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Supply chain carbon abatement under different power structures: impact of consumers' low-carbon preference and carbon tax policy

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Supply chain carbon abatement is an important way to promote low-carbon transformation of the social economy and address global climate change. This paper analyzes the issue of supply chain carbon abatement under different power structures, as well as the effect of consumers' low-carbon preference and carbon tax rate on the optimal decisions. This paper constructs five different models, namely ML-NO model, ML-CS model, RL-NO model, RL-CS model and VI model. The research finds that VI model is the most ideal model for promoting supply chain carbon abatement. The optimal abatement efforts, market demand, and total profits in the VI model are all the largest among the five models. Whether the supply chain leader is the manufacturer or the retailer, cost sharing contract can enhance optimal abatement efforts, market demand, and profits of both parties. In any model, the leader in Supply chain earns higher profits than the follower. When consumers' low-carbon preference increases, the optimal abatement efforts, market demand, and profits of both parties will all increase, and the growth rate is gradually accelerating. For the manufacturer with high carbon emissions, when the carbon tax rate increases, the optimal abatement efforts first increase and then decrease. For the manufacturer with low carbon emissions, when the carbon tax rate increases, the optimal abatement efforts will also increase.

KEYWORDS

supply chain carbon abatement, power structure, consumers' low-carbon preference, carbon tax policy, cost allocation contract

1 Introduction

In recent years, environmental issues have received widespread attention from countries around the world, and the goal of global warming within 1.5°C was reiterated at the 27th United Nations Climate Conference (Masood et al., 2022). Global warming is mainly attributed to greenhouse gas emissions caused by human activities. According to IEA (2023), global carbon emissions associated with energy consumption increased by 0.9% in 2022, reaching a historic high of 36.8 billion tons. One important reason is that enterprises increase their consumption of fossil fuels significantly in pursuit of maximizing profit, leading to negative environmental externality (Xiao et al., 2018). To enhance enterprises' enthusiasm for carbon abatement, governments around the world have introduced a large number of policies, mainly including carbon subsidy policy, carbon tax policy, cap-and-trade system, etc (Dechezleprêtre et al., 2023; Adekunle and Oseni, 2021; Chen et al., 2020).

At the same time, with the upgradation of consumers' living standards and low-carbon awareness, in order to gain competitive advantages, enterprises themselves must also increase their low-carbon investment, and produce more low-carbon products to meet the need of consumers (Lukas and Welling, 2014).

In practice, enterprises are not isolated individuals, and almost all enterprises are a node in the supply chain. Therefore, the carbon abatement decision of an enterprise is inevitably influenced by upstream and downstream enterprises. Under different power structures, the decision order of supply chain members varies, resulting in significant differences in the optimal decision outcome and profits distribution (Liu et al., 2017; Li et al., 2022). In addition, the existence and level of cooperation among supply chain members can also have a significant impact on their decisions (Li H. et al., 2019; Wang et al., 2021). Supply chain members often maximize their profits through cost sharing, revenue sharing, collaborative decision (Sharma and Jain, 2021; Heydari et al., 2017). Therefore, this paper incorporates both power structure and cost sharing contract into supply chain carbon abatement decisions, in order to draw some valuable conclusions.

This paper constructs five models, which are defined as follows:

(1) Manufacturer-led Stackelberg with no contract (ML-NO): The manufacturer, as the leader of the supply chain, makes decisions first and there is no abatement cooperation contract between the manufacturer and the retailer.
(2) Manufacturer-led Stackelberg with cost sharing contract (ML-CS): The manufacturer, as the leader of the supply chain, makes decisions first and the retailer shares a portion of abatement costs of the manufacturer.
(3) Retailer-led Stackelberg with no contract (RL-NO): The retailer, as the leader of the supply chain, makes decisions first and there is no abatement cooperation contract between the manufacturer and the retailer.
(4) Retailer-led Stackelberg with cost sharing contract (RL-CS): The retailer, as the leader of the supply chain, makes decisions first and the retailer shares a portion of abatement costs of the manufacturer.
(5) Vertical integration (VI): The manufacturer and the retailer make decisions as a whole with the goal of maximizing the profits throughout the supply chain (hereinafter referred to as total profits).

In the above models, models (1) to (4) represent decentralized decision, while model (5) represents centralized decision.

This paper is going to address the following research questions:

(1) Which of the above five models has the highest carbon abatement efforts and supply chain profits? Can centralized decision and cost sharing contract improve carbon abatement efforts and supply chain profits?
(2) How does consumers' low-carbon preference affect the decisions of supply chain members? Are there any significant differences among different models?
(3) How does carbon tax rate affect the decisions of supply chain members? Are there any significant differences among different models?

To answer the above questions, this paper solves the equilibrium solutions of each model through mathematical derivation on one hand, and visually displays the differences between different models through numerical simulation on the other hand. The remainder of this paper is structured as follows. Section 2 provides a literature review. Section 3 constructs five models and solves them. Section 4 compares the equilibrium solutions of the five models. Section 5 conducts numerical simulations. Finally, Section 6 summarizes the research conclusions.

2 Literature review

This section will review existing literature. Specifically, it mainly includes three aspects of literature: 1) Carbon abatement decision and coordination in various types of supply chains, 2) the impact of power structure on supply chain performance, and 3) the effect of consumers' low-carbon preference and carbon policies.

2.1 Carbon abatement decision and coordination in various types of supply chains

In recent years, the issue of supply chain carbon abatement has attracted the attention of scholars. Benjaafar et al. (2013) is one of the earlier literature to incorporate carbon emissions into supply chain operational decision. Afterwards, scholars conducted extensive research on carbon abatement in various supply chains. For example, Taleizadeh et al. (2018), Guo and Xi (2022) and Halat et al. (2021) discussed carbon abatement decisions in two-echelon, three-echelon, and multi-echelon supply chain, respectively; Zhou and Ye (2018) analyzed the dynamic pricing and carbon reduction strategies in dual channel supply chain; Taleizadeh et al. (2019), Cheng et al. (2022) and Mishra et al. (2020) discussed carbon reduction and product recovery issues in closed-loop supply chain.

In terms of carbon reduction cooperation, supply chain contracts have become a hot research topic for scholars as an efficient way of coordination. Cost sharing and revenue sharing are the most important ways for different members to collaborate on carbon reduction. Ghosh and Shah (2015) discussed the influence of cost sharing contract and bargaining power on product greenness, price, and profit; Sharma and Jain (2021) debated the optimality of cost sharing contract with different parameter ranges in a two-stage supply chain; Liu et al. (2021) found that carbon reduction cost sharing contract increases the order volume and profit of the retailer. Peng et al. (2018) and Li T. et al. (2019) analyzed the role of revenue sharing contract in supply chain coordination. In addition, quantity discount contract (Heydari et al., 2017), two-part pricing contract (Swami and Shah, 2013), option contract (Peng et al., 2020), and repurchase contract (Taleizadeh et al., 2018) can also effectively achieve supply chain coordination. Compared to other contracts, the two-part pricing contract is more robust (Bai et al., 2017). In addition, some scholars have found that the symmetry of information among members has prominent effects on supply chain coordination and contract design (Ma et al., 2018; Xia et al., 2023).

2.2 Impact of power structure on supply chain performance

There are significant differences in the decision-making order and profit distribution of supply chain members under different power structures and cooperation level among members. Some scholars have explored this issue. Ji and Huang (2022) established single carbon reduction models and cooperative carbon reduction models under different power structures. Sun et al. (2023) constructed a centralized and three decentralized decision models with different channel power structures. Jiang et al. (2021a) found that the centralized model has the best emission reduction effect and the highest supply chain profit without fairness concern, while the general contractor's Stackelberg model has the best emission reduction effect and the highest supply chain profit with fairness concern. Li et al. (2022) believed the carbon emissions reduction levels and profits of the supply chain were always the highest in the Nash model, while the overall economic and environmental benefits of the supply chain were the lowest in the manufacturer-led Stackelberg model. Gong and He (2023) found that the streamer's profit is optimal in the resale mode, while the manufacturer's profit is optimal in the commission mode when under the streamer-led structure. Zhang and Yu (2023) found that the government subsidy rates are dependent on the power status between manufacturers and retailers, and the weaker party will get higher subsidy rate. Liu et al. (2017) believed that the Stackelberg leaders always perform better than their corresponding followers before emission reduction, while they may not necessarily yield more benefits after emission reduction. Wang et al. (2019) summarized that dominant supply chain members always benefited and that whole supply chain gained the most profits in the Nash model. Huang et al. (2023) established three low-carbon supply chain models under different power structures, namely manufacturer-led, retailer-led and power pairs between two parties. They found that when supply chain enterprises have equal power, the supply chain will have greater social welfare and market demand, but not necessarily greater supply chain profits. Jiang et al. (2021b) found that supply chain pricing was different in different power structures but it had no influence on carbon emissions reduction decisions.

2.3 Effect of consumers' low-carbon preference and carbon policies

The green attitude of consumers is an important factor affecting their purchasing behavior. With the enhancement of consumers' environmental awareness, their desire to purchase low-carbon products will increase (Krass et al., 2013). Some literature has discussed the effect of consumers' environmental awareness and low-carbon preference on supply chain carbon reduction. For example, Hammami et al. (2018) explored the optimal decision of enterprises based on consumers' environmental awareness; Hu and Wang (2022) believed that the consumers' low-carbon preference imposes a significant effect on the producers' decision; Mantovani and Vergari (2017) believed that as consumers' low-carbon preference increases, the social welfare will also increase; Huo et al. (2022) believed that consumers' environmental awareness can accelerate cooperation among different members to reduce carbon emissions.

The effect of carbon policies is a focal issue of academic concern. Carbon policies mainly include cap-and-trade system, carbon tax policy, and carbon subsidy policy, etc. In cap-and-trade system, the initial quota and carbon price are the most core factors (Blumberg and Sibilla, 2023). In the early stage of carbon market development in many countries, the initial quota is often free, which restricts the effectiveness of carbon reduction (Zhang et al., 2019); Ji et al. (2020) found that excessive carbon quotas may harm the profit of the producer; Majumdar et al. (2023) and Leroutier (2022) found that as the carbon price increases, the gross profit initially decreases and then stabilises; Qu et al. (2021) derived a negative correlation between carbon trading price and carbon reduction of the product.

Many studies have shown that carbon tax policy can enhance manufacturers' enthusiasm for carbon reduction, thereby reducing supply chain carbon emissions level (Zhang et al., 2021; Halat et al., 2021), but the marginal carbon reduction effect is showing a downward trend (Guo and Xi, 2022). As the carbon tax rate increases, the profit of the retailer first slightly increase and then rapidly decrease, while the profit of the manufacturer continue to decline, indicating that carbon tax increase the burden on supply chain enterprises (Wu et al., 2022). Moreover, carbon tax will also cause retail price to rise, leading to a decrease of social welfare (Feng et al., 2020; Li and Wang, 2023). Therefore, the carbon tax rate should be set within a appropriate range. Some scholars have proposed differentiated carbon tax policy, which means setting different tax rates for different products and supply chain members (Yu Z. et al., 2023; Shen et al., 2022).

Government subsidies can promote the total profit of the supply chain while suppressing carbon emissions (Yang and Xu, 2019), but the effects of different subsidy policies vary. For example, Yu L. et al. (2023) compared the effects of the unified rate policy, linear growth policy, and two-step subsidy policy, and found that the uniform rate policy has the best effect. There are also some literature comparing the effects of different carbon policies, but the conclusions are not the same. Meng et al. (2022) found that there is almost no difference in the impact of carbon tax policy and cap-and-trade system on supply chain carbon reduction, while literature such as Cheng et al. (2022), Sun and Yang (2021), and Li et al. (2021) all believed that the carbon reduction performance of cap-and-trade system is better than that of carbon tax policy and carbon subsidy policy.

2.4 Differences from existing literature

(1) This paper incorporates both power structure and cost sharing contract into supply chain carbon abatement decision, and constructs five different models for comparison. However, existing literature usually only analyzes the impact of power structure or cooperative contracts on supply chain performance separately.

(2) In ML-CS model and RL-CS model, this paper divides the solving process into two stages: the first stage is to find the Stackelberg equilibrium, and the second stage is to find the

TABLE 1 Notations and meanings for the parameters and variables.

Parameters	
a	Market size of the product with no abatement efforts
b	Elasticity coefficient of demand on retail price
r	Elasticity coefficient of demand on abatement efforts (consumers' low-carbon preference)
c	Production cost per unit product of the manufacturer
e_0	Initial carbon emissions per unit product with no abatement efforts
k	Cost coefficient of abatement efforts for the manufacturer
t	Carbon tax rate (Carbon tax on unit carbon emissions)
Variables	
w	Wholesale price per unit product, $w > c$
e	Abatement efforts per unit product, $e < e_0$
p	Retail price per unit product, $p > w$
m	Marginal profit per unit product of the retailer ($m = p - w$)
q	Market demand (or production quantity)
θ	Proportion of abatement costs borne by the retailer
π_i^j	Profits of supply chain members, where $i = M$, R and T, represents the manufacturer's profits, the retailer's profits and total profits, respectively; $j = ML-NO$, $ML-CS$, $RL-NO$, $RL-CS$ and VI, represents five different models, respectively

optimal cost allocation ratio. However, existing literature generally only calculates the Stackelberg equilibrium.

(3) This paper has found some different conclusions, suggesting that the impact of carbon tax rate on abatement efforts is related to the initial carbon emissions of the manufacturer. When the initial carbon emissions are high, the abatement efforts of the manufacturer first increase and then decrease with the increase of carbon tax rate. When the initial carbon emissions are low, the abatement efforts increase with the increase of carbon tax rate.

3 Model construction and solution

3.1 Parameters and variables

This paper considers a two-echelon supply chain consisting of a single manufacturer and a single retailer. The manufacturer only produces a single product and sells it all to the retailer, who then sells it all to consumers. The manufacturer determines the abatement efforts and wholesale price per unit product, while the retailer determines the retail price (or marginal profit) per unit product. The notations for the parameters and variables used in this paper are summarized in Table 1.

3.2 Hypotheses

(1) According to Yuan et al. (2022), assume that both the manufacturer and the retailer are risk neutral and entirely rational, with symmetrical information between them, and their decision goal is to maximize their own profits. The manufacturer has sufficient production capacity, and the production quantity equals the retailer's order quantity. The retailer can fully meet market demand, regardless of shortage and inventory costs.

(2) Consumers have low-carbon preference, and the manufacturer's abatement efforts can effectively enhance market demand. According to Li and Gong (2020) and Kouvelis and Zhao (2015), assume that market demand is linearly related to the retail price and the abatement efforts, i.e., $q = a - bp + re$, where $a > bp$.

(3) The initial carbon emissions per unit product with no abatement efforts are e_0, and the abatement efforts per unit product of the manufacturer are e, which means that the carbon emissions per unit product will decline to $e_0 - e$.

(4) According to Ghosh and Shah (2012), Chen et al. (2019) and Yuan et al. (2022), the cost function of abatement efforts will meet $C'(e) > 0$ and $C''(e) > 0$ and can be set as $C(e) = ke^2/2$, where k denotes cost coefficient, which is a sufficiently large number.

(5) To strengthen the abatement efforts, the government imposes carbon tax on the manufacturer, and the carbon tax per unit carbon emissions (carbon tax rate) is t.

(6) The production cost per unit product of the manufacturer is c. In four decentralized decision models, the manufacturer sells products to the retailer at wholesale price w, and the retailer sells products to consumers at retail price p. According to Li et al. (2022), to ensure positive profits for supply chain members, assume $p > w > c + te_0$. Generally, we can set $p = w + m$, where m denotes marginal profits per unit product of the retailer.

(7) To simplify the writing, let $G = a - bc - bte_0$, $U = bk - (r + bt)^2$. Because $a > bp$, $p > c + te_0$ and k is a sufficiently large number, therefore $G > 0$, $U > 0$.

3.3 Model solution

3.3.1 Manufacturer-led Stackelberg with no contract (ML-NO)

In ML-NO model, the manufacturer, as the leader, first determines w and e, and then the retailer determines p and we will use inverse method to find the Stackelberg equilibrium. The objective functions of both players shown in Equations 1, 2.

$$\max_{(w,e)} \pi_M^{ML-NO} = [w - c - t(e_0 - e)](a - bp + re) - \frac{1}{2}ke^2 \quad (1)$$

$$\max_{(p)} \pi_R^{ML-NO} = (p - w)(a - bp + re) \quad (2)$$

Proposition 1. In ML-NO model, the optimal w, e and p are shown in Equations 3–5.

$$e^{ML-NO*} = \frac{(r + bt)G}{3bk + U} \quad (3)$$

$$w^{ML-NO*} = \frac{2k(a + bc + bte_0) - (r + bt)(at + rc + rte_0)}{3bk + U} \quad (4)$$

$$p^{ML-NO*} = \frac{k(3a + bc + bte_0) - (r + bt)(at + rc + rte_0)}{3bk + U} \quad (5)$$

Proof. Solving $\frac{d\pi_R^{ML-NO}}{dp} = 0$, we can find $p = \frac{a+re+bw}{2b}$. Substituting p into Equation 1 and solving equation group $\left\{\frac{\partial\pi_M^{ML-NO}}{\partial w} = 0; \frac{\partial\pi_M^{ML-NO}}{\partial e} = 0\right\}$, we can obtain w^{ML-NO*} and e^{ML-NO*}. Furthermore, substituting w^{ML-NO*} and e^{ML-NO*} into p yields p^{ML-NO*}.

Substituting w^{ML-NO*}, e^{ML-NO*} and p^{ML-NO*} into $q = a - bp + re$, Equations 1, 2, we can obtain the market demand, the manufacturer's profits and the retailer's profits in ML-NO model, and their expressions are shown in Equations 6–8.

$$q^{ML-NO*} = \frac{bkG}{3bk + U} \quad (6)$$

$$\pi_M^{ML-NO*} = \frac{kG^2}{2(3bk + U)} \quad (7)$$

$$\pi_R^{ML-NO\,*} = \frac{bk^2G^2}{(3bk + U)^2} \quad (8)$$

Adding π_M^{ML-NO*} and $\pi_R^{ML-NO\,*}$ yields total profits in ML-NO model, and the expression is shown in Equation 9.

$$\pi_T^{ML-NO*} = \frac{kG^2(5bk + U)}{2(3bk + U)^2} \quad (9)$$

3.3.2 Manufacturer-led Stackelberg with cost sharing contract (ML-CS)

In ML-CS model, the solution of equilibrium is divided into two stages. In the first stage, just like ML-NO model, the manufacturer first determines w and e, and then the retailer determines p and we will use inverse method to find the Stackelberg equilibrium. In the second stage, the retailer determines θ to maximize his own profits. The objective functions of both players are shown in Equations 10, 11.

$$\max_{(w,e)} \pi_M^{ML-CS} = [w - c - t(e_0 - e)](a - bp + re) - \frac{1}{2}(1 - \theta)ke^2 \quad (10)$$

$$\max_{(p)} \pi_R^{ML-CS} = (p - w)(a - bp + re) - \frac{1}{2}\theta ke^2 \quad (11)$$

Proposition 2. In the first stage of ML-CS model, the optimal w, e and p are shown in Equations 12–14.

$$e^{ML-CS*}\big|_\theta = \frac{(r + bt)G}{4(1 - \theta)bk - (r + bt)^2} \quad (12)$$

$$w^{ML-CS*}\big|_\theta = \frac{2(1 - \theta)k(a + bc + bte_0) - (r + bt)(at + rc + rte_0)}{4(1 - \theta)bk - (r + bt)^2} \quad (13)$$

$$p^{ML-CS*}\big|_\theta = \frac{(1 - \theta)k(3a + bc + bte_0) - (r + bt)(at + rc + rte_0)}{4(1 - \theta)bk - (r + bt)^2} \quad (14)$$

Proof. Solving $\frac{d\pi_R^{ML-CS}}{dp} = 0$, we can find $p = \frac{a+re+bw}{2b}$. Substituting p into Equation 10 and solving equation group $\left\{\frac{\partial\pi_M^{ML-CS}}{\partial w} = 0; \frac{\partial\pi_M^{ML-CS}}{\partial e} = 0\right\}$, we can obtain $w^{ML-CS*}|_\theta$ and $e^{ML-CS*}|_\theta$. Furthermore, substituting $w^{ML-CS*}|_\theta$ and $e^{ML-CS*}|_\theta$ into p yields $p^{ML-CS*}|_\theta$.

Substituting $w^{ML-CS*}|_\theta$, $e^{ML-CS*}|_\theta$ and $p^{ML-CS*}|_\theta$ into $q = a - bp + re$, Equations 10, 11, we can obtain the market demand, the manufacturer's profits and the retailer's profits in ML-CS model, and their expressions are shown in Equations 15–17.

$$q^{ML-CS*}\big|_\theta = \frac{(1 - \theta)bkG}{4(1 - \theta)bk - (r + bt)^2} \quad (15)$$

$$\pi_M^{ML-CS*}\big|_\theta = \frac{(1 - \theta)kG^2}{2\left[4(1 - \theta)bk - (r + bt)^2\right]} \quad (16)$$

$$\pi_R^{ML-CS*}\big|_\theta = \frac{kG^2\left[2(1 - \theta)^2bk - \theta(r + bt)^2\right]}{2\left[4(1 - \theta)bk - (r + bt)^2\right]^2} \quad (17)$$

Proposition 3. Compared to ML-NO model, Pareto improvement can be achieved in ML-CS model when θ meets $0 < \theta < \theta_1$, where $\theta_1 = \frac{(r+bt)^2[4bk-(r+bt)^2]}{2bk[8bk-(r+bt)^2]}$.

Proof. Solving $\pi_M^{ML-CS*}|_\theta > \pi_M^{ML-NO*}$, $\pi_R^{ML-CS*}|_\theta > \pi_R^{ML-NO*}$ and $4(1-\theta)bk > (r+bt)^2$, we can obtain $0 < \theta < \frac{(r+bt)^2[4bk-(r+bt)^2]}{2bk[8bk-(r+bt)^2]}$.

Proposition 4. In the second stage of ML-CS model, the optimal θ is shown in Equation 18.

$$\theta^{ML-CS*} = \frac{(r + bt)^2}{8bk} \quad (18)$$

Proof. Solving $\frac{\partial\pi_R^{ML-CS*}|_\theta}{\partial\theta} = 0$, we can obtain $\theta^{ML-CS*} = \frac{(r+bt)^2}{8bk}$.

It can be observed that $\theta^{ML-CS*} < \theta_1$, indicating that when the manufacturer is the leader in the supply chain, cost sharing contract can effectively achieve Pareto improvement. Substituting θ^{ML-CS*} into $e^{ML-CS*}|_\theta$, $w^{ML-CS*}|_\theta$, $p^{ML-CS*}|_\theta$, $q^{ML-CS*}|_\theta$, $\pi_M^{ML-CS*}|_\theta$ and

$\pi_R^{ML-CS^*}|_\theta$, we can obtain the optimal value for each variable in ML-CS model, as shown in Equations 19–24.

$$e^{ML-CS^*} = \frac{2G(r+bt)}{5bk+3U} \tag{19}$$

$$w^{ML-CS^*} = \frac{(7bk+U)(a+bc+bte_0) - 4b(r+bt)(at+rc+rte_0)}{2b(5bk+3U)} \tag{20}$$

$$p^{ML-CS^*} = \frac{(7bk+U)(3a+bc+bte_0) - 8b(r+bt)(at+rc+rte_0)}{4b(5bk+3U)} \tag{21}$$

$$q^{ML-CS^*} = \frac{G(7bk+U)}{4(5bk+3U)} \tag{22}$$

$$\pi_M^{ML-CS^*} = \frac{G^2(7bk+U)}{8b(5bk+3U)} \tag{23}$$

$$\pi_R^{ML-CS^*} = \frac{G^2\left[8bk+(r+bt)^2\right]}{16b(5bk+3U)} \tag{24}$$

Adding $\pi_M^{ML-CS^*}$ and $\pi_R^{ML-CS^*}$ yields total profits in ML-CS model, as shown in Equation 25.

$$\pi_T^{ML-CS^*} = \frac{G^2(23bk+U)}{16b(5bk+3U)} \tag{25}$$

3.3.3 Retailer-led Stackelberg with no contract (RL-NO)

In RL-NO model, the retailer, as the leader, first determines m ($m = p - w$), and then the manufacturer determines w and e, and we will use inverse method to find the Stackelberg equilibrium. The objective functions of both players are shown in Equations 26, 27.

$$\max_{(w,e)} \pi_M^{RL-NO} = [w - c - t(e_0 - e)](a - bm - bw + re) - \frac{1}{2}ke^2 \tag{26}$$

$$\max_{(m)} \pi_R^{RL-NO} = m(a - bm - bw + re) \tag{27}$$

Proposition 5. In RL-NO model, the optimal m, w, e and p are shown in Equations 28–31.

$$m^{RL-NO^*} = \frac{G}{2b} \tag{28}$$

$$e^{RL-NO^*} = \frac{(r+bt)G}{2(bk+U)} \tag{29}$$

$$w^{RL-NO^*} = \frac{k(a+3bc+3bte_0) - (r+bt)(at+bct+bt^2e_0+2rc+2rte_0)}{2(bk+U)} \tag{30}$$

$$p^{RL-NO^*} = \frac{bk(3a+bc+bte_0) - (r+bt)(2abt+ra+rbc+rbte_0)}{2b(bk+U)} \tag{31}$$

Proof. Solving equation group $\left\{\frac{\partial \pi_M^{RL-NO}}{\partial w} = 0; \frac{\partial \pi_M^{RL-NO}}{\partial e} = 0\right\}$, we can obtain $w = \frac{k(a-bm+bc+bte_0)-(r+bt)(at-btm+rc+rte_0)}{2bk-(r+bt)^2}$ and $e = \frac{(r+bt)(a-bm-bc-bte_0)}{2bk-(r+bt)^2}$. Substituting w and e into Equation 27 and solving $\frac{d\pi_R^{RL-NO}}{dm} = 0$, we can obtain m^{RL-NO^*}. Substituting m^{RL-NO^*} into w and e yields w^{RL-NO^*} and e^{RL-NO^*}. Furthermore, adding w^{RL-NO^*} and m^{RL-NO^*} yields p^{RL-NO^*}.

Substituting w^{RL-NO^*}, e^{RL-NO^*}, m^{RL-NO^*} and p^{RL-NO^*} into $q = a - bp + re$, Equations 26, 27, we can obtain the market demand, the manufacturer's profits and the retailer's profits in RL-NO model, and their expressions are shown in Equations 32–34.

$$q^{RL-NO^*} = \frac{bkG}{2(bk+U)} \tag{32}$$

$$\pi_M^{RL-NO^*} = \frac{kG^2}{8(bk+U)} \tag{33}$$

$$\pi_R^{RL-NO^*} = \frac{kG^2}{4(bk+U)} \tag{34}$$

Adding $\pi_M^{RL-NO^*}$ and $\pi_R^{RL-NO^*}$ yields total profits in RL-NO model, as shown in Equation 35.

$$\pi_T^{RL-NO^*} = \frac{3kG^2}{8(bk+U)} \tag{35}$$

3.3.4 Retailer-led Stackelberg with cost sharing contract (RL-CS)

In RL-CS model, the solution of equilibrium is divided into two stages. In the first stage, just like RL-NO model, the retailer first determines m ($m = p - w$), and then the manufacturer determines w and e, and we will use inverse method to find the Stackelberg equilibrium. In the second stage, the retailer determines θ to maximize its own profits. The objective functions of both players are shown in Equations 36, 37.

$$\max_{(w,e)} \pi_M^{RL-CS} = [w - c - t(e_0 - e)](a - bm - bw + re) - \frac{1}{2}(1-\theta)ke^2 \tag{36}$$

$$\max_{(m)} \pi_R^{RL-CS} = m(a - bm - bw + re) - \frac{1}{2}\theta ke^2 \tag{37}$$

Proposition 6. In the first stage of RL-CS model, the optimal m, w, e and p are shown in Equations 38–41.

$$m^{RL-CS^*}\big|_\theta = \frac{G}{2b} \tag{38}$$

$$e^{RL-CS^*}\big|_\theta = \frac{(r+bt)G}{2\left[2(1-\theta)bk-(r+bt)^2\right]} \tag{39}$$

$$w^{RL-CS^*}\big|_\theta = \frac{(1-\theta)k(a+3bc+3bte_0) - (r+bt)(at+bct+bt^2e_0+2rc+2rte_0)}{2\left[2(1-\theta)bk-(r+bt)^2\right]} \tag{40}$$

$$p^{RL-CS^*}\big|_\theta = \frac{(1-\theta)bk(3a+bc+bte_0) - (r+bt)(2abt+ra+rbc+rbte_0)}{2b\left[2(1-\theta)bk-(r+bt)^2\right]} \tag{41}$$

Proof. Solving equation group $\left\{\frac{\partial \pi_M^{RL-CS}}{\partial w} = 0; \frac{\partial \pi_M^{RL-CS}}{\partial e} = 0\right\}$, we can obtain $w = \frac{(1-\theta)k(a-bm+bc+bte_0)-(r+bt)(at-btm+rc+rte_0)}{2(1-\theta)bk-(r+bt)^2}$ and $e = \frac{(r+bt)(a-bm-bc-bte_0)}{2(1-\theta)bk-(r+bt)^2}$. Substituting w and e into Equation 37 and solving $\frac{d\pi_R^{RL-CS}}{dm} = 0$, we can obtain $m^{RL-CS^*}|_\theta$. Substituting $m^{RL-CS^*}|_\theta$ into w and e yields $w^{RL-CS^*}|_\theta$ and $e^{RL-CS^*}|_\theta$. Furthermore, adding $w^{RL-CS^*}|_\theta$ and $m^{RL-CS^*}|_\theta$ yields $p^{RL-CS^*}|_\theta$.

Substituting $w^{RL-CS^*}|_\theta$, $e^{RL-CS^*}|_\theta$, $m^{RL-CS^*}|_\theta$ and $p^{RL-CS^*}|_\theta$ into $q = a - bp + re$, Equations 36, 37, we can obtain the market demand, the manufacturer's profits and the retailer's profits in RL-CS model, and their expressions are shown in Equations 42–44.

$$q^{RL-CS^*}\big|_\theta = \frac{(1-\theta)bkG}{2\left[2(1-\theta)bk-(r+bt)^2\right]} \tag{42}$$

$$\pi_M^{RL-CS^*}\big|_\theta = \frac{(1-\theta)kG^2}{8\left[2(1-\theta)bk-(r+bt)^2\right]} \tag{43}$$

$$\pi_R^{RL-CS^*}\big|_\theta = \frac{kG^2\left[4(1-\theta)^2bk-(2-\theta)(r+bt)^2\right]}{8\left[2(1-\theta)bk-(r+bt)^2\right]^2} \tag{44}$$

Proposition 7. Compared to RL-NO model, Pareto improvement can be achieved in RL-CS model when θ meets $0<\theta<\theta_2$, where $\theta_2 = \frac{2bk-(r+bt)^2}{4bk}$.

Proof. Solving $\pi_M^{RL-CS^*}|_\theta > \pi_M^{RL-NO^*}, \pi_R^{RL-CS^*}|_\theta > \pi_R^{RL-NO^*}$ and $2(1-\theta)bk > (r+bt)^2$, we can obtain $0<\theta<\frac{2bk-(r+bt)^2}{4bk}$.

Proposition 8. In the second stage of RL-CS model, the optimal θ is shown in Equation 45.

$$\theta^{RL-CS^*} = \frac{2bk-(r+bt)^2}{6bk} \tag{45}$$

Proof. Solving $\frac{\partial \pi_R^{RL-CS^*}|_\theta}{\partial\theta} = 0$, we can obtain $\theta^{RL-CS^*} = \frac{2bk-(r+bt)^2}{6bk}$.

It can be observed that $\theta^{RL-CS^*} < \theta_2$, indicating that when the retailer is the leader in supply chain, cost sharing contract can effectively achieve Pareto improvement. Substituting θ^{RL-CS^*} into $e^{RL-CS^*}|_\theta$, $w^{RL-CS^*}|_\theta$, $p^{RL-CS^*}|_\theta$, $q^{RL-CS^*}|_\theta$, $\pi_M^{RL-CS^*}|_\theta$ and $\pi_R^{RL-CS^*}|_\theta$, we can obtain the optimal value for each variable in RL-CS model , as shown in Equations 46–51.

$$e^{RL-CS^*} = \frac{3G(r+bt)}{4(bk+U)} \tag{46}$$

$$w^{RL-CS^*} = \frac{\left[4bk+(r+bt)^2\right](a+3bc+3bte_0)-6b(r+bt)(at+bct+bt^2e_0+2rc+2rte_0)}{8b(bk+U)} \tag{47}$$

$$p^{RL-CS^*} = \frac{\left[4bk+(r+bt)^2\right](3a+bc+bte_0)-6(r+bt)(2abt+ra+rbc+rbte_0)}{8b(bk+U)} \tag{48}$$

$$q^{RL-CS^*} = \frac{G\left[4bk+(r+bt)^2\right]}{8(bk+U)} \tag{49}$$

$$\pi_M^{RL-CS^*} = \frac{G^2\left[4bk+(r+bt)^2\right]}{32b(bk+U)} \tag{50}$$

$$\pi_R^{RL-CS^*} = \frac{G^2\left[16bk+(r+bt)^2\right]}{64b(bk+U)} \tag{51}$$

Adding $\pi_M^{RL-CS^*}$ and $\pi_R^{RL-CS^*}$ yields total profits in RL-CS model, as shown in Equation 52.

$$\pi_T^{RL-CS^*} = \frac{G^2\left[24bk+3(r+bt)^2\right]}{64b(bk+U)} \tag{52}$$

3.3.5 Vertical integration (VI)

In VI model, the manufacturer and the retailer are considered as a whole and jointly determine e and p. The objective function is shown in Equation 53.

$$\max_{(e,p)} \pi_T^{VI} = \left[p-c-t(e_0-e)\right](a-bp+re)-\frac{1}{2}ke^2 \tag{53}$$

Proposition 9. In VI model, the optimal e and p are shown in Equations 54, 55.

$$e^{VI^*} = \frac{(r+bt)G}{bk+U} \tag{54}$$

$$p^{VI^*} = \frac{k(a+bc+bte_0)-(r+bt)(at+rc+rte_0)}{bk+U} \tag{55}$$

Proof. Solving equation group $\left\{\frac{\partial\pi_T^{VI}}{\partial p}=0; \frac{\partial\pi_T^{VI}}{\partial e}=0\right\}$, we can obtain e^{VI^*} and p^{VI^*}.

Substituting e^{VI^*} and p^{VI^*} into $q=a-bp+re$ and Equation 53, we can obtain the market demand and total profits in VI model, and their expressions are Equations 56, 57

$$q^{VI^*} = \frac{bkG}{bk+U} \tag{56}$$

$$\pi_T^{VI^*} = \frac{kG^2}{2(bk+U)} \tag{57}$$

4 Model analysis

4.1 Comparison of equilibrium solutions in different models

4.1.1 Differences in main variables

Proposition 10. The comparison of the main variables in each model is as follows:

(i) $e^{ML-NO^*} < e^{ML-CS^*} < e^{RL-NO^*} < e^{RL-CS^*} < e^{VI^*}$; (ii) $q^{ML-NO^*} < q^{ML-CS^*} < q^{RL-NO^*} < q^{RL-CS^*} < q^{VI^*}$; (iii) $\pi_T^{ML-NO^*} < \pi_T^{ML-CS^*} < \pi_T^{RL-NO^*} < \pi_T^{RL-CS^*} < \pi_T^{VI^*}$; (iv) $\pi_M^{ML-CS^*} > \pi_M^{ML-NO^*} > \pi_M^{RL-CS^*} > \pi_M^{RL-NO^*}$; (v) $\pi_R^{ML-NO^*} < \pi_R^{ML-CS^*} < \pi_R^{RL-NO^*} < \pi_R^{RL-CS^*}$; (vi) $\pi_M^{ML-NO^*} > \pi_R^{ML-NO^*}$, $\pi_M^{ML-CS^*} > \pi_R^{ML-CS^*}$, $\pi_M^{RL-NO^*} < \pi_R^{RL-NO^*}$, $\pi_M^{RL-CS^*} < \pi_R^{RL-CS^*}$.

Proof. Subtracting the optimal e^* in different models yields $e^{ML-NO^*} - e^{ML-CS^*} = \frac{-(r+bt)^3G}{(3bk+U)(5bk+3U)} < 0$, $e^{ML-CS^*} - e^{RL-NO^*} = \frac{-(r+bt)^3G}{2(bk+U)(5bk+3U)} < 0$, $e^{RL-NO^*} - e^{RL-CS^*} = \frac{-(r+bt)G}{4(bk+U)} < 0$ and $e^{RL-CS^*} - e^{VI^*} = \frac{-(r+bt)G}{4(bk+U)} < 0$, therefor $e^{ML-NO^*} < e^{ML-CS^*} < e^{RL-NO^*} < e^{RL-CS^*} < e^{VI^*}$. Similarly, the other conclusions in Proposition 10 can be obtained.

According to conclusions (i) to (iii) in Proposition 10, the optimal abatement efforts, market demand and total profits in VI model are all the largest among the five models, while they are all the smallest in ML-NO model. It indicates that centralized decision can effectively improve supply chain performance, while stimulating the manufacturer's abatement efforts and market demand for low-carbon products, making it the most ideal decision model. When making decentralized decisions, both the manufacturer and the retailer pursue their own maximum profits. The effect of "double marginalization" makes it difficult to maximize total profits, and also leads to lower abatement efforts and market demand. Compared to the manufacturer-led models, the retailer-led models have higher abatement efforts, market demand, and total profits. The main reason is that the retailer will use its dominant power to influence the manufacturer's decisions, enabling the manufacturer to produce products with higher abatement efforts to meet market demand while increasing the total profits of both parties. This is similar to the conclusions of Jiang et al. (2021a) and Li et al. (2022), where Jiang et al. (2021a) believed that centralized model has the best emission reduction effect, Li et al. (2022) found the overall economic were the lowest in the manufacturer-led Stackelberg model.

According to conclusions (iv) to (v) in Proposition 10, whether in the manufacturer-led model and the retailer-led model, when the retailer shares the manufacturer's carbon abatement costs, the profits of both parties will increase. It means that cost sharing contract can effectively achieve Pareto improvement, which confirms the previous conclusion. According to conclusion (vi) in Proposition 10, regardless of whether there is a cost sharing contract or who is dominant in the supply chain, the profit of the leader is higher than that of the follower. This is different from the conclusion of Liu et al. (2017). According to Liu et al. (2017), the profits of Stackelberg leaders are higher than that of followers before emission reduction, but it may not necessarily be the case after emission reduction.

Proposition 11. Among the two cost sharing models, the proportion of abatement costs borne by the retailer is as follows: $\theta^{ML-CS*} < \theta^{RL-CS*}$.

Proof. $\theta^{ML-CS*} - \theta^{RL-CS*} = \frac{-(bk+7U)}{24bk} < 0$, therefor $\theta^{ML-CS*} < \theta^{RL-CS*}$.

According to Proposition 11, when the retailer is dominant, it is willing to bear a higher proportion of abatement costs. The main reason is that when this retailer is dominant, it can gain higher profits from the manufacturer's abatement efforts, and is therefore willing to share more costs to incentivize the manufacturer's abatement efforts.

4.1.2 Conditions for achieving vertical integration through profits distribution

As mentioned earlier, vertical integration is the most ideal model to maximize the manufacturer's abatement efforts and total profits. However, in practice, both the manufacturer and the retailer make decisions based on maximizing their own profits, and "double marginalization" leads to inefficient resource allocation. Therefore, it is difficult for both players to spontaneously form a comprehensive cooperation, and a certain incentive contract must be established. Existing literature has conducted extensive research on this topic (Sharma and Jain, 2021; Li T. et al., 2019; Swami and Shah, 2013; Heydari et al., 2017). This paper will no longer analyze the specific contract and coordination effectiveness, but only provide the basic conditions that need to be met to achieve vertical integration.

Obviously, to achieve vertical integration, it is necessary to ensure that the manufacturer and the retailer earn more profits in VI model. Assuming that in VI model, the profit sharing ratios of the manufacturer and the retailer are α and $1-\alpha$, respectively.

Proposition 12. The condition for vertical integration is $\alpha_1 \le \alpha \le 0.5$, where $\alpha_1 = \frac{bk+U}{3bk+U}$.

Proof. To achieve vertical integration, it is necessary to meet $\alpha\pi_T^{VI*} \ge \max(\pi_M^{ML-NO*}, \pi_M^{RL-NO*})$ and $(1-\alpha)\pi_T^{VI*} \ge \max(\pi_R^{ML-NO*}, \pi_R^{RL-NO*})$. Solving the inequality system, we can obtain $\frac{bk+U}{3bk+U} \le \alpha \le 0.5$.

According to Proposition 12, to achieve vertical integration, the maximum profit sharing ratio of the manufacturer is 0.5, and the minimum is related to consumers' low-carbon preference and carbon tax rate. Due to $\partial\alpha_1/\partial r < 0$ and $\partial\alpha_1/\partial t < 0$, when r and t increase, α_1 will decrease, which means that the manufacturer is willing to accept lower profit sharing ratio and vertical integration will be easier to achieve.

4.2 Impact of consumers' low-carbon preference and carbon tax rate

Proposition 13. The impact of consumers' low-carbon preference on supply chain decisions is as follows:

(i) $0 < \frac{\partial e^{ML-NO*}}{\partial r} < \frac{\partial e^{ML-CS*}}{\partial r} < \frac{\partial e^{RL-NO*}}{\partial r} < \frac{\partial e^{RL-CS*}}{\partial r} < \frac{\partial e^{VI*}}{\partial r}$; (ii) $0 < \frac{\partial q^{ML-NO*}}{\partial r} < \frac{\partial q^{ML-CS*}}{\partial r} < \frac{\partial q^{RL-NO*}}{\partial r} < \frac{\partial q^{RL-CS*}}{\partial r} < \frac{\partial q^{VI*}}{\partial r}$; (iii) $0 < \frac{\partial \pi_T^{ML-NO*}}{\partial r} < \frac{\partial \pi_T^{ML-CS*}}{\partial r} < \frac{\partial \pi_T^{RL-NO*}}{\partial r} < \frac{\partial \pi_T^{RL-CS*}}{\partial r} < \frac{\partial \pi_T^{VI*}}{\partial r}$; (iv) $0 < \frac{\partial \pi_M^{ML-NO*}}{\partial r} < \frac{\partial \pi_M^{ML-CS*}}{\partial r} < \frac{\partial \pi_M^{RL-NO*}}{\partial r} < \frac{\partial \pi_M^{RL-CS*}}{\partial r}$; (v) $0 < \frac{\partial \pi_R^{ML-NO*}}{\partial r} < \frac{\partial \pi_R^{ML-CS*}}{\partial r} < \frac{\partial \pi_R^{RL-NO*}}{\partial r} < \frac{\partial \pi_R^{RL-CS*}}{\partial r}$.

Proof. Taking the first-order partial derivative of e^* over r in each model, we can obtain $\frac{\partial e^{ML-NO*}}{\partial r} = \frac{G[4bk+(r+bt)^2]}{(3bk+U)^2}$, $\frac{\partial e^{ML-CS*}}{\partial r} = \frac{2G[8bk+3(r+bt)^2]}{(5bk+3U)^2}$, $\frac{\partial e^{RL-NO*}}{\partial r} = \frac{G[2bk+(r+bt)^2]}{2(bk+U)^2}$, $\frac{\partial e^{RL-CS*}}{\partial r} = \frac{3G[2bk+(r+bt)^2]}{4(bk+U)^2}$ and $\frac{\partial e^{VI*}}{\partial r} = \frac{G[2bk+(r+bt)^2]}{(bk+U)^2}$. Subtracting the derivative values yields $0 < \frac{\partial e^{ML-NO*}}{\partial r} < \frac{\partial e^{ML-CS*}}{\partial r} < \frac{\partial e^{RL-NO*}}{\partial r} < \frac{\partial e^{RL-CS*}}{\partial r} < \frac{\partial e^{VI*}}{\partial r}$. Similarly, the other conclusions in Proposition 13 can be obtained.

According to Proposition 13, in any model, the first-order partial derivative of e^* over r is positive, indicating that when consumers' low-carbon preference ascends, the abatement efforts of the manufacturer will also rise. Li and Gong (2020), Cheng et al. (2022) and Huo et al. (2022) hold a similar view, believing that consumers' low-carbon awareness can promote carbon reduction.

Compared to other models, in VI model, the marginal abatement effect of consumers' low-carbon preference is the largest. The main reason is that the enhancement of consumers' low-carbon preference can effectively stimulate the market demand for low-carbon products. In order to meet market demand and reduce carbon tax expenditure, the manufacturer will continuously strengthen the abatement efforts. Meanwhile, due to the increase of market demand, the profits of both the manufacturer and the retailer will also increase. When the manufacturer and the retailer make decisions as a whole (VI model), the marginal profit of consumers' low-carbon preference is also the largest among all models. Furthermore, when implementing decentralized decision, the marginal effect of consumers' low-carbon preference in the retailer-led model is higher than that in the manufacturer-led model, and the cost sharing contract can also amplify the marginal effect of consumers' low-carbon preference.

Proposition 14. The impact of carbon tax rate on supply chain decisions is as follows:

(i) If $t < t_0$, then $\frac{\partial e^j}{\partial t} > 0$, if $t > t_0$, then $\frac{\partial e^j}{\partial t} < 0$, where $t_0 = \frac{a-bc-re_0}{2be_0}$; (ii) $\frac{\partial q^j}{\partial t} < 0$; (iii) $\frac{\partial \pi_i^j}{\partial t} < 0$. Among them, $i = M, R$ and T, $j = ML-NO, ML-CS, RL-NO, RL-CS$ and VI.

Proof. Taking the first-order partial derivative of e^* over t in each model, we can obtain $\frac{\partial e^{ML-NO*}}{\partial t} = \frac{b[4bkA+(r+bt)^2 B]}{(3bk+U)^2}$, $\frac{\partial e^{ML-CS*}}{\partial t} = \frac{2b[8bkA+3(r+bt)^2 B]}{(5bk+3U)^2}$, $\frac{\partial e^{RL-NO*}}{\partial t} = \frac{b[2bkA+(r+bt)^2 B]}{2(bk+U)^2}$, $\frac{\partial e^{RL-CS*}}{\partial t} = \frac{3b[2bkA+(r+bt)^2 B]}{4(bk+U)^2}$ and $\frac{\partial e^{VI*}}{\partial t} = \frac{b[2bkA+(r+bt)^2 B]}{(bk+U)^2}$, where $A = a - bc - 2bte_0 - re_0$, $B = a - bc + re_0$. Due to k being a sufficiently large number and

$B > 0$, the sign of the above derivative is related to the sign of A. Therefore, when $A > 0$ (i.e., $t < t_0$), the sign of the above derivative is positive. When $A < 0$ (i.e., $t > t_0$), the sign of the above derivative is negative. Similarly, other conclusions in Proposition 14 can be obtained.

According to conclusions (i) in Proposition 14, when the carbon tax rate is below a certain threshold, the first-order partial derivative of e^* over t is positive, meaning that the larger the carbon tax rate, the greater the manufacturer's abatement efforts. On the contrary, when the carbon tax rate exceeds this threshold, the first-order partial derivative of e^* over t is negative, meaning that the larger the carbon tax rate, the smaller the manufacturer's abatement efforts. Further observation reveals that the size of this threshold is negatively correlated with e_0, meaning that the larger e_0, the smaller the threshold, and the smaller e_0, the greater the threshold. Therefore, we can conclude that carbon tax rate is more effective in promoting abatement efforts of the manufacturer with lower initial carbon emissions, while the incentive effect on the manufacturer with higher initial carbon emissions is relatively poor. This differs significantly from the research findings of Zhang et al. (2021) and Halat et al. (2021). They believe that carbon tax will definitely reduce carbon emissions levels.

According to conclusions (ii) to (iii) in Proposition 14, in any model, the first-order derivatives of q and π over t are both negative, meaning that as t increases, both q and π will decrease. The main reason is that when the carbon tax rate increases, the operating costs of the manufacturer increases, leading to a decrease in production and profits for both parties. This is different from the viewpoint of Wu et al. (2022). According to Wu et al. (2022), an initial increase in carbon tax may lead to an increase in retailer profits.

5 Numerical simulation

To more intuitively display the impact of consumers' low-carbon preference and carbon tax rate on supply chain decisions in different models, we will conduct numerical simulations in this section. Due to the difficulty in finding a true and accurate case, this paper will set parameter values based on the conditions in the research hypothesis, which is often used in existing literature (Jiang et al., 2021a; Li et al., 2022; Gong and He, 2023; Zhang and Yu, 2023). According to $G > 0$ and $U > 0$, we set the initial values of each parameter to $a = 400, b = 10, c = 5, t = 1, r = 5, k = 40$ and $e_0 = 20$, respectively.

5.1 Numerical simulation of the impact of consumers' low-carbon preference

Assuming the assignment of other parameters remains unchanged, it can be determined that the range of r is $0 < r < 10$ based on $G > 0$ and $U > 0$. The simulation results of the impact of r on supply chain decisions are shown in Figures 1–4.

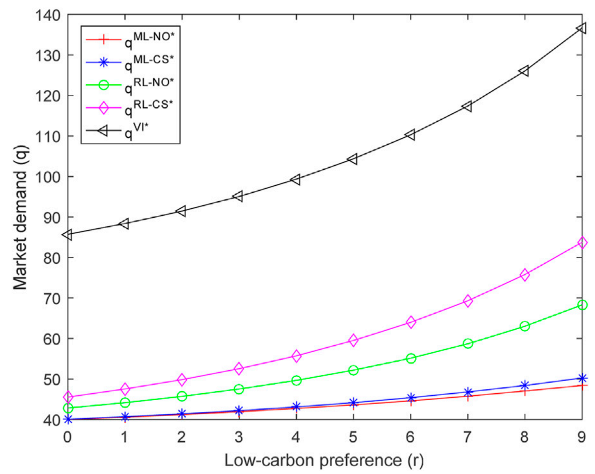

FIGURE 2
The impact of r on q^*.

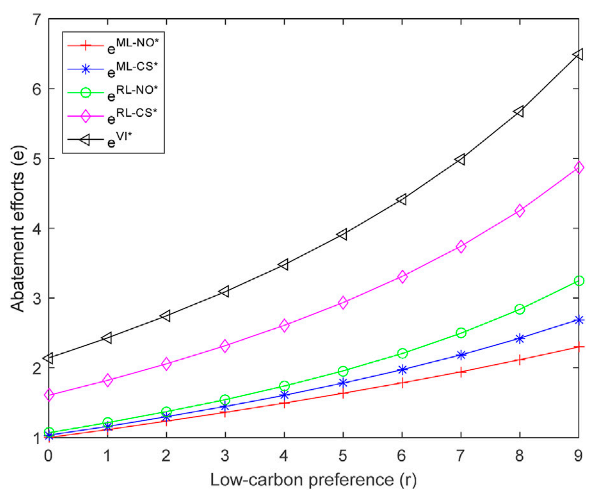

FIGURE 1
The impact of r on e^*.

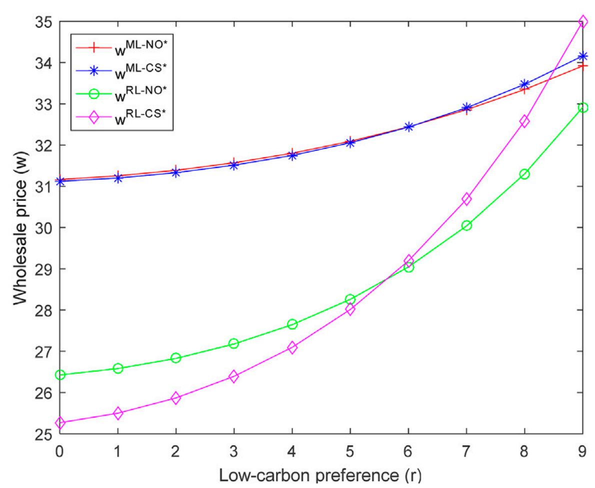

FIGURE 3
The impact of r on w^*.

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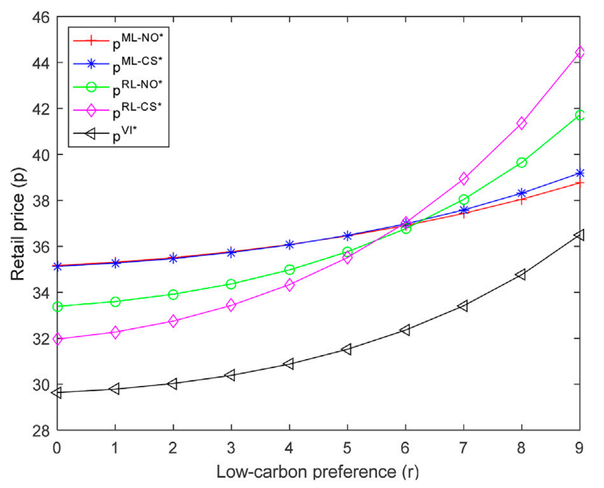

FIGURE 4
The impact of r on p^*.

From Figures 1, 2, it can be seen that consumers' low-carbon preference has a similar impact on abatement efforts and market demand. Let's take Figure 1 as an example for analysis. According to Figure 1, we can see in any model, as consumers' low-carbon preference increases, the abatement efforts show an increasing trend, and the growth rate becomes faster and faster. Based on the position and shape of each curve, it can be determined that $e^{ML-NO*} < e^{ML-CS*} < e^{RL-NO*} < e^{RL-CS*} < e^{VI*}$ and $0 < \frac{\partial e^{ML-NO*}}{\partial r} < \frac{\partial e^{ML-CS*}}{\partial r} < \frac{\partial e^{RL-NO*}}{\partial r} < \frac{\partial e^{RL-CS*}}{\partial r} < \frac{\partial e^{VI*}}{\partial r}$, which confirms the previous conclusion. The main reason has been explained earlier and will not be repeated.

From Figures 3, 4, we can find that consumers' low-carbon preference has a similar impact on wholesale and retail price. In any model, both wholesale price and retail price increase with the increase of consumers' low-carbon preference, and the growth rate becomes faster and faster. The main reason is that when consumers' low-carbon preference increase, the demand for low-carbon products will also increase, leading to a bidding effect and an increase in wholesale price and retail price. Moreover, due to the exponential growth of abatement costs and production capacity limitation of the manufacturer, the growth rate of wholesale price and retail price is gradually accelerating.

From the comparison of different models, when consumers' low-carbon preference is low, the wholesale price and retail price in the retailer-led model are lower than those in the manufacturer-led model. When consumers have a greater preference for low-carbon, the situation is exactly the opposite. Similarly, when consumers' low-carbon preference is low, the wholesale price and retail price in the cost-sharing model are lower than those in the non cost-sharing model, and vice versa. In addition, the retail price in the VI model is the lowest among all models, mainly because integrated decision aims to maximize the total profits, and will choose to obtain greater market demand at a lower price.

5.2 Numerical simulation of the impact of carbon tax rate

Assuming the assignment of other parameters remains unchanged, it can be determined that the range of t is $0 < r < 1.5$ based on $G > 0$ and $U > 0$. The simulation results of the impact of t on supply chain decisions are shown in Figures 5–9.

According to Figure 5, when the initial carbon emissions per unit product are large ($e_0 = 20$), as the carbon tax rate increases, the abatement efforts of the manufacturer show a trend of first increasing and then decreasing. When the initial carbon emissions per unit product are small ($e_0 = 10$), the abatement efforts of the manufacturer increase with the increase of carbon tax rate. It can be explained as in the early stage of low-carbon transformation, the manufacturer has lower abatement costs, so when carbon tax rate increases, the manufacturer will strengthen its abatement efforts to reduce carbon taxes. With the deepening of low-carbon transformation, the abatement costs of the manufacturer are increasing exponentially and far exceeds the

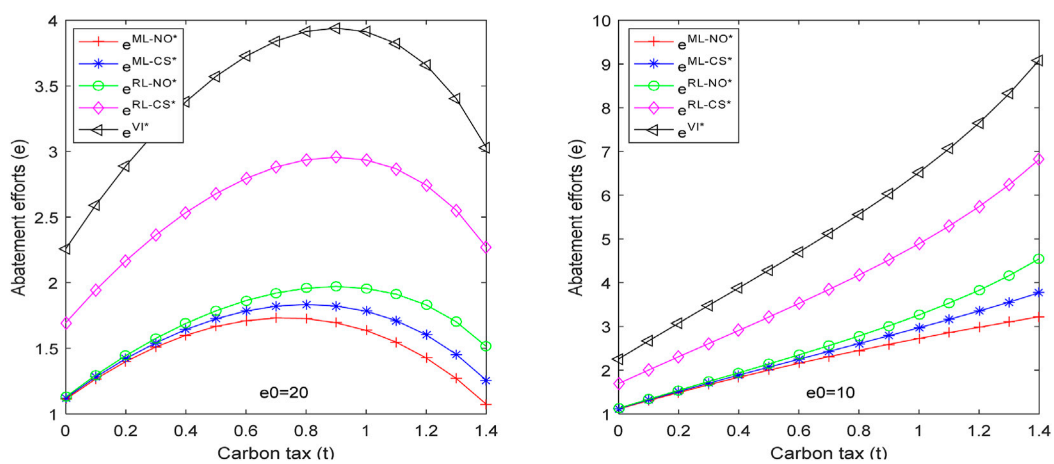

FIGURE 5
The impact of t on e^*.

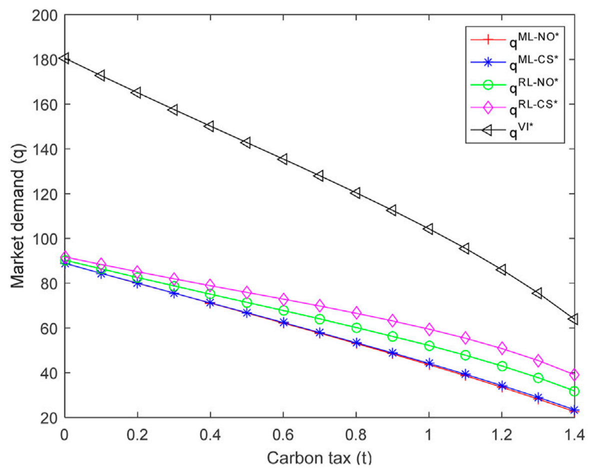

FIGURE 6
The impact of *t* on *q**.

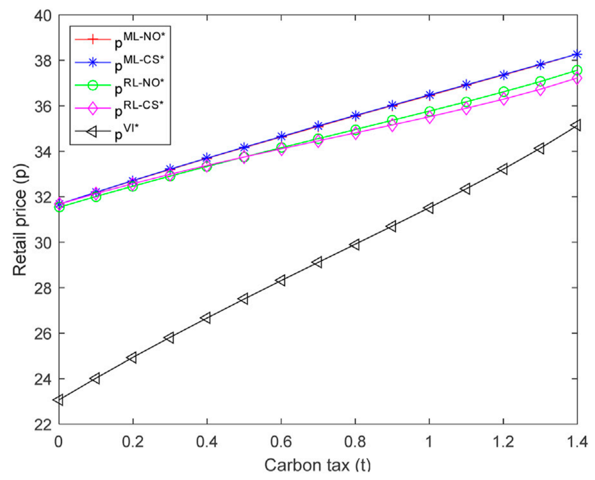

FIGURE 8
The impact of *t* on *p**.

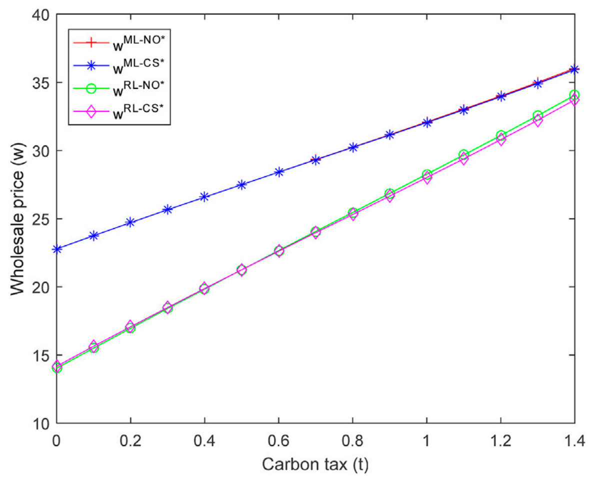

FIGURE 7
The impact of *t* on *w**.

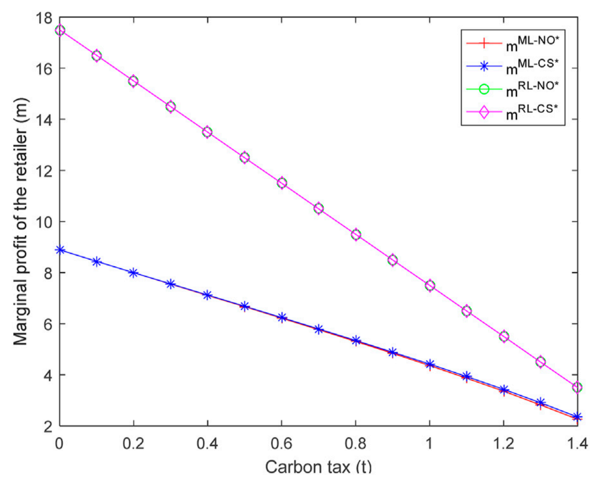

FIGURE 9
The impact of *t* on *m**.

carbon taxes. Therefore, when the carbon tax rate increases, the manufacturer will prefer to bear the carbon taxes and weaken abatement efforts.

From Figures 6–8, it can be seen that as carbon tax rate increases, market demand decreases, while both wholesale price and retail price increase. The main reason is that the increase of carbon tax rate has led to increased operating costs for the manufacturer. In order to ensure its own profits, the manufacturer will pass on some of the costs to the retailer, who will continue to pass on some costs to consumers, resulting in an increase in wholesale price and retail price, further suppressing market demand. Feng et al. (2020) and Li and Wang (2023) hold similar views, believing that carbon tax will cause retail price to rise and lower social welfare.

According to Figure 9, as carbon tax rate increases, the marginal profits of the retailer will decrease. The main reason is that although both wholesale price and retail price increase, the increase in wholesale price exceeds the increase in retail price, leading to a decrease in marginal profits of the retailer. It means that the increased carbon taxes will be shared by the manufacturer, the retailer and consumers. Compared to manufacturer-led model, the marginal profits of the retailer in retailer-led model is higher, which is caused by the leading advantage.

5.3 Impact of consumers' low-carbon preference and carbon tax rate on supply chain profits

Furthermore, we analyze the impact of simultaneous changes in consumers' low-carbon preference and carbon tax rate on supply chain profits, and the numerical simulation results are shown in Figures 10–12.

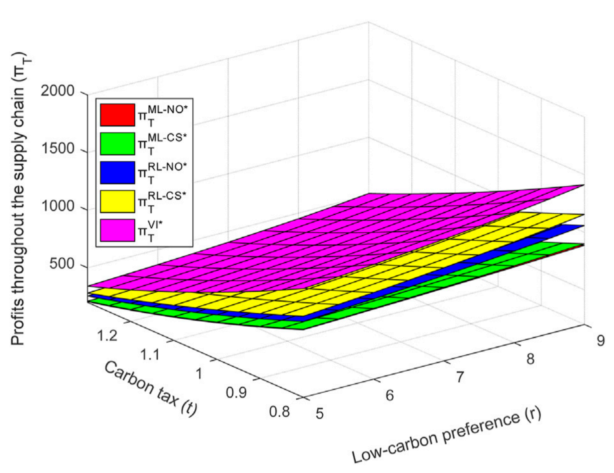

FIGURE 10
The effect of r and t on π_T^*.

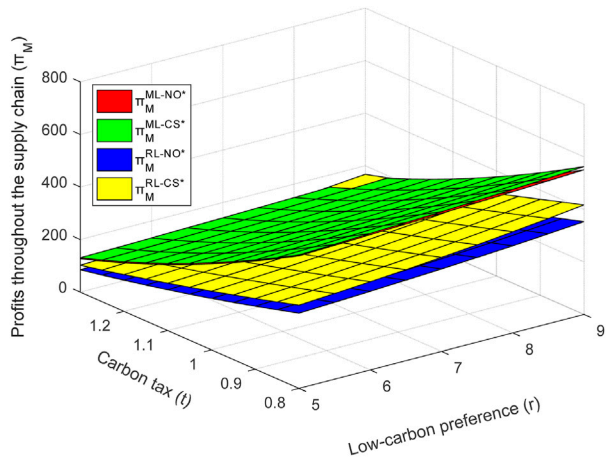

FIGURE 11
The effect of r and t on π_M^*.

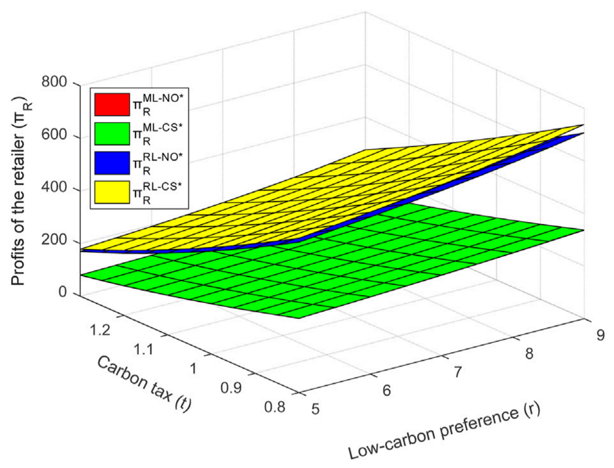

FIGURE 12
The effect of r and t on π_R^*.

From Figures 10–12, we can observe that in any model, as consumers' low-carbon preference increase, the manufacturer's profits, the retailer's profits and total profits will all increase (i.e., $\partial\pi_M/\partial r > 0$, $\partial\pi_R/\partial r > 0$, and $\partial\pi_T/\partial r > 0$). However, when the carbon tax rate increases, the manufacturer's profits, the retailer's profits and total profits will all decrease (i.e., $\partial\pi_M/\partial t < 0$, $\partial\pi_R/\partial t < 0$, and $\partial\pi_T/\partial t < 0$). The main reason is that consumers' low-carbon preference can stimulate market demand for low-carbon products, both wholesale price and retail price will also rise, leading to an increase in profits for both the manufacturer and the retailer. However, an increase in carbon tax rate will lead to increased operating costs for the manufacturer and it will transfer some of these costs to the retailer, resulting in a decrease in profits for both parties. By comparison, the manufacturer's profits in manufacturer-led model is higher than that in retailer-led model, and the retailer's profits in retailer-led model is higher than that in manufacturer-led model, which is determined by the leading advantage. And whether in manufacturer-led model or retailer-led model, cost sharing contract can effectively improve the profits of both parties. The reason has been mentioned earlier and will not be repeated.

6 Conclusion and prospect

The main conclusions are as follows:

(1) Promote cooperative decision in the supply chain. This study finds that VI is the most ideal model. In VI model, the optimal abatement efforts, market demand, and total profits are all the largest among all models. When the profit distribution ratio meets certain conditions, the manufacturer and the retailer can form vertical integration and cooperative decision. Moreover, when consumers' low-carbon preference or carbon tax rate increases, cooperative decision is easier to achieve.

(2) Sign cost sharing contract. This study finds that cost sharing contract can achieve Pareto improvement in both manufacturer-led model and retailer-led model. Moreover, in the retailer-led model, the retailer is willing to bear a higher proportion of abatement costs. Similarly, according to Sharma and Jain (2021) and Li T. et al. (2019), supply chain members can also achieve a "win-win" situation through other contracts, such as revenue sharing contract, two-part pricing contract, etc.

(3) Strengthen consumers' low-carbon preference. This study finds that consumers' low-carbon preference can enhance abatement efforts, market demand, and total profits, with marginal effects gradually increasing. Some measures can be adopted to strengthen consumers' low-carbon preference, such as carbon labeling, carbon credits, and carbon subsidies (Yang and Xu, 2019).

(4) Implement differentiated carbon tax rate. Note that Yu Z. et al. (2023) and Shen et al. (2022) have proposed similar suggestions. This study finds that carbon tax rate provides different abatement incentives for the manufacturer with different initial carbon emissions. For a low carbon

emission manufacturer, higher carbon tax rate can be implemented. For a high carbon emission manufacturer, the carbon tax rate should not be too high, and can be incentivized through cap-and-trade system.

It should be pointed out that although this paper has drawn some valuable conclusions, there are still some expandable content. 1) This paper only considers the case of a single cycle and is based on linear demand for research. In the future, we can conduct research based on multi cycle and stochastic demand to verify the robustness of the research results. 2) This paper only studies a two-echelon supply chain comprised of a manufacturer and a retailer. In the future, more complicated supply chain systems, such as three-echelon or even multi-echelon supply chain, can be studied.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

GL: Conceptualization, Writing–original draft. MJ: Visualization, Writing–review and editing. YY: Methodology, Writing–review and editing. XC: Supervision, Writing–review and editing. DF: Resources, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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