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Carbon Emissions and Sustainable Supply Chains: A Stackelberg Game Analysis of Multinational Firm Relationships

Bo Tian [1,2,†], Meiqi Liu [1,†], Bin Pan [1], Guanghui Yuan [3] and Fei Xie [4,5,*]

1 School of Information Management and Engineering, Shanghai University of Finance and Economics, Shanghai 200090, China; tian.bo@mail.shufe.edu.cn (B.T.); liumeiqi@163.sufe.edu.cn (M.L.); pbqian@163.sufe.edu.cn (B.P.)
2 MoE Key Laboratory of Interdisciplinary Research of Computation and Economics, Shanghai University of Finance and Economics, Shanghai 200433, China
3 School of Economics and Management, Shanghai University of Political Science and Law, Shanghai 201701, China; guanghuiyuan@outlook.com or flame_yuan@163.sufe.edu.cn
4 School of Finance, Shanghai University of Finance and Economics, Shanghai 200090, China
5 Shanghai Financial Intelligent Engineering Technology Research Center, Shanghai University of Finance and Economics, Shanghai 200090, China
* Correspondence: xiefei@mail.shufe.edu.cn; Tel.: +86-021-6590-4318
† These authors contributed equally to this work.

Abstract: Against the backdrop of global climate change and sustainable development, carbon emissions within transnational closed-loop supply chains have become a critical area of research. This paper utilizes a Stackelberg game model to analyze the relationship between a single export manufacturer and an import retailer. The study investigates the optimal solutions of the supply chain model—wholesale price, retail price, sales volume, and profit—across three consumer preference scenarios: no obvious preference, pure green preference, and pure new preference. Furthermore, this paper examines the impact of carbon emissions per unit of product on supply chain decision-making under two scenarios: with and without carbon trading. Carbon trading, which significantly increases unit costs, exerts a profound influence on the strategic decisions of both manufacturers and retailers. In addition, this paper incorporates carbon tariffs and taxes into its analysis, providing a theoretical foundation for governments and policymakers to promote sustainable production and consumption practices. The validity of the model is confirmed through numerical simulations, which reveal that under pure green and pure new preference scenarios, original equipment manufacturers (OEMs) are more inclined to invest in emissions reduction to minimize tariff costs. In contrast, under no obvious preference scenarios, OEMs are more likely to adjust product portfolios to evade carbon tariffs. This research advances the understanding of low-carbon production strategies in transnational supply chains, offering both theoretical insights and practical guidance for balancing economic and environmental objectives.

Keywords: remanufacturing decisions; consumption preferences; carbon tax; carbon tariff; carbon markets; carbon trading

MSC: 91A65; 91A40; 91B76

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1. Introduction

Carbon taxes, carbon tariffs, and carbon allowances are the core policy tools utilized by many countries to combat climate change and reduce greenhouse gas emissions. A carbon tax, as a form of domestic taxation, internalizes the environmental costs of carbon dioxide emissions by imposing a fixed charge per unit of emissions, thereby encouraging firms to lower their carbon footprint. In contrast, carbon allowances operate within a cap-and-trade system, where governments establish an overall emissions cap and allocate allowances to organizations. Companies with surplus allowances can trade them in the market, improving resource allocation efficiency [1].

Carbon tariffs, implemented as part of the EU's carbon border adjustment mechanism, are designed to prevent carbon leakage by imposing levies on high-carbon products during cross-border trade. This ensures parity in carbon costs between domestic and foreign producers, promoting fair competition [2,3]. Together, these policy instruments combine pricing mechanisms with quantitative controls, providing a theoretical and practical foundation for global climate governance and supporting the low-carbon transformation of international trade.

Lee et al. [4] simulated the impact of carbon tax policies on carbon emission reductions across industries and found that such policies significantly influence industrial GDP and enterprise management. However, they also concluded that applying a uniform carbon tax policy across industries may lead to inconsistent outcomes. According to the International Energy Agency, the manufacturing industry is a major contributor to global greenhouse gas emissions, accounting for approximately 20% to 30% of total emissions worldwide. In China, as of the end of 2021, the manufacturing sector's energy consumption and carbon emissions comprised two-thirds of the secondary sector and one-third of the country's total emissions. This evidence highlights the critical role of carbon tariffs in shaping cross-border trade in the remanufacturing sector and underscores the manufacturing industry as a focal point for global emission reduction efforts [5]. Consequently, implementing targeted carbon tariff policies for the manufacturing sector can not only promote emissions reduction but also optimize the structure of cross-border trade.

The implementation of carbon tariffs has increased market preference for low-carbon products, driving up their demand. Conversely, high-carbon products have experienced rising costs due to heavier tax burdens, which have eroded their global price competitiveness and reduced import demand. In addition, consumer acceptance of remanufactured goods varies significantly across regions. Regions such as Europe, characterized by stronger green consumption preferences, demonstrate higher acceptance of remanufactured goods, while other regions remain relatively less receptive. These trends suggest that carbon tariff policies not only influence product costs and demand but also serve as a critical mechanism for accelerating the transition to a low-carbon economy.

Investigations in the European market indicate that 80% of consumers consider environmental protection characteristics as key purchasing factors, whereas only 4% regard them as unimportant [6]. Vanclay et al. [7] further demonstrated that consumers are more likely to purchase green-labelled goods when provided with appropriate guidance on the carbon emissions of food products. These findings underscore the critical role of consumer preferences in cross-border remanufacturing trade, emphasizing the need for businesses to address consumers' environmental awareness under the rising trend of green consumption. Such preferences not only shape product demand but also drive enterprises to adjust their production and marketing strategies, enabling them to gain a competitive edge in the global market.

Existing research on remanufacturing decisions has primarily focused on the effects of various carbon policies within closed-loop supply chains. However, limited attention has been paid to pricing strategies from the perspective of consumer demand and preferences. In the context of global supply chains, studies that simultaneously address carbon taxes, carbon tariffs, carbon market prices, and consumer preferences remain scarce. Consumer demand and preferences are critical in shaping supply chain decisions, particularly in driving the adoption of low-carbon products and optimizing the structure of cross-border trade. This paper aims to examine cross-border remanufacturing decisions under the influence of consumer preferences, analyzing how these factors affect supply chain decision-making within the constraints of carbon quotas. The study ultimately seeks to optimize remanufacturing strategies for cross-border supply chains, thereby supporting both economic and environmental sustainability.

The practical significance of this research lies not only in advancing global carbon neutrality goals and addressing climate change but also in providing valuable guidance for enterprises' remanufacturing decisions. These insights aim to achieve a win–win outcome of reducing carbon emissions while maintaining high profitability. Moreover, this study explores strategies to meet the diverse product preferences of consumers across different exporting countries, thereby contributing to the optimization and sustainability of transnational supply chains. Additionally, the research equips enterprises with actionable strategies to comply with carbon emission-related policies and regulations, enhancing both their economic efficiency and market competitiveness. Finally, the findings provide theoretical support for governments in designing policies that facilitate the transition toward green production and consumption.

This study employs a Stackelberg game model to examine the impact of carbon taxes, tariffs, and consumer preferences on cross-border remanufacturing decisions [8]. The model considers three consumer preference scenarios: no apparent preference, green preference, and purely new preference. The data utilized in our model are derived from a combination of public government reports and previous research. For instance, carbon tax rates are sourced from the World Bank, ensuring a robust empirical foundation for key parameters. Consumer preference parameters, such as acceptance levels for remanufactured goods, are informed by survey-based research (e.g., Li et al. [9]), offering an empirically grounded range of values for behavioral inputs. By integrating these elements, the study provides actionable insights for policymakers and enterprises, enabling the alignment of supply chain practices with sustainable development goals.

The remainder of the paper is organized as follows. Section 2 reviews the current state of research on cross-border remanufacturing. Section 3 presents the modeling framework and outlines the assumptions for the cross-border remanufacturing decision-making problem. Section 4 explores and analyzes different consumer preference patterns through the proposed model. Section 5 evaluates the effectiveness of the model using numerical simulations. Section 7 summarizes the main conclusions and provides an outlook for future research.

2. Literature Review

Existing research primarily focuses on four dimensions: carbon tax, carbon tariff, carbon emission quotas, and carbon trading, as well as the impact of carbon trading markets on enterprise decision-making within supply chains. Qi et al. [10] investigated the influence of carbon taxes on corporate decision-making and profits, concluding that carbon taxes do not lower corporate profits. Instead, they incentivize firms to mitigate high carbon risks and achieve greater profitability. Liu et al. [11] corroborated this finding through a study on China's textile industry. Similarly, Carl et al. [12] demonstrated that both carbon taxes and carbon trading effectively reduce carbon emissions while generating fiscal revenue for governments.

However, Haites [13] highlighted significant disparities in carbon tax rates and trading rules across countries, with rates ranging from less than EUR 1 to EUR 137 per ton of CO_2. For example, Sweden and Switzerland impose higher rates, whereas Singapore and Japan maintain relatively lower rates despite broader coverage. These disparities hinder the achievement of global emission reduction targets and have driven the introduction of carbon tariffs. Zhou et al. [14] suggested that carbon tariffs encourage low-carbon regulatory countries to reduce costs through carbon quota allocations or subsidies. Similarly, Chen and Guo [15] analyzed the impact of carbon tariffs on Chinese industries, finding that carbon tariffs reduce the export of high-carbon products, limit the import of low-carbon products, and significantly encourage high-emission enterprises to invest in emission reductions.

In summary, existing studies highlight the significant influence of differentiated carbon tax and tariff policies on cross-border trade and emission reduction strategies. At the same time, carbon quotas and trading mechanisms provide flexibility for corporate responses, enabling firms to adapt to evolving regulatory and market conditions.

In addition to carbon taxes and carbon tariffs, carbon quotas represent another critical tool for reducing carbon emissions. For example, Cao et al. [16] studied manufacturers' production and emission reduction decisions under carbon allowances and low-carbon subsidy policies. Similarly, Xu et al. [17] analyzed the impact of carbon quotas and trading policies on manufacturers' investments in emissions reduction. Their findings indicate that when initial emissions are low, carbon quota constraints effectively incentivize firms to reduce emissions.

To address climate change at the lowest cost, China formally launched its national carbon market on 19 December 2017 [18]. Following this, several scholars have incorporated carbon trading prices into analyses of closed-loop supply chain decision-making, evaluating their effects on supply chain costs and efficiency. For instance, Huang et al. [19] examined the influence of carbon taxes, carbon trading prices, and recycling rates on optimal decisions and total supply chain profits. Xing et al. [20] analyzed the supply chain of dual third-party recyclers and found that carbon trading is often negatively correlated with the benefits of both manufacturers and recyclers.

Carbon trading prices, therefore, play a significant role in transnational remanufacturing supply chains. They not only contribute to reducing carbon emissions but also influence environmental costs domestically and across the import/export chain, highlighting their importance in balancing economic and environmental objectives.

The growing concern for eco-friendliness has led to a steady increase in the demand for green products. In the context of remanufacturing, scholars have extensively explored the impact of consumer preferences on pricing strategies. For instance, Abbey et al. [21] confirmed the significant influence of varying consumer preferences on pricing strategies. Zhang et al. [22] used numerical analysis to explore the role of product heterogeneity and consumer preferences, concluding that strong consumer preference for remanufactured products results in comparable pricing between new and remanufactured products but reduces overall profits.

To investigate influencing factors in remanufacturing supply chains, scholars widely adopt the Stackelberg game model. For example, Huang et al. [23] utilized the model to study equilibrium pricing in a closed-loop supply chain under supplier cost disruptions. Hamzaoui et al. [24] applied the Stackelberg game framework to analyze decentralized dual-channel supply chains involving reverse logistics and multi-period remanufacturing decisions. These studies demonstrate the versatility and effectiveness of the Stackelberg game model in optimizing remanufacturing supply chains, not only by enhancing pricing strategies across various scenarios but also by offering valuable insights for policymakers in designing effective carbon reduction policies.

3. Modelling Analysis and Assumptions for Cross-Border Remanufacturing Decisions

Research question 1: How do carbon tariffs in importing countries affect the decision-making of remanufacturers in exporting countries?

Carbon tariffs were initially introduced to address "carbon leakage", a phenomenon where countries with high carbon taxes risk losing carbon-intensive industries to nations with lower or no carbon taxes. This mechanism seeks to reduce global carbon dioxide emissions and promote green synergy. In the import and export process, high-carbon products are subject to tariffs or carbon allowance refunds, significantly increasing supply chain costs and influencing the decisions of manufacturers and retailers. While carbon tariffs can incentivize manufacturers in exporting countries to invest in emissions reduction, excessively high tariffs risk disrupting product system continuity, whereas overly low tariffs may fail to achieve environmental protection objectives. Against this backdrop, this paper investigates how to design appropriate carbon tariff policies based on product emission levels and consumer preferences to balance environmental and trade objectives.

Research question 2: What is the relationship between consumer preferences on the demand side and optimal decisions in the cross-border remanufacturing supply chain?

In the cross-border remanufacturing supply chain, consumer preferences in importing countries play a pivotal role in shaping remanufacturers' pricing and marketing strategies. When consumers exhibit a strong preference for environmentally friendly products, remanufacturers are more inclined to export higher volumes of remanufactured goods and improve their quality. Conversely, price-sensitive consumers drive manufacturers to prioritize cost control and competitive pricing. However, the acceptance of remanufactured products varies significantly across countries, ranging from high acceptance to outright rejection. To address these variations, this paper establishes a consumer utility function to analyze how carbon tariffs can be optimized to account for different levels of green preference, ultimately maximizing profits for both original equipment manufacturers (OEMs) and retailers.

3.1. Model Description

This study investigates a cross-border closed-loop supply chain model comprising a single OEM in the exporting country and a single retailer in the EU importing country [25]. In this model, the exporting country imposes carbon taxes and carbon quota constraints on the OEM, while the importing country applies carbon tariffs on exported products, which are also subject to carbon quota regulations. Under these policies, the OEM actively invests in carbon emission reduction technologies to lower emissions and comply with regulatory requirements [26]. Additionally, consumer preferences vary across countries, significantly influencing the market demand for new and remanufactured products.

The supply chain includes two types of products: new products and remanufactured products. Both the OEM and the retailer aim to maximize profits, with the OEM setting the wholesale prices for products supplied to the retailer, and the retailer determining retail prices based on these wholesale prices. This study assumes that the quality of remanufactured products is consistent, regardless of whether they are produced by the OEM or the retailer. The analysis focuses on remanufacturing Model O, where the OEM produces both new and remanufactured products. During production, the OEM pays carbon taxes, and upon export, carbon tariffs are applied. The OEM is responsible for covering the cost difference between the carbon tariff in the importing country and the domestic carbon tax for each unit of carbon emissions per product. In contrast, the retailer is not subject to carbon taxes. To mitigate these costs and enhance profitability, the OEM invests in emission-reduction technologies [27]. This model is shown in Figure 1.

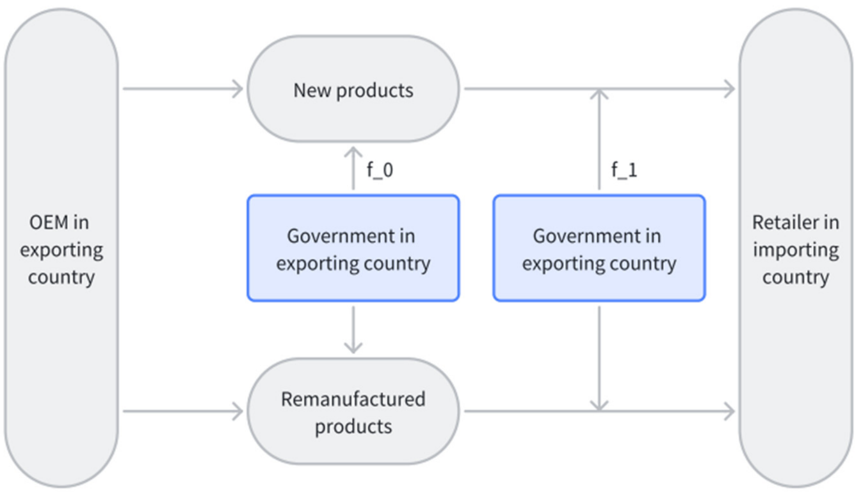

Figure 1. OEM remanufacturing process.

This paper develops a master–slave game model to maximize the profits of both the Original Equipment Manufacturer (OEM) and the retailer. The Stackelberg game model is adopted because it effectively captures decision-making scenarios with clearly defined leader and follower roles, allowing for a structured analysis of their optimization processes.

In Model O, the OEM, possessing greater market influence and decision-making authority, naturally assumes the role of the leader, while the retailer, as the follower, adjusts its strategies based on the OEM's decisions. This framework not only clarifies the sequence of decisions but also enables the leader to anticipate the follower's responses, thereby optimizing its strategy and achieving an equilibrium state that maximizes profits for both parties.

In the game process, the OEM determines emission reduction investments, remanufacturing decisions, and wholesale prices from a profit-maximization perspective. The retailer in the importing country reacts to these decisions by setting the retail price to maximize its own profits. Although direct communication between the two parties is not feasible, the OEM predicts the retailer's responses and adjusts its strategies accordingly. This iterative process continues until neither party can achieve higher profits by modifying their strategies, resulting in an equilibrium. The solution flowchart of the model is illustrated in Figure 2.

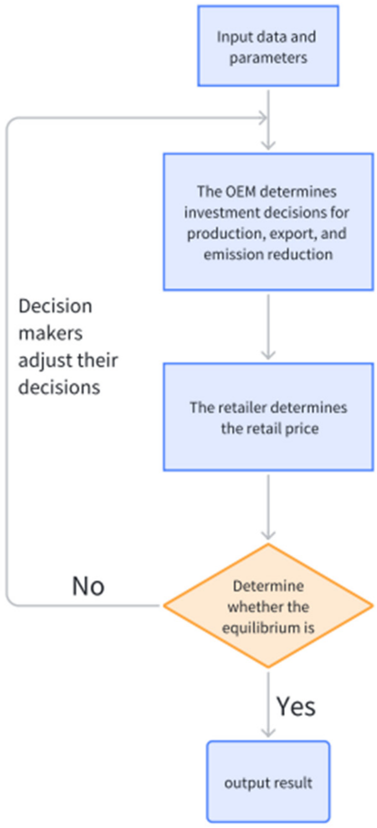

Figure 2. Model solving flowchart.

In Stackelberg games, mathematical models are widely employed to describe the strategy selection and implementation processes of both participants, referred to as the leader and the follower. The strategy sets of the leader and the follower are denoted as S_1 and S_2, respectively. After the leader selects a strategy $s_1 \in S_1$, the follower responds by choosing a strategy $s_2 \in S_2$. The respective payoff functions of the leader and the follower are $\pi_1(s_1, s_2)$ and $\pi_2(s_1, s_2)$, where the leader aims to maximize its payoff, and the follower optimizes its response to the leader's strategy. The solution of the Stackelberg game involves determining the optimal strategies for both players by listing and optimizing their respective payoff functions. The detailed solution steps are as follows:

1. Define the payoff functions $\pi_1(s_1, s_2)$ and $\pi_2(s_1, s_2)$ for the leader and the follower, respectively.

2. For the follower, given the leader's strategy s_1, determine the optimal response s_2^* that maximizes (or minimizes, as appropriate) $\pi_2(s_1, s_2)$.
3. Express the follower's optimal response as $s_2^* = f(s_1)$, which serves as the follower's response function.
4. The leader selects the optimal strategy s_1^* to maximize its own payoff $\pi_1(s_1, f(s_1))$.

This optimization process can be implemented and solved using MATLAB.

3.2. Modelling Assumptions

Assumption 1. *Whether it is the government's carbon tax on domestic enterprises or the carbon tariffs of exported countries, it has a certain tax rate. The carbon emissions of each unit determine the tax burden levied. Assuming that the carbon emissions of the unit of new products are e_n [1], due to the tax burden pressure, OEM will take the initiative to make emission reduction investments, so the carbon emissions of the unit of Remanufactured products are ρe_n $(0 < \rho < 1)$ [28].*

Assumption 2. *In profit calculation, the transportation costs incurred during the product recycling process are ignored.*

Assumption 3. *Considering the purpose of establishing carbon taxes and tariffs, as well as emission reduction targets, both carbon taxes and tariffs in this paper are positive numbers. The carbon tax of the exporting country is represented by f_0, and the carbon tariff is represented by f_1, with $f_1 > f_0$.*

Assumption 4. *Due to the existence of carbon allowances and carbon markets, new products and remanufactured goods need to purchase carbon credits if their carbon emissions exceed their carbon allowances, with the exporter's carbon allowances denoted by M and the average price per unit of carbon credits denoted by μ.*

Assumption 5. *The emission reduction investment effort of OEM is X_{oo}. The cost of carbon emission reduction technology is directly proportional to the square of the amount of carbon emission reduction, so the cost of carbon emission reduction of OEM can be set to λX_{oo}^2 $(0 < \delta < 1)$.*

Assumption 6. *According to [29,30], we assume that α represents the potential demand for the product that is, the number of products that consumers may buy when all other conditions remain unchanged; p_{or}, p_{on} is the price of the remanufactured and new product; ρ represents the degree of carbon aversion of the consumer (green preference), the higher the degree of patience of consumers for remanufactured products, the higher the market demand for making products.*

The utility function covers the information conveyed by the preference relationship, which can measure the satisfaction of consumers. Assuming that consumers' valuation of new products is z, then the utility function of new and remanufactured products can be expressed as $U_n = z - p_{on}$, $U_r = \rho z - p_{or}$.

When consumers do not have distinct preferences, i.e., when $\rho \in [p_r/p_n, 1-(p_n-p_r)/a]$:

Demand function for remanufactured products:

$$q_{or} = \frac{(1-\rho)\alpha - p_n + p_r}{1-\rho}, \tag{1}$$

Demand function for new products:

$$q_{on} = \frac{\rho p_n - p_r}{\rho(1-\rho)}, \tag{2}$$

When the consumer's carbon aversion is very low, a situation occurs where the demand for remanufactured products drops to 0 when $\rho < p_{or}/p_{on}$, $q_r = 0$, $q_{on} = a - p_{on}$.

When consumer tolerance for remanufactured products is extremely good due to the price advantage of remanufactured products, it can lead to a situation where the market demand for the new product drops to zero when the $\rho > 1-(p_{on}-p_{or})/a$, $q_{on} = 0$, $q_{or} = a - p_{on}/\rho$.

Assumption 7. *Considering the transportation cost generated by OEM in the process of recycling old products, OEMs have higher unit remanufacturing costs than retailers.*

Assumption 8. *Given the cost-saving nature of remanufacturing, the cost per unit of a new product produced by OEM is higher than a remanufactured product [31].*

Assumption 9. *According to [32], we assume the degree of reprocessing and quality of the remanufactured product is the same whether the OEM or the retailer remanufactures it.*

Assumption 10. *Let $\delta > \beta$, because emission reduction investment may occur in the packaging and transportation of the product [33]. It is reasonable to assume that δ is a larger value.*

To improve readability, the main symbols used in this study are summarized in Table 1.

Table 1. Variable definition.

Variables	Meaning
M	Exporting country's Carbon allowances
μ	Price per unit of carbon rights
f_0	Carbon tax in exporting countries
f_1	Carbon tariff
e_n	Carbon emissions per unit of new product
β	The ratio of carbon emissions per unit of remanufactured product to new product
X_{oo}	OEM emission reduction investment efforts
δ	The ratio of emission reductions per unit of remanufactured product to a new product for the same emission reduction investment
λ	OEM reduction investment cost coefficient
p_{or}	Price of remanufactured product
p_{on}	Price of new product
w_{or}	Wholesale price of remanufactured product
w_{on}	Wholesale price of new product
π_{oi}	Total profit of OEM in scenario i
π_{ri}	Total profit of the retailer in scenario i
c_n	Production cost of unit new product
c_r	Recycling and remanufacturing costs of unit remanufactured product
q_{or}	Sales of remanufactured product
q_{on}	Sales of new product

4. Modeling Analysis of Cross-Border Remanufacturing Decisions

This paper classifies consumer preferences into three modes: no apparent preference, green preference, and purely new preference, reflecting consumers' attitudes toward carbon reduction and their acceptance of remanufactured products. A parameter ρ is introduced to quantify consumers' carbon aversion (green preference). When ρ is small, consumers derive negligible utility from remanufactured products, and market demand for them may disappear entirely, representing the purely new preference mode. Conversely, when ρ is large and approaches 1, consumers exhibit high acceptance of remanufactured products and shift entirely toward purchasing them due to price advantages, effectively reducing the demand for new products to zero, which characterizes the green preference mode. When ρ is moderate, consumers show no clear preference between new and remanufactured products, making purchasing decisions based on price and other factors, representing the no apparent preference mode.

Building on these three modes, this paper investigates whether the total carbon emissions of the Original Equipment Manufacturer (OEM) exceed the carbon quota. If emissions exceed the quota, the OEM must purchase additional carbon rights through the carbon trading market. Integrating these conditions, this study develops master–slave game models under six scenarios, combining the three consumer preference modes with whether the OEM's emissions exceed the carbon quota. The equilibrium solutions derived from these models offer insights into how OEMs and retailers can optimize their decisions to maximize profits and achieve equilibrium. Additionally, the findings provide valuable decision-making guidance for remanufacturers in balancing profitability with carbon reduction objectives.

4.1. No Obvious Preference Mode

Consumers are neutral towards new and remanufactured products in a market environment with no clear preference. They buy in conjunction with prices and other related factors instead of choosing a certain product alone. As a result, new and remanufactured products maintain their respective shares in the market. In this case, $\rho \in [\frac{p_{or}}{p_{on}}, 1 - \frac{p_{on}-p_{or}}{a}]$, ρ is at a moderate level, sales volume depends on the demand function. Specifically, consumers will weigh the product's effectiveness, price, and possible factors such as quality, brand reputation, and environmental protection attributes to determine the final purchase option.

4.1.1. Total Carbon Emissions Lower than Carbon Allowances

In no obvious preference mode, the OEM in the exporting country decides the production and emission reduction investment based on the carbon tariff in the importing country and exports new or remanufactured products at wholesale prices to retailers, who determine their retail sale prices.

When the total carbon emissions of the OEM are lower than carbon allowances, the OEM does not need to pay extra penalty costs for exceeding the carbon allowances. OEM's profit equals the product of the unit profit of new and remanufactured products and their sales volume, minus emission reduction investment costs. The unit profit is the sales price minus production and carbon emissions costs. A retailer's profit equals the product of the unit profit of new and remanufactured products and their sales volume, where unit profit is the retail price minus the wholesale price. The profit functions of OEM and retailers are:

$$\pi_{o1} = [w_{on} - c_n - (f_1 - f_0)(e_n - X_{oo})]q_{on} + [w_{or} - c_r - (f_1 - f_0)(\beta e_n - \delta X_{oo})]q_{or} - \lambda X_{oo}^2, \quad (3)$$

$$\begin{gathered} \pi_{r1} = (p_{on} - w_{on})q_{on} + (p_{or} - w_{or})q_{or}, \\ q_{on}(e_n - X_{oo}) + (\beta e_n - \delta X_{oo})q_{or} \leq M \end{gathered} \quad (4)$$

In no obvious preference mode, the range of ρ is usually considered to be in a moderate position, about 0.5~0.7; as for the ratio of carbon emissions per unit of remanufactured and new products, since the recycling of product parts can only be carried out partially, while still needing to be processed again, β may be at a low level, so this paper, so this paper argues that $\delta > \rho > \beta$.

The equilibrium solution based on the Stackelberg model is as follows:

Let $D = 8\rho^2\lambda - 2\rho\delta(f_0 - f_1)^2 + \rho(f_0 - f_1)^2 - 8\rho\lambda + \delta^2(f_0 - f_1)^2$; $E = c_n + (f_1 - f_0)e_n$; $C = c_r + \beta(f_1 - f_0)e_n$

$$w_{on}^* = \frac{-(f_1 - f_0)^2\left[\alpha\rho^2 + (\delta - \rho)C - 2\alpha\rho + \alpha\rho\delta + \left(\rho\delta - \delta^2 + 8\rho\lambda(1-\rho)\right)(E + \alpha)\right]}{2D}, \quad (5)$$

$$w_{or}^* = \frac{\rho\alpha + C}{2} + \frac{\delta(f_0 - f_1)^2\left[\alpha\rho + \rho E(\delta - 1) - a\rho^2 - (\delta - \rho)C\right]}{2D}, \quad (6)$$

$$x_{OO}^* = \frac{-(f_0 - f_1)\left[\alpha\rho + \rho(\delta - 1)E - a\rho^2 - (\delta - \rho)C\right]}{D}, \quad (7)$$

$$q_{on}^* = \frac{(f_1 - f_0)^2\left[\delta^2(\alpha - E) + \delta C - \alpha\rho\delta\right] + 8\rho\lambda(\rho\alpha + E - a - C)}{4D}, \quad (8)$$

$$q_{or}^* = \frac{(f_1 - f_0)^2[-C + \alpha\rho - \alpha\delta + \delta E + \beta(f_1 - f_0)e_n] + 8\lambda(C - \rho E)}{4D}. \quad (9)$$

The maximum profit for OEM and retailer is:

$$\pi_{o1}^* = \frac{\begin{gathered}\alpha^2\left[(f_0 - f_1)^2(\delta - \rho)^2 + 8\lambda\rho(\rho - 1)\right] + 2a(f_0 - f_1)^2(\delta - \rho)(\beta e_n(f_0 - f_1) - c_n\delta) \\ +16\lambda\alpha\rho(1 - \rho)E + 2\alpha(\delta - \rho)\left[c_r(f_0 - f_1)^2 - e_n(f_0 - f_1)^3\delta\right] + \left[(f_0 - f_1)^2 - 8\lambda\right][C\beta e_n(f_0 - f_1) \\ +\beta(f_0 - f_1)\, c_r e_n + \delta^2] + \left(8\lambda\rho - \delta(f_0 - f_1)^2\right)[(f_0 - f_1)e_n(2\beta c_n + 2C - E - c_n) + c_n(2c_r - c_n)]\end{gathered}}{8D}, \quad (10)$$

$$\pi^*_{r1} = (p^*_{on} - w^*_{on})q^*_{on} + (p^*_{or} - w^*_{or})q^*_{or}. \quad (11)$$

In the course of analyzing the variation of the equilibrium solution with e_n, we find that

$$x^{*}_{oo} = \frac{(\rho-\beta)(f_0-f_1)^3 + 8(f_0-f_1)\lambda(\rho-\beta)}{4\left[(\delta-1)^2(f_0-f_1)^2\rho + \delta^2(f_0-f_1)^2(1-\rho) + 8\lambda\rho(\rho-1)\right]}. \quad (12)$$

$(\rho-\beta)(f_0-f_1)^3 + 8(f_0-f_1)\lambda(\rho-\beta)$ is always bigger than 0. Therefore, to simplify the analysis, the cost of reduction of emission reduction is much higher than the difference between carbon tariffs and domestic carbon taxes, that is, $(\delta-1)^2(f_0-f_1)^2\rho + \delta^2(f_0-f_1)^2(1-\rho) + 8\lambda\rho(\rho-1) < 0$.

Theorem 1. *When the total carbon emissions are less than the carbon allowances, the optimal wholesale and retail prices of the two products increase with the carbon emissions of the products. The difference between carbon tariffs and domestic carbon taxes influences the optimal sales of the two products. When the difference is low* $(f_1 - f_0)^2(\rho-\delta) < 8\lambda(\beta-\rho)$*, the higher the carbon emission per unit product, the lower the sales of new products, because when the difference is lower, the cost of products brought by carbon tariffs is not obvious, with the rise of carbon emission per unit, the cost difference between new products and remanufactured products gradually increase, so the decrease in sales of new products is higher than old products; When the difference is high* $(f_1 - f_0)^2(\rho-\delta) > 8\lambda(\beta-\rho)$*, the higher the carbon emissions per unit of product, the higher the sales of remanufactured products. The reason is that when the difference is higher, the cost brought by the carbon tariff rises, and the cost advantage of remanufactured products is obvious, so sales naturally increase.*

Theorem 2. *When the total carbon emissions are less than the carbon allowances, the OEM emission reduction investment decision decreases with the increase in unit product emissions, and this trend is not affected by the difference between carbon tariffs and domestic carbon taxes. This inference shows that excessive carbon tariffs do not effectively inspire enterprises to invest in emission reduction but are instead passed on to consumers, consistent with the conclusions reached by Zhou et al. [34].*

4.1.2. Total Carbon Emissions Higher than Carbon Allowances

When the total carbon emissions of the OEM are higher than carbon allowances, the OEM needs to pay an additional cost for exceeding carbon allowances $[(q_{on}(e_n - X_{oo}) + (\beta e_n - \delta X_{oo})q_{or}] - M]$, which is used to purchase emission rights for the portion of the exceeded carbon allowance. Since each extra ton of carbon dioxide emitted needs to buy one ton of carbon emission right, the price of one ton of carbon emission right is μ, so the additional cost is $\mu[[(q_{on}(e_n - X_{oo}) + (\beta e_n - \delta X_{oo})q_{or}] - M]$. The profit functions of OEM and retailers are:

$$\begin{aligned}\pi_{O2} = {} & [w_{on} - c_n - (f_1 - f_0)(e_n - X_{oo})]q_{on} + [w_{or} - c_r - (f_1 - f_0)(\beta e_n - \delta X_{oo})]q_{or} \\ & -\lambda_o X^2_{oo} - \mu[[(q_{on}(e_n - X_{OO}) + (\beta e_n - \delta X_{oo})q_{or}] - M],\end{aligned} \quad (13)$$

$$\pi_{r2} = (p_{on} - w_{on})q_{on} + (p_{or} - w_{or})q_{or}, \quad (14)$$

$$q_{on}(e_n - X_{oo}) + (\beta e_n - \delta X_{oo})q_{or} > M$$

By combining the demand function equation, the profit function can be expressed as: Let $H = ((f_1 - f_0) + \mu)^2(\delta^2 - 2\delta\rho + \rho) + 8\lambda\rho(\rho-1)$, $L = (f_1 - f_0) + \mu$

$$\begin{aligned}w^*_{on} = {} & \frac{\rho^2\left[-\alpha L^2 + 8e_n\lambda L + 8\lambda(a+c_n)\right] + L^2\left[(\alpha+c_n)\delta^2 - c_r\delta\right] + L^3\delta e_n(\delta-\beta)}{2H} \\ & + \frac{\rho\left[L^2(2\alpha + c_r - 2\alpha\delta - c_n\delta) - 8e_n\lambda L - 8\lambda(\alpha+c_n) + e_n(\beta-\delta)L^3\right]}{2H},\end{aligned} \quad (15)$$

$$
\begin{aligned}
w_{or}^{*} = {} & \rho\frac{(a-c_n)\delta\mu^2+(\alpha+c_n)\left(\delta^2+\mu^2\right)-8\lambda c_{or}}{2H}+\frac{8\alpha\lambda\rho^3+\rho^2\left[8\lambda(c_{or}-a)+aL^2(1-3\delta)+8\beta e_n\lambda L\right]}{2H} \\
& +\rho\frac{(1-\delta)e_n(\beta-\delta)L^3+L^2c_r(1-\delta)+[c_n\delta(f_1-f_0)(\delta-1)+\alpha\delta(f_1-f_0)(\delta+1)](2\mu+(f_1-f_0))-8\beta e_n\lambda L}{2H},
\end{aligned} \tag{16}
$$

$$
x_{OO}^{*} = \frac{L[e_nL(\rho(1-\delta)+\beta(\delta-\rho))+c_r(\delta-\rho)+c_n\rho(1-\delta)+\alpha\rho(\rho-1)]}{H}, \tag{17}
$$

$$
\begin{aligned}
p_{on}^{*} = {} & \frac{\rho^2\left[-\alpha L^2+8e_n\lambda L+8\lambda(c_n+3\alpha)\right]+L^2\left(c_n\delta^2+3\alpha\delta^2-c_r\delta\right)+\delta e_nL^3(\delta-\beta)}{4H}-\frac{2\rho\delta\mu(f_1-f_0)(6\alpha+c_n)}{4H} \\
& +\frac{\rho\left[(4\alpha+c_r)L^2-8e_n\lambda L-(6\alpha\delta+c_n\delta)\left((f_1-f_0)^2+\mu^2\right)-8\lambda(c_n+3\alpha)+e_n(\beta-\delta)L^3\right]}{4H},
\end{aligned} \tag{18}
$$

$$
\begin{aligned}
p_{or}^{*} = {} & \frac{6a\lambda\rho^3}{H}+\frac{\rho^2\left[8\lambda(c_r+\beta e_n\mu+\beta e_n(f_1-f_0))+(3\alpha-7a\delta)L^2\right]}{4H}+ \\
& \frac{\rho\left[L^3e_n\left(\beta-\delta+\delta^2-\beta\delta\right)+L^2\left(3a\delta^2+c_r\right)+\left((f_1-f_0)^2+\mu^2\right)\left(c_n\delta^2-c_n\delta+\alpha\delta-c_{or}\delta\right)\right]}{4H}+ \\
& \frac{\rho[2\delta(f_1-f_0)\mu(a-c_r)+2c_n\delta(f_1-f_0)\mu(\delta-1)-8\beta e_n\lambda L-8c_{or}\lambda]}{4H},
\end{aligned} \tag{19}
$$

$$
q_{on}^{*} = \frac{8\alpha\lambda\rho^2+\rho\left[-\alpha\delta L^2+8e_n\lambda L(1-\beta)+8\lambda(c_n-a-c_r)\right]+L^2\left(a\delta^2-c_n\delta^2+c_r\delta\right)+L^3\left(\beta\delta e_n-\delta^2e_n\right)}{4H}, \tag{20}
$$

$$
q_{or}^{*} = \frac{\rho\left[-\alpha L^2+8e_n\lambda L+8c_n\lambda\right]+L^2(c_r+\alpha\delta-c_n)+L^3(\beta e_n-\delta e_n)-8\beta e_n\lambda L-8c_r\lambda}{4H}, \tag{21}
$$

$$
\begin{aligned}
\pi_{o2}^{*} = {} & [w_{on}^{*}-c_n-(f_1-f_0)(e_n-x_{oo}^{*})]q_{on}^{*}+[w_{or}^{*}-c_r-(f_1-f_0)(\beta e_n-\delta x_{oo}^{*})] \\
& q_{or}^{*}-\lambda_o{x_{oo}^{*}}^2-\mu[[(q_{on}^{*}(e_n-x_{oo}^{*})+(\beta e_n-\delta x_{oo}^{*})q_{or}^{*}]-M],
\end{aligned} \tag{22}
$$

$$
\pi_{r2}^{*} = (p_{on}^{*}-w_{on}^{*})q_{on}^{*}+(p_{or}^{*}-w_{or}^{*})q_{or}^{*}. \tag{23}
$$

Theorem 3. *When the total carbon emissions are higher than the carbon allowances, The optimal wholesale price, retail price, and emission reduction investment of the two products increase with the increase in carbon emissions of the product. The difference between carbon tariffs and domestic carbon taxes does not affect this trend. However, the increase in emission reduction investment is higher than the wholesale and retail prices. Because the unit cost of products is increased by the double impact of carbon tariff costs and carbon trading costs, OEM take the initiative to invest in low-carbon technologies; however, with the investment in emission reduction technologies, carbon emissions per unit of product have declined, so the trend of rising costs has leveled off. In summary, the trend of increase in wholesale and retail prices is smaller than emission reduction investments.*

Theorem 4. *When the total carbon emissions are higher than the carbon allowances, the trend of the optimal sales volume of the two products with the changes in the carbon emissions are related to the parameters when* $8\rho\lambda L(1-\beta) > L^3\delta(\delta-\beta)$*, sales of new products increase with increasing carbon emissions per unit, and the opposite decreases; when* $8\lambda L(\beta-\rho) > L^3(\beta-\delta)$*, sales of remanufactured products increase with rising carbon emissions per unit and the opposite decreases.*

4.2. Purely Green Mode

In a supply chain that is sensitive to carbon emissions, consumers prefer to buy low-carbon products, and this preference drives an interesting situation for firms: reducing carbon emissions increases production costs but, at the same time, stimulates demand, presenting an unconventional phenomenon of inverse demand. This means that despite higher production costs, these additional costs can be compensated by increased sales and may even lead to additional profits due to high consumer demand for low-carbon products [35].

In pure green mode, the consumer is sensitive to carbon emissions. Because there is a price and environmental advantage of remanufactured products [36], the demand for the new product market will be reduced to 0 at this time $\rho > 1 - (p_{on} - p_{or})/a$, $q_{on} = 0$, $q_{or} = a - p_{or}/\rho$. In this market environment, the OEM will no longer only produce new products but recycle and remanufacture all products after use. OEM will produce new products without exporting them, and all remanufactured products will be exported for sale.

4.2.1. Total Carbon Emissions Lower than Carbon Allowances

OEM export only remanufactured products, which are subject to carbon taxes and tariffs during production and export; retailer sell remanufactured products

In decision-making, OEM decides production quantity and emission reduction investment based on the carbon tax and tariff, and at the same time, exports the products at the wholesale price, then the retailer decides the sales strategy.

When the total carbon emissions of the OEM are lower than carbon allowances, the profit functions of OEM and retailers are:

$$\pi_{o3} = [w_r - c_r - (f_1 - f_0)(\beta e_n - \delta X_{oo})]q_{or} - \lambda X_{oo}^2, \tag{24}$$

$$\pi_{r3} = (p_{or} - w_r)q_{or}, \tag{25}$$

$$q_{or}(e_n - X_{oo}) + (\beta e_n - \delta X_{oo})q_{or} \leq M,$$

The equilibrium solution based on the Stackelberg model is:

$$w_{on}^* = 0, \tag{26}$$

$$w_{or}^* = \frac{\rho(-\alpha\delta^2(f_1 - f_0)^2 + 4\beta e_n\lambda(f_1 - f_0) + 4c_r\lambda + 4\alpha\rho\lambda)}{8\lambda\rho - \delta^2(f_1 - f_0)^2}, \tag{27}$$

$$x_{oo}^* = \frac{-(\delta(f_1 - f_0)[c_r - \alpha\rho + \beta e_n(f_1 - f_0)])}{8\lambda\rho - \delta^2(f_1 - f_0)^2}, \tag{28}$$

$$p_{on}^* = 0, \tag{29}$$

$$p_{or}^* = \frac{\rho(-\alpha\delta^2(f_1 - f_0)^2 + 2\beta e_n\lambda(f_1 - f_0) + 2c_r\lambda + 6\alpha\rho\lambda)}{8\lambda\rho - \delta^2(f_1 - f_0)^2}, \tag{30}$$

$$q_{on}^* = 0, \tag{31}$$

$$q_{or}^* = \frac{2\lambda[c_r - \alpha\rho + \beta e_n(f_1 - f_0)]}{8\lambda\rho - \delta^2(f_1 - f_0)^2}, \tag{32}$$

$$\pi_{o3}^* = \frac{\lambda(c_r - \alpha\rho + \beta e_n(f_1 - f_0))^2}{8\lambda\rho - \delta^2(f_1 - f_0)^2}, \tag{33}$$

$$\pi_{r3}^* = \frac{4\lambda^2\rho(c_r - \alpha\rho + \beta e_n(f_1 - f_0))^2}{8\lambda\rho - \delta^2(f_1 - f_0)^{2^2}}, \tag{34}$$

Theorem 5. *In pure green mode, when the total carbon emissions are less than the carbon allowances, the trend of the optimal wholesale price, retail price, and emission reduction decision with the changes in the carbon emissions are related to the difference between carbon tariffs and domestic carbon taxes. When the difference is low* $\left(\delta^2(f_1 - f_0)^2 < 8\lambda\rho\right)$*, the higher the carbon emissions per unit of product, the higher the wholesale and retail prices of the product, and the lower the level of investment in emission reduction; when the difference is high* $\left(\delta^2(f_1 - f_0)^2 > 8\lambda\rho\right)$*, the higher* *the carbon emissions per unit of product, the lower the wholesale and retail prices of the product, and the higher the degree of investment in emission reduction.*

From a realistic point of view, when the difference is low, the cost of products brought about by carbon tariffs is lower than the cost of carbon reduction investment, so OEMs do not have the incentive to invest; instead are willing to pay carbon tariffs and balance the cost by raising prices; while when the difference is high, OEMs are more willing to invest in carbon emission reduction technologies to reduce their costs and improve profits, at the same time, the wholesale and retail prices of the products will be reduced. Accordingly, sales volume will increase.

Theorem 6. *In pure green mode, when the total carbon emissions are less than the carbon allowances, the trend of optimal sales with the changes in the carbon emissions is related to parameters. When the difference is low* $\left(\delta^2(f_1 - f_0)^2 < 8\lambda\rho\right)$*, the product sales decrease with the increase in carbon emissions per unit; when the difference is high* $\left(\delta^2(f_1 - f_0)^2 > 8\lambda\rho\right)$*, the sales increase with the rise of carbon emissions per unit.*

4.2.2. Total Carbon Emissions Higher than Carbon Allowances

When the total carbon emissions of the OEM are higher than carbon allowances, the purchase cost of carbon emission rights needs to be distributed to new products and remanufactured products; since it is purchased based on carbon emissions, the proportion borne by remanufactured products is $\frac{(\beta e_n - \delta X_{oo})}{(e_n - X_{oo})}$, for the convenience of calculation simplified to β.

The profit functions of OEM and retailers are:

$$\begin{gathered}\pi_{o4} = [w_r - c_r - (f_1 - f_0)(\beta e_n - \delta X_{oo})]q_{or} - \lambda X_o^2 - \\ [q_{or}(e_n - X_{oo}) + (\beta e_n - \delta X_{oo})q_{or} - M]\mu\beta,\end{gathered} \quad (35)$$

$$\pi_{r4} = (p_r - w_r)q_{or}, \quad (36)$$

$$q_{or}(e_n - X_{oo}) + (\beta e_n - \delta X_{oo})q_{or} > M,$$

The equilibrium solution based on the Stackelberg model is

Let $F = \beta^2\mu^2(\delta+1)^2 + 2\beta\delta\mu(\delta+1)(f_1 - f_0) - 8\lambda\rho + \delta^2(f_1 - f_0)^2$, $L = (f_1 - f_0) + \mu$.

$$w_{on}^* = 0, \quad (37)$$

$$w_{or}^* = \frac{4\rho(-\beta e_n\lambda(\beta\mu + (f_1 - f_0) + \mu) - c_r\lambda + \alpha\rho\lambda)}{F} + \alpha\rho, \quad (38)$$

$$x_{oo}^* = \frac{(\delta(f_1 - f_0) + \beta\mu + \beta\delta\mu)\left[c_r - a\rho + \beta e_n(f_1 - f_0) + \beta e_n\mu + \beta^2 e_n\mu\right]}{F}, \quad (39)$$

$$p_{on}^* = 0, \quad (40)$$

$$p_{or}^* = \frac{2\rho(-\beta e_n\lambda(\beta\mu + (f_1 - f_0) + \mu) - c_r\lambda + \alpha\rho\lambda)}{F} + \alpha\rho, \quad (41)$$

$$q_{on}^* = 0, \quad (42)$$

$$q_{or}^* = \frac{2\lambda[c_{or} - \alpha\rho + \beta e_n[(f_1 - f_0) + \mu + \beta\mu]}{F}, \quad (43)$$

$$\begin{gathered}\pi_{o4}^* = -\frac{\lambda a^2\rho^2 + \rho[2\beta\lambda\mu(M - \alpha e_n) - 2\alpha\beta e_n\lambda((f_1 - f_0) + \beta\mu) - 2\alpha c_{or}\lambda]}{F} \\ -\frac{\lambda c_{or}^2 - M\beta\delta^2\mu(f_1 - f_0)^2 + 2\lambda\beta^3 e_n^2\mu L + \lambda\beta^4 e_n^2\mu^2 + 2\lambda\beta^2 c_{or} e_n\mu}{F} \\ -\frac{L^2\left(\lambda\beta^2 e_n^2\right) + 2L\beta c_{or}\lambda e_n - 2M\beta^2\delta(f_1 - f_0)\mu^2(\delta+1) - M\beta^3\mu^3(\delta+1)^2}{F},\end{gathered} \quad (44)$$

$$\pi_{r4}^* = \frac{4\lambda^2\rho\left(c_r - \alpha\rho + \beta e_n(f_1 - f_0) + \beta e_n\mu + \beta^2 e_n\mu\right)^2}{F}, \tag{45}$$

Theorem 7. *In pure green mode, when the total carbon emissions are higher than the carbon allowances, the trend of the optimal wholesale price and retail price with the changes in the carbon emissions are not affected by the difference between carbon tariffs and domestic carbon taxes, wholesale and retail prices in the export process of remanufactured products decrease with higher carbon emissions per unit.*

Theorem 8. *In pure green mode, when the total carbon emissions are higher than the carbon allowances, the trend of the optimal sales with the changes in the carbon emissions are related to parameters when* $\beta^2\mu^2(\delta+1)^2 + 2\beta\delta\mu(\delta+1)(f_1 - f_0) + \delta^2(f_1 - f_0)^2 > 8\lambda\rho$*, the sales volume increases with the increase of carbon emissions, the opposite decreases.*

Theorem 9. *The trend of the carbon reduction investment with the changes in carbon emissions are related to parameters when* $\beta^2\mu^2(\delta+1)^2 + 2\beta\delta\mu(\delta+1)(f_1 - f_0) + \delta^2(f_1 - f_0)^2 > 8\lambda\rho$*, the degree of investment in emission reduction increases with the increase in carbon emissions per unit, due to the existence of carbon trading, as carbon emissions rise, the increase in the cost of the product not only includes carbon tariffs but also includes the cost of trading carbon allowances, thus the higher the carbon emissions, the higher the incentive for OEM to invest emission reduction technologies. While when* $\beta^2\mu^2(\delta+1)^2 + 2\beta\delta\mu(\delta+1)(f_1 - f_0) + \delta^2(f_1 - f_0)^2 < 8\lambda\rho$*, the degree of investment in carbon reduction decreases with the increase in carbon emissions per unit. In this case, the difference between the carbon tariff and the domestic carbon tax is small; the emission reduction investment cost coefficient is high, so additional investment increases costs.*

4.3. Purely New Mode

Consumers are not receptive to remanufactured products in pure new mode, so they prefer to buy new ones. In this case, the demand for the remanufactured product q_{or} drops to 0, and the market for the new products q_{on} is determined by the demand function, $q_{on} = a - p_{on}$, α represents the maximum demand for new products, OEMs no longer engage in product recycling and remanufacturing activities, but are focusing on the production and sale of new products.

4.3.1. Total Carbon Emissions Lower than Carbon Allowances

The profit functions of OEMs and retailers are:

$$\pi_{o5} = [w_{on} - c_n - (f_1 - f_0)(e_n - X_{oo})]q_{on} - \lambda X_{oo}^2, \tag{46}$$

$$\pi_{r5} = (p_{on} - w_{on})q_{on}, \tag{47}$$

$$q_{on}(e_n - X_{oo}) \le M.$$

The equilibrium solution based on the Stackelberg model is

$$w_{on}^* = \frac{(-4\alpha - 4c_n - 4e_n(f_1 - f_0))\lambda + \alpha(f_1 - f_0)^2}{(f_1 - f_0)^2 - 8\lambda}, \tag{48}$$

$$w_{or}^* = 0, \tag{49}$$

$$x_{oo}^* = \frac{(f_1 - f_0)(c_n - \alpha + e_n(f_1 - f_0))}{(f_1 - f_0)^2 - 8\lambda}, \tag{50}$$

$$p_{on}^* = \frac{a}{2} + \frac{\alpha(f_1 - f_0)^2 - \lambda(4\alpha + 4c_n + 4e_n((f_1 - f_0)))}{2\left((f_1 - f_0)^2 - 8\lambda\right)}, \quad (51)$$

$$p_{or}^* = 0, \quad (52)$$

$$q_{on}^* = \frac{-2\lambda(c_n - a + e_n(f_1 - f_0))}{(f_1 - f_0)^2 - 8\lambda}, \quad (53)$$

$$q_{or}^* = 0, \quad (54)$$

$$\pi_{o5}^* = \frac{-\lambda(c_n - \alpha + e_n(f_1 - f_0))^2}{(f_1 - f_0)^2 - 8\lambda}, \quad (55)$$

$$\pi_{r5}^* = \frac{4\lambda^2(c_n - \alpha + e_n(f_1 - f_0))^2}{(-f_1 - f_0)^2 + 8\lambda\Big)^2}, \quad (56)$$

Theorem 10. *In pure new mode, when the total carbon emissions are less than the carbon allowances, the trend of the optimal wholesale price, retail price, and emission reduction decision of new products with the changes in the carbon emissions are related to the difference between carbon tariffs and domestic carbon taxes. When the difference is low $(f_1 - f_0)^2 < 8\lambda$, the higher the carbon emissions per unit of product, the higher the wholesale and retail prices of the product, and the lower the level of investment in emission reduction; when the difference is high $(f_1 - f_0)^2 > 8\lambda$, the higher the carbon emissions per unit of product, the lower the wholesale and retail prices of the product, and the higher the degree of investment in emission reduction. Consistent with pure green mode.*

Theorem 11. *In the pure new mode, when the total carbon emissions are less than the carbon allowances. In exporting, the trend of optimal sales with the changes in carbon emissions is related to parameters. When $(f_1 - f_0)^2 > 8\lambda$, the sales of new products increased with the increase in carbon emission of the unit, and the opposite decreased. That is, when the difference between the carbon tariff and the domestic carbon tax is large, the cost of the product decreases even with an increase in carbon emissions per unit due to the presence of carbon reduction investments. As a result, wholesale and retail prices have fallen, and sales have increased. When the differential is small, the degree of investment is small, so the increase in carbon emissions per unit leads to a rise in the cost and retail price, therefore, a consequent decrease in sales volumes.*

4.3.2. Total Carbon Emissions Higher than Carbon Allowances

In pure new mode, OEM only produces new products for sale, when the total carbon emissions are higher than carbon allowances, the cost of purchasing carbon emission rights does not need to be apportioned.

The profit functions of OEM and retailers are:

$$\pi_{o6} = [w_{on} - c_n - (f_1 - f_0)(e_n - X_{oo})]q_{on} - \lambda X_{oo}^2 - [q_{on}(e_n - X_{oo}) - M]\mu(1 - \beta), \quad (57)$$

$$\pi_{r6} = (p_{on} - w_{on})q_n, \quad (58)$$

$$q_{on}(e_n - X_{oo}) > M$$

The equilibrium solution based on the Stackelberg model is

Let $G = \left(\beta^2 - 2\beta + 1\right)\mu^2 + 2(f_1 - f_0)\mu(1 - \beta) + (f_1 - f_0)^2 - 8\lambda$

$$w_{on}^* = \frac{\alpha\mu^2(\beta - 1)^2 + 2\alpha(f_1 - f_0)\mu(1 - \beta) - 4\lambda e_n(\mu + \mu\beta + (f_1 - f_0)) + \alpha(f_1 - f_0)^2 - 4\alpha\lambda - 4\lambda c_n}{G}, \quad (59)$$

$$w_{or}^* = 0, \quad (60)$$

$$x_{oo}^{*} = \frac{((f_1 - f_0) + \mu - \beta\mu)[c_n - a + e_n(f_1 - f_0) + e_n\mu - \beta e_n\mu]}{G}, \tag{61}$$

$$p_{on}^{*} = \frac{a}{2} - \frac{4\alpha\lambda + 4\lambda c_n - a(f_1 - f_0)^2 - \mu^2\alpha(\beta - 1)^2 + 4e_n\lambda((f_1 - f_0) + \mu - \mu\beta) - 2\alpha(f_1 - f_0)(\beta\mu - \mu)}{2G}, \tag{62}$$

$$p_{or}^{*} = 0, \tag{63}$$

$$q_{on}^{*} = \frac{2\lambda(c_n - a + e_n(f_1 - f_0) + e_n\mu - e_n\beta\mu)}{G}, \tag{64}$$

$$q_{or}^{*} = 0, \tag{65}$$

$$\pi_{o6}^{*} = \frac{M_O\left[\mu^3(1-\beta)^3 + 2(f_1-f_0)\mu^2(\beta-1)^2 + (1-\beta)\left((f_1-f_0)^2\mu - 8\mu\lambda\right)\right]}{G} - \frac{-2\alpha\lambda(c_n+e_n\mu) + \lambda e_n^2\mu^2(\beta-1)^2 + \lambda e_n^2(f_1-f_0)^2 + 2\lambda e_n(f_1-f_0)(c_n-a+e_n\mu)}{G} - \frac{\lambda a^2 + 2\lambda e_n\mu(\alpha\beta + c_n - \beta c_n)}{G}, \tag{66}$$

$$\pi_{r6}^{*} = \frac{4\lambda^2(c_n - \alpha + e_n(f_1 - f_0) + e_n\mu - \beta e_n\mu)^2}{G^2}, \tag{67}$$

Theorem 12. *In the pure new mode, when the total carbon emissions are higher than the carbon allowances, the trend of the optimal wholesale price, retail price, and emission reduction decision with the changes in the carbon emissions are not affected by the difference between carbon tariffs and domestic carbon taxes. Wholesale and retail prices in the export process of new products decrease, and the degree of investment in emission reduction increases with the unit's carbon emission increase. Due to the existence of carbon trading, the higher the carbon emissions, the higher the incentive for OEM to invest in carbon reduction technologies because the increase in the cost of the product not only includes carbon tariffs but also includes the cost of trading carbon allowances, the cost will be increased significantly so that investment in emission reduction rises significantly. This is consistent with the purely green preference scenario.*

Theorem 13. *In pure new mode, when the total carbon emissions are higher than the carbon allowances, the trend of the optimal sales with the changes in the carbon emissions are related to parameters when* $\left(\beta^2 - 2\beta + 1\right)\mu^2 + 2(f_1 - f_0)\mu(1 - \beta) + (f_1 - f_0)^2 > 8\lambda$, *sales of new products increase with the increase in carbon emissions per unit, and the opposite decreases.*

4.4. Expectations Model

In any country, the consumer is not a single preference. Still, rather, three preferences exist in proportion, so we use x, y and z to denote the proportion of people, respectively, with the proportions summing to one.

Assume that the consumer preference for no obvious preference is a proportion x, and the proportion of purely green and purely new preferences is y, z ($x + y + z = 1$). Clearly $0 < x < 1, 0 < y < 1, 0 < z < 1$.

Assume that $\overline{U_o}, \overline{U_r}$ represent the average expected profit of the remanufacturer and retailers, such as (68), (69).

$$\overline{U_o} = x \times \pi_{o1} + y \times \pi_{o3} + (1 - x - y) \times \pi_{o5}, \tag{68}$$

$$\overline{U_r} = x \times \pi_{r1} + y \times \pi_{r3} + (1 - x - y) \times \pi_{r5}, \tag{69}$$

By substituting the parameters and solving, we can obtain:

$$x_{oo}^{*} = \frac{(f_1-f_0)[399c_n y-399\alpha(1-y+\delta y)+399e_n(f_1-f_0)(1-y)-1330e_n(f_1-f_0)x(\delta+\beta)]}{\left[931-399(1-y)+420\delta^2 y\right](f_1-f_0)^2-3192\lambda-\delta(f_1-f_0)^2 x(2660-1900\delta)} + \frac{c_n x(931-1330\delta)+c_{or}x(1900\delta-1330)+420c_{or}\delta y}{\left[931-399(1-y)+420\delta^2 y\right](f_1-f_0)^2-3192\lambda-\delta(f_1-f_0)^2 x(2660-1900\delta)} + \frac{e_n(f_1-f_0)(931x+1900\beta\delta x+420\beta\delta y)}{\left[931-399(1-y)+420\delta^2 y\right](f_1-f_0)^2-3192\lambda-\delta(f_1-f_0)^2 x(2660-1900\delta)}, \tag{70}$$

$$x_{oo}^{*\prime} = \frac{(f_1-f_0)^2[931x(1-\delta)+399(1-y)-1330\beta x-399\delta x+1900\beta\delta x+420\beta\delta y]}{(f_1-f_0)^2[931x(1-\delta)+399(1-y)+1900\delta x(\delta-1)+171\delta x+420y\delta^2]-3192\lambda}, \tag{71}$$

From the above equation, it can be derived that the OEM's emission reduction investment decision is related to the proportion of consumer preferences. Once the population proportion is determined, it is also necessary to judge the relationship between the emission reduction investment decision and the per unit carbon emission based on the difference between the size of a carbon tax difference between the importing and domestic countries and the cost of emission reduction investment. Therefore, once key parameters such as the domestic carbon tax of the OEM, the carbon tax of the importing country, the environmental awareness of consumers, and the OEM's emission reduction cost coefficient are determined, the carbon tax policy's incentive effect on OEM's emission reduction investment can be revealed. A reference for government decision-makers is provided.

5. Numerical Analysis of Transnational Remanufacturing Decision-Making

In this section, the above conclusions will be verified and further analyzed through numerical simulation (only for the no-carbon trading scenario) for the three consumption preferences, respectively. Let $a = 200$, $\delta = 0.85$, $\lambda = 30$, $c_r = 6$, $c_n = 10$, $\beta = 0.6$, $M = 1000$, $\mu = 60$. To verify the impacts of different values on the optimal decision, the difference between a carbon tariff and a domestic carbon tax is taken as $A = f_1 - f_0 = 10$ and $A = f_1 - f_0 = 20$, the trend of the optimal decision of remanufacturing enterprises with e_n and $f_1 - f_0$ is explored through numerical analysis.

As shown in Figure 3, The trend of the carbon reduction investment with the changes in the carbon emissions are not related to the difference between carbon tariffs and domestic carbon taxes, always decreasing with the increase of carbon emissions; when the difference between the carbon tax and domestic carbon tax is small, both new products and remanufactured products decrease with the increase in carbon emissions, while as the difference gradually increases, the cost advantage begins to show, the optimal sales volume of remanufactured goods gradually exceeds new products, which is consistent with conclusions 1 and 2.

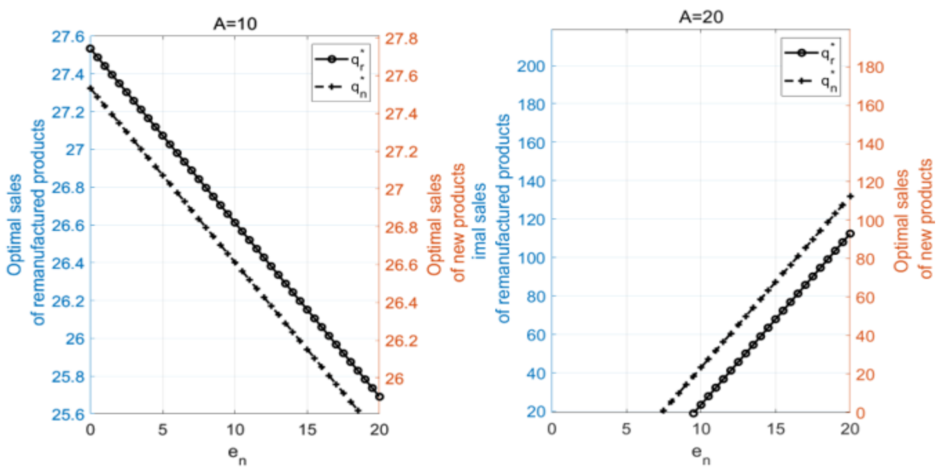

Figure 3. Trend of optimal solutions in the case of no obvious preference.

As shown in Figure 4, under pure green preferences, the trend of the carbon reduction investment and optimal sales with the changes in the carbon emissions are influenced by the difference between the carbon tax and domestic carbon tax ($A = f_1 - f_0$). When the difference is low, the sales volume of remanufactured products and the degree of OEM emission reduction investment decrease with the increase in carbon emissions; when the difference is high, they increase as the per-unit carbon emission increases, which is consistent with conclusions 5 and 6.

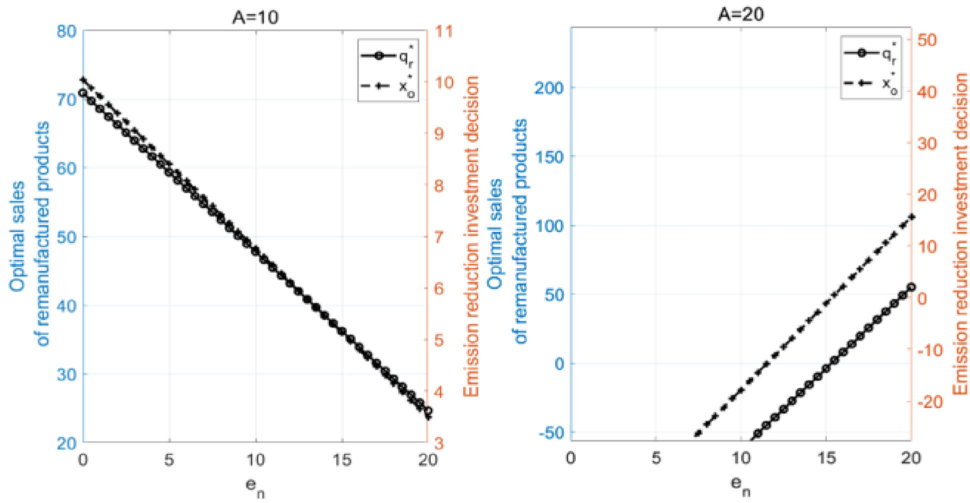

Figure 4. Trend of optimal solutions in the case of purely green preferences.

As shown in Figure 5, under pure new preferences, the export volume of remanufactured products is zero. The trend of the carbon reduction investment and optimal sales with the changes in carbon emissions are influenced by the difference between the carbon tax and domestic carbon tax ($A = f_1 - f_0$). When the difference is low, the sales volume of new products and the OEM's emission reduction investment decrease as the per-unit carbon emission of the product increases; in this case, the rise in carbon emissions per unit will lead to a decrease in the willingness to invest, i.e., industries with high carbon emissions will instead invest less in emission reduction, which is not conducive to the promotion of dual-carbon policies; when the difference is high, the sales volume of new products and the emissions reduction investment of the OEM increase as the per-unit carbon emission increases, which is consistent with conclusions 10 and 11.

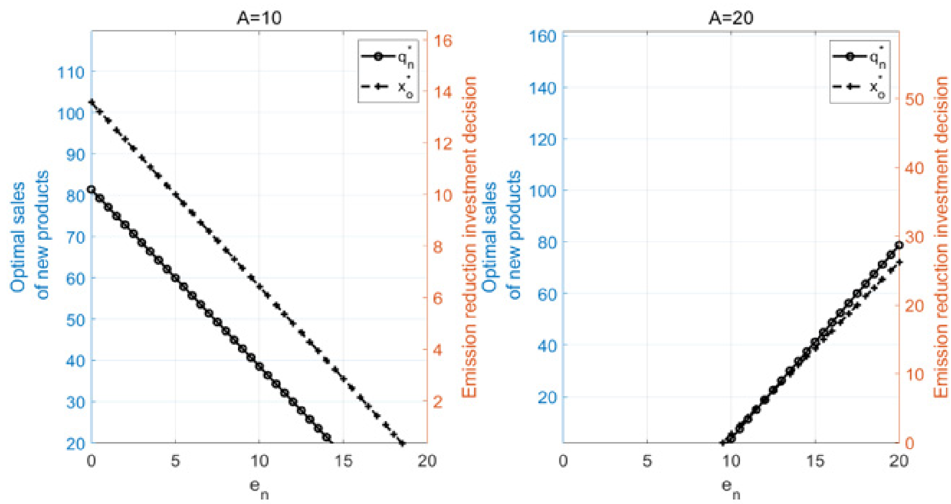

Figure 5. Trend of optimal solutions in the case of purely new preferences.

6. Discussions

6.1. Discussion on Project-Level GHG Accounting and Registries

The model proposed in this paper relies on accurate, transparent, and reliable greenhouse gas (GHG) accounting and registration, which critically depend on precise carbon emission data from the remanufacturing process. GHG accounting and registration form the foundation for implementing effective emission reduction initiatives and facilitating the green transformation of the economy. Additionally, they play a pivotal role in supporting China's active participation in international climate change negotiations.

Accurate carbon accounting enables companies to directly quantify their emissions, providing a clear understanding of their carbon footprint. Without baseline emission data, it is impossible to establish well-defined reduction targets. Furthermore, tracking emissions at the project level motivates companies to adopt innovative and effective reduction strategies. Through a comprehensive analysis of their operations, product lifecycles, and supply chains, businesses can identify potential reduction opportunities and optimize their approaches. This systematic methodology is essential for achieving carbon neutrality goals.

Moreover, project-level carbon accounting and registration are indispensable for the operation of carbon trading markets. They provide reliable data to support transactions, improve market transparency, and enhance market credibility. By ensuring that emission data are both accurate and verifiable, carbon accounting strengthens the integrity and functionality of carbon trading systems, which are vital for fostering a low-carbon economy.

Compared to developed countries, China's carbon trading market began relatively late. However, in 2021, the national carbon emissions trading market was officially launched, initially focusing on the power industry. Since its inception, China has made continuous advancements in the accounting, registration, monitoring, and reporting of carbon emissions. Among these processes, statistical accounting and registration remain particularly complex, involving multiple levels, diverse stakeholders, and various methods tailored to different objectives and purposes. Carbon emissions data provide a direct reflection of enterprises' emissions within a specific timeframe and are closely tied to quota payments, compliance with reduction targets, and carbon trading activities.

A major challenge faced by China's carbon market is the risk of data falsification. In 2022, some institutions were found to have falsified carbon emission reports. Since China's current carbon market primarily relies on the free allocation of allowances, unchanged allocation schemes and accounting methods may incentivize enterprises to falsify data for financial benefits. For example, reducing carbon emissions by 1 million tons can save enterprises up to CNY 60 million costs. This highlights the urgency of establishing a robust and credible carbon accounting and registration system. Such a system is essential to ensuring market fairness, maintaining trust in carbon trading, and promoting the long-term development of China's carbon market.

In recent years, China has made significant progress in developing a comprehensive carbon emission data collection and monitoring system, achieving notable improvements in carbon emission data quality management. However, certain deficiencies persist. Compared to countries such as Europe and the United States, which have established clear and unified quality control standards for carbon market data, China still lacks standardized guidelines for carbon emission data. With the ongoing enhancement of China's MRV (Monitoring, Reporting, and Verification) regulatory mechanism in the carbon market, the need for robust data quality control is becoming increasingly critical.

To address these challenges, it is essential to further optimize the technical methods and monitoring approaches for carbon accounting. Improving scientific rigor and standardization in data collection processes while minimizing accounting errors will strengthen the credibility of China's carbon market. Detailed project-level data plays a pivotal role in supporting the development of more effective and targeted policies. For example, governments can tailor regulations to specific emission sources or adjust policies based on the performance of individual projects.

Carbon emission data serves as the foundation of carbon market trading, and its authenticity, accuracy, and scientific validity directly influence the fairness of carbon allowance allocations and the trust of stakeholders. Maintaining detailed and transparent project-level accounting and registration is indispensable for ensuring market integrity. Such practices are crucial to fostering confidence among regulators, investors, and the public, thereby sustaining the credibility and long-term development of China's carbon market.

From an international perspective, aligning project-level carbon accounting and registration with international standards is vital for promoting cooperation and compatibility within the global carbon market. Harmonizing standards enhances the transparency and reliability of carbon data, fostering greater international trust and facilitating fair carbon trading. Coordination and collaboration among nations are essential for achieving global emission reduction targets, and such alignment strengthens the foundation for collective action in the carbon market.

For China, as one of the largest greenhouse gas emitters globally, active participation in global climate governance is particularly significant. By adopting international standards and practices, China can enhance the maturity of its domestic carbon market, engage more effectively in global carbon market cooperation, and facilitate the exchange of technology and expertise. This approach not only strengthens China's position in international climate negotiations but also drives global carbon reduction efforts. Moreover, such collaboration enables China to access additional international financial and technical support, accelerating its green development and low-carbon transformation.

In summary, project-level GHG accounting and registration enhance the accuracy, transparency, and effectiveness of China's carbon market while ensuring alignment with global standards. These improvements foster innovation, strengthen market credibility, and support China's broader climate goals, positioning the country as a leader in advancing global carbon reduction initiatives.

6.2. General Discussion

This paper holds significant practical implications. As global climate change and environmental challenges intensify, coupled with the rapid growth of import and export trade under globalization, managing carbon emissions and promoting a green economy have become an international consensus. Against this backdrop, this study innovatively integrates the carbon trading mechanism with consumer preference theory, exploring its application in closed-loop supply chain management. It provides new perspectives and strategies for building a more environmentally friendly and efficient supply chain system. By incorporating carbon trading prices into the research framework of the closed-loop supply chain, this study conducts an in-depth analysis of the transmission mechanism of carbon costs across various supply chain segments and its influence on production decisions, emission reduction investments, and product pricing strategies of enterprises.

The findings suggest that governments should adopt differentiated carbon tariff policies by imposing higher tariff rates on high-carbon products to incentivize enterprises to increase investments in emission reduction, optimize production processes, and reduce greenhouse gas emissions. Such policies not only facilitate the green transformation of industries but also contribute to advancing a low-carbon economy in international trade. Additionally, this paper highlights the importance of considering cross-country differences in consumer preferences when formulating carbon tax policies. For countries with no distinct consumer preferences, arbitrarily increasing carbon tariffs may disrupt the trade market, undermining the healthy development of the global economy. Therefore, governments are advised to design flexible and precise carbon tax policies based on thorough research and analysis to effectively promote carbon reduction while ensuring fairness and stability in international trade.

This paper has certain limitations. The modeling process assumes that the ratio of unit carbon emissions between remanufactured and new products is a fixed constant β.

However, in practice, recycled products often vary in quality due to differences in condition, wear, and recycling time, leading to variations in technological methods, material inputs, and energy consumption during remanufacturing. As a result, the ratio of unit carbon emissions between remanufactured and new products is a dynamic variable rather than a fixed constant. Additionally, the calculation of carbon quota constraints in this study primarily focuses on carbon emissions during the production and remanufacturing stages, while emissions from transportation are excluded. However, in the context of globalization, long-distance transportation from production sites to consumption regions has become a significant source of carbon emissions. As a critical component of indirect carbon dioxide emissions, transportation-related emissions should be incorporated into the management of carbon allowances.

This paper also identifies directions for future research. Future studies could extend the analysis to include the logistics links in the supply chain, incorporating transportation emissions into the carbon allowance framework and exploring strategies to reduce transportation-related emissions. Additionally, dynamic carbon emission models could be established to account for the varying conditions of recycled products, allowing for a more accurate depiction of carbon footprints during the remanufacturing process. These advancements would facilitate the optimization of remanufacturing models, achieving a balance between environmental and economic objectives.

7. Conclusions

This paper examines the impact of carbon allowances, carbon trading, and dual-carbon policies on remanufacturing and marketing decisions within a multinational closed-loop supply chain, consisting of a single Original Equipment Manufacturer (OEM) from the exporting country and a single retailer from the EU importing country. Based on three consumer preference modes—no apparent preference, green preference, and purely new preference—and whether the OEM's carbon emissions exceed its carbon quota, the study constructs Stackelberg game models under six scenarios to explore how enterprises optimize profits under carbon taxes and quotas. The findings reveal significant influences of consumer preferences and carbon emissions on the optimal decision-making trends of both OEMs and retailers.

Our results are as follows: (1) Green preference mode: When the gap between domestic carbon taxes and carbon tariffs is small, manufacturers prefer to pay the tariff and offset the cost by raising prices. Conversely, when carbon tariffs exceed emission-reduction investment costs, manufacturers opt to invest in emission-reduction technologies to lower costs. (2) Purely new preference mode: A similar trend is observed in the green preference mode. (3) However, in the no apparent preference mode, OEMs adjust the ratio of new to remanufactured exports to partially evade carbon tariffs, with minimal impact on reduction investment decisions.

Regardless of consumer preferences, exceeding carbon quotas significantly increases unit costs due to the need to purchase additional emission rights. This incentivizes OEMs to invest more in reduction technologies to reduce costs and maintain competitiveness. Furthermore, the study demonstrates that manufacturers of high-carbon products subject to strict carbon policies are more likely to increase their reduction investments as unit emissions rise, thereby lowering product prices and expanding market share.

In conclusion, this research highlights the importance of identifying key parameters, such as consumer preferences, carbon taxes, and carbon quota constraints, in providing actionable guidance for remanufacturers to optimize supply chain strategies. It also underscores the critical influence of carbon policies on the management and competitiveness of cross-border supply chains.

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