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# Research on Cost Sharing and Coordination of Low Carbon Supply Chain in the Context of Carbon Neutrality Strategy

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## Abstract

**For carbon emissions under the limit of supply chain cost sharing problem, based on the Shared contract perspective starkerberg game model includes the manufacturers and retailers, analyzes the cost sharing ratio, carbon trading price and unit carbon tax emissions on the supply chain, and the optimal strategy combination and carbon reduction cost allocation ratio is studied. The results show that the one-way cost sharing model is beneficial to the reduction of low carbon supply chain, while the two-way cost sharing model has a positive effect on the reduction of supply chain within the small allocation ratio. In addition, the sharing proportion of manufacturers is within a certain range, and the two-way emission reduction mode is the optimal choice for the supply chain. Meanwhile, the sharing proportion will affect the choice between decentralized and centralized decisions. In addition, the numerical analysis shows that the carbon emission reduction levels increase with the increase of carbon trading prices. The results have good reference significance for the carbon emission reduction decision and carbon reduction cost sharing contract among members of the low-carbon supply chain.**

## Keywords

**Carbon Emission Reduction Level; Low Carbon Supply Chain; Cost Apportionments.**

## 1. Introduction

Realizing carbon peak and carbon neutrality is of great significance to promoting Chinese-style modernization, achieving high-quality development and building a great modern socialist country in an all-round way. The party's 20th congress proposed to accelerate the green transformation of the development mode, and actively yet prudently promote carbon peak and carbon neutrality. The development of green supply chain is an important way to practice the concept of green development and promote the high-quality development of China's economy. In 2022, the Ministry of Industry and Information Technology and other three departments jointly issued the Implementation Plan for Carbon Peak in the Industrial Field, proposing to build a green and low-carbon supply chain, support leading enterprises in the industry to play a leading role in key areas such as supply chain integration and innovative low-carbon management, and promote the green and low-carbon development of the whole supply chain. Large manufacturing enterprises haier group will "through scientific and technological innovation in the field of energy conservation and emissions reduction" as one of the four pillars of low carbon development, retail giant wal-mart will "green supply chain" as the core of sustainable development, prompting many upstream manufacturers active low carbon transformation, in production, warehousing and transportation to achieve low carbon operation. The above practice shows that manufacturers actively invest in low carbon emission reduction technologies and assist retailers to implement low carbon transformation has become the development trend of low carbon supply chain. Therefore, the study of emission reduction cost sharing in the low-carbon supply chain (the practical problem to solve) from the perspective of shared contract will help to optimize and coordinate carbon emission reduction decisions among members of the low-carbon supply chain and the government to better

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implement carbon tax policies to further encourage enterprises' low-carbon transformation. Based on this, this paper established a starkerberg game model including manufacturers and retailers, considering the one-way and two-way cost sharing contract between members of the supply chain, analyzes the cost sharing ratio, carbon trading price and unit carbon tax reduction impact on the supply chain, and the optimal strategy combination and carbon reduction cost allocation ratio, the research conclusion helps to promote carbon reduction between low carbon supply chain members.

## 2. Literature Review

Low-carbon supply chain management has become a research hot topic due to government control of carbon and the change in public attitude to environmental protection. Most studies investigate the carbon policies in supply chains at the macro levels (Liu et al., 2015; Cheng et al., 2016). [1]Studies related to this work can be divided into two aspects. The first aspect studies supply chain decisions under cap-and-trade regulation, and the second investigates sharing contracts between firms in supply chains.The relevant research on low-carbon supply chain led by manufacturers mainly includes three aspects: supply chain emission reduction effect, product green degree, and cost-sharing contract. First of all, in terms of the emission reduction effect of low-carbon supply chain, Ding et al studied two game models, including Steinberg game and vertical Nash game. [2]Under the background of manufacturers as small and medium-sized enterprises, found that the altruistic preference of the dominant retailers promotes manufacturers and improves the system efficiency of the supply chain. The above study only considered the carbon reduction of manufacturers in the manufacturing process, and did not consider the potential participation of retailers in carbon reduction in the subsequent logistics link, thus not studying the joint emission reduction decision of the supply chain, which is also one of the entry points of this study.

Secondly, in terms of the product greening degree of the low-carbon supply chain. The green degree of products reflects the results of emission reduction, and the two are highly correlated. Zhou [3]focus on low carbon supply chain of old recycling problems, analyzes the green effect, sales effort effect on the influence of product green and pricing decisions, build the green marketing strategy and low price promotion strategy Dan [4]studied the influence of the government subsidies on green products, found that subsidies will improve the product green degree, in the market low carbon preference should subsidize manufacturers, when the marketing effect is good should subsidize retailers. These literature only explores the various factors about the greening degree of the product, and does not directly study the emission reduction problem of the supply chain, let alone involve the joint emission reduction decision problem of the supply chain. Jun et al found that the cost sharing contract can coordinate the supply chain in both retailer-led and manufacturer-led supply chain; Tchorzewska[5] et al targeted the logistics service supply chain, which favored the cost sharing contract, but was bad for logistics service providers. Yang [6] et al analyzed the impact of promotion cost sharing ratio on the supply chain pricing decision and profit, and found that the appropriate cost sharing ratio can achieve a win-win situation for manufacturers and retailers. This literature studies the sharing contract of manufacturers' innovation cost, research and development cost, logistics service cost and promotion cost, not on the sharing of emission reduction cost; and only analyzes the impact of sharing proportion change on innovation, research and development, promotion, service, etc., without finding the optimal sharing ratio, that is, the design of emission reduction cost sharing contract. In terms of carbon tax, studied the problem of multi-product production and pricing under aggregate control and emission trading regulations and carbon tax mechanism, compared the impact of two carbon emission policies on carbon emission, product production and profits of supply chain members, and further

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obtained the optimal policy in different situations. Wang Yuyan compared and analyzed four different carbon emission policies, but focused on their impact on supply chain channel coordination. Zhou Shihua [7]et al built a two-stage closed-loop supply chain game model including manufacturers, re-manufacturers and retailers, and analyzed the characteristics of the system dynamics. Considering the altruistic behavior of the subject of decision making, Fan analyzed the influence of price adjustment parameters on the stability of the supply chain system. Xu consider manufacturers disappointed avoid behavior perspective, Jiang from the perspective of retailers fair preference and Wang [8]respectively for low carbon propaganda differential countermeasures research decision, many scholars discusses the carbon policy intervention of supply chain reduction decisions, including subsidy policy, carbon tax policy, carbon trading policy, etc. Other scholars are focusing on the realization of low carbon emission reduction targets, and have conducted rich research on the issue of supply chain contract coordination.

In conclusion, when the existing literature studies the emission reduction problem of manufacturer-led low-carbon supply chain, it focuses more on the emission reduction of manufacturers in the production process, and less involves the joint emission reduction decision of supply chain. Meanwhile, when studying the retailer-led low-carbon supply chain cost sharing contract, it studies the retailers' innovation cost, research and development cost, logistics service cost and promotion cost, ignores the carbon reduction cost and lacks the optimal sharing ratio of cost-sharing contract design. In response, this paper studies the cost sharing contract joint emission reduction of low carbon supply chain, considers the emission reduction of manufacturers and retailers, designs the cost sharing contract to support retailers to share the carbon reduction cost of manufacturers, analyzes the influence of cost sharing contract on joint emission reduction, pricing and profit, and the sensitivity to consumer environmental awareness, so as to provide decision reference for the design of joint emission reduction and cost reduction contract of low carbon supply chain.[9-10].

## 3. Problem Description and Assumptions

This paper considers the carbon emission problem of low carbon supply chain based on the carbon credit first provided by its national government, and the additional carbon quota exceeds the initial credit; if the government approved carbon quota is not used, then the enterprise can sell the excess carbon quota to the carbon emission trading market. In low-carbon supply chains, manufacturers are directly involved in carbon emission reduction, while retailers participate in low-carbon promotion to make sales efforts. Given the pressure on carbon emissions, the two establish a two-way cost-sharing contract, which may allow them to share the cost. Supply chains must trade off between profits and carbon reduction levels. Therefore, the supply chain should reasonably determine commodity production, carbon emission reduction level, profit sharing ratio and other operational strategies. This study considers a two-stage supply chain that includes a manufacturer and a retailer, operating under carbon C. Manufacturers and retailers work directly and indirectly to reduce carbon emissions, respectively.

The manufacturer's unit production cost is c, the unit wholesale price is w, and the initial carbon emission level in the manufacturing process of this type of product is $e_0$. The retail price of this type of product is p. The manufacturer's product output is q, which can be equated to the market demand. Consumers have a green preference and tend to buy products that emit less carbon per unit of carbon in the manufacturing process. Driven by policies, to promote "carbon peak" and "carbon neutrality", the government levies a unit tax on the excessive carbon dioxide emissions in the production process of manufacturers. Driven by consumers' green preference and carbon tax policies, manufacturers are adopting emission reduction processes to reduce

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the unit carbon emissions in the production process. The following assumptions are made for the modeling: the manufacturer's unit carbon emission reduction level is e, and its abatement cost is $\frac{1}{2}k_1e^2$, where the $k_1$ is the manufacturer's abatement cost factor. For retailers to invest more in the promotion and advertising costs of low-carbon products, $\frac{1}{2}k_2r^2$is used to represent the retailer's low-carbon advertising cost, where $k_2$is the retailer's promotion cost coefficient and r is the retailer's promotion and publicity intensity.

## 3.1. Parameter Settings

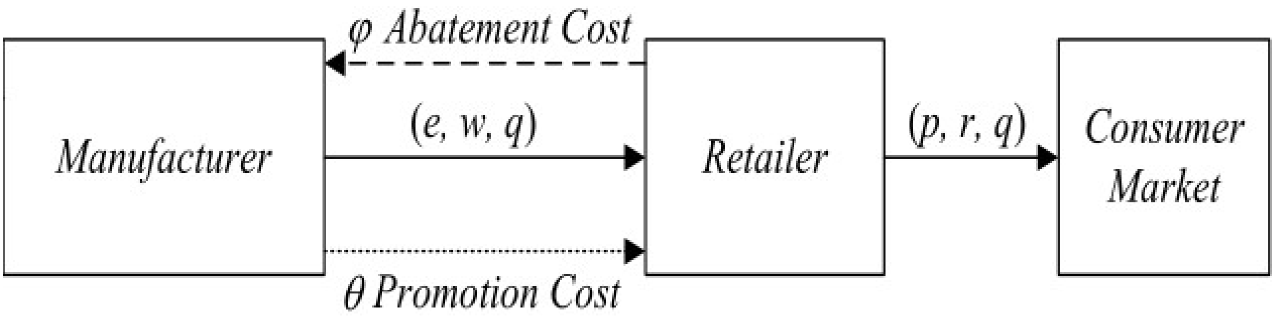


**Figure 1.** Supply chain structure

**Table 1.** Parameter Settings

| Symbol | Meaning |
|---|---|
| w | Wholesale price per unit of product |
| p | The retail price of a unit of product |
| c | The manufacturer's unit manufacturing cost |
| q | Manufacturer's product output |
| a | Potential market demand |
| $e_0$ | The initial level of carbon emissions per unit of product |
| e | The level of carbon reduction per unit of productLow-carbon advocacy |
| r | Low-carbon advocacy for retailers |
| E | The initial carbon credits allocated by the government |
| $p_c$ | The trading price per unit of carbon allowance |
| $k_1$ | The manufacturer's abatement cost factor |
| $k_2$ | The retailer's promotional cost factor |
| $b_1$ | The sensitivity coefficient of emission reduction level to demand for product |
| $b_2$ | The sensitivity coefficient of promotion strength to product demand |
| $\varphi$ | The proportion of the retailer that shares the manufacturer's abatement costs |
| $\theta$ | The manufacturer shares the proportion of the retailer's promotional costs |
| $t$ | The government levies a carbon tax on the unit of emissions |

## 3.2. Mathematical Model

Unidirectional sharing mode in decentralized Decision making (sd)

In this case, the manufacturer accepts the cost sharing of the retailer's emission reduction, and both the manufacturer and the retailer aim to maximize their own profits. There is a Stackelberg game between the two. The manufacturer, as the leader of the Stackelberg game, determines the wholesale price w of the product and the carbon emission reduction level e in the decision order. Then the retailer sets the product retail price p. Accordingly:

The demand function of the product:

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$$\mathrm{q} = \mathrm{a} - \mathrm{p} + \mathrm{b}_1\mathrm{e} \tag{1}$$

Manufacturer profit function:

$$\pi_M = [w - c - t(e_0 - e)]q + [E - (e_0 - e)q]p_c - \tfrac{1}{2}(1 - \varphi)k_1 e^2 \tag{2}$$

Retailer profit function:

$$\pi_R = (p - w)q - \tfrac{1}{2}\varphi k_1 e^2 \tag{3}$$

The optimal solution of the model is obtained by backward induction. The following propositions are about the optimal product price, carbon emission reduction level, product output and supply chain enterprise profit.

$$w^{sd*} = \frac{{b_1}^2[c+e_0(p_c+t)]+b_1(p_c+t)[a+c+e_0(p_c+t)]+a[(p_c+t)^2+2k_1(\varphi-1)]+2k_1[c+e_0(p_c+t)](\varphi-1)}{(b_1+p_c+t)^2+4k_1(\varphi-1)} \tag{4}$$

$$p^{sd*} = \frac{{b_1}^2[c+e_0(p_c+t)]+b_1(p_c+t)[a+c+e_0(p_c+t)]+a[(p_c+t)^2+3k_1(-1+\varphi)]+\mathrm{k1}[(c+\mathrm{e0}(\mathrm{pc}+t))(-1+\varphi)]}{(b_1+p_c+t)^2+4k_1(-1+\varphi)} \tag{5}$$

$$e^{sd*} = \frac{(b_1+p_c+t)[-a+c+e_0(p_c+t)]}{(b_1+p_c+t)^2+4k_1(-1+\varphi)} \tag{6}$$

Substitute (1), (2) and (3) to obtain the optimal product output and supply chain profit,

$$q^{DC*} = \frac{k_1(a-c+e_0\mathrm{Ep}_c-e_0 t)(-1+\varphi)}{(b_1-\mathrm{Ep}_c+t)^2+4k_1(-1+\varphi)} \tag{7}$$

$$\pi_{R^{DC*}} = \frac{k_1[-a+c+e_0(p_c+t)]^2[2k_1(-1+\varphi)^2-(b_1+p_c+t)^2\varphi]}{2[(b_1+p_c+t)^2+4k_1(-1+\varphi)]^2} \tag{8}$$

$${\pi_M}^{DC*} = \frac{[2{k_1}^2(1-\varphi)^2-\frac{1}{2}k_1(1-\varphi)(b_1+p_c+t)^2][a-c-(p_c+t)e_0]^2}{[4k_1(1-\varphi)-(b_1+p_c+t)^2]^2} + (p_c + t)E \tag{9}$$

Corollary: (1) $\frac{\partial e^{\mathrm{DC}^*}}{\partial \varphi} > 0; \frac{\partial q^{\mathrm{DC}^*}}{\partial \varphi} > 0$, (2)$q^{\mathrm{DC}^*} > q^{DC*}_{\varphi=0}$

Proof:

(1) The derivation of the optimal carbon emission reduction level and product yield can be obtained.

$$\frac{\partial e}{\partial \varphi} = \frac{4k_1(b_1-\mathrm{Ep}_c+t)(a-c+e_0\mathrm{Ep}_c-e_0 t)}{((b_1-\mathrm{Ep}_c+t)^2+4k_1(-1+\varphi))^2} > 0, \frac{\partial q}{\partial \varphi} = \frac{k_1(b_1-\mathrm{Ep}_c+t)^2(a-c+e_0\mathrm{Ep}_c-e_0 t)}{((b_1-\mathrm{Ep}_c+t)^2+4k_1(-1+\varphi))^2} > 0$$

According to the derivative in inference 3.1 (1), the decision variables e and q all increase with the increase of parameter φ. So when φ=0, $e_{\varphi=0}$ , $q_{\varphi=0}$ both are minimum values. Upon completion of the certificate.

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Corollary (1) shows the effect of the retailer's share on the level of carbon reduction and output of the product. It follows that the retailer's share has the same effect on the level of carbon reduction and product output. As the retailer's share increases, so does the manufacturer's level of carbon reduction and product output. This shows that when retailers are willing to share the cost of emission reduction of manufacturers, manufacturers are more willing to participate in carbon emission reduction, so as to produce more low-carbon and environmentally friendly products. This is also consistent with the market scenario, where manufacturers' carbon abatement becomes relatively easy as the cost of abatement shared by retailers increases, leading to an increase in the level of carbon abatement of products. Therefore, at this time, the products of the supply chain become more low-carbon and environmentally friendly and popular in the market.

Corollary (2) analyzes the changes of carbon emission reduction level and product output before and after retailers share the emission reduction cost of manufacturers. When retailers share the cost of reducing emissions with manufacturers, there is a significant increase in both the level of carbon reduction and the volume of products produced. Therefore, the inference shows that the one-way cost-sharing contract of retailers is conducive to carbon reduction and product production in the supply chain.

Unidirectional sharing mode in centralized decision making(sc).

In this case, the manufacturer and the retailer jointly make operational decisions to maximize the overall profit of the supply chain. Therefore, the overall profit function of the supply chain is:

$$\pi = \pi_M + \pi_R = [(p-c) - t(e_0 - e)]q + p_c(E - (e_0 - e)q) - \frac{1}{2}k_1\varphi e^2 \tag{10}$$

From this, the following propositions are about the optimal product price, carbon reduction level, product output, and the overall profit of the supply chain.

$$p^{sc^*} = \frac{(b_1+p_c+t)[a(p_c+t)+b_1(c+e_0(p_c+t))]-k_1[a+c+e_0(p_c+t)]\varphi}{(b_1+p_c+t)^2-2k_1\varphi} \tag{11}$$

$$e^{sc^*} = \frac{(b_1+p_c+t)[-a+c+e_0(p_c+t)]}{(b_1+p_c+t)^2-2k_1} \tag{12}$$

$$q^{sc^*} = \frac{k_1[a-c-e_0(p_c+t)]\varphi}{2k_1\varphi-(b_1+p_c+t)^2} \tag{13}$$

$$\pi^{sc^*} = \frac{2{b_1}^2 Ep_c+4b_1Ep_c(p_c+t)-k_1(-a+c+e_0(p_c+t))^2\varphi+2\mathrm{Ep}_c[(p_c+t)^2-2k_1\varphi]}{2(b_1+p_c+t)^2-4k_1\varphi} \tag{14}$$

Corollary: $\frac{1}{3} < \varphi < 1, e^{DC^*} > e^{SD^*}$ ; $0 \le \varphi < \frac{1}{3}, e^{DC^*} < e^{SD^*}$

$$e^{sd^*} - e^{sc^*} = \frac{(\mathrm{Ep}_c - b_1 - t)(a - c + e_0\mathrm{Ep}_c - e_0 t)}{(b_1 - Ep_c + t)^2 + 4k_1(-1+\varphi)} - \frac{(b_1 + p_c + t)(-a + c + e_0(p_c + t))}{(b_1 + p_c + t)^2 - 2k_1\varphi}$$

The above expression value greater than zero depends on $\frac{1}{\varphi-1} + \frac{1}{2\varphi} > 0, \varphi > \frac{1}{3}$. Corollary is a comparative analysis of the differences between product output and carbon emission reduction levels under decentralized and centralized scenarios, and it is concluded that the centralized decision-making scenario is not always optimal for carbon emission reduction and product production. $\frac{1}{3} < \varphi < 1$, The level of carbon emission reduction under decentralized decision-making is higher than that under centralized decision-making. $0 \leq \varphi < \frac{1}{3}$, The carbon emission reduction level is higher in the case of centralized decision-making. The results suggest that decentralised decision-making is better when retailers are willing to share more of the cost of carbon reduction with manufacturers. On the contrary, the low-carbon supply chain will choose centralized decision making, and when the retailer does not share the cost of emission reduction of the manufacturer, centralized decision making is undoubtedly the best for decentralized decision making.

Two-way sharing model in decentralized decision making(jd).

In this case, there is a two-stage game between the manufacturer and the retailer to maximize their own profits. First, the manufacturer, as the leader of the Stackelberg game, simultaneously determines the wholesale price w of low-carbon products and the carbon emission reduction level e. Then, after receiving the decision combination, the retailer simultaneously determines the retail price p of the product and the low-carbon publicity intensity r. According to the previous assumption, the profit function of each member of the low-carbon supply chain is as follows:

$$\pi_M = [w - c - t(e_0 - e)]q + [E - (e_0 - e)q]p_c - \frac{1}{2}(1-\varphi)k_1e^2 - \frac{1}{2}\theta k_2 r^2 \quad (15)$$

$$\pi_R = (p - w)q - \frac{1}{2}\varphi k_1 e^2 - \frac{1}{2}(1-\theta)k_2 r^2 \quad (16)$$

$$e^{\text{jd}^*} = \frac{{k_2}^2(1-\theta)^2(b_1+p_c+t)[a-c-(p_c+t)e_0]}{k_1k_2(1-\varphi)[4k_2(1-\theta)^2-2{b_2}^2+3\theta {b_2}^2]-[k_2(1-\theta)(b_1+p_c)]^2} \quad (17)$$

$$r^{\text{jd}^*} = \frac{2k_1(1-\varphi)k_2(1-\theta)b_2(a-c-p_ce_0)t}{k_1k_2(1-\varphi)[4k_2(1-\theta)^2-2{b_2}^2+3\theta {b_2}^2]-[k_2(1-\theta)(b_1+p_c)]^2} \quad (18)$$

$$w^{\text{jd}^*} = a + b_1e^{\text{jd}\star} - \frac{k_1(1-\varphi)e^{\text{jd}\star}[2k_2(1-\theta)-{b_2}^2]}{k_2(1-\theta)(b_1+p_c)} \quad (19)$$

$$p^{\text{jd}\star} = \frac{k_2(1-\theta)(a+b_1e^{\text{jd}\star}+w^{\text{jd}\star})-{b_2}^2w^{\text{jd}\star}}{2k_2(1-\theta){b_2}^2} \quad (20)$$

$$q^{\text{jd}*} = \frac{k_1(1-\varphi){k_2}^2(1-\theta)^2(a-c-p_ce_0)}{k_1k_2(1-\varphi)[4k_2(1-\theta)^2 2{b_2}^2+3\theta {b_2}^2]-[k_2(1-\theta)(b_1+p_c)]^2} \quad (21)$$

$${\pi_M}^{\text{jd}*} = \{\frac{{k_1}^2(1-\varphi)^2[2{k_2}^2(1-\theta)^2-k_2{b_2}^2+\frac{3}{2}\theta k_2{b_2}^2]}{{k_2}^2(1-\theta)^2(b_1+p_c)^2} - \frac{1}{2}k_1(1-\varphi)\}e^{\text{jd}*^2} + p_cE \quad (22)$$

$${\pi_R}^{\text{jd}*} = \{\frac{{k_1}^2(1-\varphi)^2[{k_2}^2(1-\theta)^2-\frac{1}{2}(1-\theta)k_2{b_2}^2]}{{k_2}^2(1-\theta)^2(b_1+p_c)^2} - \frac{1}{2}k_1\varphi\}e^{\text{jd}*^2} \quad (23)$$

Corollary:

(1) $\theta < \frac{1}{3}, \frac{\partial e}{\partial \theta} > 0, \frac{\partial q}{\partial \theta} > 0; \theta > \frac{1}{3}, \frac{\partial e}{\partial \theta} < 0, \frac{\partial q}{\partial \theta} < 0$

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(2) $0<\theta<\frac{1}{2}, e^{\mathrm{jd}*}>e^{\mathrm{jd}*}_{\theta=0}, \frac{1}{2}<\theta<1, e^{\mathrm{jd}*}<e^{\mathrm{jd}*}_{\theta=\frac{1}{2}}$

Proof:

(1) Derivation of the optimal carbon emission reduction level and product output in proposition can be obtained:

$$\frac{\partial e}{\partial \theta}=\frac{(1-3\theta){b_2}^2 k_1 k_2[a-c+e_0(p_c-t)](b_1-p_c+t)(-1+\theta)(-1+\varphi)}{\{k_2(-1+\theta)^2[(b_1-p_c+t)^2+4k_1(-1+\varphi)]+{b_2}^2 k_1(-2+3\theta)(-1+\varphi)\}^2}$$
$$\frac{\partial q}{\partial \theta}=\frac{(1-3\theta)b_1{b_2}^2 k_1 k_2[a-c+e_0(p_c-t)](b_1-p_c+t)(-1+\theta)(-1+\varphi)}{\{k_2(-1+\theta)^2[(b_1-p_c+t)^2+4k_1(-1+\varphi)]+{b_2}^2 k_1(-2+3\theta)(-1+\varphi)\}^2}$$

(2) Fraction simplification:

$$e^{\mathrm{jd}*}=\frac{{k_2}^2[a-c-(p_c+t)e_0](b_1+p_c+t)}{k_1k_2(1-\varphi)[4k_2+\frac{(3\theta-2){b_2}^2}{(1-\theta)^2}]-[k_2(b_1+p_c)]^2}$$

$e^{\mathrm{jd}*}_{\theta=\frac{1}{2}}=e^{\mathrm{jd}*}_{\theta=0}$,associative derivative condition, $0<\theta<\frac{1}{2}, e^{\mathrm{jd}*}>e^{\mathrm{jd}*}_{\theta=0}; \frac{1}{2}<\theta<1, e^{\mathrm{jd}*}<e^{\mathrm{jd}*}_{\theta=\frac{1}{2}}$.

Corollary (1) analyzes the effects of manufacturers' cost sharing ratio on carbon emission reduction level and product output. As the proportion of the manufacturer's share of the retailer's promotional costs increases θ, the change in the level of carbon reduction and product output is consistent and non-monotonic. When 0<θ<1/3, the carbon emission reduction level and product output decrease with the increase of the manufacturer's cost sharing ratio, while when 1/3<θ<1, the carbon emission reduction level and product output increase with the increase of the manufacturer's cost sharing ratio. This shows that manufacturers sharing a certain proportion of retailers' low-carbon promotion costs is conducive to reducing carbon emissions and improving product output, but this proportion must be within a certain range. Once the share of the manufacturer is higher than a certain threshold, it is not conducive to carbon emission reduction and product production. Because manufacturers share the low carbon promotion cost of retailers in a small amount, it will reduce the low carbon promotion pressure of retailers and encourage them to increase promotion efforts. This will not only increase the sales of low-carbon products but also drive manufacturers to produce more environmentally friendly products. On the other hand, the higher cost sharing ratio of manufacturers will affect their normal operations, and ultimately have a negative impact on low-carbon product production and carbon emission reduction.

(2) When $e^{\mathrm{jd}*}$(θ=0, single cost sharing mode between manufacturer and retailer) and two-way cost sharing mode between supply chain parties, the change of carbon emission reduction level and product output is analyzed. When 1/2<θ<1, the level of carbon reduction and product output after manufacturers share the cost of retailer promotion is higher than if manufacturers did not share the cost of retailer promotion. When 0<θ<1/2, the case that the manufacturer shares the promotion cost of the retailer is better than the case that the manufacturer does not share the promotion cost. At the same time, the carbon emission reduction level and product output in the case that retailers share the emission reduction cost are significantly higher than those in the case that retailers do not share the emission reduction cost, which also conforms to inference 3.1. Therefore, this inference shows that both one-way and two-way cost-sharing contracts of manufacturers or retailers can promote carbon emission reduction and product

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production in low-carbon supply chains, where the proportion of manufacturers' share of retailers' promotional costs should be within the interval [0,1/2].

Two-way sharing mode in centralized decision making(jc)

In this model, manufacturers and retailers jointly make operational decisions, and the profit function of the low-carbon supply chain is as follows.

$$\pi = \pi_M + \pi_R = [p - c - t(e_0 - e)]q + [E - (e_0 - e)q]p_c - \tfrac{1}{2}k_1 e^2 - \tfrac{1}{2}k_2 r^2 \tag{24}$$

The following propositions are derived about the optimal product price, carbon reduction level, promotion intensity, product output, and profit of supply chain members:

$$e^{\mathrm{jc}^*} = \frac{k_2(b_1+p_c+t)(-a+c+e_0(p_c+t))}{{b_2}^2k_1+k_2[-2k_1+(b_1+p_c+t)^2]} \tag{25}$$

$$p^{\mathrm{jc}^*} = \frac{{b_2}^2k_1M+k_2\{{b_1}^2M-k_1M+b_1(p_c+t)[a+M]+a[-k_1+(p_c+t)^2]\}}{{b_2}^2k_1+k_2[-2k_1+(b_1+p_c+t)^2]} \tag{26}$$

$$q^{\mathrm{jc}^*} = \frac{-k_1k_2[a-c-e_0(p_c+t)]}{{b_2}^2k_1+k_2[-2k_1+(b_1+p_c+t)^2]} \tag{27}$$

$$r^{\mathrm{jc}^*} = \frac{b_2k_1[-a+c+e_0(p_c+t)]}{{b_2}^2k_1+k_2[-2k_1+(b_1+p_c+t)^2]} \tag{28}$$

$$M = c + e_0(p_c + t) \tag{29}$$

$$\pi^{\mathrm{jc}*} = \frac{k_1k_2[k_1k_2-\frac{1}{2}k_1{b_2}^2-\frac{1}{2}k_2(b_1+p_c+t)^2][a-c-(p_c+t)e_0]^2}{[k_1(2k_2-{b_2}^2)-k_2(b_1+p_c+t)^2]^2}(p_c+t)E \tag{30}$$

$\varphi < \frac{2-{b_2}^2}{2}$, $e^{\mathrm{jc}*} > e^{\mathrm{sc}*}$; $\varphi > \frac{2-{b_2}^2}{2}$, $e^{\mathrm{jc}*} < e^{\mathrm{sc}*}$

Proof:

$$e^{\mathrm{jc}*}/e^{\mathrm{sc}*} = \frac{k_2(b_1+p_c+t)[-a+c+e_0(p_c+t)]}{{b_2}^2k_1+k_2[-2k_1+(b_1+p_c+t)^2]} \Big/ \frac{(b_1+p_c+t)[-a+c+e_0(p_c+t)]}{(b_1+p_c+t)^2-2k_1\varphi}$$

$$= \frac{k_2(b_1+p_c+t)^2-2k_1k_2\varphi}{k_2(b_1+p_c+t)^2-2k_1k_2+k_1{b_2}^2}$$

$k_2(b_1+p_c+t)^2-2k_1k_2\varphi > k_2(b_1+p_c+t)^2-2k_1k_2+k_1{b_2}^2$, $\varphi < 1-\frac{{b_2}^2}{2k_2}$ , $e^{\mathrm{jc}*} > e^{\mathrm{sc}*}$, $\varphi > 1-\frac{{b_2}^2}{2k_2}$, $e^{\mathrm{sc}*} > e^{\mathrm{jc}*}$.

The carbon emission reduction level and product output of one-way emission reduction model and two-way emission reduction model are compared and analyzed. Under certain conditions, the two-way emission reduction model is superior to the one-way emission reduction model, that is, the carbon emission reduction cost sharing ratio is controlled within a certain range, which can not only improve the carbon emission reduction level in the whole range of the supply chain, respond to the green and low-carbon concept, but also increase the overall output demand of the supply chain.

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## 4. Numerical Analysis

In order to make the comparative analysis more specific, we conducted the following series of numerical studies in order to better discuss the influence of the relevant parameters, and also to analyze the parameters that are not convenient for direct comparison. Based on theprevious research literature and the inequality conditions that the parameters should meet , some basic parameter assumptions are as follows. $a = 40, c = 5, b_1 = 2, b_2 = 1, e_0 = 2, p_c = 2, E = 5, k_1 = 100, k_2 = 20, \varphi = 0.2, \theta = 0.2, t = 0.5$ .The numerical analysis is divided into three parts. The first part analyzes the impact of the proportion of the manufacturer's share of the promotion cost generated by the retailer's previous sales efforts on the members of the low-carbon supply chain. In the second and third parts, the impacts of carbon trading price and unit carbon tax on carbon emission reduction level, output and supply chain members of low-carbon products are analyzed respectively.

### 4.1. The Impact of Manufacturer Cost Sharing Ratio

In order to make the theoretical model more close to the needs of realistic cost-sharing contracts, the simulation interval of cost-sharing ratio in this study is set to vary between [0,0.8], because it is unrealistic for manufacturers to fully share the promotion costs brought by retailers' sales efforts. As shown in Figure 2, the impact of the cost sharing ratio of the manufacturer on the profit of each member of the supply chain is described.

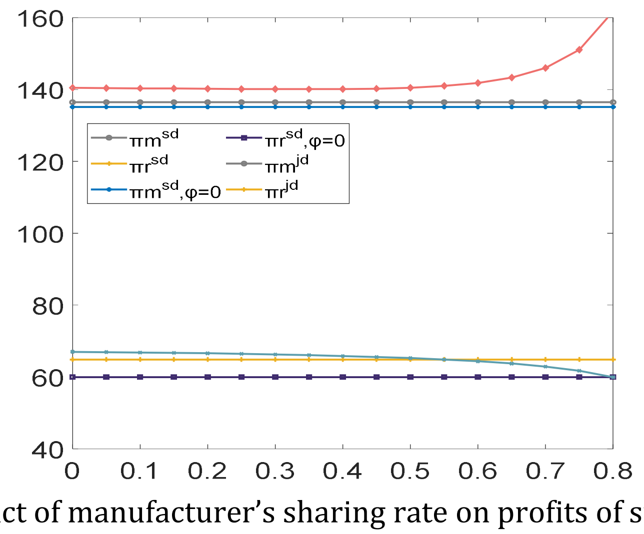


**Figure 2.** Impact of manufacturer’s sharing rate on profits of supply chain members

As can be seen from the figure, in the single emission reduction model, the profit of supply chain members after retailers share the emission reduction cost of manufacturers is significantly higher than that without sharing the emission reduction cost. This indicates that when retailers share the emission reduction cost, the profit of both manufacturers and retailers will increase at the same time, resulting in a win-win situation for both sides. Therefore, the one-way cost-sharing contract of retailers is conducive to the low-carbon supply chain. In the joint emission reduction model, with the increase of manufacturers' cost-sharing ratio, manufacturers' profits increase slowly at first and then decrease. When the manufacturer's cost sharing ratio θ=1/3, the manufacturer's profit reaches the maximum. Compared with the unidirectional and bidirectional emission reduction models in the figure, when the cost sharing ratio θ<2/3, the profit of the bidirectional emission reduction model is higher than that of the unidirectional emission reduction model, whereas the profit of the manufacturer in the single emission reduction model is higher. In addition, when the cost sharing ratio meets θ<1/2, the retailer's profit in the two-way emission reduction model is higher than that in the one-way emission reduction model.

## 4.2. The Impact of Carbon Trading Prices

The carbon trading price is determined jointly by the external carbon trading market and the government, so as to regulate the carbon trading behavior of the carbon trading market. We assume that the carbon trading price changes within the range [0,8]. Figure 3 specifically describes the impact of carbon trading price on the carbon emission reduction level in the four types of cases.

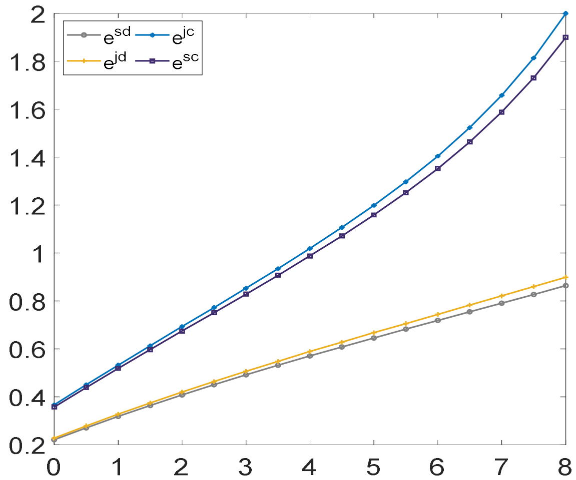


**Figure 3.** Impact of carbon trading price on emission abatement level

Figure 3 shows that in all cases, the level of carbon emission reduction increases with the increase of carbon trading price. In addition, in the case of centralized decision-making, the higher the price of carbon trading, the faster the level of carbon reduction increases. This indicates that appropriately raising carbon trading prices can effectively promote manufacturers to reduce carbon emissions. Based on the cap-and-trade policy, if the carbon emission level of the unit product is still higher than the initial allocation of carbon credits after the manufacturer has reduced the carbon emission of the product, the manufacturer still needs to purchase additional carbon credits from the carbon trading market to maintain the normal operation of the supply chain. Therefore, the increase of carbon trading price will lead to the increase of carbon quota acquisition cost. However, if the level of carbon emissions per unit product after emission reduction is lower than the initial allocation of carbon credits, the manufacturer can sell the remaining carbon credits to the carbon trading market for additional profits. Thus, an increase in the price of carbon trading leads to an increase in additional profits. Therefore, when the price of carbon trading increases, manufacturers will actively reduce carbon emissions in both cases. As a result of cap-and-trade policies, the acquisition costs or additional profits generated by manufacturers' carbon trading activities are affected by the carbon trading price. From a policy perspective, in the early stage of carbon emission reduction, the level of carbon emission reduction is generally low, and the carbon trading market can increase the carbon trading price to force the low-carbon supply chain to reduce carbon emissions. In the middle and later stages of carbon emission reduction, when the level of carbon emission reduction is high, manufacturers will sell the remaining carbon allowances to the carbon trading market, so the market can appropriately raise the carbon trading price to avoid losses. Therefore, the carbon trading market can promote the low-carbon supply chain to reduce carbon emissions by regulating carbon trading prices.

### 4.3. The Impact of Unit Carbon Tax

The unit carbon tax is determined by the government, and the government sets the upper limit of carbon emissions. Enterprises exceeding the upper limit will incur more production costs. The following table analyzes the profits and total profits of each member of the low-carbon supply chain under one-way and two-way cost sharing.

**Table 2.** Profit and total profit of each member of low-carbon supply chain under one-way cost sharing under different carbon tax rates

| | | t | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1 |
| Decentralized decision making | $\pi_M{}^{sd}$ | 131.62 | 143.82 | 142.93 | 142.11 | 141.34 | 140.63 |
| | $\pi_R{}^{sd}$ | 64.88 | 63.74 | 62.62 | 61.53 | 60.47 | 59.43 |
| Centralized decision | $\pi^{sc}$ | 271.14 | 266.73 | 262.44 | 258.27 | 254.22 | 250.28 |

**Table 3.** Profit and total profit of each member of low-carbon supply chain under two-way cost sharing under different carbon tax rates

| | | t | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0 | 0.2 | 0.4 | 0.6 | 0.8 | 1 |
| Decentralized decision making | $\pi_M{}^{jd}$ | 425.19 | 385.50 | 351.23 | 321.46 | 295.44 | 272.625 |
| | $\pi_R{}^{jd}$ | 212.34 | 192.07 | 174.51 | 159.19 | 145.74 | 133.875 |
| Centralized decision | $\pi^{jc}$ | 278.43 | 274.97 | 271.63 | 268.41 | 265.16 | 262.83 |

Table 2 and Table 3 respectively show the changes of the profits and total profits of each member of the supply chain with the change of t under the two decision-making situations. By comparison, it can be concluded that when the two parties adopt a one-way sharing contract, the profit of the manufacturer is maximized within a certain range ($0<t<0.2$), and beyond the range, the profit of the manufacturer is increased with the increase of the unit carbon tax. The profit of each member of the supply chain and the supply chain as a whole decreases with the increase of the unit carbon tax. However, when the two sides adopt two-way cost sharing contract, the profits of both manufacturers and retailers can increase significantly, and the overall profit of the supply chain will increase slightly compared with that of one-way cost sharing. This provides theoretical proof in practical practice that adopting two-way cost-sharing contract is beneficial to the development of each supply chain member. While improving the carbon emission reduction level of the supply chain as a whole, the overall profit can increase steadily instead of decreasing.

## 5. Conclusion

This paper studies the model of low carbon supply chain system consisting of single manufacturer and single retailer, and discusses the production and carbon emission reduction decision of supply chain based on unit carbon tax and emission trading regulations. Manufacturers directly participate in carbon reduction, while retailers indirectly participate in carbon reduction. Considering the sequence of carbon emission reduction process in low-

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carbon supply chain, the single emission reduction mode in which only manufacturers participate in carbon emission reduction and the joint emission reduction mode in which manufacturers and retailers participate in carbon emission reduction are further analyzed, and the one-way cost sharing contract and two-way cost sharing contract among supply chain members are discussed. The optimal solution of the low-carbon supply chain model is discussed in two cases: decentralized decision making and centralized decision making. The supply chain decision making under different emission reduction modes is further compared, and the impact of cost sharing ratio and market carbon trading price on the decision making of low-carbon supply chain is analyzed.

First, in the single emission reduction model of low-carbon supply chain, it is considered that retailers only share part of the emission reduction cost of manufacturers. When retailers share the cost of emission reduction, the level of product carbon reduction and product output in the supply chain are improved, and the profits of manufacturers and retailers are correspondingly increased. Therefore, the one-way cost-sharing contract of retailers is conducive to the production and operation of low-carbon supply chain. And when the cost sharing ratio is low, the low-carbon supply chain preferentially chooses the centralized decision-making situation; When the cost sharing ratio exceeds a certain threshold, decentralized decision-making is the best choice for low-carbon supply chain. In the joint emission reduction model of low-carbon supply chain, the bidirectional cost-sharing contract between manufacturers and retailers is considered. The proportion of the manufacturer's share of the retailer's promotion costs will affect the carbon reduction level of the product, the output of the product, and the profits of each member of the supply chain. When the share ratio is small, the level of product carbon reduction, product output and manufacturer's profit all increase, and these three variables will further increase with the increase of the cost share ratio. When the share ratio exceeds a certain value, all three variables decrease, and further decrease with the increase of the share ratio. When manufacturers share the cost of promotion, retailers' profits decrease. Therefore, under certain conditions, two-way cost-sharing contracts are beneficial to carbon reduction, product production and manufacturers' profits in low-carbon supply chains, but not to retailers' profits. In addition, the cost sharing ratio of manufacturers will also affect the choice between decentralized and centralized decision-making in the supply chain.

Secondly, in the case of decentralized decision-making, when the proportion of manufacturers' one-way cost-sharing contract is low, the comparison between the single emission reduction model and the joint emission reduction model shows that the carbon emission reduction level of products, product output and profit of each member of the supply chain are better under the joint emission reduction model. When the share ratio is higher, the single emission reduction model is more beneficial to the supply chain. In the case of centralized decision-making, the joint emission reduction model is superior to the single emission reduction model in terms of carbon emission reduction, product production and profit of each member of the supply chain.

Finally, the impact of market carbon trading price on low-carbon supply chain carbon emission reduction and production and operation decision is analyzed. Considering the cap-and-trade regulations, the transaction cost in the process of carbon trading will be affected by the carbon trading price, which will affect the carbon emission reduction and production operation of the supply chain. Among them, the level of carbon reduction increases with the increase of carbon trading price. With the increase of carbon trading price, the product output in the decentralized decision case decreases, while the product output in the centralized decision case first decreases and then increases. But the profits of each member of the supply chain will decrease as this price increases.

Through this study, the following management implications can be drawn. For low-carbon supply chain enterprises, retailers will take the initiative to share the carbon emission reduction costs of manufacturers, while manufacturers will only consider sharing the low-

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carbon promotion costs of retailers when the share ratio is small. When the cost sharing ratio of both parties is small, manufacturers and retailers should focus on making decisions, and otherwise choose to maximize their own profits. For government managers, considering the economic performance of low-carbon supply chain at the policy level, carbon trading market can increase carbon trading price in the early stage of carbon emission reduction to promote the supply chain to reduce carbon emissions. In the middle and later stages, as the level of carbon reduction of products increases, the market can appropriately reduce this price. Therefore, the government can promote the low-carbon supply chain to reduce carbon emissions by adjusting the price of carbon trading, but it cannot ignore its impact on the production and profits of the supply chain products.

It should be pointed out that there are many research directions that can be extended in this paper. For example, it can be extended from the case of a single manufacturer and a single retailer to the case of multiple manufacturers and multiple retailers, and it can be extended from a single-cycle decision model to a multi-cycle decision model.

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