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Article

Decision-Making in Dual-Channel Supply Chains Based on Different Carbon Quota Allocation Policies

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Abstract

This paper constructs a decision-making model of a dual-channel supply chain based on different carbon trading policies and discusses the impact of different carbon quota allocation methods adopted by the government on the dual-channel supply chain. Under the restriction of carbon quota trading policy, with the goal of maximizing enterprise profit, the paper compares and analyzes the influence of carbon emission quota and carbon trading price on the profits of dual-channel supply chain and obtains the optimal decision-making model of enterprise channel selection. The example calculation shows that the profit level of manufacturers and retailers will be significantly affected by different carbon quota allocation policies along with the development of channels. The profit of manufacturers is positively correlated with the amount of carbon allowances, and the relationship with carbon trading price shows different trends under different allocation policies of carbon allowances. The retailer's profit in the dual channel is not affected by the amount of carbon quota and the price of carbon trading, and the relationship between the retailer's profit and the amount of carbon quota and the price of carbon trading in the single channel shows different trends under different carbon quota allocation policies.

Keywords: carbon trading; grandfathering; benchmarking; dual channel supply chain

1. Introduction

At present, the problem of global warming and over-consumption of resources is becoming more and more serious. As an important mechanism for pricing greenhouse gas emissions, carbon emissions trading has become increasingly important, has played an important role in promoting enterprises to save energy consumption and control greenhouse gas emissions, and has been adopted and implemented by an increasing number of countries and regions, it has become an important tool for the international community to tackle climate and resource issues. In 1997, the United Nations Framework Convention on Climate Change established the Kyoto Protocol, which proposed a cooperative mechanism for international trading of emission reduction credits. In 2005, EU countries started establishing a greenhouse gas emissions trading system (EU-ETS); the system covers more than 31 countries and controls about 45% of Europe's total carbon emissions. Since 2007, the United States has adopted the Western Climate Initiative (WCI) and regional greenhouse gas emission reduction initiative (RGGI). China's carbon market is also developing rapidly, in the decision of the Central Committee of the Communist Party of China on further deepening reform in an all-round way and promoting chinese-style modernization adopted at the third plenary session of the 20th Central Committee of the Communist Party of China in 2024, stressing the need to deepen institutional reform for ecological conservation, promote carbon reduction, pollution reduction,

green expansion and growth in a coordinated manner, and improve the mechanism for green and low-carbon development, while responding to government regulation and the allocation of carbon emission rights and quotas, enterprises will also be affected by the low-carbon consumption tendency of consumers and thus choose to develop low-carbon production technologies (Wang & Xu, 2018), therefore, enterprises in the supply chain have to consider the impact of low-carbon preferences of consumers on the overall profits of the supply chain, with the booming development of e-commerce economy, more and more enterprises are actively developing online channel operations, in order to achieve sustained profits in the fierce market competition, online and offline dual-channel supply chain has become the preferred strategy for most enterprises to operate (Tian et al., 2018). In the operation environment of two-channel supply chain, the Low-carbon preference and channel preference of consumers make the decision-making process more complicated. Therefore, it is of great significance to study how dual-channel supply chain enterprises make decisions to improve their profit level when facing different carbon allocation policies of historical emission law and benchmark law.

The current research focuses on supply chain management under the government's carbon quota allocation policy and the dual-channel supply chain channel selection under the background of carbon quota trading. Benjaafar and his colleagues first discussed the impact of carbon trading on supply chain operations and management under government carbon allocation policies; they found that the existence of carbon regulation can significantly increase the value of supply chain collaboration (Benjaafar et al., 2012). Zhang Lihao and his colleagues studied the supply chain strategy selection under the consideration of carbon quotas and trading mechanisms, carbon emission reduction technology input, and consumers' low-carbon preferences (Zhang et al., 2019). Wang et al. examined the impact of carbon quota policies on supply chain members to verify the effectiveness of government carbon quota policies (Wang et al., 2020). Xia Liangjie and others studied how to make decisions and coordinate the supply chain when the consumers' Low-carbon preference is considered under the government's mandatory emission reduction regulation (Xia et al., 2019). Wang et al. studied supply chain production and carbon reduction strategies based on carbon policy regulation (Wang et al., 2020). Xia Xiqiang and his colleagues studied the impact of government subsidies on original manufacturers and remanufacturers in a closed-loop supply chain under two different carbon allocation modes: the historical emission method and the baseline method (Xia et al., 2024). Xu Jianteng and other analyses of the historical method and baseline allocation of carbon allowances under the business of robust emission reduction strategy (Xu et al., 2023). Chang et al. examined the impact of carbon costs generated by the historical and baseline approaches to allocating free carbon allowances on firms' manufacturing and remanufacturing production decisions (Chang et al., 2017). Liao et al. compared the impact of historical and baseline approaches on reducing carbon emissions in supply chain enterprises (Liao et al., 2015), while Ji et al. compared the impact of historical and baseline approaches on corporate decision-making, profits, and social welfare; the benchmark approach was found to be more effective than the historical approach in motivating manufacturers to produce low-carbon products and in motivating retailers to promote low-carbon products (Ji et al., 2017). Han Xiaoya et al. found that carbon caps, trade policy, and consumer awareness of environmental protection significantly impact the choice of business marketing model (Han et al., 2024). Wang Kai et al. found that different government policies on carbon allocation would affect the determination of optimal supply chain policies (Wang et al., 2023). Leimin et al. found that firms using the benchmark approach make more profits when factors change than those using the grandfathering (historical emission method) approach and are more stable in market competition (Abdulrehman et al., 2024). Existing studies have focused on the carbon reduction behaviour and production decisions of manufacturers and retailers in a single-channel supply chain under the government's carbon quota allocation mechanism; there is little consideration of the impact of consumer channel preferences on a dual-channel supply chain subject to different government carbon allocation mechanisms when the supply chain opens up online channels. In the study of channel selection in a dual-channel supply chain in the context of carbon quota trading, Zhang et al.

studied the emission reduction behaviour of supply chain members in the retail channel and dual channel situations when considering both cap-and-trade regulation and low-carbon preferences of consumers, they found that joint emission reduction strategies were more beneficial to both manufacturers and retailers (Ji et al., 2017). Yang et al. studied the impact of low-carbon policies on channel coordination in a two-echelon supply chain consisting of one supplier and one retailer. This paper analyzes and compares the impacts of four low-carbon policies on channel coordination: the basic model, carbon emission model, carbon emission trading model and carbon tax model (Yang et al., 2014). Yang Shihui and others have studied the impact of the cost of carbon emissions and Manufacturers' investment in carbon reduction on a two-channel low-carbon supply chain dominated by manufacturers; it is found that the carbon emission cost per unit product sold in traditional retail channels determines the existence of dual-channel supply chain (Yang & Xiao, 2017). Sun Jiannan and other comprehensive considerations of low-carbon consumer and channel preferences seek low-carbon supply chain optimal emission reduction boundary (Sun & Xiao, 2018). Zhang and his colleagues have studied how hard a two-channel supply chain is to reduce emissions and how to make optimal decisions on channel selection with the goal of profit maximization. Manufacturers can make more profits by opening online channels or investing in carbon reduction, and retailers' profits are not affected by carbon cap-and-trade policies (Zhang et al., 2023). Wu Wenqi et al found that carbon cap-and-trade policies improved the profitability of the power battery recycling supply chain (Wu & Zhang, 2024). Zhang Danlu et al. compared the impact of carbon trading price and carbon emission coefficient on enterprises' optimal decision-making (Zhang et al., 2024). Wang Dao et al. found that the government's allocation of carbon allowances to retailers can improve the overall carbon emission reduction benefits of the supply chain (Wang et al., 2024). Li Jin et al. found that only the appropriate carbon price can guarantee the promotion of manufacturers to achieve optimal emission reduction (Li et al., 2024). The existing research mainly focuses on the comparative analysis of the carbon quota level, with or without carbon emission reduction behaviour of the two-channel supply chain emission reduction decision-making and channel selection decision-making; little consideration has been given to the impact of different carbon allocation policies on profits and channel selection in a two-channel supply chain. Therefore, given the existing research on the government's implementation of different carbon allocation policies, the supply chain enterprises lack a single dual-channel operating strategy for profit changes; in this paper, the single-channel and double-channel supply chain decision-making models of carbon allocation policy based on historical emission method and carbon allocation policy based on benchmark method are constructed, taking the supply chain composed of government, single manufacturer, single retailer and consumer as the research object, the profit situation of single-channel supply chain and double-channel supply chain under two kinds of carbon quota allocation policies are analyzed comparatively. Furthermore, the influence of carbon emission quota and carbon trading price on the profit of single-channel and double-channel supply chains is analyzed by numerical simulation.

The structure of this paper is as follows: the second part introduces the logical framework, model parameters and research assumptions; The decision-making models of single-channel and double-channel supply chains under carbon allocation policy based on historical emission method and carbon allocation policy based on benchmark method are constructed, and the optimal profit situation is solved, the fifth part discusses the innovation, limitation and prospect of this paper, and the sixth part summarizes the content of this paper.

2. Research Framework and Basic Assumptions

This study considers a supply chain consisting of one manufacturer and one retailer under the constraints of different carbon trading policies, in which the retailer is engaged in the sales activities of the product, the manufacturer is involved in the production of the product and the sales activities of the carbon quota, they are also subject to a set carbon quota and receive free carbon allowances from the government within a certain period, in the absence of carbon allowances, it is necessary to purchase the corresponding carbon allowances from the carbon trading market at a price per unit of

carbon allowances or to carry out carbon emission reduction activities to reduce carbon emissions, the surplus carbon allowances can be sold in the carbon market at a price per unit of carbon allowances, thus making corresponding profits. At the same time, manufacturers have two sales channels: they can sell products directly to consumers through online channels, and they can also sell products to consumers through retailers through offline channels; consumer purchasing behaviour is determined by the consumer’s utility, which is influenced by the channel preference of online or offline shopping and the low-carbon preference of products. Considering two channels and two kinds of carbon allocation, the paper analyzes the overall profit of the supply chain from channel preference and Low-carbon preference. Building the model is shown in Figure 1.

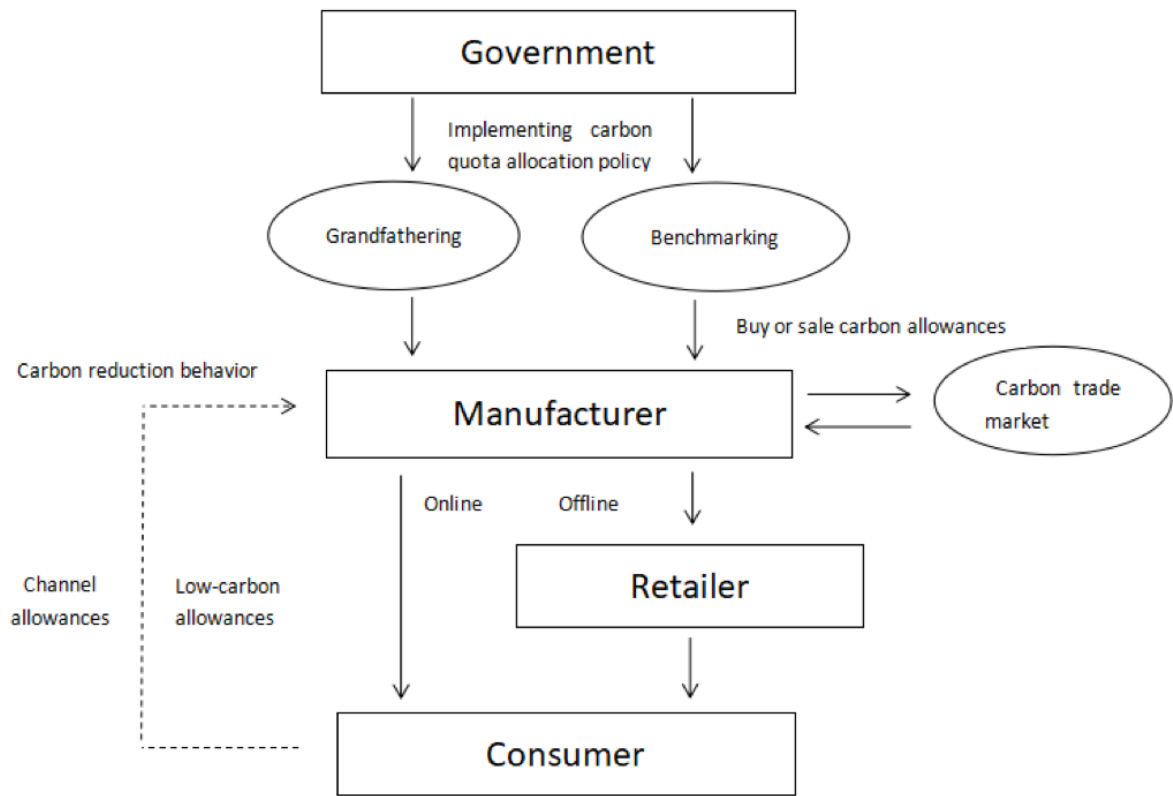


Figure 1. Two-channel supply chain structure under carbon quota allocation policy.

2.1. Model Parameters

The model parameters used in this article and their implications are described in Table 1.

Table 1. Model parameters and their implications.

Parameters	Meaning
Q	Product demand
θ	Carbon emission reduction rate per unit product
μ	Consumer acceptance of online channels
β	Coefficient of consumer utility to carbon reduction rate per unit

u_i	Consumer Utility
v_i	Consumer value
p_i	Unit Price
w_i	Wholesale price per unit
C_i	Channel cost per unit of product
M	Cost coefficient of carbon reduction
e	Carbon emissions per unit of product
E	Total carbon allowances under the historical approach
α	Carbon quota per unit product under the benchmark method
p_e	Carbon trading price per unit
r	Offline channels
m	Online channels
s	Single Channel
d	Double Channel
T	The law of history
U	Benchmark method

2.2. Model Assumptions

Assumption 1: the supply chain is faced with the historical emissions law and the benchmark law two most typical current free carbon quota allocation policies, the historical emission method is to determine the total amount of carbon emission quota as E based on the carbon emission data of the enterprise’s history, the standard method is to determine the carbon emission quota of unit product as α based on the carbon emission data of the industry to which the enterprise produces the product.

Assumption 2: when a manufacturer makes an investment in reducing carbon emissions, the level of emission reduction is positively correlated with the cost of investment in reducing carbon emissions, but we need to consider the cost of investment in carbon emission reduction and the price

of carbon quota trading is $\frac{1}{2}M\theta^2$. The cost of investment in carbon emission reduction is the cost of carbon quota trading is $p_e(e-g)$.

Assumption 3: the supply chain in this paper is a single manufacturer and a single retailer, the manufacturer produces and sells a single product, the retailer sells a single product, and the product market demand is uniformly distributed $[0,1]$ (Zhang et al., 2023), consumer purchasing behavior depends on consumer utility u_i .

3. Model Construction and Solution

Building a model of consumer utility when consumers buy products through offline channels: $u_r = v - p_r + \beta\theta$. Consumers' willingness to buy also depends on channel preference, while consumers' acceptance of online channels is μ , $0 < \mu < 1$. The expression of the consumer utility function that the consumer acquires when making an online purchase is $u_r = \mu v - p_m + \beta\theta$. When the consumer benefit function is satisfied $u_r > u_m$ and $u_r > 0$, the consumer can only buy the product through the offline channel; when the consumer benefit function is satisfied $u_r < u_m$ and $u_m > 0$, the consumer can only buy the product through the online channel; When the consumer benefit function is satisfied $u_r = u_m > 0$, on-line and off-line channels exist at the same time, when the two-channel supply chain on-line and off-line channel demand is simplified as follows:

$$\begin{cases} Q_r = 1 - \frac{p_r - p_m}{1 - \mu} \\ Q_m = \frac{\mu p_r - p_m + \beta\theta(1 - \mu)}{\mu(1 - \mu)} \end{cases} \quad [13].$$

In single-channel and double-channel supply chains, the profit function of the retailer is composed of the income and expenditure of the products sold offline. In contrast, in single-channel supply chains, the profit function of the manufacturer consists of the profit and loss of the product sold offline, the profit and loss of trading carbon emission allowances and the cost of reducing emissions the profit function of the manufacturer consists of four parts: the profit and loss of the products sold online, the profit and loss of the products sold offline, the profit and loss of the trading of carbon emission allowances, and the cost of reducing emissions. In addition, in order to distinguish between the historical emission method and the baseline method, the profit and loss of trading carbon emission allowances in constructing the profit function of the supply chain, when calculating the profit and loss carbon quota of an enterprise under the historical emission method, it is calculated by multiplying the carbon emission quota per unit product consumed by the enterprise and the sales volume of the product, and then subtracting the total carbon quota of the historical method, when calculating a company's profit and loss carbon allowances under the baseline method, using the method of multiplying the difference between the carbon emission allowances per unit of product consumed by the enterprise in the process of production minus the carbon allowances per unit of the baseline method and the sales volume of the product, this paper analyzes and calculates the profit situation of enterprises under the single-channel and double-channel production and management mode when they are faced with different carbon quota allocation policies.

3.1. Single Channel Decision-Making Under the Historical Emission Method

Profit function:

$$Q_r^{sT} = 1 - p_r^{sT} + \beta\theta^{sT}$$

$$\pi_m^{sT} = (w^{sT} - c_r)Q_r^{sT} - [e(1 - \theta^{sT})Q_r^{sT} - E]p_e - \frac{1}{2}M\theta^{sT2}$$

$$\pi_r^{sT} = (p_r^{sT} - w^{sT})Q_r^{sT}$$

Theorem 1: under this model, the optimal decision of supply chain is p_r^{sT*} , w^{sT*} , θ^{sT*} , and the profit of each main body of supply chain is π_r^{sT*} , π_m^{sT*} . In the single channel decision-making model under the historical emission method, there are optimal unit price p_r^{sT*} , wholesale price w^{sT*} and carbon emission reduction rate θ^{sT*} which make manufacturers and suppliers obtain optimal profits.

The certification process is as follows:

Solution:

$$p_r^{sT} = \frac{w^{sT}}{2} + \frac{\beta\theta^{sT}}{2} + \frac{1}{2}$$

The second-order Heather Matrix on sum is easy to find by substituting:

$$H_1 = \begin{pmatrix} -1 & \frac{\beta}{2} - \frac{ep_e}{2} \\ \frac{\beta}{2} - \frac{ep_e}{2} & \beta ep_e - M \end{pmatrix}$$

At that time, the negative definite of the heather matrix, that is, there exists an equilibrium solution for the sum, and the simultaneous solution of the sum is obtained:

$$w^{sT*} = \frac{\beta^2 c_r - 2Mc_r - 2M + e^2 p_e^2 + \beta e^2 p_e^2 - 2Mep_e + \beta ep_e + \beta^2 ep_e + \beta c_r ep_e}{\beta^2 + 2\beta ep_e + e^2 p_e^2 - 4M}$$

$$\theta^{sT*} = \frac{(\beta + ep_e)(c_r + ep_e - 1)}{\beta^2 + 2\beta ep_e + e^2 p_e^2 - 4M}$$

To solve by combining and substituting:

$$p_r^{sT*} = \frac{\beta^2 c_r - Mc_r - 3M + e^2 p_e^2 + \beta e^2 p_e^2 - Mep_e + \beta ep_e + \beta^2 ep_e + \beta c_r ep_e}{\beta^2 + 2\beta ep_e + e^2 p_e^2 - 4M}$$

Put, , and into the profit function of each subject, the solution is:

$$\pi_r^{sT*} = \frac{M^2(c_r + ep_e - 1)^2}{(\beta^2 + 2\beta ep_e + e^2 p_e^2 - 4M)^2}$$

$$\pi_m^{sT*} = -\frac{-2E\beta^2 p_e - 4E\beta ep_e^2 + Mc_r^2 + 2Mc_r ep_e - 2Mc_r - 2Ee^2 p_e^3 + Me^2 p_e^2 - 2Mep_e + 8EM p_e + M}{2(\beta^2 + 2\beta ep_e + e^2 p_e^2 - 4M)}$$

Corollary 1: in the single-line under-channel decision-making model of historical emission method, the optimal profit of manufacturers is affected by the total carbon quota of historical method, and increases with the increase of total carbon quota of historical method, the proof is as follows:

$$\frac{\partial \pi_m^{sT*}}{\partial E} > 0$$

$$\frac{\partial \pi_m^{sT*}}{\partial E} = p_e > 0$$

There was a positive correlation between them.

3.2. Single-Line Channel Decision-Making Under the Benchmark Method

$$\begin{aligned} Q_r^{sU} &= 1 - p_r^{sU} + \beta \theta^{sU} \\ \pi_m^{sU} &= (w^{sU} - c_r) Q_r^{sU} - [e(1 - \theta^{sU}) - \alpha] Q_r^{sU} p_e - \frac{1}{2} M \theta^{sU 2} \\ \pi_r^{sU} &= (p_r^{sU} - w^{sU}) Q_r^{sU} \end{aligned}$$

Theorem 2: under this model, the optimal decision of supply chain is p_r^{sU*} , w^{sU*} , and the optimal profit of each main body of supply chain is π_r^{sU*} , π_m^{sU*} . That is, in the single-line channel decision-making model based on the benchmark method, the optimal unit price p_r^{sU*} and wholesale price w^{sU*} make the manufacturer and supplier obtain the optimal profit.

$$\begin{aligned} w^{sU*} &= \frac{\beta^2 c_r - 2M c_r - 2M + e^2 p_e^2 + \beta e^2 p_e^2 + 2M \alpha p_e}{b^2 + 2\beta e p_e + e^2 p_e^2 - 4M} \\ p_r^{sU*} &= \frac{b^2 c_r - M c_r - 3M + e^2 p_e^2 + \beta e^2 p_e^2 + M \alpha p_e}{\beta^2 + 2\beta e p_e + e^2 p_e^2 - 4M} \end{aligned}$$

Put, put into the profits of the main body, solution:

$$\begin{aligned} \pi_r^{sU*} &= \frac{M^2 (c_r - \alpha p_e + e p_e - 1)^2}{(\beta^2 + 2\beta e p_e + e^2 p_e^2 - 4M)^2} \\ \pi_m^{sU*} &= -\frac{M (c_r - \alpha p_e + e p_e - 1)^2}{2(\beta^2 + 2\beta e p_e + e^2 p_e^2 - 4M)} \end{aligned}$$

Corollary 2: in the single-channel decision-making model under the baseline method, the profits of manufacturers and retailers are affected by the carbon quota of the baseline unit product, and increase with the increase of the carbon quota of the baseline unit product. The proof is as follows:

$$\begin{aligned} \frac{\partial \pi_r^{sU*}}{\partial \alpha} &= -\frac{2M^2 p_e (c_r - \alpha p_e + e p_e - 1)}{(\beta^2 + 2\beta e p_e + e^2 p_e^2 - 4M)^2} > 0 \\ \frac{\partial \pi_m^{sU*}}{\partial \alpha} &= \frac{M p_e (c_r - \alpha p_e + e p_e - 1)}{\beta^2 + 2\beta e p_e + e^2 p_e^2 - 4M} > 0 \end{aligned}$$

And were positively correlated with each other

Corollary 3: in the single-channel decision-making model under the baseline method, the profits of manufacturers and retailers are affected by the carbon price, and when the carbon emission per unit product is lower than the carbon quota per unit product under the baseline method, the optimal profits of manufacturers and retailers increase as the carbon price increases. Here's how:

At that time,

$$\frac{\partial \pi_m^{sU*}}{\partial p_e} = \frac{M(4p_e e^2 + 4\beta e)(c_r - \alpha p_e + e p_e - 1)^2}{(2\beta^2 + 4\beta e p_e + 2e^2 p_e^2 - 8M)^2} + \frac{2M(\alpha - e)(c_r - \alpha p_e + e p_e - 1)}{2\beta^2 + 4\beta e p_e + 2e^2 p_e^2 - 8M} > 0$$

$$\frac{\partial \pi_r^{sU*}}{\partial p_e} = -\frac{2M^2(2p_e e^2 + 2\beta e)(c_r - \alpha p_e + e p_e - 1)^2}{(\beta^2 + 2\beta e p_e + e^2 p_e^2 - 4M)^3} - \frac{2M^2(\alpha - e)(c_r - \alpha p_e + e p_e - 1)}{(\beta^2 + 2\beta e p_e + e^2 p_e^2 - 4M)^2} > 0$$

And were positively correlated with each other

3.3. Two-Channel Decision-Making Under Historical Emission Method

$$Q_r^{dT} = 1 - \frac{p_r^{dT} - p_m^{dT}}{1 - \mu}$$

$$Q_m^{dT} = \frac{\mu p_r^{dT} - p_m^{dT} + \beta \theta^{dT}(1 - \mu)}{\mu(1 - \mu)}$$

$$\pi_m^{dT} = (p_m^{dT} - c_m)Q_m^{dT} + (w^{dT} - c_r)Q_r^{dT} - [e(1 - \theta^{dT})(Q_m^{dT} + Q_r^{dT}) - E]p_e - \frac{1}{2}M\theta^{dT2}$$

$$\pi_r^{dT} = (p_r^{dT} - w^{dT})Q_r^{dT}$$

Theorem 3: under this model, the optimal decision of supply chain is p_m^{dT*} , p_r^{dT*} , w^{dT*} , and the optimal profit of each main body of supply chain is π_r^{dT*} , π_m^{dT*} . That is, in the two-channel decision-making model based on the historical emission method, there exists a p_m^{dT*} , p_r^{dT*} , w^{dT*} .

$$p_m^{dT*} = \frac{\beta^2 e p_e + c_m \beta^2 + \beta e^2 p_e^2 + \beta e \mu p_e + c_m \beta e p_e + e^2 \mu p_e^2 - M e \mu p_e - M \mu^2 - M c_m \mu}{\beta^2 + 2\beta e p_e + e^2 p_e^2 - 2M \mu}$$

$$w^{dT*} = \frac{\beta^2 c_m - 2M \mu + \beta^2 c_r - \beta^2 \mu + \beta^2 + e^2 p_e^2 + 2\beta e^2 p_e^2 - c_m e^2 p_e^2 + c_r e^2 p_e^2 + e^2 \mu p_e^2 - 2M c_r \mu + 2\beta e p_e + 2\beta^2 e p_e - 2M e \mu p_e + 2\beta c_r e p_e}{2(\beta^2 + 2\beta e p_e + e^2 p_e^2 - 2M \mu)}$$

$$p_r^{dT*} = \frac{2M \mu^2 - 6M \mu + 3\beta^2 c_m + \beta^2 c_r - 3\beta^2 \mu + 3\beta^2 + 3e^2 p_e^2 + 4\beta e^2 p_e^2 - c_m e^2 p_e^2 + c_r e^2 p_e^2 + e^2 \mu p_e^2 - 2M c_m \mu - 2M c_r \mu + 6\beta e p_e + 4\beta^2 e p_e - 2\beta e \mu p_e - 4M e \mu p_e + 2\beta c_m e p_e + 2\beta c_r e p_e}{4(\beta^2 + 2\beta e p_e + e^2 p_e^2 - 2M \mu)}$$

Put , into the profits of the main body, the solution:

$$\pi_r^{dT*} = -\frac{(c_m - c_r - \mu + 1)^2}{16(\mu - 1)}$$

$$\pi_m^{dT*} = \frac{1}{8} \left(\frac{1 + 2c_m - 2c_r - 4M - \frac{(c_m - c_r)^2}{-1 + \mu} - \mu + 8E p_e}{-2M \mu + (\beta + e p_e)^2} + \frac{4M(\beta^2 - c_m^2 + 2c_m \mu - \mu(2M + \mu) + 2e(\beta - c_m + \mu)p_e)}{-2M \mu + (\beta + e p_e)^2} \right)$$

Corollary 4: in the two-channel decision-making model of historical emission method, the profits of manufacturers are affected by the historical total carbon quota, and increase with the increase of the historical total carbon quota. The proof is as follows:

$$\frac{\partial \pi_m^{dT*}}{\partial E} = p_e > 0$$

Positive correlation

3.4. Two-Channel Decision-Making Under the Benchmark Method

$$Q_r^{dU} = 1 - \frac{p_r^{dU} - p_m^{dU}}{1 - \mu}$$

$$Q_m^{dU} = \frac{\mu p_r^{dU} - p_m^{dU} + \beta \theta^{dU} (1 - \mu)}{\mu(1 - \mu)}$$

$$\pi_m^{dU} = (p_m^{dU} - c_m)Q_m^{dU} + (w^{dU} - c_r)Q_r^{dU} - [e(1 - \theta^{dU}) - \alpha](Q_m^{dU} + Q_r^{dU})p_e - \frac{1}{2}M\theta^{dU2}$$

$$\pi_r^{dU} = (p_r^{dU} - w^{dU})Q_r^{dU}$$

Theorem 4: under this model, the optimal decision of supply chain is p_m^{dU*} , p_r^{dU*} , w^{dU*} , and the profit of each main body of supply chain is π_r^{dU*} and π_m^{dU*} respectively. That in the two-channel decision-making model based on the benchmark method, there exists the p_m^{dU*} , p_r^{dU*} , w^{dU*} .

$$p_m^{dU*} = \frac{\beta^2 e p_e - \alpha \beta^2 p_e + c_m \beta^2 + \beta e^2 p_e^2 + \beta e \mu p_e - \alpha \beta e p_e^2 + c_m \beta e p_e + e^2 \mu p_e^2 - M e \mu p_e - M \mu^2 + M \alpha \mu p_e - M c_m \mu}{\beta^2 + 2 \beta e p_e + e^2 p_e^2 - 2 M \mu}$$

$$w^{dU*} = \frac{\beta^2 c_m - 2 M \mu + \beta^2 c_r - \beta^2 \mu + \beta^2 + e^2 p_e^2 + 2 \beta e^2 p_e^2 - c_m e^2 p_e^2 + c_r e^2 p_e^2 + e^2 \mu p_e^2 - 2 M c_r \mu + 2 \beta e p_e - 2 \alpha \beta^2 p_e + 2 \beta^2 e p_e - 2 \alpha \beta e p_e^2 + 2 M \alpha \mu p_e - 2 M e \mu p_e + 2 \beta c_r e p_e}{2(\beta^2 + 2 \beta e p_e + e^2 p_e^2 - 2 M \mu)}$$

$$p_r^{dU*} = \frac{2 M \mu^2 - 6 M \mu + 3 \beta^2 c_m + \beta^2 c_r - 3 \beta^2 \mu + 3 \beta^2 + 3 e^2 p_e^2 + 4 \beta e^2 p_e^2 - c_m e^2 p_e^2 + c_r e^2 p_e^2 + e^2 \mu p_e^2 - 2 M c_m \mu - 2 M c_r \mu + 6 \beta e p_e - 4 \alpha \beta^2 p_e + 4 \beta^2 e p_e - 2 \beta e \mu p_e - 4 \alpha \beta e p_e^2 + 4 M \alpha \mu p_e - 4 M e \mu p_e + 2 \beta c_m e p_e + 2 \beta c_r e p_e}{4(\beta^2 + 2 \beta e p_e + e^2 p_e^2 - 2 M \mu)}$$

Put , into the profit function of each subject, the solution is:

$$\pi_r^{dU*} = -\frac{(c_m - c_r - \mu + 1)^2}{16(\mu - 1)}$$

$$\begin{aligned}
& -(2\beta c_r^2 e p_e + 2\beta e \mu^2 p_e + 4M\alpha^2 \mu p_e^2 + 4M e^2 \mu p_e^2 - 2c_m c_r e^2 p_e^2 - 2c_m e^2 \mu p_e^2 \\
& + 2c_r e^2 \mu p_e^2 + 4M c_m c_r \mu + 8M \alpha c_m p_e - 8M c_m e p_e - 8M \alpha \mu p_e + 8M e \mu p_e + 4\beta c_m e p_e \\
& - 4\beta c_r e p_e - 8M \alpha c_m \mu p_e + 8M c_m e \mu p_e - 4\beta c_m c_r e p_e - 4\beta c_m e \mu p_e + 4\beta c_r e \mu p_e - 8M \alpha e \mu p_e^2 \\
& + 2M \mu^3 - 4M c_m^2 - 2M \mu + 2\beta^2 c_m - 2\beta^2 c_r - 2\beta^2 \mu + \beta^2 + \beta^2 c_m^2 + \beta^2 c_r^2 + \beta^2 \mu^2 + e^2 p_e^2 \\
& - 4M \alpha^2 p_e^2 - 4M e^2 p_e^2 + 2c_m e^2 p_e^2 - 2c_r e^2 p_e^2 - 2e^2 \mu p_e^2 + 4M c_m \mu + 4M c_r \mu + 2\beta e p_e \\
& + c_m^2 e^2 p_e^2 + c_r^2 e^2 p_e^2 - 2\beta^2 c_m c_r - 2\beta^2 c_m \mu + 2\beta^2 c_r \mu + 2\beta c_m^2 e p_e - 4\beta e \mu p_e + 2M c_m^2 \mu \\
& - 4M c_m \mu^2 - 2M c_r^2 \mu - 4M c_r \mu^2 + e^2 \mu^2 p_e^2 - 8M e \mu^2 p_e + 8M \alpha e p_e^2 + 8M \alpha \mu^2 p_e) \\
\pi_m^{dU*} = & \frac{(8\mu - 8)(\beta^2 + 2\beta e p_e + e^2 p_e^2 - 2M \mu)}{
\end{aligned}$$

Corollary 5: in the two-channel decision-making model of the benchmark method, the optimal profit of the manufacturer is affected by the carbon quota per unit product of the benchmark method and increases with the increase of the carbon quota per unit product of the benchmark method, the proof is as follows:

$$\frac{\partial \pi_m^{dU*}}{\partial \alpha} = \frac{M p_e (c_m - \mu - \alpha p_e + e p_e)}{\beta^2 + 2\beta e p_e + e^2 p_e^2 - 2M \mu} > 0$$

And positive correlation

Corollary 6: in the two-channel decision model of the benchmark method, the best profit of the manufacturer is affected by the carbon price, and at that time, the best profit of the manufacturer increases with the increase of the carbon price. The proof is as follows:

At that time.

Positive correlation.

4. Example Analysis

In order to demonstrate and test the above conclusions more intuitively, and further analyze the impact of carbon quota and carbon trading price on the profits of dual-channel supply chain, according to the range of relative parameters of Xia Xiqiang (Xia et al., 2024) and Zhang Lingrong (Zhang et al., 2023), the relevant parameters are selected for single-channel and double-channel supply chain decision-making models under historical emission method and benchmark method. $\beta = 0.5$, $e = 1.8$, $p_e = 0.4$, $C_m = 0.19$, $C_r = 0.08$, $M = 20$, $E = 2$, $\alpha = 0.9$, $\mu = 0.9$.

4.1. Sensitivity Analysis of Manufacturer and Retailer Profits to Carbon Allowances

4.1.1. Sensitivity Analysis of the Gross Carbon Allowances of Manufacturers and Retailers to the Gross Carbon Allowances Under the Historical Emissions Approach

Under the historical emission method, the total carbon quota is determined according to the historical emission of the enterprise, and the interval is found near the basic model parameters [1.5, 2.5].

From Figures 2 and 3, we can find that the profits of manufacturers and retailers in the two-channel supply chain under the historical emission method are more significant than those of manufacturers and retailers in the single-channel supply chain; this shows that when the government implements the carbon quota allocation policy of the historical emission law, opening a double channel supply chain can effectively improve the profit level of each main body in the supply chain; The total carbon allocation under the historical carbon allocation policy has a positive impact on the profits of manufacturers, and the earnings of manufacturers under both single and double channels increase with the increase of the total carbon allocation under the historical method, this is because manufacturers are subject to carbon quotas during the manufacturing process. As the total carbon quota increases, the pressure on manufacturers to reduce emissions decreases, and the costs of

reducing emissions decrease accordingly; the prices of the products produced are reduced, consumer demand is increased, and the profits of manufacturers and enterprises are increased. The profits of retailers are not affected by the total amount of carbon allowances under the historical carbon allocation policy; this is because, compared with the unit carbon quota of the baseline method, the historical emission method allocates a fixed total carbon quota according to the carbon emission level of the enterprise in the past period, which is not related to the sales volume of the enterprise's products in the current cycle, retailers' profits are determined by wholesale prices and sales volumes, so they are not affected by the historical total carbon quota.

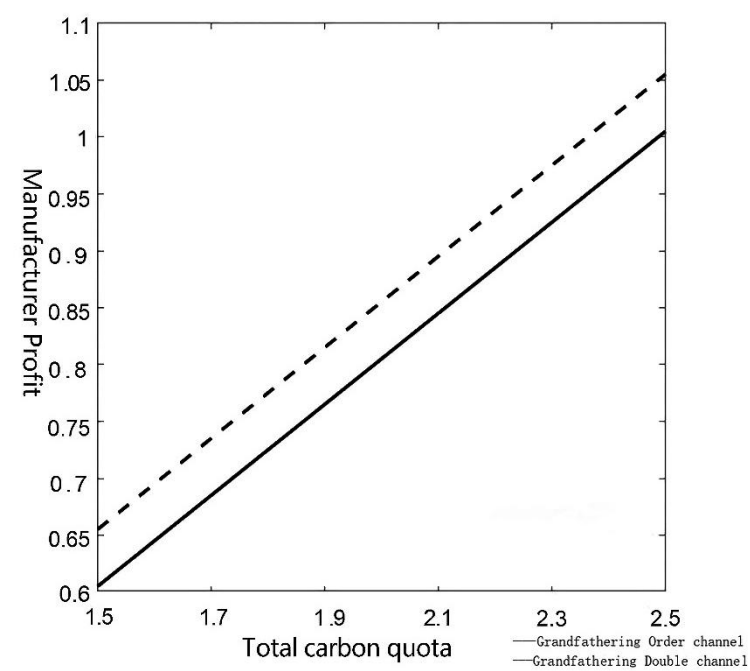


Figure 2. Effects in models 1 and 3.

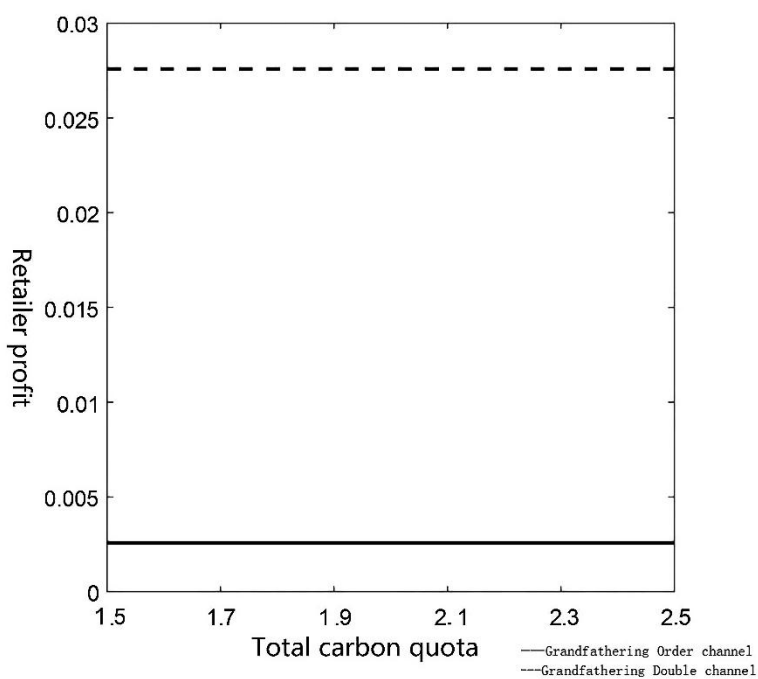


Figure 3. Effects in models 1 and 3.

4.1.2. Sensitivity Analysis of Manufacturer and Retailer Profits to Unit Carbon Allowances Under the Baseline Approach

Under the baseline method, the carbon quota is determined according to the industry’s emissions in which the enterprise is located, and the interval is found near the basic model parameters [0.2,1.2].

From Figures 4 and 5, it can be found that when the government implements the carbon quota allocation policy of the benchmark law, the profit level of the manufacturers and retailers under the single channel increases with the increase of the carbon quota; this is because, with the increase in carbon allowances per unit of product, there is less pressure on companies to reduce emissions, reducing the cost of reducing emissions for supply chain companies and thus making the total cost fall, which in turn reduces the price of products and stimulates consumer demand, increased sales of products, resulting in higher overall profits in the supply chain, and compared to the historical emissions method, the baseline method allocates carbon allowances based on the level of carbon emissions per unit of the product produced by the enterprise, in practice, it also needs to consider the actual sales volume of products, which has an impact on the profit level of retailers. In the two-channel supply chain, the profit level of manufacturers increases with the increase of carbon quota per unit product; the profits of the manufacturers in the two-channel supply chain are higher than those in the single-channel supply chain, which shows that the two-channel supply chain can effectively improve the profits of the manufacturers when the government implements the carbon quota allocation policy When the unit carbon quota is low, the profit level of the retailers in the two-channel supply chain is higher than that of the single-channel retailers,When $\alpha >$

$$cr + epe + \frac{(cm - cr - \mu + 1)(b^2 + 2bepe + e^2pe^2 - 4M)}{4M\sqrt{1 - \mu}} - 1$$

and $cm - cr - \mu + 1 > 0$, the profit of single-channel retailers surpasses that of dual-channel retailers, and the profit gap between single-channel and dual-channel retailers widens as the unit carbon quota increases. This indicates that establishing an online channel supply chain negatively impacts retailers’ profits.

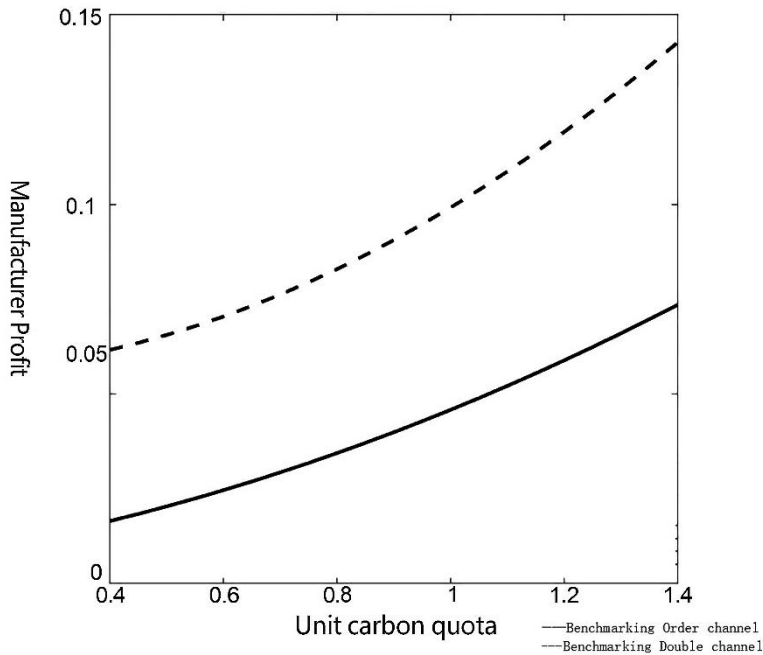


Figure 4. Effects in models 2 and 4.

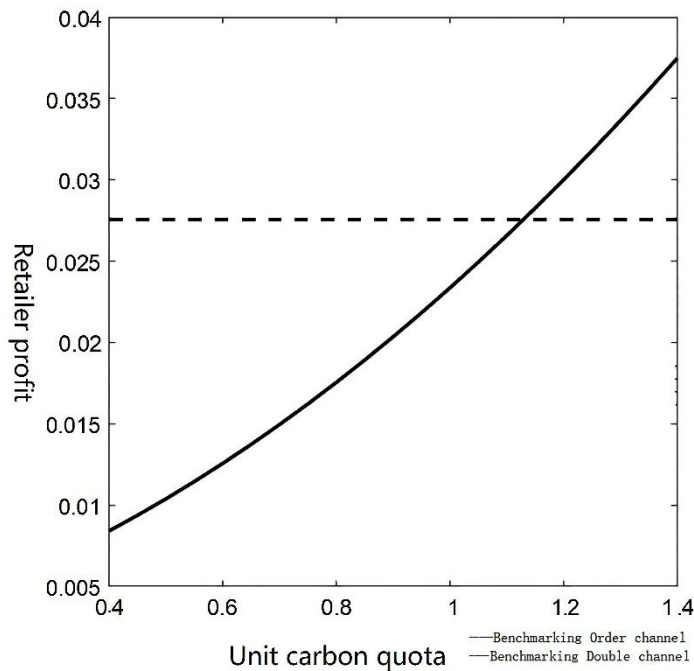


Figure 5. Effects on models 2 and 4.

4.2. Sensitivity of Manufacturers’ and Retailers’ Profits to Carbon Prices

To analyze the impact of carbon prices on the profits of manufacturers and retailers and to further analyze the difference in the impact of carbon prices on profits under the two modes of carbon allocation, select near the basic model parameters [0,0.8] to study the impact of changes on profits.

4.2.1. Sensitivity Analysis of Manufacturers’ and Retailers’ Profits to Carbon Trading Prices Under the Historical Emissions Approach

From figures 6 and 7, it can be found that when the government implements the carbon quota allocation policy of the historical emission law, the profits of the manufacturers under both single and double channels increase with the increase of the carbon quota trading price; this is because as carbon prices rise, manufacturers’ carbon management costs rise, but at the same time manufacturers can make a profit by selling their remaining carbon allowances on the carbon market. As carbon prices rise, the marginal cost of reducing carbon emissions falls as the scale of investment in reducing carbon emissions increases. At this point, reducing carbon emissions costs less than the profit from selling the remaining carbon allowances. With the rise in the price of carbon quotas, retailers’ profits under a single channel will decrease and then increase. In the two-channel supply chain, the price of carbon quota does not affect the profit of the retailers; this is because the difference between sales through the offline channel and the wholesale price through the offline channel has nothing to do with the carbon quota trading price, the profits of the manufacturers in the two-channel supply chain are higher than those in the single-channel supply chain, opening up an online channel can effectively provide manufacturers with profits, which is consistent with the reasoning above. When the price of carbon allowances is low, the profits of single-channel retailers are greater than those of dual-channel retailers; with the increase of the price of carbon trading, the profit of the retailers in single channel is gradually lower than that of the retailers in double channels, the creation of online channels does not necessarily increase the profits of retailers. It also needs to consider factors such as the amount of carbon allowances and the price of carbon trading in the carbon market to decide whether to open a dual-channel supply chain.

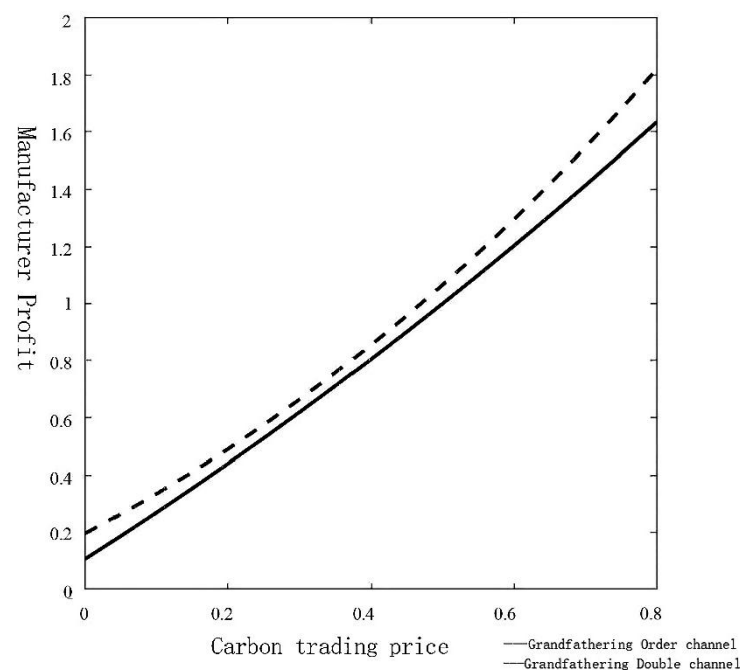


Figure 6. Effects in models 1 and 3.

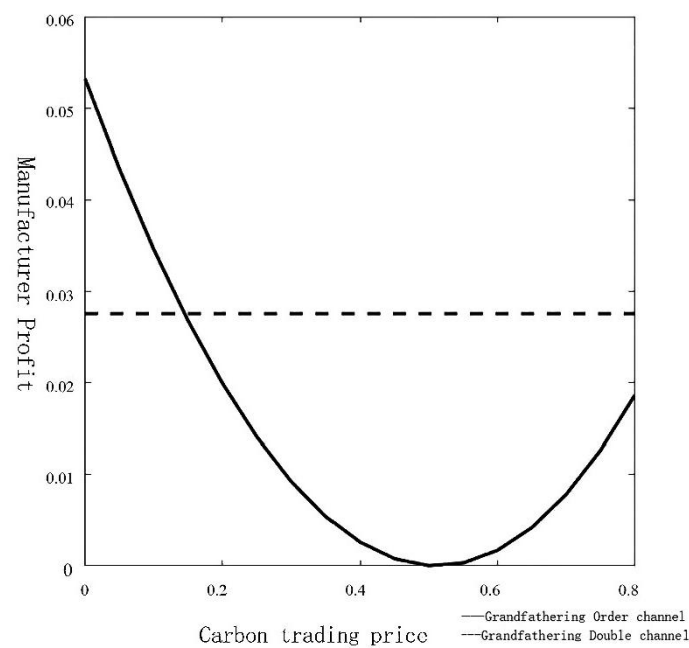


Figure 7. Effects in models 1 and 3.

4.2.2. Sensitivity Analysis of Manufacturers’ and Retailers’ Profits to Carbon Trading Prices Under the Manufacturing Benchmark Under the Historical Emissions Approach

Figures 8 and 9 show that when the government implements the carbon quota allocation policy of the benchmark law, the profits of both single-channel and dual-channel manufacturers decrease as the carbon price increases, this is because manufacturers need to invest heavily in emissions reduction under the benchmark policy to meet the requirements for carbon emissions, and when the price of carbon trading increases, the cost to manufacturers of carbon credits from the carbon market to meet emissions requirements also increases; profits for single-channel retailers decrease as the price of carbon increases, while for dual-channel retailers, retailers’ profits are not affected by the

carbon price because the difference between sales in the offline channel and the wholesale price in the offline channel is independent of the carbon price; it is the same as the historical emissions method, when the government implements the carbon quota allocation policy of the benchmark law, the profits of manufacturers after opening up online channels are higher than those of manufacturers under a single channel, this suggests that opening up online channels in the face of benchmarking (baseline method) policies can also lead to higher profits for manufacturers, while the profits of retailers in a single channel are higher than those of retailers in a dual channel when carbon prices are lower, as carbon prices rise, the profits of single-channel retailers continue to fall below those of dual-channel retailers, which also shows that opening up online channels does not necessarily increase retailers' profits, it is necessary to consider the influence of carbon quota and carbon trading price in carbon market in order to make decision on channel selection in supply chain management.

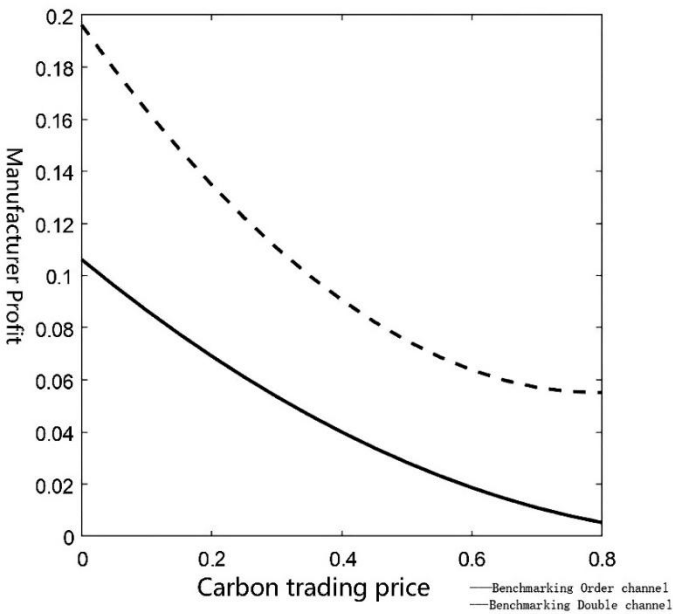


Figure 8. Effects in models 2 and 4.

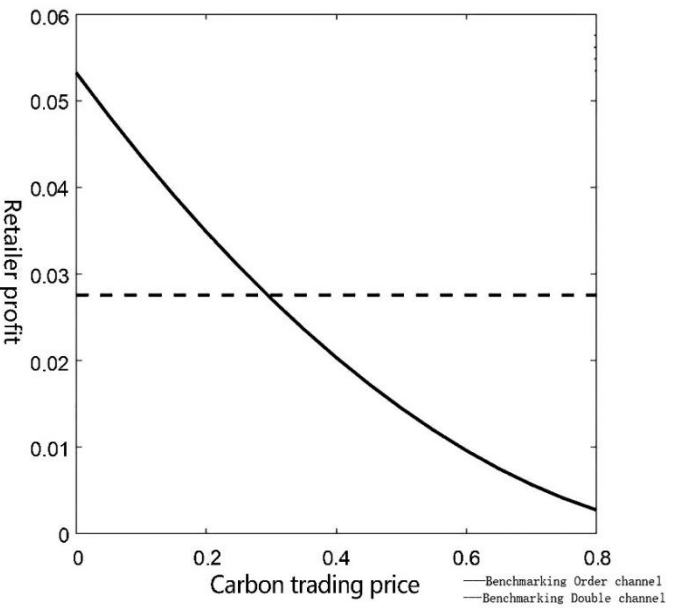


Figure 9. Effects in models 2 and 4.

5. Discussion

5.1. Research Significance

The research results of this paper suggest that when faced with the government's implementation of historical emission law and benchmark law of carbon quota allocation policy, active attention should be paid to the total carbon quota under the historical method and the unit carbon quota under the benchmark method, as well as the carbon trading price under the two allocation policies, and to the selection of appropriate channels according to the market environment, actively explore online marketing channels, improve the operation of dual-channel supply chain to achieve the maximum of their interests. For retailers to open a dual-channel supply chain, they need to pay attention to the difference in profit levels under the two carbon allocation policies as carbon allowances change and actively open up online channels when the government implements historical emission laws, seeking cooperation to improve their profit level, the government needs to take into account factors such as unit carbon quota and carbon trading price when implementing the benchmark law and make a careful decision on the selection of supply chain channels. The government can set a reasonable carbon quota trading policy, set a reasonable carbon quota and take appropriate measures to regulate the carbon price to promote the emission reduction of supply chain enterprises and multi-channel supply chain development and improvement; at the same time, we should increase low-carbon publicity to improve consumers' low-carbon preference, improve the profit level of supply chain enterprises, and promote the healthy development of social and environmental benefits and economic benefits.

5.2. Points of Innovation

(1) This paper integrates the government's various carbon quota allocation policies with profit variations of supply chain enterprises under single- and dual-channel models for analysis. Previous studies have provided preliminary exploration in this area. For instance, Wang et al. (2023) examined the impact of different carbon quota allocation policies on the optimal strategies of supply chains (Wang et al., 2023), while Zhang et al. investigated the emission reduction behaviors of supply chain members under cap-and-trade regulation and consumer low-carbon preferences in single and dual-channel contexts. Their findings revealed that a joint emission reduction strategy benefits both manufacturers and retailers (Ji et al., 2017). Building on these studies, this paper further analyzes the impact of different carbon quota policies on the profits of enterprises under dual-channel and single-channel models, thereby establishing a novel research perspective.

(2) Based on the aforementioned innovations, this paper delves deeper into the influence of carbon quota allocation and carbon trading prices on the profits of single- and dual-channel supply chains under different carbon quota allocation policies. Existing research, such as that by Zhang et al., compared the effects of carbon trading prices and carbon emission coefficients on firms' optimal decisions (Zhang et al., 2024). Similarly, Li et al. found that appropriate carbon prices could effectively promote manufacturers to achieve optimal emission reduction levels (Li et al., 2024). Building upon these findings, this paper provides a more granular analysis of the impacts of changes in carbon quota levels and carbon trading prices under different policy scenarios, offering practical insights for supply chain stakeholders in channel selection and operational decision-making.

5.3. Research Limitations and Prospects

➤ The study has the following limitations.

(1) In simulating the profit models of single-channel and dual-channel supply chains under different carbon quota allocation policies, the parameter values used were primarily based on the ranges proposed by previous scholars in authoritative journals. This reliance on existing literature may impact the practical applicability of the models.

(2) This paper assumes that supply chain enterprises' decision-making objective is profit maximization. However, in real-world scenarios, factors such as corporate social image may also influence these enterprises' operational decisions. This singular assumption may result in an incomplete representation of actual corporate behaviour.

➤ Future research can consider the following aspects for optimization and improvement.

(1) Collaborating with relevant institutions and enterprises to collect more extensive and representative data, thereby conducting broader numerical simulations to comprehensively validate and refine the profit models.

(2) Incorporating social image and corporate rationality into the models to account for their potential influence on supply chain decision-making. This approach would enable the development of decision-making models more aligned with real-world scenarios and provide a more comprehensive understanding of supply chain enterprises' decision-making behaviour.

6. Conclusion

This paper designs four supply chain decision models based on two different carbon quota allocation policies: the historical emission method and the benchmarking method. These models include the single offline channel under the historical method, the single offline channel under the benchmarking method, the dual channel under the historical method, and the dual channel under the benchmarking method. The study finds that establishing an online dual-channel supply chain can effectively enhance manufacturers' profits when the government implements carbon quota allocation policies based on the historical emission method or the benchmarking method. Additionally, opening an online channel can increase retailers' profits when the initial carbon quota and carbon trading price fall within a specific range.

Under the historical emission method, manufacturers' profits positively correlate with the total carbon quota and carbon trading price; as the total carbon quota and carbon trading price increase, manufacturers' profits also increase. However, in a dual-channel supply chain, retailers' profits are not influenced by the total carbon quota or carbon trading price. Similarly, in a single offline channel, retailers' profits are unaffected by the total carbon quota but decrease first and then increase as the carbon trading price rises.

Under the benchmarking method, manufacturers' profits are positively correlated with the unit carbon quota but negatively correlated with the carbon trading price. In a dual-channel supply chain, retailers' profits are unaffected by the unit carbon quota or the carbon trading price. However, in a single offline channel, retailers' profits increase with the unit carbon quota but decrease with rising carbon trading prices.

In a single-channel supply chain, retailers' profitability differs under the two carbon quota allocation policies. Under the historical emission method, retailers' profits are unaffected by the total carbon quota, and opening a dual-channel supply chain can effectively enhance their profits. In contrast, under the benchmarking method, retailers' profits increase with the unit carbon quota. However, opening a dual-channel supply chain may harm retailers' profits when the unit carbon quota becomes sufficiently large.

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