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Operations of a Cross-Border Remanufacturing Supply Chain Under Carbon Tariffs and Cap-and-Trade Regulation

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Abstract

Cross-border remanufacturing trade is developing steadily. Carbon tariffs and carbon cap-and-trade regulation have emerged as two important instruments for carbon governance, yet their independent and combined effects on supply chain operations remain insufficiently discussed, which delivers supplementary analytical space for cross-border remanufacturing supply chain research. This paper examines a cross-border supply chain consisting of an exporting manufacturer and an importing retailer that distributes both new and remanufactured products. Four research scenarios are established: no regulation, carbon tariffs only, cap-and-trade only, and dual mixed regulation. Adopting a two-stage Stackelberg game, we analyze equilibrium pricing, production, and carbon abatement decisions, and further evaluate environmental performance and overall social welfare. Firms with different initial carbon emission levels respond differently to regulatory stringency. The results show that carbon tariffs reduce total emissions but erode corporate profits and social welfare, while cap-and-trade regulation can mitigate such adverse effects. When carbon tariffs are stringent and carbon quotas are sufficient, dual regulation improves all participants' profitability alongside better environmental quality and higher consumer surplus only within this paper's simplified analytical context. This study offers tentative operational references for remanufacturing firms and theoretical and analytical implications for governments to design compatible cross-border carbon regulatory systems.

Keywords: carbon tariffs; carbon cap-and-trade; remanufacturing production; cross-border supply chain

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1. Introduction

Industrialization and technological innovation have shortened product lifecycles, resulting in massive waste generation and growing greenhouse gas emissions [1,2]. The global volume of e-waste reached approximately 57 million metric tons in 2021 [3] and is projected to surge to 74.7 million metric tons by 2030 [4]. The Emissions Gap Report 2025 shows that global greenhouse gas emissions increased by 2.3% between 2023 and 2024, and a 26% global emission cut by 2030 is mandatory to cap temperature rise at 1.5 °C above pre-industrial levels [5]. Rising carbon emissions have induced severe environmental crises such as global warming, glacial retreat, and sea level rise [6], highlighting the urgent demand for global low-carbon governance.

To accelerate global carbon emission reduction, the 2022 United Nations Climate Change Conference issued the Sharm El-Sheikh Implementation Plan and established a dedicated Loss and Damage Fund to promote coordinated global climate governance [7]. Nevertheless, inconsistent national carbon abatement regulations and tax rates trigger cross-border production relocation, which causes severe carbon leakage and undermines the economic and environmental benefits of high-regulation countries [6]. As a balanced regulatory tool for climate governance and industrial competition, carbon tariffs represented by the Carbon Border Adjustment Mechanism (CBAM) have been widely applied to curb cross-border carbon leakage and protect domestic industrial competitiveness, evolving into a core environmental regulation for international trade [8,9].

Formally launched by the EU in April 2023, the CBAM requires emission reporting for imported products starting in October 2023 and will enforce official carbon tariff collection from 2026. It initially covers high-emission industries, including steel, aluminum, cement, and power sectors, with a continuous expansion of regulatory scope planned for the future [10]. Accordingly, carbon tariffs have become an essential factor that export manufacturing enterprises must consider in cross-border operational decisions.

Remanufacturing, as a key circular economy practice, delivers prominent low-carbon advantages. Relevant studies show that circular strategies effectively reduce industrial material consumption and carbon footprints by 30% [11], and remanufactured products can cut electricity consumption by 60% and air pollutant emissions by 80% compared with newly manufactured products [12,13]. Benefiting from improving public environmental awareness and governmental regulation support, the global remanufacturing industry has maintained steady growth, with market sales exceeding $150 billion as early as 2013 [14,15].

However, the implementation of carbon tariffs imposes additional cost burdens on exporting remanufacturing enterprises, squeezing corporate profits and hindering the sustainable development of cross-border remanufacturing. In this context, carbon cap-and-trade regulation serves as a vital supporting tool to help manufacturers balance emission abatement obligations and operational efficiency via quota allocation and market trading mechanisms [16]. Nevertheless, the uncertainty of initial carbon quota allocation brings decision-making complexity to firms' production, remanufacturing, and export strategies under increasingly stringent global carbon regulations.

Regarding carbon tariffs, carbon cap-and-trade systems, and remanufacturing supply chains, existing studies on carbon border tariffs have well elaborated how border carbon regulations affect firms' production, pricing, and emission abatement choices, and confirmed their role in curbing cross-border carbon leakage. Most literature related to cap-and-trade and remanufacturing, however, concentrates merely on the emission abatement performance of domestic carbon trading regulations [9,17]. They largely overlook whether exporting carbon market rules can alleviate the adverse impacts of carbon tariffs on cross-border supply chain operations. Accordingly, it remains unclear whether carbon cap-and-trade regulation in exporting countries can effectively offset the negative shocks brought by import-side carbon tariffs, an issue that requires in-depth and systematic exploration.

Existing studies commonly decouple importing carbon tariffs and exporting cap-and-trade regulation into two isolated analytical contexts. Carbon tariffs literature only focuses on exogenous cost shocks and carbon leakage suppression, ignoring that manufacturers can adjust domestic emission abatement behaviors and carbon quota strategies to respond to border regulatory pressure [6]. In parallel, cap-and-trade studies only discuss equilibrium decisions under domestic carbon quota constraints and fail to consider the extra cost penalties caused by cross-border carbon tariffs.

Furthermore, ordinary cross-border supply chain scenarios cannot reflect the unique operational attributes of remanufacturing systems. Different from traditional manufacturing, cross-border remanufacturing involves dual product categories, heterogeneous consumer quality preferences, and distinct carbon-emission characteristics. Such differences lead to unique regulatory adaptation strategies and carbon arbitrage risks under dual carbon constraints. Therefore, constructing a targeted cross-border remanufacturing framework is essential to accurately capture supply chain equilibrium changes and deliver refined regulatory implications.

Based on this research gap, this paper puts forward several core research questions.

(1) How do standalone carbon tariffs and cap-and-trade regulations affect carbon abatement decisions, product structure adjustment, and operational strategies of cross-border supply chain members?
(2) How do varying carbon tariffs and carbon quota levels influence the profit optimization decision adopted by supply chain members?
(3) What impacts do carbon regulations exert on carbon emissions, consumer surplus, and aggregate social welfare across cross-border trading markets?

To answer the above research questions, this paper further clarifies the research assumptions, research goal, and research objectives. In terms of basic assumptions, this study assumes a two-echelon cross-border remanufacturing supply chain consisting of one exporting manufacturer and one importing retailer. All participants are fully rational and pursue profit maximization. The manufacturer acts as the Stackelberg leader to determine abatement levels, production quantities, and wholesale prices, while the retailer acts as the follower to decide retail prices. In terms of its research goal, this study aims to reveal the independent and interactive mechanisms by which import-side carbon tariffs and export-side cap-and-trade regulations affect supply chain operational decisions, environmental performance, and social welfare. In terms of research objectives, this paper first derives equilibrium solutions under multiple regulatory scenarios, then compares the heterogeneous effects of single- and dual-carbon regulation, identifies the threshold-switching characteristics of firms' strategies, and finally proposes targeted operational and institutional suggestions.

We establish four analytical scenarios strictly consistent with our modeling setup: Scenario without carbon tariffs and cap-and-trade regulation, Scenario with carbon tariffs only, Scenario with cap-and-trade regulation only, and Scenario with carbon tariffs and cap-and-trade regulation. We derive Stackelberg game equilibria on pricing, production, and carbon abatement in each case, and then make cross-scenario comparisons on carbon-emission performance, consumer surplus, and social welfare.

This study expands research on cross-border remanufacturing supply chains and low-carbon governance. It embeds superimposed cross-border carbon regulatory constraints into a unified Stackelberg game framework tailored to cross-border remanufacturing systems. Few existing studies systematically examine the interactive mechanisms of dual cross-border carbon regulatory instruments, which constitute the main analytical focus of this work. Most prior literature only investigates one carbon regulation separately, and this paper presents three supplementary theoretical observations based on the simplified assumptions and preset parameters of our Stackelberg model. First, this work extends the applicable scenarios of Stackelberg game analysis within multi-layer, cross-border, low-carbon contexts. We construct an equilibrium model combining import carbon tariff regulation and export cap-and-trade regulation, and sort out the mutual incentive and restraint relationships between these two overlapping regulatory tools. Second, this paper offers supplementary analytical observations regarding firms' operational choices under dual carbon regulation. We capture multi-level threshold traits linked to manufacturers'

initial carbon emission intensity. Equilibrium outcomes from single-regulation models tend to show monotonic trends. By contrast, dual overlapping regulatory constraints bring about regime switching and non-monotonic changes in abatement investment, product pricing, and remanufacturing output mix, which complements the comparative analysis framework for low-carbon remanufacturing supply chains under this model setup. Third, we establish four separate regulatory scenarios to compare firms' operational strategies, environmental performance, and social welfare in a consistent manner. This paper constructs a refined analytical framework for evaluating coordinated cross-border low-carbon governance and provides scenario-specific analytical logic to assess mixed carbon regulatory portfolios within our modeling context. Beyond these theoretical observations, the model generates context-bound practical references. We summarize targeted low-carbon production and remanufacturing suggestions for export manufacturers affected by dual-carbon constraints, and provide tentative regulation references for regulators to design matched cross-border carbon regulatory schemes.

The remainder of this paper is organized as follows. Section 2 reviews the literature on remanufacturing supply chains for carbon abatement and cross-border supply chains under carbon regulations. Section 3 specifies the problem description and assumptions. Section 4 derives the equilibrium solutions for the decision variables of supply chain players under various scenarios. Section 5 conducts numerical analysis, including profit-comparison simulations and parameter-impact analysis on consumer surplus, social welfare, and environmental performance. Section 6 concludes with key research outcomes, puts forward targeted managerial suggestions, summarizes research limitations, and prospects future extended exploration directions.

2. Literature Review

This study investigates cross-border supply chain management in the context of carbon tariffs. To systematically review the research status and identify existing research gaps, we classify the relevant literature into three interconnected research streams: (i) decision-making in remanufacturing supply chains considering carbon emission abatement; (ii) supply chain operations and management under government regulations; (iii) operational decision-making in cross-border supply chains.

2.1. Decision-Making in Remanufacturing Supply Chains Considering Carbon Emission Abatement

Most existing research on carbon-constrained remanufacturing supply chains remains confined to closed domestic industrial scenarios, with few papers exploring the interactive coupling of importing carbon tariffs and exporting carbon cap-and-trade regulations within cross-border dual-product frameworks. Against this research background, abundant literature has analyzed manufacturers' remanufacturing and emission reduction strategies under single or hybrid domestic carbon regulations, thereby forming two core research branches.

In terms of single-carbon regulatory scenarios, prior studies have clarified the differentiated incentive mechanisms of carbon tax and cap-and-trade regulation on green production. Luo [18] revealed that properly designed carbon tax regulation effectively motivates manufacturers to upgrade abatement technologies and expand remanufacturing scale, while excessively stringent tax settings may conversely suppress remanufacturing incentives. Similarly, cap-and-trade regulation is widely verified as an efficient low-carbon governance tool that promotes corporate green investment and encourages OEMs to participate in remanufacturing market competition [19,20]. Such studies uniformly confirm the positive abatement value of standalone carbon regulation, yet they mainly focus on isolated regulatory tools without discussing potential superposition effects when multiple cross-border carbon constraints coexist.

With the improvement of domestic low-carbon governance systems, several studies have further explored remanufacturing operational behaviors under multiple domestic carbon regulatory combinations. Lu [21] indicated that increased carbon prices and regulatory stringency may trigger differentiated emission changes across supply chain participants. Huang [16] comparatively verified that hybrid carbon regulation generally outperforms single regulation in environmental governance. Targeting power battery remanufacturing systems, Wang [17] adopted multi-scenario game models to analyze the influence of carbon price volatility on remanufacturing decisions. Beyond traditional domestic carbon rules, Li et al. [22] further pointed out that differentiated carbon constraints for new and remanufactured products can restructure manufacturers' optimal remanufacturing layouts.

Taken together, this strand of literature fully explains how domestic carbon regulations shape remanufacturing and abatement decisions. However, the analytical boundaries of these works do not extend to cross-border supply chains with importing carbon tariff constraints, and the threshold-dependent, non-monotonic operational effects brought by dual overlapping cross-border carbon regulations have not been fully discussed in existing remanufacturing research.

2.2. Supply Chain Operations and Management Under Government Regulations

While EU CBAM has raised widespread concerns about the economic losses and industrial distortions caused by unilateral border carbon tariffs, existing relevant research forms two parallel analytical branches that separately evaluate the emission-reduction benefits and economic side effects of border carbon regulations, yet rarely integrate exporting carbon trading mechanisms into a unified cross-border research framework.

In terms of environmental governance effectiveness, most studies support the positive role of carbon tariffs in mitigating global carbon leakage. Larch and Wanner [23] verified that border carbon regulation restructures cross-border production layouts and restrains transnational emission transfer behaviors. Zhou et al. [6] further confirmed that carbon tariff constraints effectively reduce cross-border carbon emissions and optimize global emission distribution. These studies collectively validate the necessity of border carbon regulation for global low-carbon transition, yet they mostly treat carbon tariffs as unilateral exogenous constraints and ignore the coordinating adjustment role of domestic carbon quota instruments.

From a critical perspective of economic cost and regulatory defects, recent papers have uncovered inherent limitations of standalone carbon tariffs. Even under tariff constraints, partial carbon leakage still persists, and corporate production adjustments cannot completely eliminate global incremental emissions [24]. More importantly, asymmetric cross-border regulatory stringency may induce strategic emission rebound in low-regulation regions, further weakening global abatement efficiency [25]. From the perspective of economic welfare loss, carbon tariffs significantly raise the market entry threshold for export-oriented manufacturers and compress the profit space of cross-border supply chains, thereby damaging global social welfare to a certain extent [26].

A small number of scholars have attempted to offset the negative economic impacts of border tariffs via domestic carbon regulatory design. Zhu et al. [27] proved that differentiated domestic carbon regulation can balance emission reduction and economic stability, whereas unified regulatory settings fail to achieve such dual optimization. Nevertheless, relevant studies, including Wang et al. [28] only focus on domestic carbon tax or cap-and-trade systems in isolation, without constructing a coordinated analytical framework combining external carbon tariffs and domestic carbon trading regulation.

In summary, existing literature has fully identified the dual attributes of carbon border regulation: environmental emission-reduction advantages and potential economic

distortions. However, most scholars treat carbon tariffs and domestic carbon markets as two distinct research objects, and few systematically analyze how domestic carbon quotas buffer or hedge the cost shocks brought by cross-border carbon tariffs.

2.3. Operational Decision-Making in Cross-Border Supply Chains

The unequal cost burdens and distorted industrial competition caused by unilateral border carbon rules have become a core controversial topic in global cross-border supply chain research. Existing papers have thoroughly discussed how border carbon tariffs reshape corporate operational strategies and global emission distribution, yet few studies integrate remanufacturing dual-product operational characteristics and domestic carbon quota mechanisms into cross-border regulatory game analysis.

One dominant research strand investigates heterogeneous operational reactions of export manufacturers to fixed border carbon tariff pressures. Li et al. [29] comparatively analyzed the carbon tax and carbon tariff regulations, and pointed out that high-stringency carbon tariffs lack sustainable industrial governance capacity and may destabilize cross-border product operation systems, while domestic carbon regulation presents more stable abatement incentives. Wu et al. [30] further revealed the negative regulatory interaction between cross-border tariffs and domestic environmental strategies, demonstrating that stringent import carbon tariffs may induce exporting economies to relax domestic regulatory intensity, resulting in distorted global abatement effects. Weng et al. [31] quantified the severe negative impacts of CBAM carbon tariffs on China's energy-intensive export sectors, and verified that low-carbon technological transformation can effectively offset the profit compression caused by unilateral carbon border rules. Shen et al. [32] highlights that exporters bear the full carbon tariff burdens under CBAM, while upstream supply sides lack proactive mitigation incentives, which further motivates our analysis of dual-carbon regulatory coordination in cross-border remanufacturing supply chains.

Another research branch systematically discusses the institutional fairness defects in unilateral border carbon regulation. Li et al. [33] indicated that asymmetric cross-border regulatory intensity leads to unbalanced operational burdens for export enterprises. Although export-side cap-and-trade regulation can improve regulatory fairness to a certain degree, it may weaken the governance efficiency of import carbon tariffs. Similarly, Li et al. [34] confirmed that unilateral border carbon regulation only produces localized emission reduction effects and cannot fundamentally resolve global carbon leakage problems, reflecting the inherent limitations of single-border regulatory tools. Thivierge [35] further confirms that upstream carbon tariffs under unilateral border carbon rules will trigger downstream carbon leakage via industrial input-output linkages, partially offsetting the emission-reduction effects of import carbon tariffs.

Overall, existing cross-border supply chain literature has clarified the operational and environmental impacts of unilateral carbon tariffs and briefly touched on the correlation between border regulations and domestic low-carbon production. However, prior research rarely embeds remanufacturing decision optimization into dual cross-border carbon regulatory scenarios, and the joint, interactive influence of importing carbon tariffs and exporting carbon quotas on transnational remanufacturing supply chains remains insufficiently explored.

2.4. Research Review and Research Gaps

Synthesizing the above three literature streams, existing studies have established basic analytical frameworks for remanufacturing low-carbon decisions, carbon tariff governance mechanisms, and cross-border supply chain operational responses. Nevertheless, current research still presents obvious fragmentation and marginal deficiencies in scenario integra-

tion, regulatory interaction, and research perspectives, which further highlight the necessity and innovation of this study.

First, most existing studies discuss domestic remanufacturing abatement regulation and cross-border carbon tariff independently, failing to construct a unified transnational analytical framework. Second, prior literature mainly focuses on the governance effects of single regulatory tools, lacking systematic comparative analysis and interactive mechanism exploration under the joint superposition of importing carbon tariffs and exporting cap-and-trade regulation. Third, existing research cannot sufficiently explain how dual cross-border regulation reshapes the remanufacturing product structure, threshold abatement behaviors, and differentiated social welfare distribution.

To fill the above research gaps, this study constructs four comparative regulatory scenarios to systematically explore the independent and joint impacts of a carbon tariff and cap-and-trade regulation on cross-border remanufacturing supply chain equilibrium decisions, environmental emission performance, and transnational social welfare. The research findings complement existing literature by revealing the threshold interaction characteristics of dual cross-border carbon regulation and providing targeted operational and regulatory implications for transnational remanufacturing low-carbon governance. To clarify the research gaps between existing studies and this paper, we systematically compare representative literature from three dimensions: model framework settings, carbon regulatory instruments, and core research outcomes, as summarized in Table 1.

Table 1. Literature comparison.

Literature	Carbon Regulatory Instruments	Cross-Border Supply Chain	Remanufacturing Included	Joint Interaction of Carbon Tariff and Carbon Cap-and-Trade	Main Conclusions
Li et al. [29]	Domestic carbon cap-and-trade only	No (domestic only)	Yes	Not involved	Carbon trading strengthens emission abatement and remanufacturing incentives.
Zhou et al. [6]	Importing carbon tariff only	Yes	No	Not involved	Strict carbon tariffs reduce the exporting quantity and the manufacturer's profit.
Wang et al. [28]	Domestic carbon trading + domestic carbon tax	No (domestic only)	Yes	Not involved (no cross-border tariff)	Mixed domestic carbon regulations optimize the proportion of remanufactured products.
Zhang et al. [36]	Importing carbon tariff and exporting carbon quota (no carbon trading)	Yes	No	Not involved (no carbon trading mechanism)	Carbon tariffs reshape manufacturers' overseas production layout.
Liu et al. [37]	Exporting carbon cap-and-trade only	Yes	No	Not involved (no importing carbon tariffs)	Carbon trading raises exporting costs and promotes emission abatement.
This paper	Exporting carbon cap-and-trade and importing carbon tariff (dual cross-border regulations)	Yes	Yes	Jointly considered	The interaction of dual regulations alters optimal abatement, remanufacturing, and exporting decisions.

3. Problem Description and Assumptions

We consider a cross-border supply chain (CBSC), as depicted in Figure 1, consisting of a manufacturer from an exporting country and a retailer from an importing country, which are abbreviated as the exporting manufacturer and the importing retailer, respectively. In this cross-border trade, to reduce the country's carbon emissions, the importing country imposes carbon tariffs on imported products; thus, the exporting manufacturer invests in carbon emissions abatement during the production of new and remanufactured products. The importing retailer wholesales these two types of products and sells them to consumers. In order to control carbon emissions and mitigate the impact of carbon tariffs, the exporting country sets carbon emissions limits for the exporting manufacturer and establishes a carbon trading market, encouraging the exporting manufacturer to reduce carbon emissions and allowing them to trade the portion of emissions that are below the carbon emissions limits, namely, implementing a cap-and-trade regulation. The core research assumptions

are that the superimposition of carbon tariffs and cap-and-trade regulation will generate threshold effects on the manufacturer's abatement investment, product mix, and total carbon emissions. To verify this conjecture, we build four game models for comparative analysis. To explore the interactive effects of the carbon tariffs and cap-and-trade regulation on the decisions of CBSC members, we first construct a benchmark scenario without carbon tariffs and cap-and-trade regulation (model NN). Then, we found two scenarios: one implementing carbon tariffs only (model CN) and another implementing cap-and-trade regulation only (model NT). Finally, we develop a scenario in which carbon tariffs and cap-and-trade regulations are simultaneously implemented (model CT). In the four models of CBSC, the exporting manufacturer and the importing retailer play a manufacturer-dominant Stackelberg game.

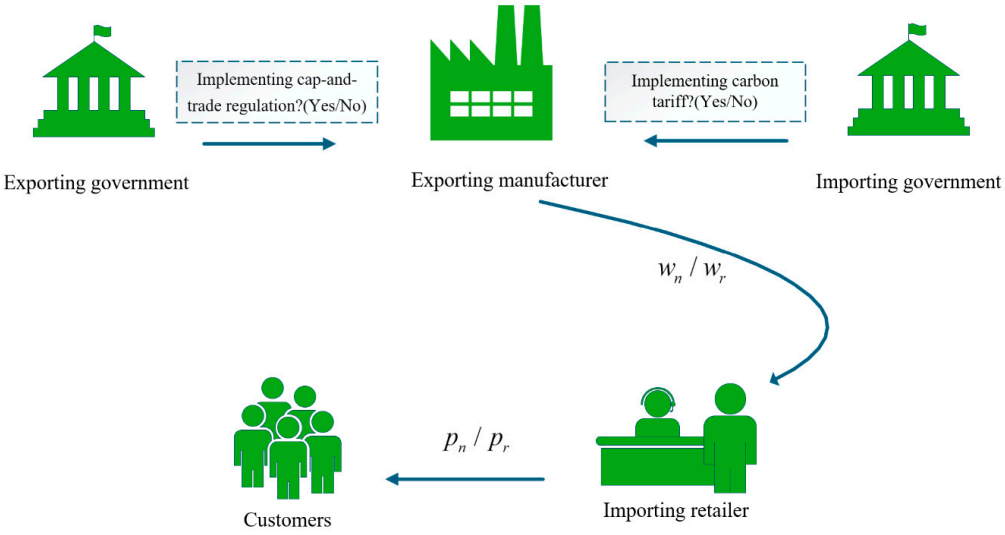


Figure 1. Decision framework diagram.

The relevant parameters used in this study are shown in Table 2 below.

Table 2. Description of reference notations.

Notations	Definitions
θ	Consumer willingness to pay for new products
δ	Consumer value discount for remanufactured products
β	The ratio of unit carbon emissions from remanufactured products to unit carbon emissions generated by new products
$e_n / \beta e_n$	Unit initial carbon emissions of new/remanufactured products
b	Carbon trading price
λ	Carbon emissions abatement cost coefficient of the exporting manufacturer
h	Unit carbon quota
f	Unit tariff rate imposed by the importing country on the carbon emissions of products
c_n / c_r	Unit production cost of new/remanufactured products
c	Unit cost savings per remanufactured product
e^i	Carbon abatement level in the model i, $i \in \{NN, CN, NT, CT\}$
w_n^i / w_r^i	Wholesale price for new/remanufactured products in the model i, $i \in \{NN, CN, NT, CT\}$
p_n^i / p_r^i	Sales price for new/remanufactured products in the model i, $i \in \{NN, CN, NT, CT\}$
q_n^i / q_r^i	Market demand for new products/remanufactured products in the model i, $i \in \{NN, CN, NT, CT\}$
π_M^i	Exporting the manufacturer's profit in the model i, $i \in \{NN, CN, NT, CT\}$
π_R^i	Importing the retailer's profit into the model i, $i \in \{NN, CN, NT, CT\}$
CS^i	Consumer surplus in the model i, $i \in \{NN, CN, NT, CT\}$
SW^i	Overall social welfare under the model i, $i \in \{NN, CN, NT, CT\}$

To make the research feasible, we propose the following assumptions, drawing on existing studies and practical experience.

Following the mainstream modeling framework of existing remanufacturing supply chain game research, we adopt a linear demand function to characterize market demand. This classic linear specification can clearly capture price sensitivity and keep the Stackelberg game analytically tractable, which has been widely used in the remanufacturing decision literature under carbon regulatory constraints. We set up a supply chain consisting of one manufacturer and one retailer. This simplified two-echelon structure enables us to concentrate on the manufacturer's remanufacturing mode selection and emission abatement decisions, eliminating the interference caused by multi-member horizontal competition. This single-chain structure is commonly adopted in transnational low-carbon supply chain models.

Consistent with prior remanufacturing studies, we fix the cost difference between new products and remanufactured products. Such cost-homogeneity settings ensure that we can concentrate our analysis on the impacts of cross-border carbon regulations rather than production cost heterogeneity. We use a fixed consumer preference structure for remanufactured goods. This stable preference setting helps us isolate the regulatory effect and avoid mixing preference shocks with carbon regulatory shocks, which conforms to the research design of most remanufacturing supply chain equilibrium papers.

Assumption 1. *The total market size is normalized to 1 for analytical convenience* [8,38]. *Since remanufactured products are usually inferior to new products in terms of appearance and functionality, consumers' willingness to pay for new and remanufactured products is denoted by* θ *and* $\delta\theta$ *respectively. Here,* θ *is uniformly distributed over* $[0,1]$*, and* δ *(*$0 < \delta < 1$*) represents the relative valuation discount of remanufactured products compared with new ones* [6]. *Therefore, the utility functions for purchasing new and remanufactured products are expressed as* $U_n = \theta - p_n$ *and* $U_r = \delta\theta - p_r$*, respectively* [16,28,29].

Consumers will purchase the new product only if $U_n \geq U_r$ and $U_n > 0$, and they will purchase the remanufactured product only if $U_r \geq U_n$ and $U_r > 0$. Otherwise, consumers will not purchase any product. Based on consumers' utility-maximizing behavior, the corresponding demand functions for new and remanufactured products are denoted by $q_n = 1 - \frac{p_n - p_r}{1-\delta}$ and $q_r = \frac{\delta p_n - p_r}{\delta(1-\delta)}$, respectively.

Assumption 2. *Consistent with existing studies* [29] *it is assumed that the unit production cost of new products is higher than that of remanufactured products, i.e.,* $c_n > c_r > 0$*. We denote* $c = c_n - c_r$ *to describe the unit cost saved in producing remanufactured products. For the purpose of simplifying calculations, we assume* $c_r = 0$*, thus* $c_n = c$ [37].

Assumption 3. *Following Li et al.* [22] *and Li et al.* [29]*, under the carbon emissions abatement efforts of the exporting manufacturer, the unit carbon emissions of new and remanufactured products become* $e_n - e$ *and* $\beta e_n - e$*, respectively. The cost of carbon abatement for the exporting manufacturer is a convex function of carbon abatement level, i.e.,* $\frac{1}{2}\lambda e^2$ [36,39,40]. *Moreover, in order to motivate the exporting manufacturer to invest in carbon emissions abatement, it is assumed that* $0 < \beta < \delta < 1$ [6].

Assumption 4. *To incentivize carbon emission abatement, the exporting government allocates a unit carbon quota* h *to the exporting manufacturer, where* $0 < h$ [6]. *We also focus on the case of* $(f+b)^2 < 4\lambda\delta$ *and* $e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta + bh}{\beta(f+b)}\}$.

4. Model Constructions

In this part, we explore the equilibrium outcomes for the four models. For ease of analysis, we denote $\phi_1 = 1 + \delta + c$, $\phi_2 = 1 - \delta - c$ and $\psi = (1 - \beta)e_n$.

4.1. Scenario Without Carbon Tariffs and Cap-and-Trade Regulation (Model NN)

In the model NN, the importing country does not impose carbon tariffs, and the exporting country does not implement cap-and-trade regulation. The exporting manufacturer first determines the wholesale prices for two types of products and the carbon abatement level. Subsequently, the importing retailer sets the retail prices. The optimization problem is given as

$$\max_{w_n^{NN}, w_r^{NN}, e^{NN}} \pi_M^{NN} = (w_n^{NN} - c)q_n^{NN} + w_r^{NN} q_r^{NN} - \frac{1}{2}\lambda e^{NN^2}, \tag{1}$$

$$s.t. \max_{p_n^{NN}, p_r^{NN}} \pi_R^{NN} = (p_n^{NN} - w_n^{NN})q_n^{NN} + (p_r^{NN} - w_r^{NN})q_r^{NN}. \tag{2}$$

By using backward induction to solve the problem of the model NN, the optimal equilibrium outcomes are presented in Table 3.

Table 3. Optimal equilibrium results in the model NN.

Notations	Equilibrium Results
w_n^{NN*}	$\frac{1+c}{2}$
w_r^{NN*}	$\frac{\delta}{2}$
p_n^{NN*}	$\frac{3+c}{4}$
p_r^{NN*}	$\frac{3\delta}{4}$
e^{NN*}	0
q_n^{NN*}	$\frac{1-\delta-c}{4(1-\delta)}$
q_r^{NN*}	$\frac{c}{4(1-\delta)}$
π_M^{NN*}	$\frac{(1-\delta)(1-2c)+c^2}{8(1-\delta)}$
π_R^{NN*}	$\frac{(1-\delta)(1-2c)+c^2}{16(1-\delta)}$

Proof. See Appendix A. □

To ensure the validity of our analysis, the optimal value must satisfy the following conditions: $0 < \delta < 1$, $e^{NN*} \geq 0$, $e^{NN*} \leq \beta e_n$, $w_n^{NN*} \geq c + f(e_n - e^{NN*})$, $w_r^{NN*} \geq f(\beta e_n - e^{NN*})$, $p_n^{NN*} \geq w_n^{NN*}$, $p_r^{NN*} \geq w_r^{NN*}$, $q_n^{NN*} = 1 - \frac{p_n^{NN*} - p_r^{NN*}}{1-\delta} \geq 0$, and $q_r^{NN*} = \frac{\delta p_n^{NN*} - p_r^{NN*}}{\delta(1-\delta)} \geq 0$.

4.2. Scenario with Only Carbon Tariffs (Model CN)

In the model CN the importing country unilaterally announces a carbon tariff rate f on unit carbon emissions from imported products. The exporting country does not implement a cap-and-trade regulation. The exporting manufacturer first decides the wholesale prices and the carbon abatement level, and then the importing retailer determines the retail prices. The optimization problem is given as

$$\max_{w_n^{CN}, w_r^{CN}, e^{CN}} \pi_M^{CN} = (w_n^{CN} - c)q_n^{CN} + w_r^{CN} q_r^{CN} - f((e_n - e^{CN})q_n^{CN} + (\beta e_n - e^{CN})q_r^{CN}) - \frac{1}{2}\lambda e^{CN^2}, \tag{3}$$

$$s.t. \max_{p_n^{CN}, p_r^{CN}} \pi_R^{CN} = (p_n^{CN} - w_n^{CN})q_n^{CN} + (p_r^{CN} - w_r^{CN})q_r^{CN}. \tag{4}$$

By using backward induction to solve the problem of the model CN, the optimal equilibrium outcomes are presented in Table 4.

Table 4. Optimal equilibrium results in the model CN.

Notations	Equilibrium Results
w_n^{CN*}	$\frac{4\lambda\delta(1+c+fe_n)-f^2(\phi_1+f\psi)}{2(4\lambda\delta-f^2)}$
w_r^{CN*}	$\frac{\delta(2\lambda(\delta+\beta fe_n)-f^2)}{4\lambda\delta-f^2}$
p_n^{CN*}	$\frac{4\lambda\delta(3+c+fe_n)-f^2(2+\phi_1+f\psi)}{4(4\lambda\delta-f^2)}$
p_r^{CN*}	$\frac{\delta(\lambda(3\delta+\beta fe_n)-f^2)}{4\lambda\delta-f^2}$
e^{CN*}	$\frac{f(\delta-\beta fe_n)}{4\lambda\delta-f^2}$
q_n^{CN*}	$\frac{\phi_2-f\psi}{4(1-\delta)}$
q_r^{CN*}	$\frac{4\lambda(\delta c+\delta fe_n-\beta fe_n)-f^2(\phi_2-f\psi)}{4(1-\delta)(4\lambda\delta-f^2)}$
π_M^{CN*}	$\frac{4\lambda\left(\delta((1-\delta)(1-2c)+c^2\right)-2\delta(\phi_2+\beta c)fe_n+\left(\delta+\beta^2-2\delta\beta\right)f^2{e_n}^2\right)-f^2(\phi_2-f\psi)^2}{8(1-\delta)(4\lambda\delta-f^2)}$
π_R^{CN*}	$\frac{16\lambda^2\delta\left(\delta((1-\delta)(1-2c)+c^2\right)-2(\phi_2+\beta)c)fe_n+\left(\delta+\beta^2-2\delta\beta\right)f^2{e_n}^2\right)-(8\lambda\delta-f^2)f^2(\phi_2-f\psi)^2}{16(1-\delta)(4\lambda\delta-f^2)^2}$

Proof. See Appendix B. □

To ensure the validity of our analysis, the optimal value must satisfy the following conditions: $f^2 < 4\lambda\delta$, $e^{CN*} \geq 0$, $e^{CN*} \leq \beta e_n$, $w_n^{CN*} \geq c + f(e_n - e^{CN*})$, $w_r^{CN*} \geq f(\beta e_n - e^{CN*})$, $p_n^{CN*} \geq w_n^{CN*}$, $p_r^{CN*} \geq w_r^{CN*}$, $q_n^{CN*} = 1 - \frac{p_n^{CN*} - p_r^{CN*}}{1-\delta} \geq 0$, and $q_r^{CN*} = \frac{\delta p_n^{C*N} - p_r^{CN*}}{\delta(1-\delta)} \geq 0$.

4.3. Scenario with Only Cap-and-Trade Regulation (Model NT)

In this model NT, the exporting country unilaterally allocates a carbon quota h for the unit product to the exporting manufacturer. The exporting manufacturer can purchase carbon emissions allowances exceeding its carbon quota from the carbon market, or sell surplus carbon quotas in the carbon market to obtain additional profits, with the unit carbon trading price b in the carbon market. On the premise of being informed of the carbon quota, the exporting manufacturer first determines the wholesale prices of new and remanufactured products, as well as the carbon abatement level; subsequently, the importing retailer decides on the retail prices. The optimization problem is given as

$$\max_{w_n^{NT}, w_r^{NT}, e^{NT}} \pi_M^{NT} = (w_n^{NT} - c)q_n^{NT} + w_r^{NT} q_r^{NT} - \frac{1}{2}\lambda {e^{NT}}^2 + b((h - (e_n - e^{NT}))q_n^{NT} + (h - (\beta e_n - e^{NT}))q_r^{NT}), \quad (5)$$

$$s.t. \max_{p_n^{NT}, p_r^{NT}} \pi_R^{NT} = (p_n^{NT} - w_n^{NT})q_n^{NT} + (p_r^{NT} - w_r^{NT})q_r^{NT}. \quad (6)$$

Using backward induction to solve the problem of the model NT, we denote $F_1 = \delta^2(2c + 2be_n - 2bh - 1) + b^2(h - e_n\beta)^2$ and $F_2 = 1 + c^2 - 2c(1 - be_n + \beta be_n)$, and derive the optimal equilibrium outcomes, which are presented in the following Table 5.

Table 5. Optimal equilibrium results in the model NT.

Notations	Equilibrium Results
w_n^{NT*}	$\frac{4\delta(1+c+be_n-bh)\lambda-b^2(\phi_1+b\psi)}{2(4\delta\lambda-b^2)}$
w_r^{NT*}	$\frac{\delta(2\lambda(\delta+\beta be_n-bh)-b^2)}{4\delta\lambda-b^2}$
p_n^{NT*}	$\frac{4\delta(3+c+be_n-bh)\lambda-b^2(\phi_1+b\psi)}{4(4\delta\lambda-b^2)}$

Table 5. *Cont.*

Notations	Equilibrium Results
p_r^{NT*}	$\frac{\delta(3\delta\lambda+\beta\lambda be_n-b^2-bh)}{4\delta\lambda-b^2}$
e^{NT*}	$\frac{b(\delta-\beta be_n+bh)}{4\delta\lambda-b^2}$
q_n^{NT*}	$\frac{\phi_2-b\psi}{4(1-\delta)}$
q_r^{NT*}	$\frac{4(\delta c+b(\delta e_n+h-\delta h-\beta e_n))\lambda+\phi_2-b\psi}{4(1-\delta)(4\delta\lambda-b^2)}$
π_M^{NT}	$\frac{4(F_1+\delta(F_2-b(2-(1-2\beta)be_n-bh)(e_n-h)))\lambda-b^2(\phi_2-b\psi)^2}{8(1-\delta)(4\delta\lambda-b^2)}$
π_R^{NT}	$\frac{16\delta(F_1+\delta(F_2-b(e_n-h)(2-b(1-2\beta)(e_n-h))))\lambda^2-(8b^2\delta\lambda-b^4)(\phi_2-b\psi)^2}{16(1-\delta)(4\delta\lambda-b^2)^2}$

Proof. See Appendix C. □

To ensure the validity of our analysis, the optimal value must satisfy the following conditions: $b^2 < 4\lambda\delta$, $e^{NT*} \geq 0$, $e^{NT*} \leq \beta e_n$, $w_n^{NT*} \geq c$, $w_r^{NT*} \geq 0$, $p_n^{NT*} \geq w_n^{NT*}$, $p_r^{NT*} \geq w_r^{NT*}$, $q_n^{NT*} = 1 - \frac{p_n^{NT*}-p_r^{NT*}}{1-\delta} \geq 0$, and $q_r^{NT*} = \frac{\delta p_n^{NT*}-p_r^{NT*}}{\delta(1-\delta)} \geq 0$.

4.4. Scenario with Carbon Tariffs and Cap-and-Trade Regulation (Model CT)

In this model CT the importing country announces carbon tariff rates f for carbon emissions from imported products, while the exporting country allocates a carbon quota h for the unit product to the exporting manufacturer. The exporting manufacturer can purchase additional emissions rights from the carbon market to cover excess emissions beyond its allocated quotas, or sell surplus quotas to generate extra profits at a carbon trading price b. In this CBSC, the exporting manufacturer determines the wholesale prices for new and remanufactured products, along with their respective carbon abatement level. Subsequently, the importing retailer sets the retail prices. The optimization problem is given as

$$\max_{w_n^{CT},w_r^{CT},e^{CT}} \pi_M^{CT} = (w_n^{CT} - c - f(e_n - e^{CT}))q_n^{CT} + (w_r^{CT} - f(\beta e_n - e^{CT}))q_r^{CT} - \frac{1}{2}\lambda e^{CT^2}, \\ +b(h - (e_n - e^{CT}))q_n^{CT} + b(h - (\beta e_n - e^{CT}))q_r^{CT} \tag{7}$$

$$s.t. \max_{p_n^{CT},p_r^{CT}} \pi_R^{CT} = (p_n^{CT} - w_n^{CT})q_n^{CT} + (p_r^{CT} - w_r^{CT})q_r^{CT}. \tag{8}$$

Using backward induction to solve the problem of the model CT, and derive the optimal equilibrium outcomes, which are presented in the following Table 6.

Table 6. Optimal equilibrium results in the model CT.

Notations	Equilibrium Results
w_n^{CT*}	$\frac{4\lambda\delta(1+c+(f+b)e_n-bh)-(f+b)^2(\phi_1+(f+b)\psi)}{2(4\lambda\delta-(f+b)^2)}$
w_r^{CT*}	$\frac{\delta(2\lambda(\delta+\beta(f+b)e_n-bh)-(f+b)^2)}{4\lambda\delta-(f+b)^2}$
e^{CT*}	$\frac{(f+b)(\delta-\beta(f+b)e_n+bh)}{4\lambda\delta-(f+b)^2}$
p_n^{CT*}	$\frac{4\lambda\delta(3+c+(f+b)e_n-bh)-(f+b)^2(2+\phi_1+(f+b)\psi)}{4(4\lambda\delta-(f+b)^2)}$
p_r^{CT*}	$\frac{\lambda\delta(3\delta+\beta(b+f)e_n-bh)-\delta(b+f)^2}{4\lambda\delta-(b+f)^2}$
q_n^{CT*}	$\frac{\phi_2-(f+b)\psi}{4(1-\delta)}$

Table 6. *Cont.*

Notations	Equilibrium Results
q_r^{CT*}	$\frac{4\lambda(\delta c+(\delta-\beta)(f+b)e_n+(1-\delta)bh)+(f+b)^2(1-\delta-c-(1-\beta)(f+b)e_n)}{4(1-\delta)(4\lambda\delta-(f+b)^2)}$
π_M^{CT*}	$\frac{(1-\beta)^2e_n{}^2b^4+F_3-f^2(\phi_1+f\psi)^2-4\lambda F_4-8bF_5+b^2F_6}{8(1-\delta)(4\delta\lambda-(b+f)^2)}$
π_R^{CT*}	$\frac{(e_n(1-\beta)(b+f)-\phi_2)((b+f)^2-4\delta\lambda)F_7+4\delta\lambda(\delta-\beta e_n(b+f)+bh)F_8}{16(1-\delta)(4\delta\lambda-(b+f)^2)^2}$

Proof. See Appendix D. Note: The auxiliary composite terms F_3–F_8 adopted in the profit expressions are fully defined at the beginning of Appendix D. □

To ensure the validity of our analysis, the optimal value must satisfy the following conditions: $(f+b)^2 < 4\lambda\delta$, $e^{CT*} \geq 0$, $e^{CT*} \leq \beta e_n$, $w_n^{CT*} \geq c + f(e_n - e^{CT*})$, $w_r^{CT*} \geq f(\beta e_n - e^{CT*})$, $p_n^{CT*} \geq w_n^{CT*}$, $p_r^{CT*} \geq w_r^{CT*}$, $q_n^{CT*} = 1 - \frac{p_n^{CT*}-p_r^{CT*}}{1-\delta} \geq 0$, and $q_r^{CT*} = \frac{\delta p_n^{CT*}-p_r^{CT*}}{\delta(1-\delta)} \geq 0$.

5. Comparative Analysis

5.1. Sensitivity Analysis

$\bar{e}_1 - \bar{e}_{14}$ are critical thresholds of e_n. All subsequent interpretations are consistent with the analytical inequalities. Analyzing the effect of the carbon tariff rate f on the optimal decisions of CBSC members in the model CN, we denote $\bar{e}_1 = \frac{8\lambda\delta^2 f}{(4\lambda\delta-f^2)^2+\beta f^2(12\lambda\delta-f^2)}$ and $\bar{e}_2 = \frac{2\delta f}{\beta(4\lambda\delta+f^2)}$, and derive the following proposition 1.

Proposition 1. *The optimal decisions in the equilibrium outcomes under the model CN satisfy*

(1) if $\bar{e}_1 < e_n < \frac{\delta}{\beta f}$, then $\frac{\partial w_n^{CN*}}{\partial f} > \frac{\partial p_n^{CN*}}{\partial f} > 0$; otherwise, $\frac{\partial w_n^{CN*}}{\partial f} \leq \frac{\partial p_n^{CN*}}{\partial f} \leq 0$;

(2) if $\bar{e}_2 < e_n < \frac{\delta}{\beta f}$, then $\frac{\partial w_r^{CN*}}{\partial f} > \frac{\partial p_r^{CN*}}{\partial f} > 0$; otherwise $\frac{\partial w_r^{CN*}}{\partial f} \leq \frac{\partial p_r^{CN*}}{\partial f} \leq 0$;

(3) if $e_n < \frac{4\lambda\delta+f^2}{8\lambda\beta f}$, then $\frac{\partial e^{CN*}}{\partial f} > 0$; otherwise $\frac{\partial e^{CN*}}{\partial f} \leq 0$.

Proof. See Appendix E. □

Proposition 1 (1) and (2) indicate that when the initial carbon emission level is larger than a certain threshold, with the increase of the carbon tariff rate f, the exporting manufacturer and the importing retailer would raise the wholesale and retail prices of new and remanufactured products. These two distinct critical thresholds are $\bar{e}_1$ for new products and $\bar{e}_2$ for remanufactured products, which divide emission ranges to distinguish whether tariff cost pass-through occurs. In practice, $\bar{e}_1$ and $\bar{e}_2$ match the differentiated emission benchmark regulations under EU CBAM, where remanufactured products enjoy lower carbon accounting standards. This pair of thresholds provides export firms with a clear judgment standard to decide whether to transfer carbon tariff costs to consumers via price adjustments. Otherwise, the CBSC members would decrease the wholesale and retail prices when the carbon tariff rate rises. Because when the initial carbon emission level is high, the carbon tariff significantly impacts exporting manufacturers' costs. With the upward adjustment of the carbon tariff rate, overall product costs expand, prompting the exporting manufacturer to adjust wholesale prices upward to cover continuous cost growth. And thus, the importing retailer also increases retail prices. Moreover, the effect of the carbon tariff rate on the exporting manufacturer's decision of the wholesale pricing is larger than that on the importing retailer's decision of retail pricing when the initial carbon

emission level is higher than a certain threshold. On the contrary, the effect of the carbon tariff rate on the retail pricing is larger than that on the wholesale pricing. This is because remanufactured products have lower production costs than new products, leaving greater room for the carbon tariff costs to increase.

Proposition 1 (3) indicates that when the initial carbon emission level is lower than a certain threshold, the exporting manufacturer is more inclined to enhance the carbon abatement level as the carbon tariff rate f rises. Conversely, the exporting manufacturer tends to reduce the carbon emission levels as the f rises. That is to say, the e_n and f jointly influence the exporting manufacturer's strategy selection regarding the carbon abatement level.

Most prior carbon tariff studies adopt single-product settings and fail to distinguish separate emission thresholds for new and remanufactured goods. While our basic cost pass-through logic aligns with mainstream CBAM literature, this paper further identifies two distinct critical thresholds that trigger non-monotonic pricing shifts, a feature rarely discussed in existing research. This finding offers supplementary insights for cross-border remanufacturing supply chain pricing decisions, and all threshold rules here only apply under this paper's simplified model assumptions.

Analyzing the effect of the carbon quota h on the decisions of CBSC members in the models NT and CT, we derive the following Proposition 2.

Proposition 2. *In the equilibrium outcomes under the models NT and CT satisfy*

(1) $\frac{\partial w_n^{CT*}}{\partial h} = \frac{\partial w_r^{CT*}}{\partial h} < \frac{\partial w_n^{NT*}}{\partial h} = \frac{\partial w_r^{NT*}}{\partial h} < 0;$

(2) $\frac{\partial p_n^{CT*}}{\partial h} = \frac{\partial p_r^{CT*}}{\partial h} < \frac{\partial p_n^{NT*}}{\partial h} = \frac{\partial p_r^{NT*}}{\partial h} < 0;$

(3) $\frac{\partial e^{CT*}}{\partial h} > \frac{\partial e^{NT*}}{\partial h} > 0.$

Proof. See Appendix F. □

Proposition 2 (1) and (2) indicate that in the scenario where the importing country imposes carbon tariffs on imported goods, and the exporting country allocates carbon quotas to the domestic manufacturer, an increase in the carbon quota h will still prompt the exporting manufacturer to lower the wholesale prices of the two product categories, thereby driving the importing retailer to reduce the corresponding retail prices accordingly. The reason is that higher carbon quotas issued by the exporting country can reduce the exporting manufacturer's carbon emissions costs by cutting wholesale prices, allowing the exporting manufacturer to expand market demand, and the importing retailer subsequently reduces retail prices to further stimulate market demand to derive more benefits. Furthermore, carbon quota constraints exert more prominent influences on wholesale and retail pricing within the model CT than model NT. That is to say, compared with the dual mixed regulation scenario, the impact of carbon quotas on CBSC members' pricing decisions is greater than that under the cap-and-trade only scenario.

Furthermore, Proposition 2 (3) points out that the carbon abatement level of the exporting manufacturers will increase with the rise in the carbon quota h. This is because a higher level of carbon abatement can not only reduce carbon costs under the cap-and-trade system (or increase carbon revenues in the carbon market) but also alleviate the cost pressure from carbon tariffs imposed on carbon emissions. Moreover, compared with the scenario with carbon tariffs, as the carbon quota increases, the exporting manufacturer will exert greater efforts to cut carbon emissions in the case of a mixed carbon regulation combining carbon tariffs and cap-and-trade regulation.

Prior studies focusing on standalone cap-and-trade markets rarely compare the differentiated pricing and abatement responses between models NT and CT. Our finding

that carbon quotas exert stronger price and abatement impacts under superimposed cross-border carbon constraints extends the single-regulation equilibrium conclusions from existing remanufacturing literature. This contrast between two carbon market scenarios provides supplementary analytical logic for coordinating exporting carbon quotas and importing carbon tariffs, and the observed comparative trends only hold within this paper's static modeling assumptions.

5.2. Comparison Analysis

To explore the effect of carbon tariffs on the decisions of CBSC members, comparing the optimal decision results between the models CN and NN, we denote $\bar{e}_3 = \frac{\delta f}{4\lambda\delta-(1-\beta)f^2}$ and $\bar{e}_4 = \frac{f}{4\lambda\beta}$, and derive $\bar{e}_4 > \bar{e}_3 > 0$, and the following conclusions.

Proposition 3. *The optimal decisions in the equilibrium outcomes under the models CN and NN satisfy*

(1) $e^{CN*} > e^{NN*}$;
(2) if $\bar{e}_3 < e_n < \frac{\delta}{\beta f}$, then $w_n^{CN*} - w_n^{NN*} > p_n^{CN*} - p_n^{NN*} > 0$; otherwise, $w_n^{CN*} - w_n^{NN*} \leq p_n^{CN*} - p_n^{NN*} \leq 0$;
(3) if $\bar{e}_4 < e_n < \frac{\delta}{\beta f}$, then $w_r^{CN*} - w_r^{NN*} > p_r^{CN*} - p_r^{NN*} > 0$; otherwise, $w_r^{CN*} - w_r^{NN*} \leq p_r^{CN*} - p_r^{NN*} \leq 0$;
(4) $q_n^{CN*} < q_n^{NN*}$ and $q_r^{CN*} > q_r^{NN*}$.

Proof. See Appendix G. □

Proposition 3 (1) indicates that compared with the case without carbon tariffs, when the importing country imposes carbon tariffs, the exporting manufacturer will increase the carbon abatement level. This is because the carbon tariff raises the manufacturer's overall cost. By cutting emissions of both new and remanufactured products, the firm effectively reduces its tariff payment burdens.

Propositions 3 (2) and (3) indicate that pricing adjustments are contingent on the initial carbon emissions level. The critical thresholds $\bar{e}_3$ and $\bar{e}_4$ denote the emission cutoffs above which manufacturers fully pass carbon tariff costs on to downstream retailers via higher product prices. These two emission thresholds $\bar{e}_3$ and $\bar{e}_4$ correspond to the tiered emission benchmark standards in EU CBAM, where remanufactured products enjoy lower carbon accounting limits. For export supply chains, the two cutoffs provide a straightforward judgment rule for manufacturers to decide whether to transfer carbon tariff costs via raising wholesale prices. When baseline emissions exceed the threshold, the manufacturer and retailer jointly raise wholesale and retail prices for two types of products. Otherwise, both parties lower prices. In addition, the wholesale price increment set by the manufacturer is larger than the retail price increment set by the retailer. Faced with demand contraction, the retailer only moderately lifts retail prices to avoid losing market share.

Proposition 3 (4) indicates that carbon tariffs reduce demand for new products, while remanufactured products in the model CN achieve higher sales than those in model NN. The retailer raises prices for new products once emissions exceed $\bar{e}_3$, but only raises remanufactured product prices when emissions exceed a higher threshold $\bar{e}_4$ (i.e., $\bar{e}_3 < \bar{e}_4$). The asymmetric price response leads to a far larger demand decline for new products.

Existing cross-border carbon governance literature mainly evaluates the aggregate emission-reduction effects of carbon regulations, while few discuss how remanufacturing activities help manufacturers hedge carbon tariff cost shocks. Our heterogeneous operational responses expand the analytical perspective of sustainable supply chain risk management and deliver tentative operational references for export firms under dual car-

bon regulatory limits. All viewpoints derived here cannot be generalized to real markets with unmodeled demand volatility and heterogeneous production costs.

To explore the effect of cap-and-trade regulation on the decisions of CBSC members, by comparing the optimal decision results between the models NT and NN, we denote $\bar{e}_5 = \frac{\delta b + 4\lambda\delta h}{4\lambda\delta - (1-\beta)b^2}$ and $\bar{e}_6 = \frac{b+4\lambda h}{4\lambda\beta}$, and derive the following conclusions.

Proposition 4. *The optimal decisions in the equilibrium outcomes under the models NT and NN satisfy*

(1) $e^{NT*} > e^{NN*}$;
(2) if $\bar{e}_5 < e_n < \frac{\delta+bh}{\beta b}$, then $w_n^{NT*} - w_n^{NN*} > p_n^{NT*} - p_n^{NN*} > 0$; otherwise, $w_n^{NT*} - w_n^{NN*} \leq p_n^{NT*} - p_n^{NN*} \leq 0$;
(3) if $\bar{e}_6 < e_n < \frac{\delta+bh}{\beta b}$, then $w_r^{NT*} - w_r^{NN*} > p_r^{NT*} - p_r^{NN*} > 0$; otherwise, $w_r^{NT*} - w_r^{NN*} \leq p_r^{NT*} - p_r^{NN*} \leq 0$;
(4) $q_n^{NT*} > q_n^{NN*}$ and $q_r^{NT*} < q_r^{NN*}$.

Proof. See Appendix H. □

Similar to the case under carbon tariffs only, Proposition 4 (1) indicates that compared with the unregulated scenario, the exporting manufacturer raises its carbon abatement level under the exporting country's cap-and-trade regulation only. Cap-and-trade mechanisms strengthen low-carbon constraints on manufacturers. By boosting emission abatement and cutting carbon output for both new and remanufactured products, the manufacturer can effectively ease regulatory pressure and sustain profitability.

Propositions 4 (2) and (3) show that, relative to the unregulated case, wholesale and retail prices of both products rise under cap-and-trade regulation when the initial carbon emission level exceeds a certain threshold. The critical thresholds $\bar{e}_5$ and $\bar{e}_6$ denote the emission cutoffs above which manufacturers fully pass carbon tariff costs on to downstream retailers via higher product prices. The dual thresholds $\bar{e}_5$ and $\bar{e}_6$ correspond to the emission quota benchmark rules of domestic cap-and-trade schemes. They offer export manufacturers a clear operational boundary to judge whether to pass carbon compliance costs to downstream retailers via wholesale price adjustments.

High baseline emissions raise the manufacturer's low-carbon operational costs, which are partially passed downstream through increased wholesale prices. Retailers correspondingly adjust retail prices to compensate for cost pressure. In contrast, prices decline when the initial emission level is below the threshold. The results further reveal that, under high initial emissions, the wholesale price increment is greater than the retail price increment under cap-and-trade regulation. Facing higher regulatory costs, exporting manufacturers tend to adopt aggressive wholesale price adjustments, whereas retailers curb retail price growth to avoid sharp demand loss and keep stable market sales.

Proposition 4 (4) shows distinct demand effects compared with the carbon tariffs-only scenario. Under cap-and-trade regulation only, the demand for new products rises relative to the unregulated benchmark, while the market demand for remanufactured products in the model NT is lower than that in the model NN. Different from carbon tariffs that favor remanufactured product penetration, domestic carbon trading regulation expands the market share of new products. This asymmetric demand variation derives from the mutual price-substitution relationship between new and remanufactured products in the dual-product market.

Combining Propositions 3 and 4, both importing carbon tariffs and exporting cap-and-trade regulation effectively motivate manufacturers' carbon abatement investment and generate conditional upward price adjustments under high-emission conditions. Neverthe-

less, the two regulatory instruments produce opposite product-structure effects: carbon tariffs promote remanufactured product demand, while domestic cap-and-trade regulation expands new product sales.

Compared with existing studies that mostly examine single-carbon regulation or homogeneous product markets, this study distinguishes and compares the heterogeneous operational responses of cross-border remanufacturing supply chains under an importing carbon tariff and an exporting cap-and-trade regulation. The complementary and divergent regulatory effects revealed in this paper clarify differentiated working mechanisms between cross-border and domestic carbon constraints, which delivers supplementary analytical space to prior literature focusing merely on unilateral low-carbon regulation within this paper's simplified modeling context. Within this paper's simplified static modeling context, these results help explain how mixed cross-regulatory environments reshape product market composition. They provide tentative operational references for exporting manufacturers and conditional regulatory insights for international low-carbon governance, and cannot be treated as universal benchmarks for all cross-border industrial scenarios with omitted cost and uncertainty factors.

To explore the different effects of hybrid carbon regulation and single carbon regulation on the decisions of CBSC members, comparing the optimal decision results between the models CT and CN, we denote $\bar{e}_7 = \frac{(4\lambda\delta-f^2)(f+b)h+4\lambda\delta^2+\delta f(f+b)}{4\lambda\delta\beta(2f+b)}$, $\bar{e}_8 = \frac{4\lambda(h\delta(4\delta\lambda-f^2)+\delta^2(b+2f))}{(1-\beta)(f^2(b+f)^2-4b^2\delta\lambda)+16\delta^2\lambda^2-4f(bf+\lambda)\delta(2-3\beta)}$, $\bar{e}_9 = \frac{b\delta-hf^2+2\delta(f+2h\lambda)}{\beta f(b+f)+4\delta\lambda\beta}$, $\bar{e}_{10} = \frac{4(b+2f)\lambda\delta(1-\delta)+4h(4\delta\lambda-f^2)\lambda(1-\delta)}{f^2(b+f)^2(1-\beta)-4\beta\lambda f(b+f)+16\lambda^2\delta(\delta-\beta)-4\delta\lambda(b^2(1-\beta)+(2-3\beta)f(b+f))}$ and derive the following conclusions.

Proposition 5. *The optimal decisions in the equilibrium outcomes under the models CT and CN satisfy*

(1) if $\bar{e}_7 < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $e^{CT*} < e^{CN*}$; otherwise, $e^{CT*} \geq e^{CN*}$;
(2) if $\bar{e}_8 < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $w_n^{CT*} - w_n^{CN*} = p_n^{CT*} - p_n^{CN*} < 0$; otherwise, $w_n^{CT*} - w_n^{CN*} = p_n^{CT*} - p_n^{CN*} \geq 0$;
(3) if $\bar{e}_9 < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $w_r^{CT*} - w_r^{CN*} > p_r^{CT*} - p_r^{CN*} > 0$; otherwise, $w_r^{CT*} - w_r^{CN*} \leq p_r^{CT*} - p_r^{CN*} \leq 0$;
(4) $q_n^{CT*} < q_n^{CN*}$ and if $\bar{e}_{10} < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $q_r^{CT*} < q_r^{CN*}$; otherwise $q_r^{CT*} \geq q_r^{CN*}$.

Proof. See Appendix I. □

Proposition 5 (1) indicates that, compared to the scenario with carbon tariffs only, the exporting manufacturer will raise carbon abatement investment under the mixed scenario of carbon tariffs and cap-and-trade regulation when e_n falls within a specific threshold range. $\bar{e}_7$ is the critical emission threshold governing the comparison of abatement levels e^{CT*} and e^{CN*}. The threshold $\bar{e}_7$ reflects the interactive constraint intensity of dual carbon regulations combining domestic cap-and-trade and cross-border CBAM. It helps exporting manufacturers judge whether joint regulation can stimulate extra emission abatement investment in actual production. The introduction of cap-and-trade alleviates low-carbon constraints. The manufacturer can lift abatement levels and curb carbon emissions to counteract tariff cost pressure and achieve higher profits. Once the initial carbon emission level exceeds this threshold, the abatement incentive under dual regulatory constraints will diminish.

Proposition 5 (2) and (3) indicate that relative to the single carbon tariff only scenario, when initial carbon emissions stay above thresholds $\bar{e}_8$ and $\bar{e}_9$, the exporting manufacturer cuts the wholesale price of new products while lifting the wholesale price of remanufactured products. The two emission thresholds $\bar{e}_8$ and $\bar{e}_9$ form a differentiated pricing decision boundary for dual-product supply chains under overlapping carbon regulations, guiding firms to balance market share and carbon compliance costs in exporting business. The two critical values represent the emission breakpoints where the manufacturer begins to implement differential pricing strategies for the two product types to balance cost pressures and market sales. The importing retailer follows this pricing pattern, reducing the retail price of new products and raising the retail price of remanufactured goods. Faced with high baseline emissions, the manufacturer stabilizes market share for new products by cutting wholesale prices and recoups profit losses via higher remanufactured product prices. The retailer adjusts retail prices correspondingly to pass cost shocks and safeguard its own profitability.

Proposition 5 (4) shows that the dual regulatory scenario reduces demand for new products compared with the carbon tariff-only case. The demand for remanufactured products presents a conditional change: remanufacturing sales rise when the initial carbon emission level stays within the threshold range bounded by $\bar{e}_{10}$, and drop once emissions go beyond this boundary. The threshold $\bar{e}_{10}$ captures the switching point of remanufactured products' low-carbon competitive advantage under overlapping carbon regulations. This critical boundary provides clear operational references for exporting manufacturers to judge the effective emission range where remanufactured products can exert low-carbon competitive advantages under mixed carbon regulatory constraints. Strengthened abatement constraints push up the production cost of new products and restrain their market demand. Within a reasonable emission range, remanufactured products gain low-carbon competitiveness under dual carbon constraints and attract more consumers. If the initial emission level becomes excessively high, tightened carbon costs will erode and even eliminate the demand advantage of remanufactured goods.

Most prior studies concentrate on standalone carbon regulations and seldom explore the interactive effects between importing carbon tariffs and exporting cap-and-trade schemes within cross-border remanufacturing supply chains. This proposition identifies the conditional complementary abatement effect under dual carbon regulation, alongside asymmetric non-monotonic trends in product pricing and demand structure. The findings provide additional analytical insights for research concerning mixed cross-border low-carbon regulatory frameworks. Within the simplified static modeling setup and calibrated parameters of this work, coordinating cap-and-trade regulation with border carbon tariff pressure enables exporting manufacturers to adjust their product mix and mitigate dual cost shocks. From the perspective of cross-border environmental governance, coordinated dual regulation can boost the market share of remanufactured products only within a specific emission interval, as illustrated in our numerical analysis. Accordingly, these outcomes cannot be generalized as universal regulation benchmarks applicable to all industrial sectors.

To explore the different effects of hybrid carbon regulation and single carbon regulation on the decisions of CBSC members, comparing the optimal decision results between the models CT and NT, we denote $\bar{e}_{11} = \frac{bf(b+f)(\delta+bh)+4\lambda\delta^2 f+4\lambda\delta fbh}{4\lambda\delta\beta f(2b+f)}$, $\bar{e}_{12} = \frac{4\delta\left(2b^2h+2b\delta+f\delta\right)\lambda+4bfh\lambda\delta}{b^4(1-\beta)-4b^2(2-3\beta)\delta\lambda+16\delta^2\lambda^2+f(2b^3(1-\beta)-4b(2-3\beta)\delta\lambda)-f^2((1-\beta)(4\delta\lambda-b^2))}$, $\bar{e}_{13} = \frac{2b\delta+\delta f+2b^2h+bfh}{b(b^2+bf+4\delta\lambda)}$, $\bar{e}_{14} = \frac{4(2b+f)(bh+\delta)\lambda f(1-\delta)}{f^2(4b\beta\lambda+4b(2-3\beta)\delta\lambda-2b^3(1-\beta))+f^3(1-\beta)(4\delta\lambda-b^2)+4f(4(\beta-\delta)\delta\lambda^2+b^2\lambda(\beta+\delta(2-3\beta)))-b^4f(1-\beta)}$ and derive the following conclusions.

Proposition 6. *The optimal decisions in the equilibrium outcomes under the models CT and NT satisfy*

(1) if $\bar{e}_{11} < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $e^{CT*} < e^{NT*}$; otherwise, $e^{CT*} \geq e^{NT*}$;
(2) if $\bar{e}_{12} < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $w_n^{CT*} - w_n^{NT*} = p_n^{CT*} - p_n^{NT*} > 0$; otherwise, $w_n^{CT*} - w_n^{NT*} = p_n^{CT*} - p_n^{NT*} \leq 0$;
(3) if $\bar{e}_{13} < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $w_r^{CT*} - w_r^{NT*} > p_r^{CT*} - p_r^{NT*} > 0$; otherwise, $w_r^{CT*} - w_r^{NT*} \leq p_r^{CT*} - p_r^{NT*} \leq 0$;
(4) $q_n^{CT*} < q_n^{NT*}$ and if $\bar{e}_{14} < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $q_r^{CT*} < q_r^{NT*}$; otherwise $q_r^{CT*} \geq q_r^{NT*}$.

Proof. See Appendix J. □

Proposition 6 (1) indicates that compared to the scenario with cap-and-trade regulation alone, the exporting manufacturer increases the carbon abatement level under the joint carbon tariff and cap-and-trade regulatory scenario when the initial carbon emission level falls within a specific threshold range. This threshold $\bar{e}_{11}$ marks the cutoff for firms' abatement incentives. When the carbon emission e_n is below this value, firms gain net benefits from abatement under dual carbon regulation; once e_n exceeds $\bar{e}_{11}$, the combined constraints of carbon tariff and cap-and-trade push firms to scale up abatement investment. This cutoff $\bar{e}_{11}$ quantifies the critical emission boundary under mixed cross-border carbon tariff and cap-and-trade regulations. For exporting manufacturers, it serves as a clear reference to judge whether dual carbon regulations can bring net gains from emission abatement investments. The dual regulatory combination further incentivizes manufacturers to reduce emissions of new and remanufactured products to sustain profitability. When the initial carbon emission levels exceed this threshold, the marginal abatement promotion effect of joint regulation is gradually weakened.

Proposition 6 (2) and (3) show that relative to the single cap-and-trade scenario, both the exporting manufacturer and importing retailer raise wholesale and retail prices for new and remanufactured products under dual regulations when initial carbon emissions lie above $\bar{e}_{12}$ and $\bar{e}_{13}$ respectively. The critical values $\bar{e}_{12}$ and $\bar{e}_{13}$ mark the emission breakpoints where dual regulatory costs begin to trigger significant cost pass-through along the supply chain. The two breakpoints $\bar{e}_{12}$ and $\bar{e}_{13}$ divide the emission intervals where upstream manufacturers start transferring dual regulatory compliance costs to retailers via price hikes. This pair of thresholds guides supply chain participants to coordinate pricing strategies when facing superimposed carbon regulation burdens. High initial emissions substantially increase the manufacturer's operational and abatement costs. The manufacturer raises wholesale prices to offset profit losses, and retailers correspondingly increase retail prices to transfer cost pressure to consumers. Affected by market demand constraints, the retailer suppresses excessive price growth, resulting in a smaller retail price increment compared with the wholesale price increment.

Proposition 6 (4) demonstrates that the joint regulatory scenario further reduces the demand for new products relative to the single cap-and-trade scenario. For remanufactured products, demand presents a threshold-based change: remanufactured product demand increases when it e_n exceeds $\bar{e}_{14}$ and stays inside the feasible range, but declines when the initial carbon emission level goes beyond this critical threshold. The threshold $\bar{e}_{14}$ corresponds to the boundary where the low-carbon competitive edge of remanufactured goods starts to take effect under dual-carbon constraints. Joint abatement and tariff cost pressures push up overall production costs and reshape the market demand structure through price transmission. Within a reasonable emission interval, the low-carbon characteristics of

remanufactured products enhance their market competitiveness. Nevertheless, excessively high baseline emissions significantly tighten carbon cost constraints, diminishing or even reversing the demand advantage of remanufactured products.

Different from existing literature that mostly investigates domestic carbon markets or border carbon tariffs in isolation, this proposition captures the superimposed interactive effect of dual cross-border regulatory constraints. All analytical outcomes are derived under the paper's simplified baseline assumptions. Our results show that carbon tariffs amplify the abatement incentives and price adjustments driven by cap-and-trade regulations. We also capture emission-threshold traits that determine the relative market advantages of remanufactured goods under mixed regulatory environments. These analytical observations supplement the research framework for interactive carbon regulation in transnational remanufacturing supply chains and provide tentative operational references for exporting manufacturers within this modeling context. All threshold switching characteristics depend on preset parameters and cannot be treated as universal benchmarks for all cross-border industrial scenarios.

5.3. Optimal Decisions for the CBSC Members

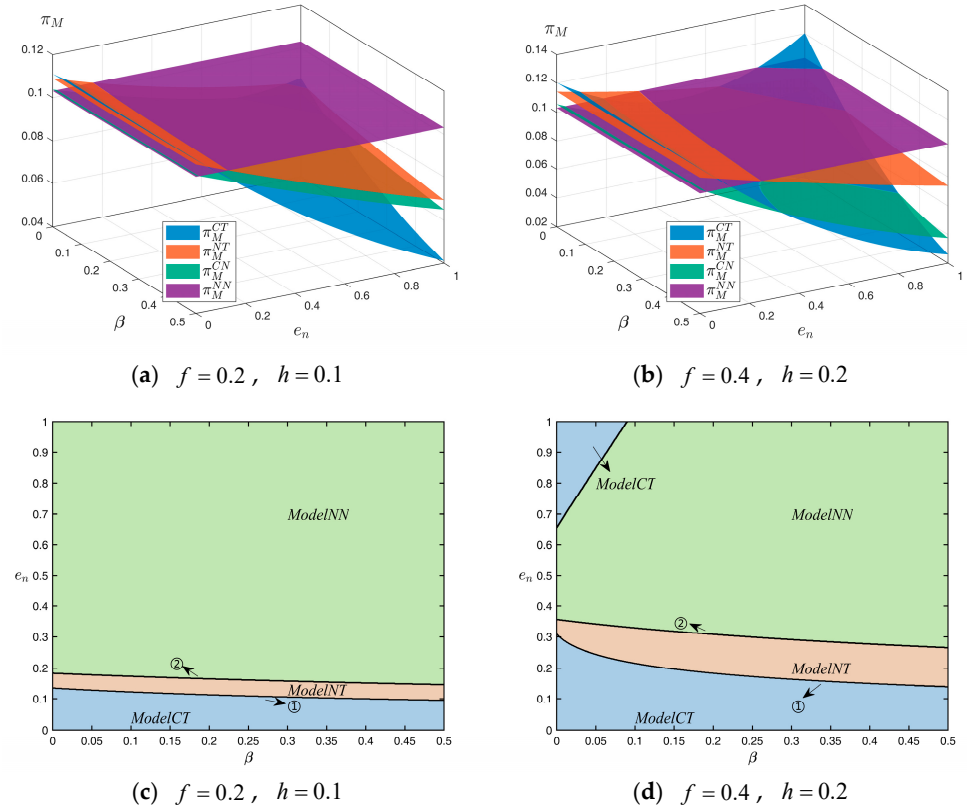
Although core operational decisions are derived analytically, comparisons of profits under different model scenarios lead to highly nonlinear expressions with multiple interdependent parameters. We thus adopt numerical simulation and graphical analysis to visualize profit gaps and draw practical managerial implications [29].

Against the background of the EU Carbon Border Adjustment Mechanism and China's national carbon cap-and-trade market, carbon-intensive cross-border remanufacturing industries face superimposed dual carbon regulatory pressures. Following the industry calibration design adopted by Li et al. [29], this paper does not restrict the analysis to a single specific sector; cross-border power battery remanufacturing is taken as a typical representative of such supply chains in their research. Although Li et al. [29] set domestic carbon tax as the core regulation tool, while our model adopts cap-and-trade regulation, the core operational conflicts arising from the concurrent implementation of importing carbon tariffs are consistent across all exporting remanufacturing manufacturers. The threshold and non-monotonic equilibrium trends illustrated in Figures 2–9 reflect the universal operational rules of remanufacturing exporters under combined carbon regulations, which further corroborate the core theoretical hypotheses derived from our Stackelberg game model.

Following Zhou et al. [6] and Li et al. [22], we calibrate baseline parameters with reference to relevant carbon supply chain literature: $\delta = 0.6$, $\lambda = 1$, $c = 0.1$, $b = 0.2$. As defined in the notation table, δ denotes consumer value discount for remanufactured products, λ is the manufacturer's abatement cost coefficient, c stands for unit cost saving per remanufactured product, and b refers to the carbon trading price. To strictly satisfy the theoretical assumption $0 < \beta < \delta < 1$, we restrict the variation range of β to $[0, 0.5]$, while e_n still varies within $[0, 1]$. The baseline parameters adopted in numerical analysis are referenced from existing relevant literature. Meanwhile, we examine the economic rationality of equilibrium results under each parameter combination and exclude groups yielding unreasonable outcomes such as negative output and negative profit, ensuring the admissibility of all selected parameter sets [29]. Only parameter combinations that yield positive demand, positive profits, and admissible carbon abatement levels are retained for analysis.

We then explore their influences on the optimal decisions and profits of the exporting manufacturer and importing retailer, as shown in Figures 2 and 3. The same parameter setting and feasibility screening are adopted in the subsequent robustness tests. This simu-

lation framework corresponds to a typical generic cross-border remanufacturing industrial scenario: manufacturers in exporting industrial regions produce remanufactured metal components, and export finished goods to developed importing markets that implement carbon tariff mechanisms analogous to the EU CBAM [29].



(**a**) $f = 0.2$, $h = 0.1$ (**b**) $f = 0.4$, $h = 0.2$

(**c**) $f = 0.2$, $h = 0.1$ (**d**) $f = 0.4$, $h = 0.2$

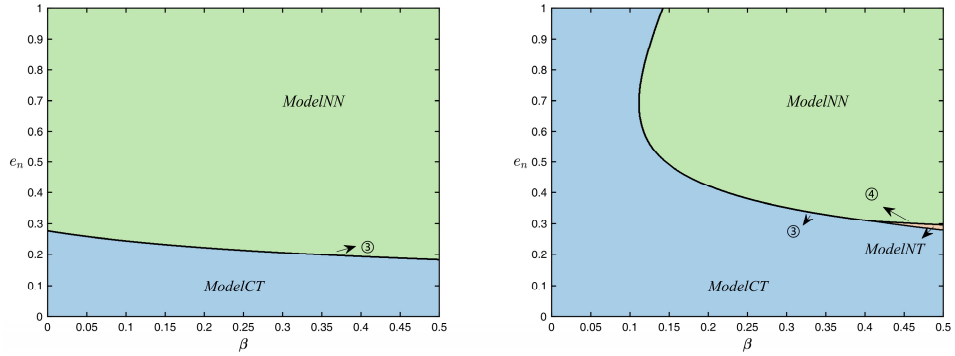
Figure 2. Impact of e_n and β on the exporting manufacturer's profits (① $\pi_M^{CT} - \pi_M^{NN} = 0$; ② $\pi_M^{NT} - \pi_M^{NN} = 0$).

Figure 2a,b demonstrates that for an exporting manufacturer, the model CN cannot obtain competitive profit advantages at both low and high carbon tariff and carbon quota levels. It follows that a unilateral carbon tariff substantially squeezes profit margins and deteriorates the overall earnings of the exporting manufacturer.

Figure 2c corresponds to the scenario with a low carbon tariff $f = 0.2$ and tight carbon cap-and-trade regulation $h = 0.1$. A smaller h denotes a tighter quota supply, and the model NN is free from all carbon regulatory restraints with no compliance costs. Under mild dual regulatory intensity, the model NN dominates most combinations of e_n and β, model NT only prevails in a narrow middle zone, and the model CT is optimal merely at low e_n and low β. This reveals that manufacturers can adopt a model NN to evade extra carbon costs and stabilize profits when the cross-border tariff is low, while the domestic carbon quota supply is constrained.

Figure 2d displays the case with a higher carbon tariff $f = 0.4$ and a loose carbon cap-and-trade regulation $h = 0.2$. The elevated tariff sharply compresses the advantage region of model NN, which only remains viable under extremely high e_n and β. Meanwhile, the dominant scope of model CT expands greatly to cover low-to-medium e_n and β, and model NT's feasible region slightly widens at medium e_n and high β. It implies that expanding domestic quota supply can mitigate tariff cost shocks, and manufacturers with low and medium baseline carbon emissions ought to switch to the model CT when the carbon tariff grows more stringent.

The regional partition trend conforms to the cost-trade-off logic of cross-border remanufacturing enterprises under dual-carbon regulatory constraints, as summarized by Zhou et al. [6].



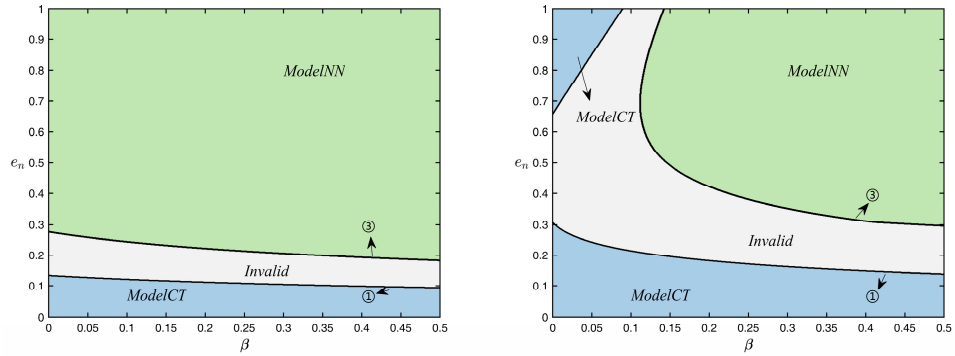
(**a**) $f = 0.2$, $h = 0.1$ (**b**) $f = 0.4$, $h = 0.2$

Figure 3. Impact of e_n and β on the importing retailer's profits (③$\pi_R^{CT} - \pi_R^{NN} = 0$; ④$\pi_R^{NT} - \pi_R^{NN} = 0$).

Similarly, for the importing retailer, the model CN cannot gain a competitive profit edge under a low carbon tariff or a tight carbon quota regulation.

Figure 3a corresponds to a low carbon tariff $f = 0.2$ and relatively tight carbon cap-and-trade regulation $h = 0.1$. Model CT dominates most combinations of new product unit carbon emission e_n and emission ratio β, as manufacturers stabilize wholesale costs via quota trading to secure steady retailer profits. Model NN only prevails under high e_n and high β, where manufacturers reduce carbon compliance expenditures and transfer cost savings to retailers through reduced wholesale prices. This suggests that retailers should prioritize cooperation with manufacturers adopting the model CT when dual carbon regulatory intensity is mild.

Figure 3b adopts a higher carbon tariff $f = 0.4$ and a looser carbon cap-and-trade regulation $h = 0.2$. The dominant region of the model CT expands further to cover low and medium e_n and β, since expanded quota supply helps manufacturers absorb carbon tariff cost shocks. The profit advantage range of the model NN shrinks significantly; only extremely high e_n and β can offset tariff pass-through losses and sustain profitable cooperation under the model NN. It indicates that loosening the domestic carbon quota supply can amplify the profit superiority of the model CT, which becomes the most reliable cooperation choice for retailers facing rising cross-border carbon tariffs.



(**a**) $f = 0.2$, $h = 0.1$ (**b**) $f = 0.4$, $h = 0.2$

Figure 4. Consistent decision for the exporting manufacturer and importing retailer. (① $\pi_M^{CT} - \pi_M^{NN} = 0$; ③ $\pi_R^{CT} - \pi_R^{NN} = 0$).

It can be seen from Figure 4 that the consistent decision regions shared by the exporting manufacturer and the importing retailer shift notably with varying regulatory parameters. The zone marked "Invalid" between curve ① and curve ③ represents conflicting profit preferences, where the two supply chain members fail to agree on a unified operational model.

Figure 4a corresponds to a low carbon tariff $f = 0.2$ and relatively tight carbon cap-and-trade regulation $h = 0.1$. A smaller h means a tighter carbon quota supply, and the model NN is free from all carbon regulatory restraints. When e_n and β stay at low-to-moderate levels, model CT is the mutually optimal consistent decision; when both e_n and β reach high values, model NN becomes the coordinated choice for both sides.

Figure 4b adopts an elevated carbon tariff $f = 0.4$ and a looser carbon cap-and-trade regulation $h = 0.2$. As carbon tariff intensity rises and the domestic carbon quota supply expands, the consistent decision region of the model CT expands remarkably, while the feasible parameter range for the coordinated model NN shrinks sharply. This implies that jointly raising the import carbon tariff and relaxing the domestic carbon quota supply can effectively broaden the scope for supply chain coordination, helping both participants secure more stable profits.

All in all, firms with higher baseline carbon emissions have stronger incentives to evade carbon regulatory restraints. As carbon regulatory intensity grows, enterprises become more sensitive to emission compliance costs, which further expands the applicable scope for matching carbon tariffs and cap-and-trade regulations. Reliance solely on the importing nation's carbon tariff delivers limited regulatory effects, whereas the coordinated deployment of a carbon tariff and cap-and-trade regulation can balance emission abatement targets and manufacturers' profitability, realizing more balanced low-carbon governance across cross-border supply chains.

5.4. Analysis of Consumer Surplus, Environmental Impact, and Social Welfare

To clearly compare the results across different scenarios and reveal the changing trends, we select four typical parameter levels: (a) $h = 0.1$, (b) $h = 0.2$, (c) $f = 0.2$, and (d) $f = 0.4$ [29]. Here we set $e_n = 0.6$, with $0 < h < e_n$. These values represent low and high levels of the key parameters, which can effectively demonstrate their impacts on equilibrium outcomes and ensure the robustness of the numerical analysis.

All parameter combinations are set against the universal cross-border remanufacturing trade background mentioned in Section 5.3, and the selected regulatory intensity levels cover the mainstream carbon tariff and cap-and-trade quota standards currently adopted in global cross-border low-carbon governance.

(1) Impact of f and h on consumer surplus

According to studies by Zhang et al. [38], Chang et al. [39] and Gong et al. [41], consumer surplus $CS = \int_{1-q_r-q_n}^{1-q_n} (\delta\theta - p_r)d\theta + \int_{1-q_n}^{1} (\theta - p_n)d\theta$ for new products and remanufactured products can be calculated. Therefore, the impact of the carbon tariff and carbon quota on consumer surplus is illustrated in Figure 5.

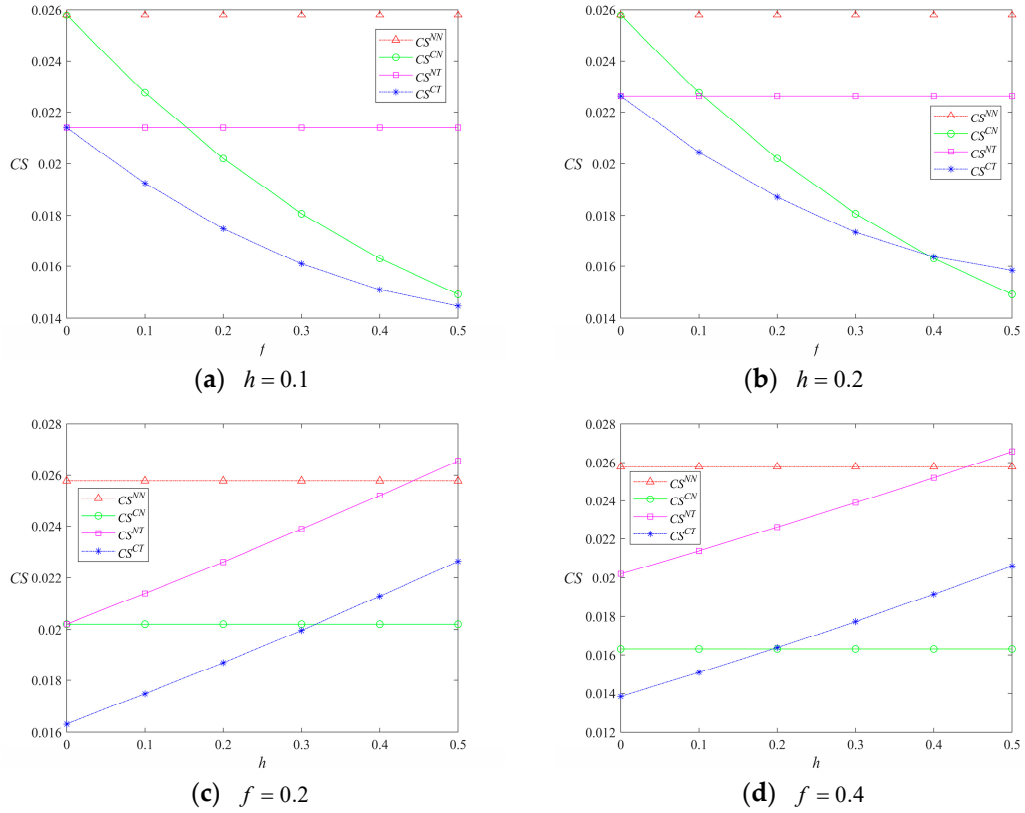


Figure 5. Impact of f and h on consumer surplus.

Figure 5a,b illustrates consumer surplus changes against the carbon tariff f under two carbon quota intensities: tight cap-and-trade regulation $h = 0.1$ and looser cap-and-trade regulation $h = 0.2$. Model NN is exempt from all carbon regulatory restraints, so its consumer surplus CS^{NN} stays constant regardless of carbon tariff variations, as manufacturers' pricing and output choices are unaffected by cross-border carbon tariffs. For model CN, which only imposes a carbon tariff without cap-and-trade constraints, CS^{CN} declines monotonically as f rises. Higher carbon tariffs increase manufacturers' export expenses, and these extra costs are fully passed to consumers through higher retail prices, suppressing market demand and continuously eroding consumer surplus.

By comparison, model CT enforces carbon tariff and cap-and-trade regulation at the same time. Compared with the model CN, the decline of consumer surplus CS^{CT} brought by the rising carbon tariff is remarkably alleviated. At low tariff levels, carbon tariff costs dominate operational expenses and push up commodity prices, reducing consumer surplus. As f continues to rise, the joint emission abatement incentive from dual carbon regulatory restraints gradually works to cut manufacturers' net carbon compliance costs, slow price hikes, and alleviate losses in consumer surplus. This buffering effect becomes more prominent when h is larger (looser carbon quota supply), which can be clearly observed by comparing Figure 5a,b. Model NT's consumer surplus remains nearly flat across all tariff levels, since its equilibrium output and pricing are bounded by predetermined carbon quota limits independent of the importing carbon tariff.

Figure 5c,d depicts consumer surplus variations with carbon quota h under a fixed low tariff $f = 0.2$ and high tariff $f = 0.4$. Again, CS^{NN} and CS^{CN} hold steady as h changes: model NN faces no carbon regulatory limits, while carbon quota regulation has no binding impact on the model CN which only follows the carbon tariff. In contrast, CS^{NT} CS^{NT} and CS^{CT} rise monotonically with expanded carbon quota supply. More sufficient carbon quotas reduce manufacturers' expenditure on carbon quota purchases, lower product

prices, and boost market consumption, lifting consumer surplus accordingly. Notably, CS^{CT} features a steeper upward slope than CS^{NT}. The dual regulatory portfolio combining carbon tariff and cap-and-trade delivers stronger emission-cost reduction effects as quotas loosen, better offsetting the adverse cost shock triggered by importing carbon tariff and driving faster growth in consumer surplus, especially under a high baseline carbon tariff, as shown in Figure 5d.

In summary, single carbon tariff (model CN) unilaterally damages consumer surplus as tariff intensity rises, while the coordinated combination of carbon tariff and cap-and-trade regulation (model CT) can effectively mitigate such negative impacts on consumers. Appropriately relaxing the carbon quota supply and matching moderate carbon tariff intensity helps stabilize and improve overall consumer surplus.

(2) Effect of f and h on environmental impact

According to studies by Zhang et al. [36], Cao et al. [42], and Xu et al. [43], the environmental impacts $E = (e_n - e)q_n + (\beta e_n - e)q_r$ of new products and remanufactured products can be calculated. Consequently, the environmental impacts of the carbon tariff and carbon quota are illustrated in Figure 6.

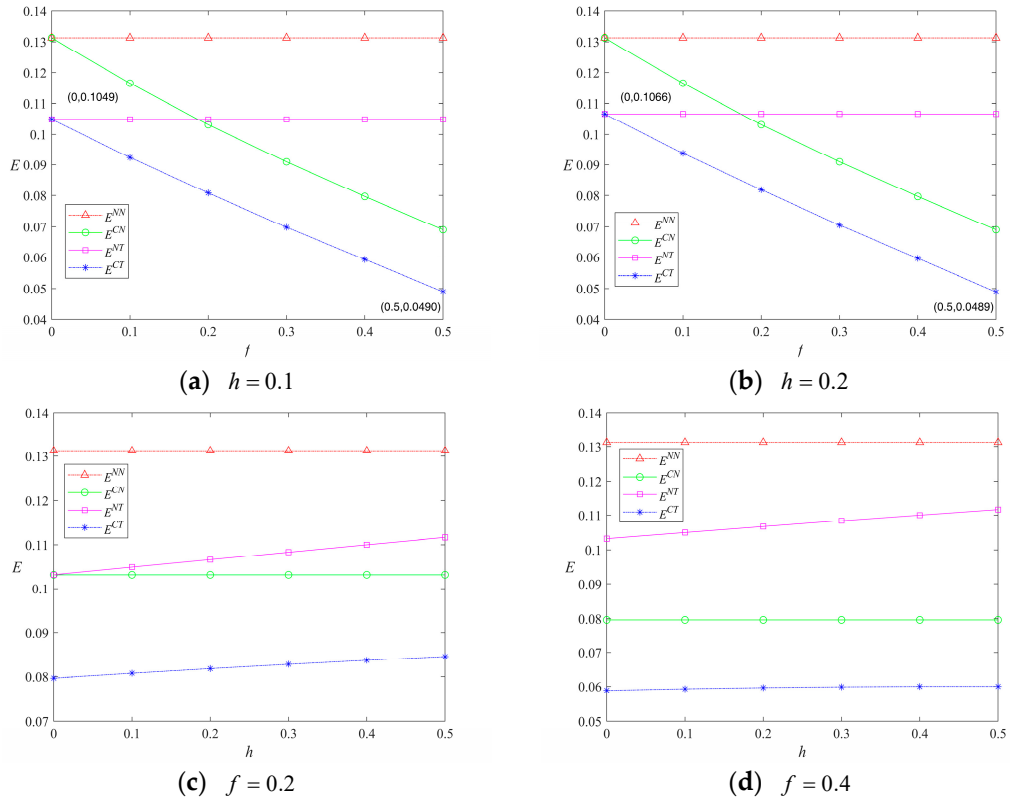


Figure 6. Effect of f and h on the environmental impact.

Figure 6a,b depicts how the carbon tariff f affects total environmental impact under two carbon quota intensities: relatively tight cap-and-trade regulation $h = 0.1$ and looser cap-and-trade regulation $h = 0.2$. Model NN is free from all carbon regulatory restraints, generating no emission abatement incentives; its total carbon emissions E^{NN} remain constant regardless of carbon tariff variations. For model NT, environmental impact also stays nearly flat across all f, since its production and abatement decisions are bounded by predetermined carbon quota limits that are unaffected by the importing carbon tariff.

By contrast, total emissions under models CN and CT both decrease monotonically as the carbon tariff rises. Higher carbon tariffs raise manufacturers' export compliance costs, curtail production output, and cut overall carbon emissions directly. Notably, the model CT achieves a far larger emission reduction magnitude than the model CN. The dual-layer carbon regulatory restraints, combining carbon tariff and cap-and-trade regulation jointly amplify firms' abatement motivation, delivering more remarkable environmental improvement than the standalone carbon tariff adopted by the model CN. Comparing Figure 6a,b, the looser carbon quota supply slightly weakens the emission abatement gap between CN and CT, yet CT still maintains the lowest total environmental impact at any given tariff level.

Figure 6c,d illustrates the response of the environmental impact to the carbon quota h under a fixed low tariff $f = 0.2$ and high tariff $f = 0.4$. Consistent with the above mechanism, E^{NN} and E^{CN} barely shift as h varies: model NN faces no carbon regulatory limits, while carbon quota regulation exerts no binding influence on the model CN which only complies with the carbon tariff. For model NT, environmental impact rises moderately with expanded carbon quota supply. Lower quotas of lower manufacturers' expenditure on carbon allowance purchases, expand production scale, and push up total carbon emissions accordingly.

Different from the model NT, E^{CT} only rises mildly and even shows a slight downtrend as h increases. The coordinated dual regulatory constraints offset the emission-boosting effect brought by relaxed quota supply, slowing the growth of total carbon emissions effectively. This environmental advantage of the model CT becomes more pronounced when the baseline carbon tariff intensity is higher, as observed in Figure 6d.

In summary, raising carbon tariff intensity helps curb total carbon emissions and mitigate environmental damage. However, overly loose carbon quota supply will drive up emissions under the standalone cap-and-trade regulation (model NT). Matching appropriate carbon tariff stringency with reasonable carbon quota allocation under the coordinated carbon tariff and cap-and-trade regulation (model CT) can effectively balance environmental conservation and manufacturers' economic benefits.

(3) Impact of f and h on social welfare

According to Zhou et al. [6], Zhang et al. [38] and Cao et al. [42], environmental damage cost is linear in total emissions E, denoted as kE, with $k = 0.5$ for the transnational remanufacturing supply chain of auto spare parts: the forging, heat treatment and electroplating of auto parts generate moderate carbon emissions and metal pollution, matching this medium environmental loss benchmark adopted in mainstream carbon regulation studies. The total social welfare (SW^i) in this study covers economic surplus from both the exporting and importing countries, including the profits of the exporting manufacturer and importing retailer, consumer surplus, and environmental damage cost. Notably, carbon tariff revenue is a pure cross-border transfer payment from the exporting manufacturer to the importing government, which merely redistributes wealth across nations without creating additional net social surplus. Thus, tariff fiscal income is excluded from the aggregate cross-border social welfare function. Formally: $SW^i = \pi_M^i + \pi_R^i + CS^i - kE^i$.

Payments for carbon emission quotas are only internal income redistribution inside the exporting country and do not generate net social loss for the whole cross-border supply chain. Therefore, allowance trading expenditures are not incorporated into the welfare calculation. The effects of carbon tariff rate and carbon quota on total social welfare are illustrated in Figure 7.

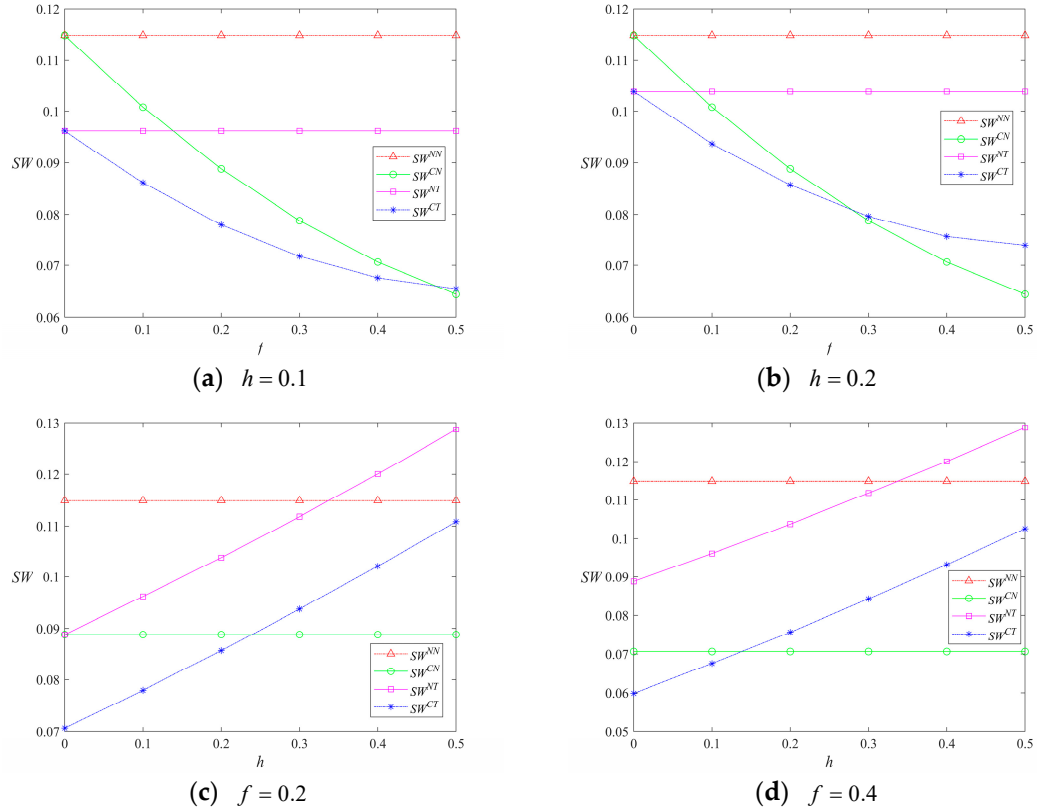


Figure 7. Impact of f and h on total social welfare.

Figure 7a,b illustrate the evolution of social welfare against carbon tariff f under two carbon quota intensities: relatively tight cap-and-trade regulation $h = 0.1$ and looser cap-and-trade regulation $h = 0.2$. Model NN is exempt from all carbon regulatory restraints, so its social welfare SW^{NN} remains constant regardless of carbon tariff adjustments. For model CN, which only implements carbon tariff without cap-and-trade constraints, social welfare declines monotonically as f rises. Higher carbon tariffs raise manufacturers' export expenses; while total carbon emissions are reduced, the shrinkage of consumer surplus and firm profits dominates the welfare change, triggering a continuous drop in overall social welfare.

By contrast, model NT relies solely on cap-and-trade regulation and excludes carbon tariff mechanisms. Its social welfare SW^{NT} remains constant across all values of carbon tariff. For model CT subject to dual carbon regulatory restraints, social welfare declines monotonically as carbon tariff intensifies. The joint constraint of carbon tariff and cap-and-trade regulation raises corporate emission abatement and exporting costs. As f grows, the combined losses in firm profits and consumer surplus outweigh the welfare gains from reduced environmental damage, driving a sustained drop in overall social welfare. Comparing Figure 7a,b, looser carbon quota supply widens the welfare gap between models CN and CT at the same carbon tariff level.

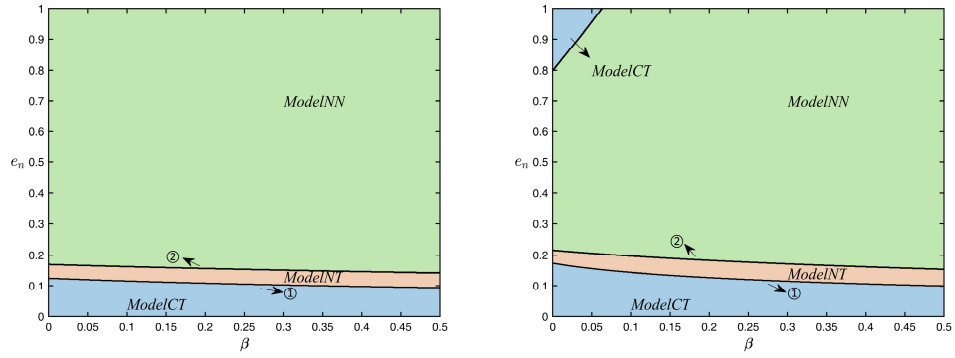
Figure 7c,d display how social welfare responds to carbon quota h under fixed low tariff $f = 0.2$ and high tariff $f = 0.4$. As elaborated above, SW^{NN} and SW^{CN} stay nearly unchanged with varying h: model NN faces no carbon regulatory limits, while carbon quota regulation has no binding effect on model CN governed only by carbon tariff. In contrast, social welfare of models NT and CT increases monotonically with looser carbon quota supply. Expanded carbon quotas relax emission constraints for manufacturers under cap-and-trade regulation, cut carbon compliance expenditures, expand output volume and lift consumer surplus, which jointly push up total social welfare. Notably, SW^{CT}

exhibits a steeper upward slope than SW^{NT}. The dual carbon regulatory portfolio delivers stronger welfare growth when quotas loosen, and this gap becomes more prominent under a higher baseline carbon tariff as shown in Figure 7d. The welfare differentiation shown in this figure echoes the cross-border welfare balance characteristics of remanufacturing enterprises under dual carbon constraints summarized by Li et al. [29].

In summary, different combinations of carbon regulatory instruments generate divergent impacts on social welfare. Overly stringent standalone carbon tariff under model *CN* tends to erode social welfare substantially. In comparison, pairing carbon tariff with reasonably relaxed cap-and-trade regulation (model *CT*) can effectively mitigate the social welfare losses induced by carbon tariff implementation. Reasonably calibrated carbon tariff and carbon quota levels enable regulation makers to fulfill environmental abatement targets: appropriate carbon quota relaxation can raise social welfare, while matching carbon tariff with cap-and-trade regulation can minimize welfare losses caused by standalone carbon tariffs.

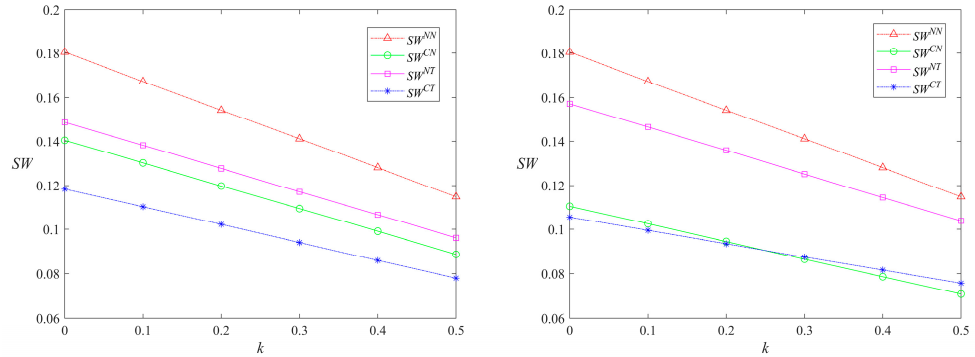
5.5. Robustness Analysis

To verify the stability and reliability of core conclusions regarding manufacturers' optimal regulatory selection and social welfare performance under varying parameter settings, this subsection carries out two groups of robustness tests focusing on two core parameters: the consumer value discount for remanufactured products δ, and the environmental damage coefficient k.



(**a**) $\delta = 0.5$ (**b**) $\delta = 0.7$

Figure 8. Robustness check of the dominant model zoning under different consumer discounts δ (① $\pi_M^{CT} - \pi_M^{NN} = 0$; ② $\pi_M^{NT} - \pi_M^{NN} = 0$).



(**a**) $f = 0.2$, $h = 0.1$ (**b**) $f = 0.4$, $h = 0.2$

Figure 9. Variations in social welfare with environmental damage coefficient k under two regulatory intensity levels.

First, Figure 8 tests whether the zoning rules of dominant regulatory models hold when consumer preference discounts δ changes. We adjust δ from 0.5 to 0.7 while all other parameters remain fixed. Comparing Figure 8a,b, the overall partition structure of the model NN, model NT and model CT never reverses; only the width of boundary intervals labeled ① and ② changes slightly with δ. This evidence proves that the division logic of manufacturers' optimal carbon regulation portfolios is robust to consumer valuation differences between new and remanufactured products.

Second, Figure 9 analyzes social welfare responses to the environmental damage coefficient k under two groups of regulatory parameters: low carbon tariff and limited quota supply ($f = 0.2$, $h = 0.1$), as well as increased tariff and expanded quota supply ($f = 0.4$, $h = 0.2$). In Figure 9a, the welfare ranking always follows $SW^{NN} > SW^{NT} > SW^{CN} > SW^{CT}$, where a standalone carbon tariff CN outperforms dual regulation CT for all k. In Figure 9b, a crossover exists between SW^{CN} and SW^{CT} SW^{CT}. SW^{CN} is higher at low k, while SW^{CT} surpasses SW^{CN} once k exceeds a threshold. As the carbon tariff rises, compliance costs surge for firms under the model CN without mitigation tools. By contrast, quota trading in the model CT cuts extra tariff expenses. Larger k weights environmental losses more heavily, and the dual incentives of CT generate greater environmental gains, lifting its total social welfare above CN.

Across both parameter groups, the social welfare of all models declines monotonically with rising k. The ranking of NN and NT stays nearly unchanged, while the comparative performance of CN and CT varies with tariff, quota, and environmental damage parameters. This finding extends the analysis in Section 5.4, revealing that the relative advantages of a single carbon tariff and dual coordinated regulation depend jointly on the tariff rate, quota supply, and environmental damage cost.

6. Conclusions

6.1. Main Findings

To examine the effects of carbon tariffs and cap-and-trade regulation on cross-border remanufacturing supply chains, we construct a baseline unregulated scenario, two single regulatory scenarios: the carbon tariff-only scenario and the standalone cap-and-trade regulation scenario, and a composite dual regulatory scenario covering both carbon governance instruments. By comparing the optimal decisions of the exporting manufacturer, consumer surplus, environmental effects, and social welfare across different scenarios, this study draws the main conclusions summarized below.

First, we analyze the differentiated impacts of independent carbon tariffs and standalone cap-and-trade regulation on supply chain members' equilibrium decisions. For low-baseline-emission manufacturers, rising carbon tariff intensity stimulates greater carbon abatement investment; high-emission manufacturers only boost abatement under moderate tariff pressure, and excessive tariff rates push firms to expand remanufactured output to cut tariff expenditure. This aligns with the research conclusion of Li et al. [29], which reveals that overly stringent carbon tariffs damage long-term industrial sustainability. Meanwhile, cap-and-trade regulation only generates prominent abatement incentives within a limited baseline emission range.

Second, we explore how varying the carbon tariff f and carbon quota h supply reshapes profit optimization decisions. Adjustments of the two regulatory tools greatly alter the feasible scope of consistent coordinated decisions for supply chain members. When carbon tariff intensity rises, and the domestic carbon quota supply becomes loose, the feasible region of the model CT (coordinated profit-oriented collaborative decisions) expands, whereas the parameter space for the model NN shrinks significantly. Consistent with Xia and Chen [44], sufficient carbon quotas help manufacturers balance profit and emission

reduction, and matched dual regulation can offset carbon tariff cost shocks to stabilize bilateral supply chain profit. Manufacturers with higher baseline emissions are more sensitive to regulatory intensity and have stronger incentives to adjust their strategies to evade carbon expenditure.

Finally, we investigate the comprehensive impacts of dual carbon regulatory portfolios on environmental performance and social welfare. Standalone carbon tariffs only (Model *CN*) suppress consumer surplus, yet they can deliver remarkable emission reduction and environmental improvement [34]. If exporting countries simultaneously implement a cap-and-trade regulation to form the dual regulatory framework of the model *CT*, the synergistic abatement effect will be further strengthened. From a social welfare perspective, solely raising carbon tariff intensity under the carbon tariffs-only scenario continuously erodes total social welfare. In contrast, coordinating moderate carbon tariff intensity with reasonably sufficient carbon quota supply under joint carbon tariff and cap-and-trade regulation delivers relatively higher social welfare within the parameter range tested in this study [6,45]. Under the simplified assumptions adopted here, coordinated carbon tariffs and cap-and-trade regulation provide a viable balancing outcome under the given model assumptions. All threshold switching points and parameter dominance zones derived from numerical simulation are sensitive to preset parameters and cannot be taken as universal benchmarks for real firms and regulators.

6.2. Management Implications

All observations below are derived from a static, highly simplified two-echelon Stackelberg model. This model excludes transport costs, remanufacturing collection costs, stochastic market demand, firm heterogeneity, and fluctuating carbon allowance prices, and all simulation parameters are cited from existing literature rather than industrial field data. The following strategic and regulatory suggestions only hold under the preset assumptions and calibrated parameters of this study, and cannot be treated as universal guidance applicable to all cross-border remanufacturing sectors or to real carbon regulatory systems.

This subsection avoids mere restatement of analytical results and summarizes targeted operational and regulatory observations tailored to cross-border remanufacturing supply chains subject to carbon tariff and cap-and-trade regulation. All insights originate strictly from our core equilibrium findings, with supplementary discussion of industrial and national heterogeneity to clarify their practical applicable scope.

First, single-carbon regulation generates differentiated abatement and production choices for firms with distinct baseline emission intensity. Supply chain participants may adopt differentiated strategies corresponding to their initial emission levels and regulatory stringency. (1) For exporting manufacturers, operational arrangements can be adjusted according to their baseline carbon intensity under different carbon tariffs and cap-and-trade regulation scenarios only. Low-baseline-emission manufacturers: As carbon tariff intensity rises, firms with low marginal abatement costs may moderately expand carbon abatement investment to cut tariff expenditure and lift net earnings. High baseline emission manufacturers: Abatement investment delivers marginal gains only under moderate carbon tariff pressure. When carbon tariffs become excessively strict, continuous decarbonization investment turns uneconomical; manufacturers may raise the proportion of remanufactured output to lower tariff expenses and stabilize profit margins. In addition, the incentive effect of cap-and-trade regulation only functions within a limited emission interval. High-carbon manufacturers can flexibly adjust total output according to available carbon quotas to avoid inefficient abatement investment when quotas are tight. (2) For overseas retailers, partnership and pricing decisions can be adjusted based on carbon tariff levels. Moderate carbon tariff: Maintaining stable long-term cooperation and steady

product pricing helps sustain downstream market demand. When cross-border carbon tariffs increase substantially, retailers can actively establish long-term partnerships with low-emission manufacturers that possess steady decarbonization capabilities. In response to higher tariff costs, retailers may adopt modest differential pricing for remanufactured products, while avoiding drastic price increases that could reduce market demand.

Second, overlapping dual carbon regulation reshapes the feasible profit–parameter range of supply chains. Regulators may consider designing matched carbon regulatory portfolios to balance corporate profitability and industrial low-carbon transition within the model's analytical boundary. (3) Exporting-country authorities can implement differentiated carbon quota allocation to alleviate cost shocks brought by importing carbon tariffs. Tight cap-and-trade regulation substantially narrows the feasible decision space for high-emission manufacturers. Regulators may allocate relatively abundant carbon quotas to high-carbon manufacturers to preserve their profit margins, while tighter quota constraints can preserve abatement incentives for low-emission producers, forming categorized incentive arrangements for heterogeneous manufacturers. (4) Importing nations may maintain carbon tariff intensity at a moderate level and promote bilateral cross-border regulatory coordination. Excessively high carbon tariffs generate limited additional emission reductions while compressing supply chain profits and destabilizing market operations. Instead of unilaterally tightening carbon tariffs, importing regulators can align tariff stringency with the restrictiveness of export-side cap-and-trade regulation to build predictable cross-border carbon regulatory environments. Reasonably matched carbon tariff and carbon quota levels can stabilize corporate earnings and mitigate sharp profit volatility triggered by uncoordinated regulatory intensity.

Third, coordinated dual carbon regulation delivers combined environmental and social welfare outcomes. Bilateral regulators may align cross-border carbon regulatory constraints according to industrial and institutional conditions to achieve comparatively favorable welfare performance within the model's parameter scope. From a welfare perspective, unilateral carbon tariff hikes under standalone carbon tariffs only reduce consumer surplus; by contrast, pairing domestic cap-and-trade regulation with importing carbon tariffs generates synergistic abatement and cuts overall carbon emissions. Within our numerical simulation range, the combination of moderately sufficient domestic carbon quotas and cross-border carbon tariffs yields comparatively better social welfare performance under dual carbon regulation. Bilateral regulatory coordination can prioritize this matched portfolio rather than separately tightening cross-border carbon constraints.

In terms of applicable scope, the above observations primarily apply to high-emission industries with large-scale cross-border remanufacturing businesses, where carbon compliance costs exert notable impacts on corporate profits and emissions performance. For low-carbon sectors less sensitive to carbon regulatory expenses, flexible carbon regulatory arrangements may be more suitable. At the national level, economies with mature cap-and-trade regulation systems can attain both emission reduction and stable corporate profitability when adopting dual coordinated carbon regulation under the model's assumptions. In contrast, regions with immature carbon regulatory institutions need gradual regulatory optimization, as rigid overlapping carbon regulation raises institutional adaptation costs for firms. It should be noted that the coordination logic discussed here only holds within the static theoretical framework of this study; real-world regulatory design requires further consideration of unmodeled practical factors, such as carbon price volatility and firm heterogeneity. Coordinated adjustment between cross-border carbon tariffs and cap-and-trade regulation represents one feasible balancing path for the low-carbon operation of transnational remanufacturing supply chains under the simplified model setup. For practical reference, as illustrated in Wang et al. [17], low-carbon manufacturers such as BYD

adopt self-operated remanufacturing, while high-carbon firms like CATL cooperate with third-party recyclers to cope with the joint pressure of carbon tariffs only and cap-and-trade regulation only.

6.3. Limitations and Future Research

Our study has several limitations that warrant further exploration in future research. First, while the EU's carbon border adjustment mechanism requires companies to declare the carbon emissions of their products upon importation, exporters face both cumbersome procedures and substantial costs when calculating the carbon footprint of products and components across the entire supply chain. Future research can incorporate these carbon accounting costs into our model to reflect the true compliance cost of cross-border emissions reporting. Second, our model focuses solely on exporting manufacturers performing remanufacturing. However, in multinational supply chains, manufacturer-led remanufacturing incurs substantial additional transportation costs. Future research will explore importing retailer-led and third-party remanufacturing scenarios, as well as their impacts on carbon abatement and supply chain economic-environmental performance. Third, this study assumes deterministic market demand. Future work could extend the model to consider stochastic demand, which is common in cross-border trade, and examine how uncertain demand affects firms' pricing, remanufacturing, and abatement strategies. Fourth, we treat carbon tariffs as pure transfer payments without considering how tariff revenue is redistributed within the importing country or internationally. Future research can incorporate different tariff revenue allocation mechanisms (e.g., consumer subsidies, green industrial investment) and analyze their differentiated distributional and environmental impacts.

In addition, this study relies on several conventional simplifying assumptions to guarantee analytical tractability. We adopt a linear demand function, a two-echelon supply chain with a single manufacturer and a single retailer, fixed production cost gaps between new and remanufactured goods, and stable consumer preference structures. If we relax these core settings, the equilibrium decisions and profit-partition intervals will change to a certain extent. We leave these extended modeling scenarios for future follow-up research, and this paper mainly focuses on the interactive effects of dual carbon regulation under the baseline analytical framework.

Fifth, all benchmark parameter values adopted in our numerical simulation are quoted from relevant existing literature, rather than obtained through on-site industrial questionnaires or field interviews. Without original first-hand industrial data for parameter calibration, the quantitative numerical results cannot perfectly match the operational characteristics of real cross-border remanufacturing industries, which weakens the practical persuasiveness of our numerical findings to a certain extent. It is worth noting that the numerical analysis of this paper only aims to intuitively illustrate the qualitative trends derived from theoretical equilibrium solutions, rather than deliver precise quantitative predictions for industrial practice. For follow-up research, scholars can collect real operational data of manufacturing enterprises via questionnaires and field interviews to calibrate model parameters and further verify the reliability of the theoretical conclusions proposed in this study. To alleviate this limitation, we select parameter values widely recognized in the mainstream remanufacturing supply chain literature and conduct a series of robustness tests on core parameters, which ensures that our core qualitative results remain stable within a reasonable range of parameter fluctuations.

Collectively, all numerical thresholds and cross-model dominance intervals presented in this analysis are specific to the preset parameters and static model structure of this study, and cannot be treated as universal benchmarks applicable to all manufacturers or cross-border carbon regulatory systems. Real-world thresholds will shift significantly when

adjusting for industry characteristics, carbon price volatility, and firm heterogeneity factors excluded from our model.

7. Discussion

This paper constructs four Stackelberg game models to characterize cross-border remanufacturing supply chains under different carbon regulatory portfolios, namely the unregulated benchmark model NN, standalone carbon tariff model CN, a standalone cap-and-trade model NT, and a joint dual carbon regulation model CT. By solving equilibrium solutions and conducting numerical partition analysis, we identify how single and overlapping carbon regulatory instruments shape firms' abatement investment, remanufacturing output, corporate profits, consumer surplus, and aggregate cross-border carbon emissions under our static modeling assumptions. Our core analytical results show that continuously raising carbon tariff intensity under the model CN erodes supply chain profitability, while matched carbon tariff intensity and domestic carbon quota supply under the model CT can deliver both emission reduction and comparatively improved social welfare within the simulated parameter range. The segmented parameter zones, where different regulatory portfolios dominate, reflect threshold-switching characteristics unique to dual carbon governance observed in this model.

We further align our outcomes with existing research on carbon border adjustment and cap-and-trade systems. Consistent with prior work, including Li et al. [29] and Xia and Chen [44], we observe that overly strict carbon regulatory constraints harm the long-run operational viability of remanufacturing industries, while properly allocated carbon quotas help firms balance economic gains and emission-reduction tasks under static equilibrium settings. Most available literature examines carbon tariffs or cap-and-trade regulation separately, with limited analysis of their joint interactive effects within a unified cross-border supply chain framework. This work provides an extra analytical perspective by identifying non-monotonic consumer surplus changes and segmented profit intervals under mixed carbon regulatory restraints. Moreover, few existing studies integrate both importing carbon tariffs and exporting cap-and-trade regulation into cross-border social welfare evaluation, and our cross-scenario welfare comparison offers an additional analytical reference for EU CBAM-related low-carbon trade research.

Beyond the simplifications mentioned in Section 6.3, we adopt additional restrictive assumptions to obtain solvable closed-form equilibria, which clearly define the applicable boundary of our conclusions. We fix carbon trading prices and regulatory intensity throughout the modeling process, ignoring dynamic carbon price fluctuations and adjustable quota supply in real carbon markets. All manufacturers and retailers are set as homogeneous agents, without accounting for gaps in emission efficiency, production scale, and operational capacity across market participants. Heterogeneous national carbon regulatory standards and industry-specific emission features are also excluded from the baseline model. Under such simplifications, our qualitative trends are more relevant for standardized manufacturing sectors with stable production and sound carbon management systems. All quantitative thresholds for abatement inputs, output volumes, and social welfare are highly parameter-sensitive; without targeted calibration fitting specific industries or national carbon regulations, these numerical intervals cannot be generalized to all cross-border trade contexts.

To further clarify the practical applicability of our findings in real international carbon regulatory environments such as CBAM, we note the limitations when translating these results into real regulation design. The relative welfare advantages of dual regulation will vary noticeably across countries with different regulatory stringency, industries with divergent emission intensity, volatile carbon allowance prices, and heterogeneous manufac-

turing firms. For industries with high collection costs, severe demand fluctuation or large cross-border transport expenditure, the relative performance gap between single and dual carbon regulation will deviate from the model's simulated trends.

All simplifying assumptions in this study create clear directions for subsequent research to expand and optimize the current analytical framework. Subsequent scholars can embed the full-process carbon accounting and reporting costs stipulated by the EU CBAM into enterprise cost functions to restore the real compliance burden of exporting manufacturers. Researchers can also construct game models centered on retailer and third-party remanufacturing, so as to compare divergence in emission reduction and profit performance across three remanufacturing operation modes. Further extensions can abandon the deterministic demand premise and introduce stochastic market demand, alongside time-varying, volatile carbon prices, to simulate the complex operating environment of real cross-border trade. It is also valuable to endogenize multiple redistribution schemes of carbon tariff revenue and compare their differentiated environmental and welfare benefits. In the long run, building a heterogeneous supply chain model and introducing cross-border gaps in carbon regulatory intensity will greatly improve the external validity of research conclusions for multi-industry and multinational carbon trade analysis. This study also provides a basic analytical framework for future theoretical exploration on coordinated international carbon regulation and sustainable cross-border remanufacturing supply chains.

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Appendix A

Proof. Proof of solution for the model NN.

The first-order conditions for the retailer's profit maximization are $\frac{\partial \pi_R^{NN}}{\partial p_n^{NN}} = \frac{\partial \pi_R^{NN}}{\partial p_r^{NN}} = 0$.

By substituting demands q_n^{NN} and q_r^{NN} into the profit functions π_M^{NN} and π_R^{NN}, the Hessian matrix of π_R^{NN} in terms of p_n^{NN} and p_r^{NN} is $H^{NN1} = \begin{bmatrix} \frac{-2}{1-\delta} & \frac{2}{1-\delta} \\ \frac{2}{1-\delta} & \frac{-2}{\delta(1-\delta)} \end{bmatrix}$. From the assumption $0 < \delta < 1$, it can be shown that $\left|H_1^{NN1}\right| = \frac{-2}{1-\delta} < 0$ and $\left|H_2^{NN1}\right| = \frac{4}{\delta(1-\delta)} > 0$. Therefore H^{NN1} is negative definite, and π_R^{NN} is strictly concave with respect to retail prices p_n^{NN} and p_r^{NN}. It can be obtained from $\frac{\partial \pi_R^{NN}}{\partial p_n^{NN}} = \frac{\partial \pi_R^{NN}}{\partial p_r^{NN}} = 0$ that, $p_n^{NN} = \frac{1+w_n^{NN}}{2}$ and $p_r^{NN} = \frac{\delta+w_r^{NN}}{2}$. Thus, the first-order conditions yield the unique retail prices for retail.

The first-order conditions for the manufacturer's profit maximization is $\frac{\partial \pi_M^{NN}}{\partial w_n^{NN}} = \frac{\partial \pi_M^{NN}}{\partial w_r^{NN}} = \frac{\partial \pi_M^{NN}}{\partial e^{NN}} = 0$.

By substituting p_n^{NN} and p_r^{NN} into π_M^{NN}, the Hessian matrix of π_M^{NN} with respect to w_n^{NN}, w_r^{NN} and e^{NN} is $H^{NN2} = \begin{bmatrix} \frac{-1}{1-\delta} & \frac{1}{1-\delta} & 0 \\ \frac{1}{1-\delta} & \frac{-1}{\delta(1-\delta)} & 0 \\ 0 & 0 & -1 \end{bmatrix}$. Since $\left|H_1^{NN2}\right| = \frac{-1}{1-\delta} < 0$, $\left|H_2^{NN2}\right| = \frac{1}{\delta(1-\delta)} > 0$, and $\left|H_3^{NN2}\right| = \frac{-1}{\delta(1-\delta)} < 0$, H^{NN2} is negative definite, and thus, π_M^{NN} is a strictly concave function of w_n^{NN}, w_r^{NN} and e^{NN}. It can be obtained from $\frac{\partial \pi_M^{NN}}{\partial w_n^{NN}} = \frac{\partial \pi_M^{NN}}{\partial w_r^{NN}} = \frac{\partial \pi_M^{NN}}{\partial e^{NN}} = 0$ that, $w_n^{NN*} = \frac{1+c}{2}$, $w_r^{NN*} = \frac{\delta}{2}$, and $e^{NN*} = 0$. Hence, the first-order conditions yield the unique equilibrium wholesale prices and abatement level for the manufacturer.

Substituting w_n^{NN*}, w_r^{NN*} and e^{NN*} into p_n^{NN} and p_r^{NN}, we have $p_n^{NN*} = \frac{3+c}{4}$, and $p_r^{NN*} = \frac{3\delta}{4}$.

The equilibrium is economically valid only if all key decision variables, market demands, carbon abatement level, and firm profits are non-negative. These conditions define the valid parameter region for this model. □

Appendix B

Proof. Proof of solution for the model CN.

The first-order conditions for the retailer's profit maximization are $\frac{\partial \pi_R^{CN}}{\partial p_n^{CN}} = \frac{\partial \pi_R^{CN}}{\partial p_r^{CN}} = 0$.

By substituting demands q_n^{CN} and q_r^{CN} into the profit functions π_M^{CN} and π_R^{CN}, the Hessian matrix of π_R^{CN} in terms of p_n^{CN} and p_r^{CN} is $H^{CN1} = \begin{bmatrix} \frac{-2}{1-\delta} & \frac{2}{1-\delta} \\ \frac{2}{1-\delta} & \frac{-2}{\delta(1-\delta)} \end{bmatrix}$. From the assumption $0 < \delta < 1$, it can be shown that $\left|H_1^{CN1}\right| = \frac{-2}{1-\delta} < 0$ and $\left|H_2^{CN1}\right| = \frac{4}{\delta(1-\delta)} > 0$. Therefore, H^{CN1} is negative definite, and π_R^{CN} is strictly concave with respect to retail prices p_n^{CN} and p_r^{CN}. It can be obtained from $\frac{\partial \pi_R^{CN}}{\partial p_n^{CN}} = \frac{\partial \pi_R^{CN}}{\partial p_r^{CN}} = 0$ that, $p_n^{CN} = \frac{1+w_n^{CN}}{2}$, and $p_r^{CN} = \frac{\delta+w_r^{CN}}{2}$. Thus, the first-order conditions yield the unique retail prices for retail.

The first-order conditions for the manufacturer's profit maximization is $\frac{\partial \pi_M^{CN}}{\partial w_n^{CN}} = \frac{\partial \pi_M^{CN}}{\partial w_r^{CN}} = \frac{\partial \pi_M^{CN}}{\partial e^{CN}} = 0$.

By substituting p_n^{CN} and p_r^{CN} into π_M^{CN}, the Hessian matrix of π_M^{CN} with respect to w_n^{CN}, w_r^{CN} and e^{CN} is $H^{CN2} = \begin{bmatrix} \frac{-1}{1-\delta} & \frac{1}{1-\delta} & 0 \\ \frac{1}{1-\delta} & \frac{-1}{\delta(1-\delta)} & -\frac{f}{2\delta} \\ 0 & -\frac{f}{2\delta} & -1 \end{bmatrix}$. From the assumption $0 < \delta < 1$, we have $\left|H_1^{CN2}\right| = \frac{-1}{1-\delta} < 0$, $\left|H_2^{CN2}\right| = \frac{1}{\delta(1-\delta)} > 0$, and $\left|H_3^{CN2}\right| = -\frac{4\lambda\delta - f^2}{4\delta^2(1-\delta)}$. To obtain the optimal results, we focus on the case when $4\lambda\delta - f^2 > 0$, i.e., $f^2 < 4\lambda\delta$. And thus, H^{CN2} is negative definite and π_M^{CN} is a strictly concave function of w_n^{CN}, w_r^{CN}, and e^{CN}. It can be obtained from $\frac{\partial \pi_M^{CN}}{\partial w_n^{CN}} = \frac{\partial \pi_M^{CN}}{\partial w_r^{CN}} = \frac{\partial \pi_M^{CN}}{\partial e^{CN}} = 0$ that $w_n^{CN*} = \frac{4\lambda\delta(1+c+fe_n) - f^2(1+\delta+c+fe_n-\beta fe_n)}{2(4\lambda\delta - f^2)}$, $w_r^{CN*} = \frac{\delta(2\lambda(\delta+\beta fe_n) - f^2)}{4\lambda\delta - f^2}$, and $e^{CN*} = \frac{f(\delta - \beta fe_n)}{4\lambda\delta - f^2}$. Hence, the first-order conditions yield the unique equilibrium wholesale prices and abatement level for the manufacturer.

Substituting w_n^{CN*}, w_r^{CN*} and e^{CN*} into p_n^{CN} and p_r^{CN}, we have $p_n^{CN*} = \frac{4\lambda\delta(3+c+fe_n) - f^2(3+\delta+c+fe_n-\beta fe_n)}{4(4\lambda\delta - f^2)}$ and $p_r^{CN*} = \frac{\delta(\lambda(3\delta+\beta fe_n) - f^2)}{4\lambda\delta - f^2}$. In this case, the assumption $e_n < \frac{\delta}{\beta f}$ is needed to ensure that the carbon abatement level e^{CN*} is positive.

The equilibrium is economically valid only if all key decision variables, market demands, carbon abatement level, and firm profits are non-negative. These conditions define the valid parameter region for this model. □

Appendix C

Proof. Proof of solution for the model NT.

The first-order conditions for the retailer's profit maximization is $\frac{\partial \pi_R^{NT}}{\partial p_n^{NT}} = \frac{\partial \pi_R^{NT}}{\partial p_r^{NT}} = 0$.

By substituting demands q_n^{NT} and q_r^{NT} into the profit functions π_M^{NT} and π_R^{NT}, the Hessian matrix of π_R^{NT} in terms of p_n^{NT} and p_r^{NT} is $H^{NT1} = \begin{bmatrix} \frac{-2}{1-\delta} & \frac{2}{1-\delta} \\ \frac{2}{1-\delta} & \frac{-2}{\delta(1-\delta)} \end{bmatrix}$. From the assumption $0 < \delta < 1$, it can be shown that $\left|H_1^{NT1}\right| = \frac{-2}{1-\delta} < 0$ and $\left|H_2^{NT1}\right| = \frac{4}{\delta(1-\delta)} > 0$. Therefore, H^{NT1} is negative definite, and π_R^{NT} is strictly concave with respect to retail prices p_n^{NT} and p_r^{NT}. It can be obtained from $\frac{\partial \pi_R^{NT}}{\partial p_n^{NT}} = \frac{\partial \pi_R^{NT}}{\partial p_r^{NT}} = 0$ that, $p_n^{NT} = \frac{1+w_n^{NT}}{2}$ and $p_r^{NT} = \frac{\delta+w_r^{NT}}{2}$. Thus, the first-order conditions yield the unique retail prices for retail.

The first-order conditions for the manufacturer's profit maximization is $\frac{\partial \pi_M^{NT}}{\partial w_n^{NT}} = \frac{\partial \pi_M^{NT}}{\partial w_r^{NT}} = \frac{\partial \pi_M^{NT}}{\partial e^{NT}} = 0$.

By substituting p_n^{NT} and p_r^{NT} into π_M^{NT}, the Hessian matrix of π_M^{NT} with respect to w_n^{NT}, w_r^{NT} and e^{NT} is $H^{NT2} = \begin{bmatrix} \frac{-1}{1-\delta} & \frac{1}{1-\delta} & 0 \\ \frac{1}{1-\delta} & \frac{-1}{\delta(1-\delta)} & \frac{-b}{2\delta} \\ 0 & \frac{-b}{2\delta} & -1 \end{bmatrix}$. Since $\left|H_1^{NT2}\right| = \frac{-1}{1-\delta} < 0$, $\left|H_2^{NT2}\right| = \frac{1}{\delta(1-\delta)} > 0$, and $\left|H_3^{NT2}\right| = -\frac{4\lambda\delta-b^2}{4\delta^2(1-\delta)}$. We only focus on the case $b^2 < 4\lambda\delta$, then we obtain H^{NT2} is negative definite and π_M^{NT} is a strictly concave function of w_n^{NT}, w_r^{NT} and e^{NT}. It can be obtained from $\frac{\partial \pi_M^{NT}}{\partial w_n^{NT}} = \frac{\partial \pi_M^{NT}}{\partial w_r^{NT}} = \frac{\partial \pi_M^{NT}}{\partial e^{NT}} = 0$ that $w_n^{NT*} = \frac{4\delta(1+c+be_n-bh)\lambda-b^2(1+c+\delta+be_n-\beta be_n)}{2(4\lambda\delta-b^2)}$, $w_r^{NT*} = \frac{\delta(2\lambda(\delta+\beta be_n-bh)-b^2)}{4\lambda\delta-b^2}$, and $e^{NT*} = \frac{b(\delta-\beta be_n+bh)}{4\lambda\delta-b^2}$. Hence, the first-order conditions yield the unique equilibrium wholesale prices and abatement level for the manufacturer.

Substituting w_n^{NT*}, w_r^{NT*} and e^{NT*} into p_n^{NT} and p_r^{NT}, we have $p_n^{NT*} = \frac{4\delta(3+c+be_n-bh)\lambda-b^2(1+\delta+c+be_n-\beta be_n)}{4(4\lambda\delta-b^2)}$, and $p_r^{NT*} = \frac{\delta(\beta\lambda be_n+3\lambda\delta-b^2-bh)}{4\lambda\delta-b^2}$. In this case, the assumption $e_n < \frac{\delta+bh}{\beta b}$ is needed to ensure that the carbon abatement level e^{NT*} is positive.

The equilibrium is economically valid only if all key decision variables, market demands, carbon abatement level, and firm profits are non-negative. These conditions define the valid parameter region for this model. □

Appendix D

Proof. Proof of solution for model CT.

To simplify the derivation of equilibrium outcomes, we first define the auxiliary polynomial terms F_3, F_4, F_5, F_6, F_7 and F_8 as follows:

$$F_3 = (\phi_1 + f\psi - (1-\beta)e_n f)(2bf(\phi_1 + f\psi) - 2(1-\beta)e_n b^3),$$

$$F_4 = \delta((1-c)^2 - (1-2c)\delta) - 2\delta(\phi_2 + \beta c)fe_n + (\beta^2 + \delta - 2\beta\delta)f^2 {e_n}^2,$$

$$F_5 = e_n\lambda(e_n f(\beta^2 + \delta - 2\beta\delta) - \delta(\beta c + \phi_2)) + (1-\delta)(\delta - \beta e_n f)h,$$

$$F_6 = \begin{array}{c} 1 + c^2 + \delta^2 - 2c(1 - \delta - 3fe_n + 3\beta fe_n) - 6fe_n(1-\beta)(1 - fe_n + \beta fe_n) \\ -4(fe_n - h)^2\lambda + 2\delta(3fe_n - 3\beta fe_n - 2(e_n - h)(e_n - 2fe_n + h)\lambda - 1) \end{array},$$

$$F_7 = (b+f)^2(e_n(1-\beta)(b+f) - \phi_2) - 4\delta\lambda(c + e_n(b+f) - bh - 1),$$

and

$$F_8 = (b+f)^2(\phi_1 + f\psi - be_n(1-\beta)) + 4\lambda(c\delta - e_n(\beta-\delta)(b+f) + bh(1-\delta)),$$

based on the above auxiliary expressions, we adopt backward induction to solve the Stackelberg game of model CT, and derive the closed-form optimal equilibrium results listed in Table 6 of the main text. The detailed backward induction solution steps are presented below.

The first-order conditions for the retailer's profit maximization is $\frac{\partial \pi_R^{CT}}{\partial p_n^{CT}} = \frac{\partial \pi_R^{CT}}{\partial p_r^{CT}} = 0$.

By substituting demands q_n^{CT} and q_r^{CT} into the profit functions π_M^{CT} and π_R^{CT}, the Hessian matrix of π_R^{CT} in terms of p_n^{CT} and p_r^{CT} is $H^{CT1} = \begin{bmatrix} \frac{-2}{1-\delta} & \frac{2}{1-\delta} \\ \frac{2}{1-\delta} & \frac{-2}{\delta(1-\delta)} \end{bmatrix}$. From the assumption $0 < \delta < 1$, it can be shown that $\left|H_1^{CT1}\right| = \frac{-2}{1-\delta} < 0$ and $\left|H_2^{CT1}\right| = \frac{4}{\delta(1-\delta)} > 0$. Therefore H^{CT1} is negative definite, and π_R^{CT} is strictly concave with respect to retail prices p_n^{CT} and p_r^{CT}. It can be obtained from $\frac{\partial \pi_R^{CT}}{\partial p_n^{CT}} = \frac{\partial \pi_R^{CT}}{\partial p_r^{CT}} = 0$ that $p_n^{CT} = \frac{1+w_n^{CT}}{2}$ and $p_r^{CT} = \frac{\delta+w_r^{CT}}{2}$. Thus, the first-order conditions yield the unique retail prices for retail.

The first-order conditions for the manufacturer's profit maximization is $\frac{\partial \pi_M^{CT}}{\partial w_n^{CT}} = \frac{\partial \pi_M^{CT}}{\partial w_r^{CT}} = \frac{\partial \pi_M^{CT}}{\partial e^{CT}} = 0$.

By substituting p_n^{CT} and p_r^{CT} into π_M^{CT}, the Hessian matrix of π_M^{CT} with respect to w_n^{CT}, w_r^{CT} and e^{CT} is $H^{CT2} = \begin{bmatrix} \frac{-1}{1-\delta} & \frac{1}{1-\delta} & 0 \\ \frac{1}{1-\delta} & \frac{-1}{\delta(1-\delta)} & \frac{-(b+f)}{2\delta} \\ 0 & \frac{-(b+f)}{2\delta} & -1 \end{bmatrix}$. Since $\left|H_1^{CT2}\right| = \frac{-1}{1-\delta} < 0$, $\left|H_2^{CT2}\right| = \frac{1}{\delta(1-\delta)} > 0$, and $\left|H_3^{CT2}\right| = \frac{4\lambda\delta-(b+f)^2}{4\delta^2(\delta-1)}$. We only focus on the case when $(f+b)^2 < 4\lambda\delta$, obtain H^{CT2} is negative definite, and π_M^{CT} is a strictly concave function of w_n^{CT}, w_r^{CT}, and e^{CT}. It can be obtained from $\frac{\partial \pi_M^{CT}}{\partial w_n^{CT}} = \frac{\partial \pi_M^{CT}}{\partial w_r^{CT}} = \frac{\partial \pi_M^{CT}}{\partial e^{CT}} = 0$ that

$$w_n^{CT*} = \frac{4\lambda\delta(1+c-bh+(f+b)e_n) - (f+b)^2(1+\delta+c+(1-\beta)(f+b)e_n)}{2(4\lambda\delta-(f+b)^2)},$$

$$w_r^{CT*} = \frac{\delta(2\lambda(\delta-bh+\beta(f+b)e_n)-(f+b)^2)}{4\lambda\delta-(f+b)^2}$$

and

$$e^{CT*} = \frac{(f+b)(\delta+bh-\beta(f+b)e_n)}{4\lambda\delta-(f+b)^2}.$$

Hence, the first-order conditions yield the unique equilibrium wholesale prices and abatement level for the manufacturer.

Substituting w_n^{CT}, w_r^{CT} and e^{CT} into p_n^{CT} and p_r^{CT}, we have $p_n^{CT*} = \frac{4\lambda\delta(3+c-bh+(f+b)e_n)-(f+b)^2(3+\delta+c+(1-\beta)(f+b)e_n)}{4(4\lambda\delta-(f+b)^2)}$, and $p_r^{CT*} = \frac{\lambda\delta(3\delta-bh+\beta(b+f)e_n)-\delta(b+f)^2}{4\lambda\delta-(b+f)^2}$. In this case, the assumption $e_n < \frac{\delta+bh}{\beta(f+b)}$ is needed to ensure that the carbon abatement level e^{CT*} is positive. □

The equilibrium is economically valid only if all key decision variables, market demands, carbon abatement level, and firm profits are non-negative. These conditions define the valid parameter region for this model.

Appendix E

Proof of Proposition 1. From the assumptions $f^2 < 4\lambda\delta$ and $e_n < \frac{\delta}{\beta f}$, by analyzing the effect of carbon tariff rate f on the optimal decisions of CBSC members in the model CN, it is derived that

(1)

$$\frac{\partial w_n^{CN*}}{\partial f} = \frac{((4\lambda\delta - f^2)^2 + \beta f^2(12\lambda\delta - f^2))e_n - 8\lambda\delta^2 f}{2(4\lambda\delta - f^2)^2},$$

$$\frac{\partial p_n^{CN*}}{\partial f} = \frac{((4\lambda\delta - f^2)^2 + \beta f^2(12\lambda\delta - f^2))e_n - 8\lambda\delta^2 f}{4(4\lambda\delta - f^2)^2}.$$

If $\frac{8\lambda\delta^2 f}{(4\lambda\delta - f^2)^2 + \beta f^2(12\lambda\delta - f^2)} < e_n < \frac{\delta}{\beta f}$, then $\frac{\partial w_n^{CN*}}{\partial f} > \frac{\partial p_n^{CN*}}{\partial f} > 0$;

if $e_n \leq \frac{8\lambda\delta^2 f}{(4\lambda\delta - f^2)^2 + \beta f^2(12\lambda\delta - f^2)}$, then $\frac{\partial w_n^{CN*}}{\partial f} \leq \frac{\partial p_n^{CN*}}{\partial f} \leq 0$;

(2) $\frac{\partial w_r^{CN*}}{\partial f} = \frac{2\lambda\delta(\beta(4\lambda\delta + f^2)e_n - 2\delta f)}{(4\lambda\delta - f^2)^2}$, $\frac{\partial p_r^{CN*}}{\partial f} = \frac{\lambda\delta(\beta(4\lambda\delta + f^2)e_n - 2\delta f)}{(4\lambda\delta - f^2)^2}$.

If $\frac{2\delta f}{\beta(4\lambda\delta + f^2)} < e_n < \frac{\delta}{\beta f}$, then $\frac{\partial w_r^{CN*}}{\partial f} > \frac{\partial p_r^{CN*}}{\partial f} > 0$; if $e_n \leq \frac{2\delta f}{\beta(4\lambda\delta + f^2)}$, then $\frac{\partial w_r^{CN*}}{\partial f} \leq \frac{\partial p_r^{CN*}}{\partial f} \leq 0$;

(3) $\frac{\partial e^{CN*}}{\partial f} = \frac{\delta(4\lambda\delta + f^2 - 8\lambda\beta f e_n)}{(4\lambda\delta - f^2)^2}$, if $e_n < \frac{4\lambda\delta + f^2}{8\lambda\beta f}$, then $\frac{\partial e^{CN*}}{\partial f} > 0$; if $\frac{4\lambda\delta + f^2}{8\lambda\beta f} \leq e_n < \frac{\delta}{\beta f}$, then $\frac{\partial e^{CN*}}{\partial f} \leq 0$. □

Appendix F

Proof of Proposition 2. From the assumptions $b^2 < 4\lambda\delta$ and $(b + f)^2 < 4\lambda\delta$, by analyzing the effect of the carbon quota h on the optimal decisions of CBSC members in the models NT and CT, it is derived that

(1) $\frac{\partial w_n^{CT*}}{\partial h} = \frac{\partial w_r^{CT*}}{\partial h} = -\frac{2\lambda\delta b}{4\lambda\delta - (f+b)^2} < \frac{\partial w_n^{NT*}}{\partial h} = \frac{\partial w_r^{NT*}}{\partial h} = -\frac{2\lambda\delta b}{4\lambda\delta - b^2} < 0$;

(2) $\frac{\partial p_n^{CT*}}{\partial h} = \frac{\partial p_r^{CT*}}{\partial h} = -\frac{\lambda\delta b}{4\lambda\delta - (f+b)^2} < \frac{\partial p_n^{NT*}}{\partial h} = \frac{\partial p_r^{NT*}}{\partial h} = -\frac{\lambda\delta b}{4\lambda\delta - b^2} < 0$;

(3) $\frac{\partial e^{CT*}}{\partial h} = \frac{b(f+b)}{4\lambda\delta - (f+b)^2} > \frac{\partial e^{NT*}}{\partial h} = \frac{b^2}{4\lambda\delta - b^2} > 0$.

□

Appendix G

Proof of Proposition 3. From the assumptions $f^2 < 4\lambda\delta$, $0 < \beta < \delta < 1$, and $e_n < \frac{\delta}{\beta f}$, by comparing the optimal decision results between the models NN and CN, it can be verified that

(1) $e^{CN*} - e^{NN*} = \frac{f(\delta - f\beta e_n)}{4\lambda\delta - f^2} > 0$;

(2) $w_n^{CN*} - w_n^{NN*} = \frac{f(4\lambda\delta e_n - (1-\beta)e_n f^2 - \delta f)}{2(4\lambda\delta - f^2)}$, $p_n^{CN*} - p_n^{NN*} = \frac{f(4\lambda\delta e_n - (1-\beta)e_n f^2 - \delta f)}{4(4\lambda\delta - f^2)}$,

if $\frac{\delta f}{4\lambda\delta - (1-\beta)f^2} < e_n < \frac{\delta}{\beta f}$, then $w_n^{CN*} - w_n^{NN*} > p_n^{CN*} - p_n^{NN*} > 0$; otherwise, $w_n^{CN*} - w_n^{NN*} \leq p_n^{CN*} - p_n^{NN*} \leq 0$;

(3) $w_r^{CN*} - w_r^{NN*} = \frac{\delta f(4\lambda\beta e_n - f)}{2(4\lambda\delta - f^2)}$, $p_r^{CN*} - p_r^{NN*} = \frac{\delta f(4\lambda\beta e_n - f)}{4(4\lambda\delta - f^2)}$.

If $\frac{f}{4\lambda\beta} < e_n < \frac{\delta}{\beta f}$, then $w_r^{CN*} - w_r^{NN*} > p_r^{CN*} - p_r^{NN*} > 0$; otherwise, $w_r^{CN*} - w_r^{NN*} \leq p_r^{CN*} - p_r^{NN*} \leq 0$;

(4) $q_n^{CN*} - q_n^{NN*} = -\frac{(1-\beta)fe_n}{4(1-\delta)} < 0$, $q_r^{CN*} - q_r^{NN*} = \frac{f((4\lambda(\delta-\beta) - (1-\beta)f^2)e_n + (1-\delta)f)}{4(1-\delta)(4\lambda\delta - f^2)}$,

when $f^2 < \frac{4\lambda(\delta-\beta)}{1-\beta} < 4\lambda\delta$, then $q_r^{CN*} - q_r^{NN*} > 0$; when $\frac{4\lambda(\delta-\beta)}{1-\beta} < f^2 < 4\lambda\delta$, since $e_n < \frac{\delta}{\beta f}$, then $(4\lambda(\delta-\beta) - (1-\beta)f^2)e_n + (1-\delta)f > (1-\delta)f - \frac{\delta((1-\beta)f^2 - 4\lambda(\delta-\beta))}{\beta f} = \frac{(4\lambda\delta - f^2)(\delta-\beta)}{\beta f} > 0$, i.e., $q_r^{CN*} - q_r^{NN*} > 0$. □

Appendix H

Proof of Proposition 4. From the assumptions $b^2 < 4\lambda\delta$, $0 < \beta < \delta < 1$, and $e_n < \frac{\delta+bh}{\beta b}$, by comparing the optimal decision results between the models NN and NT, it can be verified that

(1) $e^{NT*} - e^{NN*} = \frac{\delta+bh-\beta be_n}{4\lambda\delta-b^2} > 0$;

(2) $w_n^{NT*} - w_n^{NN*} = \frac{b(4\lambda\delta e_n-(1-\beta)b^2e_n-b\delta-4\lambda\delta h)}{2(4\lambda\delta-b^2)}$,

$p_n^{NT*} - p_n^{NN*} = \frac{b(4\lambda\delta e_n-(1-\beta)b^2e_n-b\delta-4\lambda\delta h)}{4(4\lambda\delta-b^2)}$ if $\frac{\delta b+4\lambda\delta h}{4\lambda\delta-(1-\beta)b^2} < e_n < \frac{\delta+bh}{\beta b}$, then $w_n^{NT*} - w_n^{NN*} > p_n^{NT*} - p_n^{NN*} > 0$; otherwise, $w_n^{NT*} - w_n^{NN*} \le p_n^{NT*} - p_n^{NN*} \le 0$;

(3) $w_r^{NT*} - w_r^{NN*} = \frac{b\delta(4\lambda\beta e_n-b-4\lambda h)}{2(4\lambda\delta-b^2)}$, $p_r^{NT*} - p_r^{NN*} = \frac{b\delta(4\lambda\beta e_n-b-4\lambda h)}{4(4\lambda\delta-b^2)}$.

If $\frac{b+4\lambda h}{4\lambda\beta} < e_n < \frac{\delta+bh}{\beta b}$, then $w_r^{NT*} - w_r^{NN*} > p_r^{NT*} - p_r^{NN*} > 0$; otherwise, $w_r^{NT*} - w_r^{NN*} \le p_r^{NT*} - p_r^{NN*} \le 0$;

(4) $q_n^{NT*} - q_n^{NN*} = \frac{(1-\beta)be_n}{4(1-\delta)} > 0$; $q_r^{NT*} - q_r^{NN*} = \frac{b(((1-\beta)b^2-4\lambda(\delta-\beta))e_n-(1-\delta)(4\lambda h+b))}{4(1-\delta)(4\lambda\delta-b^2)}$, if $b^2 < \frac{4\lambda(\delta-\beta)}{1-\beta} < 4\lambda\delta$, then $q_r^{NT*} - q_r^{NN*} < 0$; if $\frac{4\lambda(\delta-\beta)}{1-\beta} < b^2 < 4\lambda\delta$, since $e_n < \frac{\delta+bh}{\beta b}$, then

$$((1-\beta)b^2-4\lambda(\delta-\beta))e_n-(1-\delta)(4\lambda h+b) < ((1-\beta)b^2-4\lambda(\delta-\beta))\frac{\delta+bh}{\beta b}-(1-\delta)(4\lambda h+b) = -\frac{(4\lambda\delta-b^2)(\delta-\beta+(1-\beta)bh)}{\beta b} < 0\ ,$$

i.e., $q_r^{NT*} - q_r^{NN*} < 0$. □

Appendix I

Proof of Proposition 5. From the assumptions $(f+b)^2 < 4\lambda\delta$, $0 < \beta < \delta < 1$, and $e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, by comparing the optimal decision results between the models CT and CN, it can be verified that

(1) $e^{CT*} - e^{CN*} = \frac{b((4\lambda\delta-f^2)(f+b)h+4\lambda\delta^2+\delta f(f+b)-4\lambda\delta\beta(2f+b)e_n)}{(4\lambda\delta-f^2)(4\lambda\delta-(f+b)^2)}$,

if $\frac{(4\lambda\delta-f^2)(f+b)h+4\lambda\delta^2+\delta f(f+b)}{4\lambda\delta\beta(2f+b)} < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $e^{CT*} - e^{CN*} < 0$;

if $e_n \le \frac{(4\lambda\delta-f^2)(f+b)h+4\lambda\delta^2+\delta f(f+b)}{4\lambda\delta\beta(2f+b)}$, then $e^{CT*} - e^{CN*} \ge 0$;

(2)

$$w_n^{CT*} - w_n^{CN*} = \frac{b((e_n((2(1-\beta)f^3-4f\delta(2-3\beta)f-(1-\beta)(4\lambda\delta-f^2)b^2)b + 16\lambda^2\delta^2-4\lambda\delta(2-3\beta)f+(1-\beta)f^4)-4\lambda\delta^2(2f+b))-4\lambda\delta(4\lambda\delta-f^2)h)}{2(4\lambda\delta-f^2)(4\lambda\delta-(f+b)^2)},$$

$$p_n^{CT*} - p_n^{CN*} = \frac{b((e_n((2(1-\beta)f^3-4f\delta(2-3\beta)f-(1-\beta)(4\lambda\delta-f^2)b^2)b + 16\lambda^2\delta^2-4\lambda\delta(2-3\beta)f+(1-\beta)f^4)-4\lambda\delta^2(2f+b))-4\lambda\delta(4\lambda\delta-f^2)h)}{2(4\lambda\delta-f^2)(4\lambda\delta-(f+b)^2)}.$$

If $\frac{4\lambda(h\delta(4\delta\lambda-f^2)+\delta^2(b+2f))}{(1-\beta)(f^2(b+f)^2-4b^2\delta\lambda)+16\delta^2\lambda^2-4f(bf+\lambda)\delta(2-3\beta)} < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $w_n^{CT*} - w_n^{CN*} = p_n^{CT*} - p_n^{CN*} < 0$;

if $e_n \le \frac{4\lambda(h\delta(4\delta\lambda-f^2)+\delta^2(b+2f))}{(1-\beta)(f^2(b+f)^2-4b^2\delta\lambda)+16\delta^2\lambda^2-4f(bf+\lambda)\delta(2-3\beta)}$, then $w_n^{CT*} - w_n^{CN*} = p_n^{CT*} - p_n^{CN*} \ge 0$;

(3)

$$w_r^{CT*} - w_r^{CN*} = \frac{2\lambda\delta b(\beta e_n(4\lambda\delta+f^2+bf)-\delta(2f+b)-(4\lambda\delta-f^2)h)}{(4\lambda\delta-f^2)(4\lambda\delta-(f+b)^2)},$$

$$p_r^{CT*} - p_r^{CN*} = \frac{\lambda\delta b(\beta e_n(4\lambda\delta+f^2+bf)-\delta(2f+b)-(4\lambda\delta-f^2)h)}{(4\lambda\delta-f^2)(4\lambda\delta-(f+b)^2)}.$$

If $\frac{b\delta-hf^2+2\delta(f+2h\lambda)}{\beta f(b+f)+4\delta\lambda\beta} < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $w_r^{CT*} - w_r^{CN*} > p_r^{CT*} - p_r^{CN*} > 0$; if $e_n \le \frac{b\delta-hf^2+2\delta(f+2h\lambda)}{\beta f(b+f)+4\delta\lambda\beta}$, then $w_r^{CT*} - w_r^{CN*} \le p_r^{CT*} - p_r^{CN*} \le 0$;

(4) $q_n^{CT*} - q_n^{CN*} = -\frac{(1-\beta)be_n}{4(1-\delta)} < 0$;

$$q_r^{CT*} - q_r^{CN*} = \frac{\begin{array}{l} b(4\lambda(1-\delta)(4\lambda\delta-f^2)h+4\lambda\delta(1-\delta)(2f+b)) \\ -e_nb(f^2(b+f)^2(1-\beta)+16\delta(\delta-\beta)\lambda^2-4\beta\lambda f(b+f)-4\delta\lambda(b^2(1-\beta)+f(b+f)(2-3\beta))) \end{array}}{4(1-\delta)(4\lambda\delta-f^2)(4\lambda\delta-(f+b)^2)},$$

if $\frac{4(b+2f)\lambda\delta(1-\delta)+4h(4\delta\lambda-f^2)\lambda(1-\delta)}{f^2(b+f)^2(1-\beta)-4\beta\lambda f(b+f)+16\lambda^2\delta(\delta-\beta)-4\delta\lambda(b^2(1-\beta)+(2-3\beta)f(b+f))} < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $q_r^{CT*} - q_r^{CN*} <$; otherwise, $q_r^{CT*} - q_r^{CN*} \ge 0$. □

Appendix J

Proof of Proposition 6. From the assumptions $(f+b)^2 < 4\lambda\delta$, $0 < \beta < \delta < 1$, and $e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, by comparing the optimal decision results between the models CT and NT, it can be verified that

(1) $e^{CT*} - e^{NT*} = \frac{bf(b+f)(\delta+bh)+4\lambda\delta^2f+4\lambda\delta fbh-4\lambda\delta\beta f(2b+f)e_n}{(4\lambda\delta-b^2)(4\lambda\delta-(b+f)^2)}$,

if $\frac{bf(b+f)(\delta+bh)+4\lambda\delta^2f+4\lambda\delta fbh}{4\lambda\delta\beta f(2b+f)} < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $e^{CT*} - e^{NT*} < 0$;

if $e_n \le \frac{bf(b+f)(\delta+bh)+4\lambda\delta^2f+4\lambda\delta fbh}{4\lambda\delta\beta f(2b+f)}$, then $e^{CT*} - e^{NT*} \ge 0$;

(2)

$$w_n^{CT*} - w_n^{NT*} = \frac{\begin{array}{l} f\left(8b\delta^2\lambda+4\delta^2f\lambda+8b^2h\delta\lambda+4bfh\lambda\delta\right) \\ +e_nf\left(\begin{array}{l} \beta b^4-b^4+8b^2\lambda\delta-12\beta b^2\delta\lambda-16\lambda^2\delta^2 \\ +f^2\left(\beta b^2-b^2+4\delta\lambda-4\beta\delta\lambda\right)+f\left(2\beta b^3-2b^3+8b\delta\lambda-12\beta b\delta\lambda\right) \end{array}\right) \end{array}}{2(b^2+2bf+f^2-4\delta\lambda)(4\delta\lambda-b^2)},$$

$$p_n^{CT*} - p_n^{NT*} = \frac{\begin{array}{l} f\left(8b\delta^2\lambda+4\delta^2f\lambda+8b^2h\delta\lambda+4bfh\lambda\delta\right) \\ +e_nf\left(\begin{array}{l} \beta b^4-b^4+8b^2\lambda\delta-12\beta b^2\delta\lambda-16\lambda^2\delta^2 \\ +f^2\left(\beta b^2-b^2+4\delta\lambda-4\beta\delta\lambda\right)+f\left(2\beta b^3-2b^3+8b\delta\lambda-12\beta b\delta\lambda\right) \end{array}\right) \end{array}}{2(b^2+2bf+f^2-4\delta\lambda)(4\delta\lambda-b^2)}.$$

If $\frac{4\delta\left(2b^2h+2b\delta+f\delta\right)\lambda+4bfh\lambda\delta}{b^4(1-\beta)-4b^2(2-3\beta)\delta\lambda+16\delta^2\lambda^2+f(2b^3(1-\beta)-4b(2-3\beta)\delta\lambda)-f^2((1-\beta)(4\delta\lambda-b^2))} < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $w_n^{CT*} - w_n^{NT*} = p_n^{CT*} - p_n^{NT*} > 0$;

if $e_n \le \frac{4\delta\left(2b^2h+2b\delta+f\delta\right)\lambda+4bfh\lambda\delta}{b^4(1-\beta)-4b^2(2-3\beta)\delta\lambda+16\delta^2\lambda^2+f(2b^3(1-\beta)-4b(2-3\beta)\delta\lambda)-f^2((1-\beta)(4\delta\lambda-b^2))}$, then $w_n^{CT*} - w_n^{NT*} = p_n^{CT*} - p_n^{NT*} \le 0$;

(3)

$$w_r^{CT*} - w_r^{NT*} = \frac{2f\delta\lambda(bf(\beta e_n-h)+b^2(\beta e_n-h)+\delta(4\beta e_n\lambda-f)-2b\delta)}{(4\delta\lambda-b^2)(4\delta\lambda-(b+f)^2)},$$

$$p_r^{CT*} - p_r^{NT*} = \frac{f\delta\lambda(b^2(\beta e_n-2h)+b(\beta e_nf-2\delta-fh)-\delta(f-4\beta e_n\lambda))}{(4\delta\lambda-b^2)(4\delta\lambda-(b+f)^2)},$$

when $\beta < \frac{b^2}{2b+f}$, we have $e_n = \frac{2b\delta+\delta f+2b^2h+bfh}{b(b^2+bf+4\delta\lambda)} = \frac{(2b+f)(\delta+bh)}{b(b^2+bf+4\delta\lambda)} < \frac{(2b+f)(\delta+bh)}{b^2(f+b)} < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$,

if $\frac{2b\delta+\delta f+2b^2h+bfh}{b(b^2+bf+4\delta\lambda)} < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$, then $w_r^{CT*} - w_r^{NT*} > p_r^{CT*} - p_r^{NT*} > 0$; if $e_n \le \frac{2b\delta+\delta f+2b^2h+bfh}{b(b^2+bf+4\delta\lambda)}$, then $w_r^{CT*} - w_r^{NT*} \le p_r^{CT*} - p_r^{NT*} \le 0$;

(4) $q_n^{CT*} - q_n^{NT*} = -\frac{e_n f(1-\beta)}{4(1-\delta)} < 0$;

$$q_r^{CT*} - q_r^{NT*} = \frac{\begin{array}{c}4f(1-\delta)(2b+f)(\delta+bh)\lambda - e_n f(f^2(4\delta\lambda - b^2)(1-\beta) \\ +f(4\beta b\lambda + 4(2-3\beta)b\delta\lambda - 2(1-\beta)b^3) - (1-\beta)b^4 + 4b^2\lambda(\beta+\delta(2-3\beta)) - 16(\delta-\beta)\delta\lambda^2)\end{array}}{4(1-\delta)(4\delta\lambda-b^2)(4\delta\lambda-(b+f)^2)},$$

if $\frac{4(2b+f)(bh+\delta)\lambda f(1-\delta)}{f^2(4b\beta\lambda+4b(2-3\beta)\delta\lambda-2b^3(1-\beta))+f^3(1-\beta)(4\delta\lambda-b^2)+4f(4(\beta-\delta)\delta\lambda^2+b^2\lambda(\beta+\delta(2-3\beta)))-b^4f(1-\beta)} < e_n < \min\{\frac{\delta}{\beta f}, \frac{\delta+bh}{\beta(f+b)}\}$,

then $q_r^{CT*} - q_r^{NT*} < 0$; otherwise $q_r^{CT*} - q_r^{NT*} \geq 0$. □

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