cap-and-trade policy can no longer play a better position, the government should use other carbon emission policies, such as the carbon tax policy.

Figure 11a and b show that the manufacturer's profit is more sensitive to h than E_g. When making emission reduction decisions, compared with the carbon emission quota, the manufacturer should focus on the cost of emission reduction. Because it can be adjusted by the manufacturer independently.

Figure 12 shows the impact of carbon emission allowances on the supply chain profit. As seen from Figure 12a, when consumers' low-carbon preferences are small, if the carbon emission allowances are low, the supply chain profit in Case I is the highest. With the increase in carbon emission allowances granted by the government, the supply chain profit in Case III will increase accordingly. When consumers' low-carbon preferences are high, the supply

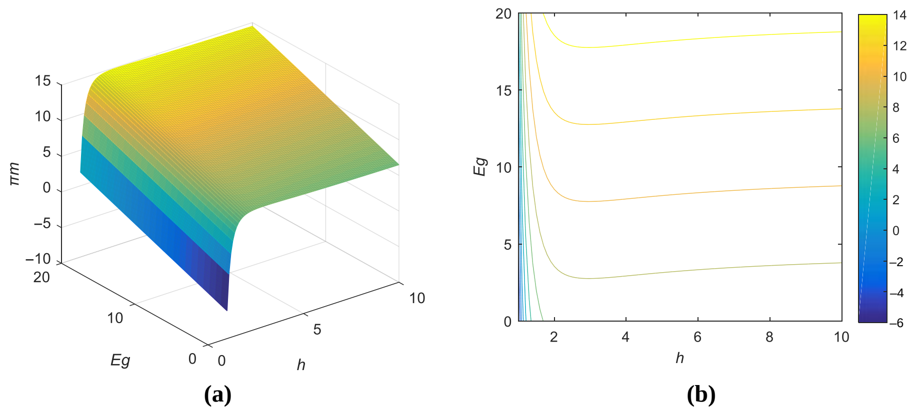

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Figure 11. (a) Impact of emission reduction cost coefficient and carbon emission quota on the manufacturer's profit; (b) Contour of the manufacturer's profit function with varying h and E_g

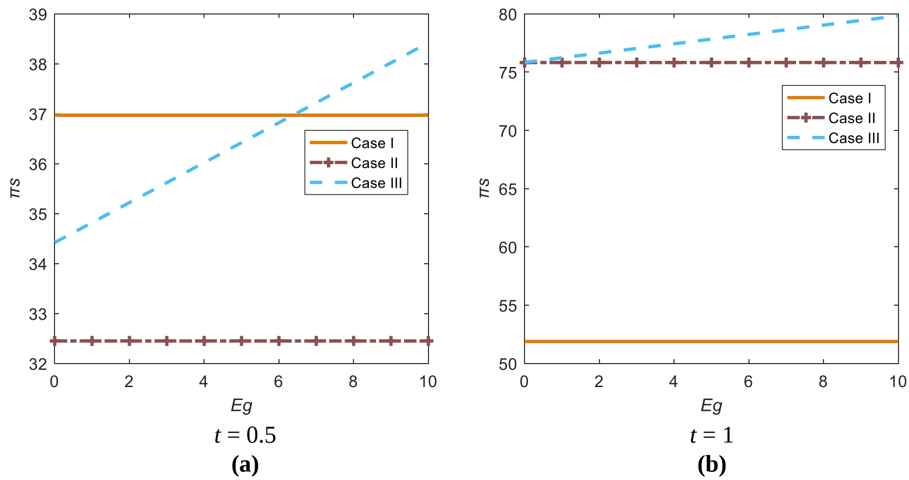

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Figure 12. Comparison of the supply chain profit among various cases

chain profit in Case I is the lowest. Case III has the highest supply chain profits. Through comparison, it can be found that when consumers have higher low-carbon preferences, the total profit of the supply chain increases after the government implements the carbon cap-and-trade policy. Thus, the role of the policy is more prominent. We can conclude from these experimental results that the government should first raise consumers' low-carbon awareness before implementing various carbon emission policies.

To solve the profit in-coordination situation, we make an extension in Section 7 and realize the coordination of supply chain profits through the revenue-sharing contract.

6.4 Managerial insights

Through game model analysis and numerical experiments of the equilibrium results, several interesting managerial insights are summarized as follows:

The uncertain low-carbon preferences of consumers in this paper are closer to the actual situation, which enriches the research on consumer behavior. The increase in consumers' low-carbon preferences will increase the demand for low-carbon products, thereby increasing the profits of enterprises. And it also promotes implementing government policies, which can enhance the effect of emission reduction policies. From the supply chain perspective, upstream enterprises should analyze consumer preferences for different products as an essential factor when making decisions. Enterprises can also cooperate with a party closer to the market for more accurate demand information.

The level of initial carbon emissions determines whether an enterprise will participate in the carbon trading market. In a low-carbon environment, more and more enterprises are considering joining the ranks of reducing emissions. However, not all enterprises can profit by participating in the carbon trading market. Enterprises must also pay attention to their initial carbon emissions. Enterprises with relatively high initial carbon emissions have to face higher costs in the carbon trading market and pay more carbon emission allowance fees. The high cost of participating in the carbon trading market may cause the enterprises to fail to realize the increase in revenue. Therefore, we do not recommend that such companies participate blindly in the carbon trading market. It is easy for enterprises with low initial carbon emissions to meet the government's carbon emission standards and obtain additional income in the carbon trading market. Therefore, such enterprises can participate in the carbon trading market after investing in emission reduction.

More importantly, the coordination of supply chain profit is a strong guarantee to achieve sustainable development. After the manufacturer increases emission reduction investment, the retailer enjoys the benefits. The cost of emission reduction is borne by the manufacturer alone, which will reduce the manufacturer's motivation to reduce emissions and may cause the failure of cooperation between the two parties and cause the supply chain to break. Therefore, both parties should improve their cooperation methods, share the benefits of emission reduction, or take the initiative to share emission reduction costs and strive to achieve a win-win situation.

This paper also gives some insight into emission reduction policy decisions for the government. Firstly, governments should pay attention to the timing of policy implementation. When consumers have low awareness of low-carbon preference, the carbon cap-and-trade policy has little effect on improving supply chain profits. The government should do an excellent job of education and publicity in the early stage, actively advocate enterprises carrying out green production and call on consumers to consume green and use low-carbon products. After raising consumer awareness of low carbon preferences, emission reduction policies will have a more significant impact. Secondly, the government can consider incorporating the emission reduction of the use process into the carbon cap-and-trade policy, which can better encourage manufacturers and consumers to reduce emissions.

7. Strategy expansion

To promote the sustainable development of the supply chain, enterprises must also consider stakeholders to ensure that each stage and activity in the supply chain positively impact society, the environment and the economy (Raza, 2018). Through the above analysis, under the decentralized model, the manufacturers' profit increases when they invest in emission reduction in two processes. But the manufacturer bears all the emission reduction costs. However, the retailer enjoys increased demand, which leads to "free-riding" behavior. This weakens the enthusiasm of the manufacturer to reduce emissions. If the retailer wants to continue to share the benefits of emission reduction investment, he/she needs to cooperate with the manufacturer and share the manufacturer's emission reduction costs. This can ensure that the manufacturer can continue to improve emission reduction. Therefore, in this section, we study the coordination effect of revenue sharing contract on the profits of both parties.

Based on Case II, we further analyze whether the manufacturer chooses to cooperate with the retailer to reduce emissions, coordinate their profits and achieve a win-win situation. We suppose they follow a contract: supply chain members share the retailer's sales revenue according to a pre-agreed share ratio. The retailer's share ratio is φ, the manufacturer's share ratio is $1-\varphi$, where φ represents the bargaining power of the retailer. The larger the φ, the stronger the retailer's bargaining power. Simultaneously, this contract is meaningful only if their profits do not decrease after implementing the cooperation contract. The following formulas should be satisfied:

$$E\left(\widetilde{\pi_r}\right) \geq E\left(\pi_r^{II}\right) E\left(\widetilde{\pi_m}\right) \geq E\left(\pi_m^{II}\right) \tag{27}$$

The optimal expected profits of supply chain members under the cooperation contract are:

$$\widetilde{E(\pi_r)} = (1-\varphi)p_2q_2 + (v_2-p_2)\int_0^{z_2}(q_2-d_2)f(\tau)d\tau - s_2\int_{z_2}^{2t}(d_2-q_2)f(\tau)d\tau - w_2q_2 \tag{28}$$

$$\widetilde{E(\pi_m})= w_2q_2 - \frac{1}{2}h(e_{2P})^2 - \frac{1}{2}k(e_{2U})^2 + \varphi p_2q_2 \tag{29}$$

According to Eq. (27), the income ratio interval $[\underline{\varphi}, \overline{\varphi}]$ can be obtained, $\overline{\varphi} > \underline{\varphi}$.

We use the Rubinstein bargaining model to determine the revenue share ratio. Mark Rubinstein used the complete information dynamic game method to simulate the basic and infinite information bargaining process and obtained the only subgame Nash equilibrium solution $x = \frac{1-\delta_2}{1-\delta_1\delta_2}$. δ_1, δ_2 represent the manufacturer's and the retailer's discount factor. That is "patient advantage". The profit negotiation in this paper is carried out in the profit ratio $[\underline{\varphi}, \overline{\varphi}]$. After negotiation, the two parties will trade at the revenue share ratio φ^*. Thus, we can obtain the respective revenue-sharing ratios of the manufacturer and the retailer:

$$1-\varphi^* = 1 - \frac{(1-\delta_2)(\overline{\varphi}-\underline{\varphi})}{1-\delta_1\delta_2} - \underline{\varphi} \tag{30}$$

$$\varphi^* = \frac{(1-\delta_2)(\overline{\varphi}-\underline{\varphi})}{1-\delta_1\delta_2} + \underline{\varphi} \tag{31}$$

Substituting the above formulas into Eqs (28) and (29) can get their profits under the contract. The profit distribution between the two parties can be realized, and the manufacturer will have more incentives to reduce emissions.

8. Conclusions

8.1 Conclusions and managerial implications

The development of smart supply chain technologies has improved the emission reduction efficiency of the manufacturing industry and provided new solutions for enterprises to reduce emissions. However, considering the investment cost factor, not all enterprises can profit from investing in smart supply chains. Therefore, this paper focuses on the issue of manufacturers' emission reduction investment strategies under the influence of the carbon cap-and-trade policy and consumers' low-carbon preferences. This paper studied two emission reduction investment strategies: (1) the manufacturer only invests in traditional emission reduction technologies in the production process and produces product 1, this is Case I; (2) the manufacturer increases investment in smart supply chain technologies in the use processes and produces product 2, this is Case II. To explore the impact of carbon cap-and-trade policy on emission reduction decisions, in Case III, we further analyzed the impact of carbon cap-and-trade policy on manufacturers' investment selection based on Case II.

We concluded several conclusions from the Stackelberg game models and experimental results by comparing the three cases. Firstly, consumer's low-carbon preferences affect the emission reduction and demand level, which in turn affect the profits of the manufacturer and retailer. Emission reduction, order quantity and retailer profit are positively related to consumers' low-carbon preferences. Improving the emission reduction is conducive to the manufacturer expanding production scale and improving the environment. However, under the carbon cap-and-trade policy, the manufacturer's profit increases first and then decreases in low-carbon preferences.

Secondly, the manufacturer does not have an absolutely optimal emission reduction strategy. The manufacturer's optimal emission reduction strategy changes with consumers' low-carbon preferences. When consumers' low-carbon preferences are low, the manufacturer's profit is the largest in Case III. And the manufacturer can only achieve higher profits in Case I compared to Case II. However, with the improvement of consumers' low-carbon preferences, the manufacturer can obtain the highest profit in Case II. Under any conditions, Case I is not the optimal choice for the manufacturer. The conclusion also explains why more enterprises are making reducing emissions a priority. Panasonic launched its long-term environmental vision, "Panasonic GREEN IMPACT" in 2022. One of its goals is to reduce customers' energy consumption by 100 million tons through on-board batteries, supply chain management software, heating ventilation, air conditioning (HVAC) and other existing areas.

Finally, the initial carbon emission and carbon emission quota also affect the manufacturer's decision-making and the effect of policies. When the manufacturer's initial carbon emission is low, the carbon cap-and-trade policy can encourage the manufacturer to reduce emissions. However, if the initial carbon emission is large, the manufacturer will not profit from the carbon trading market.

Based on the experimental results and theorems, we presented several management suggestions for improving emission reduction. The government should focus on encouraging manufacturers with high initial carbon emissions and give appropriate carbon emission quota concessions to support manufacturers in reducing emissions. Simultaneously, the government should take action to promote low-carbon production and lifestyles and improve consumers' environmental awareness. On the other hand, retailers can bear the promotion costs of high-quality low-carbon products burdening manufacturers. In addition, manufacturers should also actively respond to the government's call to take on social responsibility, increase research and development (R&D) investment, improve technology, consider emission reduction from different aspects and produce environmentally friendly products. The improvement of the environment requires the joint efforts of all parties. Cooperation and coordination are effective ways to achieve mutual benefits and win-win results.

8.2 Future directions

This study mainly provides suggestions for enterprises' investment in emission reduction, which leads to many extending directions. Firstly, our research is conducted under the assumption of complete information. Inspired by the study of Zhou and Kim (2020), asymmetric information between the manufacturer and retailer could be taken into account. Secondly, price is regarded as an exogenous variable in this paper. Different models can be considered in the future, and the price will be regarded as a decision variable. Furthermore, this paper only considers the impact of the carbon cap-and-trade policy on emission reduction, whereas its scope of application is limited. Other and mixed policies' effects on the low-carbon supply chain are other possible areas for future studies.

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Appendix
Source(s): Author's own creation/work

Appendix 1. Proof of Case I results

The first-order derivative of the retailer's expected profit function is:

$$q_1 = \frac{2te_{1P}(p_1 + s_1 - w_1)}{p_1 + s_1 - v_1} + u_0 \quad \text{(A1)}$$

Then the second derivative of q_1 is:

$$\frac{\partial^2 E(\pi_r')}{\partial q_1^2} = -\frac{p_1 + s_1 - v_1}{2te_{1P}} < 0 \quad \text{(A2)}$$

It can be seen that $E(\pi_r)$ is a concave function of the order quantity q_1, so the retailer has the largest profit.

Taking Eq. (A1) into $E(\pi_m)$, we can find the first derivative of e_{1P} and make it equal to 0:

$$e_{1P}^{I*} = \frac{2tw_1B_1}{hA_1} \quad \text{(A3)}$$

Substituting Eq. (A3) into Eq. (A1), the optimal q_1^{I*} is given by:

$$q_1^{I*} = \frac{4t^2B_1^2}{hA_1^2} + u_1 \quad \text{(A4)}$$

Appendix 2. Proof of Proposition 1

Firstly, we take the first-order derivation of Eq. (13) to q_2 and make it equal to 0:

$$\begin{aligned}\frac{\partial \pi_r}{\partial q_2} &= p_2 + (v_2 - p_2)\left[\int_0^{z_2} f(\tau)d\tau + q_2 z_2' f(z_2) - z_2 \prime d(z_2) f(z_2)\right] + s_2\left[\int_{z_2}^{2t} f(\tau)d\tau\right.\\ &\quad \left. + q_2 z_2' f(z_2) - z_2 \prime d(z_2) f(z_2)\right] - w_2 \\ &= 0 \end{aligned} \quad \text{(A5)}$$

Furthermore, the above equations are used to obtain the second-order derivation of q_2:

$$\frac{\partial^2 E(\pi_r')}{\partial q_2^2} = \frac{v_2 - p_2 - s_2}{2t(e_{2P} + e_{2U})} < 0 \quad \text{(A6)}$$

It can be seen that $E(\pi_r)$ is a concave function of the order quantity q_2, so the retailer has the largest profit.

Appendix 3. Proof of Proposition 2

(1) When $e_{1P}^{I*} - e_{2P}^{II*} = \frac{2tw_1B_1}{hA_1} - \frac{2tw_2B_2}{hA_2} > 0$, $\frac{B_1w_1}{A_1} > \frac{B_2w_2}{A_2}$.

(2) When $e_{2P}^{II*} - e_{2U}^{II*} = \frac{2tw_2B_2}{hA_2} - \frac{2tw_2B_2}{kA_2} > 0$, $h > k$.

Appendix 4. Proof of Proposition 4

(1) When $e_{2P}^{III*} - e_{2P}^{II*} = \frac{2t(w_2-\lambda p_e)B_2 + p_e u_2 A_2}{hA_2 - 4p_e t B_2} - \frac{2tw_2B_2}{hA_2} > 0$, $p_e\left(u_2A_2 - 2t\lambda B_2 + \frac{8t^2B_2^2w_2}{hA_2}\right) > 0$,

Because $p_e > 0$, $u_2 > \frac{2tB_2}{A_2} - \frac{8t^2B_2^2w_2}{hA_2^2}$.

(2) When $e_{2P}^{III*} - e_{2U}^{III*} = \frac{2t(w_2-\lambda p_e)B_2 + p_e u_2 A_2}{hA_2 - 4p_e t B_2} - \frac{2t(w_2-\lambda p_e)B_2 + p_e u_2 A_2}{kA_2 - 4p_e t B_2} > 0$, $h > k$.

Corresponding author
Yanjie Zhou can be contacted at: ieyjzhou@zzu.edu.cn

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