

Integrating ESG into remanufacturing: third-party model selection aligned with consumer eco-consciousness under the carbon cap-and-trade policy

Zhangwei Feng  · Na Luo  · Thuy-Tien Nguyen · Guiping Li

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Abstract

As global efforts to reduce carbon emissions intensify, manufacturers face increasing pressure to integrate environmental sustainability into their supply chain strategies. Carbon cap-and-trade policies have become an important market-based mechanism for reducing emissions while creating economic incentives for sustainable production. Unlike existing studies that primarily examine remanufacturing operations or carbon policies separately, this study develops an ESG-oriented closed-loop supply chain model to investigate how manufacturers choose between outsourcing and authorization third-party remanufacturing (3PR) models under carbon cap-and-trade regulation and heterogeneous consumer green preferences. The model jointly captures the strategic interactions among manufacturers, third-party remanufacturers, consumers, and the government, providing a comprehensive framework for sustainable remanufacturing decisions. The results generate several important insights. First, the authorization model leads to higher remanufactured product prices and recycling rates but lower demand for remanufactured products than the outsourcing model. Second, stronger consumer green preferences increase the profitability of both manufacturers and 3PRs, but they affect the two parties' preferred remanufacturing models differently: manufacturers increasingly favor authorization, whereas 3PRs prefer outsourcing. Third, carbon cap-and-trade policies significantly reshape model selection. Preference alignment between manufacturers and 3PRs occurs only under sufficiently asymmetric carbon quotas, while intermediate quota allocations create strategic conflicts, highlighting the importance of policy design. Finally, although manufacturers may benefit more from authorization under strong consumer green preferences, the outsourcing model consistently generates higher social welfare, suggesting a potential divergence between private incentives and societal objectives. These findings provide actionable insights for firms seeking to integrate ESG strategies into remanufacturing decisions and for policymakers designing carbon-quota trading schemes that balance corporate incentives, environmental sustainability, and social welfare.

Introduction

Supply chain carbon emissions have emerged as a critical global challenge (Wang et al., 2024; Kim et al., 2024), particularly in the manufacturing sector, where carbon emissions and waste management are closely intertwined (Chen et al., 2024; Pakseresht et al., 2020). These challenges have become increasingly important in light of the

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growing emphasis on Environmental, Social, and Governance (ESG) criteria, which are reshaping both corporate strategies and consumer decision-making (Bala et al., 2025). In particular, the environmental dimension of ESG encourages firms to reduce emissions, improve resource efficiency, and promote sustainable production (Okuyama et al., 2025; Omonijo and Zhang, 2025).

The urgency of these challenges is reflected in the rapidly increasing volume of manufacturing waste. According to the WEEE Forum (2024), 5.3 billion electronic devices, including mobile phones, were discarded worldwide in 2022, equivalent to 169 devices every second. Global electronic waste is projected to reach 74.7 million metric tons by 2030 (Rajesh et al., 2022). Improper disposal of end-of-life products releases hazardous substances, such as heavy metals, posing significant risks to both environmental quality and human health (Madaka et al., 2022; Islam et al., 2020). Consequently, recycling initiatives and related environmental policies have become increasingly important for addressing these sustainability challenges (Ahmed et al., 2024; Zwicker et al., 2023; Ghobakhloo et al., 2021). For example, China's 14th Five-Year Plan for Circular Economy Development emphasizes resource efficiency, carbon neutrality, and circular economy practices as key components of sustainable industrial development.

Against this backdrop, the circular economy has emerged as an effective approach for reducing waste and carbon emissions through reuse, recycling, and remanufacturing. Among these approaches, remanufacturing has attracted considerable attention because it simultaneously conserves resources, extends product life cycles, and reduces environmental impacts (Zhang et al., 2021; Almahri and An, 2025). Remanufactured products can cost approximately half as much as new products while reducing pollution, including carbon emissions, by up to 80% (Eco-cycle, 2025). Consequently, remanufacturing not only reduces production costs and life-cycle emissions but also supports broader ESG objectives by improving waste management, creating employment opportunities, and enhancing consumer welfare (Li et al., 2016).

In practice, many manufacturers increasingly outsource non-core recycling, remanufacturing, and resale activities to specialized third-party recyclers or remanufacturers (3PRs). This trend has given rise to two distinct third-party remanufacturing models: outsourcing and authorization (Feng et al., 2021, 2023; Zou et al., 2016). Under the outsourcing model, manufacturers delegate recycling and remanufacturing activities to a 3PR before repurchasing the remanufactured products for resale, as exemplified by Caterpillar's remanufacturing services for Land Rover. Under the authorization model, manufacturers additionally authorize the 3PR to sell remanufactured products directly, as illustrated by Apple's collaboration with Foxconn for certified refurbished products.

Meanwhile, consumer demand is becoming an increasingly important driver of remanufacturing decisions. The growing popularity of low-carbon lifestyles, together with quality and price differences between new and remanufactured products, creates substantial heterogeneity in consumers' willingness to pay (WTP) for remanufactured products (Hu et al., 2024; Yang et al., 2024). Such heterogeneity reflects consumers' green preferences (Atasu et al., 2008), which are increasingly influenced by ESG concerns, including environmental sustainability, ethical sourcing, and social responsibility (Sim and Kim, 2025). As consumers place greater value on environmentally responsible products, manufacturers face stronger incentives to incorporate sustainability into their operational and channel strategies.

Despite the growing literature on closed-loop supply chains and remanufacturing, several important research gaps remain. First, existing studies have largely examined consumer green preferences, carbon cap-and-trade policies, or third-party remanufacturing strategies separately, with limited attention to their joint influence on manufacturers' choice between outsourcing and authorization. Second, although ESG considerations are becoming increasingly important in manufacturing decisions, their implications for third-party remanufacturing model selection under environmental regulation remain insufficiently understood. Third, existing studies have not fully examined the strategic interactions among manufacturers, third-party remanufacturers, consumers, and the government within a unified analytical framework, leaving room to further evaluate how market forces and environmental policies jointly shape operational decisions and social welfare.

To address these gaps, this study develops an ESG-oriented closed-loop supply chain model comprising a manufacturer, a third-party remanufacturer (3PR), consumers, and the government. The manufacturer determines whether to adopt the outsourcing or authorization model, while the 3PR undertakes recycling and remanufacturing activities.

The primary objective is to examine how consumer green preferences and carbon cap-and-trade policies jointly influence third-party remanufacturing model selection, firms' operational decisions, and social welfare.

The analysis yields several important findings. First, compared with the outsourcing model, the authorization model results in higher remanufactured product prices and recycling rates but lower demand for remanufactured products. Second, stronger consumer green preferences increase the profitability of both manufacturers and 3PRs, although they affect their preferred remanufacturing models differently, with manufacturers tending to favor authorization and 3PRs preferring outsourcing. Third, carbon-quota trading significantly influences model selection. Manufacturers and 3PRs reach consensus only under certain carbon-quota allocations, whereas different quota structures may create conflicting strategic preferences. Finally, although manufacturers may benefit more from authorization under strong consumer green preferences, the outsourcing model consistently achieves higher social welfare. These findings contribute to the literature by integrating carbon regulation, consumer green preferences, ESG considerations, and third-party remanufacturing model selection into a unified analytical framework while providing managerial guidance for firms and policymakers seeking to balance economic performance with environmental sustainability.

The remainder of this paper is organized as follows. Section "Literature Review" reviews the literature on carbon emission reduction, carbon cap-and-trade policies, consumer green preferences, and third-party remanufacturing in closed-loop supply chains. Section "Model setup" presents the model formulation and analytical results. Section "Equilibrium solution and analysis" discusses the managerial implications. Section "Numerical analysis" concludes the paper by summarizing the theoretical and practical implications, acknowledging the study's limitations, and outlining future research directions.

Literature review

This study is closely related to three streams of literature: carbon cap-and-trade policies in supply chains, consumers' green preferences for remanufactured products, and third-party remanufacturing models in closed-loop supply chains. Although these streams provide important foundations, they have largely developed in parallel. Existing studies have not fully explained how carbon regulation, ESG-oriented consumer behavior, and third-party remanufacturing model selection jointly shape manufacturers' strategic decisions and social welfare.

Carbon cap-and-trade policies in supply chains

To achieve carbon neutrality and encourage firms to reduce emissions, governments have introduced various regulatory instruments, including carbon taxes and carbon cap-and-trade policies (Chen et al., 2024; Zhang and Yu, 2024; Su et al., 2024). These policies are closely related to the environmental dimension of ESG because they create external pressure and market-based incentives for firms to reduce carbon emissions and improve resource efficiency.

A growing body of supply chain research has examined how carbon cap-and-trade policies affect production, pricing, emission reduction, and profitability decisions (Niu et al., 2023; Zhang et al., 2024b). For example, Pun and Ghamat (2025) investigated a dual-channel supply chain consisting of a manufacturer and a retailer operating under cap-and-trade regulations with asymmetric information, where the manufacturer's carbon abatement costs are private information. Strikingly, their findings reveal that high carbon abatement costs can paradoxically benefit the manufacturer, consumers, the environment, and overall social welfare, while also demonstrating that higher carbon trading prices can actually disincentivize investments in carbon abatement. Hu et al. (2025) explored the financial market implications of environmental regulations, demonstrating that the implementation of carbon cap-and-trade policies significantly reduces companies' cost of equity and cost of debt by easing financing burdens and enhancing information disclosure, while Sun and Yang (2021) examined the effects of carbon tax and carbon-quota trading policies on competing manufacturers under consumers' environmental awareness.

These studies provide valuable insights into the operational and environmental effects of carbon policies. However, most of them focus on production or emission reduction decisions under carbon regulation, rather than on the structural choice of third-party remanufacturing models. In particular, limited attention has been paid to how carbon-quota allocations for new and remanufactured products influence manufacturers' decisions between outsourcing and authorization. This is important because different remanufacturing models determine not only who undertakes recycling and remanufacturing, but also who controls the sales channel for remanufactured products. Therefore, the effects of carbon cap-and-trade policies may differ substantially across third-party remanufacturing models.

Consumers' green preferences for remanufactured products

Consumers' environmental awareness has become an important driver of green product demand and closed-loop supply chain decisions (Pongen et al., 2026). In remanufacturing markets, consumers' green preferences are reflected in their willingness to purchase remanufactured products and their willingness to pay for products with environmental attributes (Pu et al., 2024; Lv et al., 2025). These preferences are also linked to ESG concerns, as consumers increasingly consider environmental sustainability, ethical sourcing, and social responsibility in their purchasing decisions.

Prior studies generally model consumer green preferences in two ways. The first approach captures heterogeneous willingness to pay for new and remanufactured products (Guide et al., 2010; Feng et al., 2021). The second approach divides consumers into general consumers and green consumers. For instance, Atasu et al. (2008) examined how the proportion of green consumers affects pricing and profitability in closed-loop supply chains. They showed that when the green consumer segment is small, firms adopt different pricing strategies for new and remanufactured products; as the green segment expands, manufacturers may raise the price of remanufactured products to improve profitability. Feng et al. (2021) further analyzed how consumer segmentation based on green preferences affects remanufacturing mode selection.

Although these studies highlight the importance of consumer heterogeneity, they mainly examine market demand effects and pricing implications. Less is known about how consumer green preferences interact with carbon cap-and-trade policies to influence third-party remanufacturing model selection. This interaction is theoretically and practically important because consumers' acceptance of remanufactured products can change the profitability of remanufacturing, while carbon regulation can change the relative cost advantage of new and remanufactured products. Examining either factor alone may therefore provide an incomplete understanding of firms' strategic choices under ESG-oriented supply chain management.

Third-party remanufacturing models

Third-party remanufacturing has received increasing attention in operations and closed-loop supply chain research. In practice, manufacturers often rely on specialized 3PRs to conduct recycling and remanufacturing activities. Two common models are outsourcing and authorization (Ma et al., 2026; Jin et al., 2022). Under outsourcing, the 3PR remanufactures used products for the manufacturer, and the manufacturer sells the remanufactured products. Under authorization, the manufacturer grants the 3PR the right to sell remanufactured products directly.

Existing studies have examined the economic consequences of these two models under different operational conditions. Zhang et al. (2024a), for example, analyzed selection and coordination mechanisms between outsourcing and authorization when blockchain technology is introduced. Their results show that blockchain is not always beneficial for both manufacturers and 3PRs, and that both parties may prefer outsourcing under certain conditions. Jin et al. (2022) compared dealer authorization and remanufacturer authorization and showed that the optimal strategy depends on profitability, product life cycle, and environmental implications.

Other studies have explored additional factors influencing third-party remanufacturing decisions. Feng et al. (2021) developed a game-theoretic closed-loop supply chain model with one manufacturer and one 3PR and found that preference differences between green consumers for new and remanufactured products can affect whether

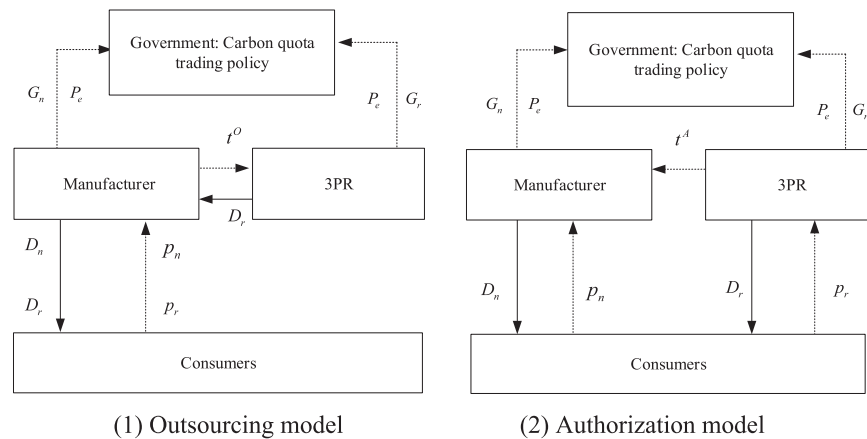


Fig. 1 The two third-party remanufacturing models.

outsourcing or authorization is preferred. Zhang et al. (2021) examined how financial constraints and manufacturer behavior influence the choice between outsourcing and authorization, showing that authorization can improve total supply chain profit when manufacturers are not financially constrained. Ma and Li (2023) further incorporated financing strategies and found that OEMs' financing choices differ between outsourcing and authorization models.

These studies have significantly advanced the understanding of third-party remanufacturing. However, most of them focus on market demand, financing, blockchain adoption, or channel coordination, while the role of carbon cap-and-trade regulation remains insufficiently examined. Moreover, ESG considerations are often discussed as background motivation rather than being incorporated into the analysis through the combined effects of environmental policy, consumer green preferences, and social welfare. As a result, existing research has not fully clarified how manufacturers should choose between outsourcing and authorization when facing both regulatory pressure and ESG-driven consumer demand.

Summary of knowledge gaps

The above review shows that prior research has provided important insights into carbon regulation, consumer green preferences, and third-party remanufacturing models. However, three gaps remain.

First, existing studies on carbon cap-and-trade policies mainly focus on production, pricing, and emission reduction decisions, while less attention has been given to how carbon-quota trading affects the manufacturer's structural choice between outsourcing and authorization in third-party remanufacturing.

Second, studies on consumer green preferences have shown that consumers' willingness to pay affects pricing and demand for remanufactured products. However, the joint effect of consumer green preferences and carbon cap-and-trade policies on third-party remanufacturing model selection remains underexplored.

Third, although the literature on third-party remanufacturing has compared outsourcing and authorization under different operational settings, relatively limited attention has been paid to the strategic interactions among manufacturers, 3PRs, consumers, and the government within a unified ESG-oriented framework. This limits our understanding of how firms' private incentives, environmental regulation, and social welfare outcomes are jointly determined.

To address these gaps, this study develops a closed-loop supply chain model consisting of one manufacturer, one 3PR, consumers, and the government. Unlike previous studies that examine carbon policies, consumer preferences, or remanufacturing models separately, this paper jointly investigates how carbon cap-and-trade regulation and consumer green preferences influence the manufacturer's choice between outsourcing and authorization. By incorporating ESG considerations, this study extends the literature on sustainable closed-loop supply chain management and provides managerial implications for firms and policymakers seeking to balance profitability, environmental sustainability, and consumer welfare.

Table 1 Notation.

Symbols	Definition
Model parameters	
θ	Consumers' WTP (WTP) for the quality of new products
δ	The WTP discount rate for remanufactured products relative to new products
β_r	Consumer preference for the remanufactured products
α	The parameter of production costs for new products
γ	The discount rate of production costs for remanufactured relative to new products
η	The scale coefficient of recycling costs
φ	Carbon emission discount rate of remanufactured relative to new products
e	Carbon emission per unit of new products
P_e	Carbon trading price per unit of new products
G_i	i product's carbon quota
Functions	
U_1	Utility of new products (stage 1)
D_1	Demand for new products (stage 1)
U_i	i product utility (stage 2)
D_i	i product demand (stage 2)
π_M^j	The profit function of the manufacturer
π_{3PR}^j	The profit function of the 3PR
CS^j	Consumer surplus
SW^j	Social welfare
Decision variables	
q	Quality of new products
p_1	Price of new products (stage 1)
λ	Recycling rate
p_i	i produce price (stage 2)
t^O	Outsourcing price per unit
t^A	Authorization price per unit
Superscript	$j = \{O, A\}$, O means outsourcing, A means authorization

Model setup

Problem description

Our study examines a closed-loop supply chain for remanufacturing, involving a government regulator, a manufacturer, a third-party remanufacturer (3PR), and consumers. The manufacturer, drawing from cases like Apple, selects one of two remanufacturing models: outsourcing or authorization. Under the outsourcing model, the manufacturer retains control over the business but delegates the operational remanufacturing process to the 3PR in exchange for an outsourcing fee. In the authorization model, the manufacturer grants the 3PR both the rights to remanufacturing and direct sales, receiving a technological licensing fee in return (Feng et al., 2021; Feng et al., 2024). The foundational structures of these two distinct institutional models are established by mapping the system boundaries and the closed-loop interactions among the core stakeholders, where directional arrows in Fig. 1 represent the concurrent forward material flows of new products and reverse collection flows of end-of-life products.

Furthermore, these structural decisions are deeply embedded within a comprehensive ESG paradigm, where the economic profit trade-offs act as the precise operational mechanisms through which ESG mandates are executed. The environmental dimension is explicitly formalized through the unit carbon emission parameters of new and remanufactured production, the carbon discount rate achieved via circular processing, and the empirical product recycling rate. The social dimension is standardly integrated directly into the market demand functions derived from consumer surplus and utility. By modeling increasingly environmentally conscious consumers who derive a distinct

psychological utility from high recycling rates, carbon footprint reductions, and waste minimization, the framework mathematically captures how society's shifting expectations generate a tangible green premium. This premium directly reshapes the economic incentives for both the manufacturer and the 3PR, forcing them to internalize social stewardship into their commercial actions. Finally, the governance dimension is rigorously modeled through the internal institutional structure and contractual game-theoretic alignment of the supply chain, namely, the choice between outsourcing and authorization regimes, which dictates the distribution of channel power, pricing control, and decision sequences. This corporate governance is simultaneously bound from the top down by regulatory governance, implemented through a government carbon-quota trading policy that imposes rigid carbon allocations and trading prices as binding operational constraints.

Ultimately, this study explores how these interactive ESG factors, spanning regulatory carbon constraints, green consumer welfare utility, and institutional game structures, shape the strategic trade-offs within the closed-loop supply chain, highlighting the critical intersection of sustainability and corporate profitability in third-party remanufacturing. The structural frameworks and interaction dynamics of the two models are shown in Fig. 1, with Table 1 summarizing the notation used in our model.

Assumptions

Assumption 1. Consumers are willing to pay (WTP) a baseline value θ for a new product with an intrinsic quality level q , such that a consumer's absolute valuation for a brand-new product is explicitly defined as θq .

This assumption, widely applied in extant operational research literature (e.g., Atasu and Souza, 2013; Feng et al., 2023; Lacourbe, 2016), provides a mathematically tractable method to capture market heterogeneity. By scaling the baseline valuation θ by the quality parameter q , the model establishes that consumer WTP is not static but dynamically driven by product specification. This enables an in-depth exploration of how vertical product differentiation influences the manufacturer's foundational pricing power, especially when balancing economic returns with strict ESG compliance targets.

Assumption 2. There exists a WTP discount rate for remanufactured products relative to new products when consumers make a purchase $\delta < 1$ (Abbey et al., 2019). However, consumers exhibit a green preference for remanufactured products, denoted as β_r .

This formulation models the real-world psychological trade-off consumers make in circular economies. In reality, consumers do not perceive remanufactured products as perfect substitutes for new ones, typically associating them with a baseline risk or lower perceived quality (Kerber et al., 2024). However, this functional deficit is countered by a growing environmental awareness where consumers derive psychological utility from purchasing sustainable goods. By multiplying the green preference by the actual recycling rate λ (Feng et al., 2021), the model captures a highly realistic market mechanism: consumers' WTP for a premium for a circular product is directly proportional to the visible environmental performance and recycling transparency of the supply chain (Quariguasi-Frota-Neto and Bloemhof, 2012).

Assumption 3. A positive market demand and valid consumer utility for remanufactured products exist if and only if the green preference coefficient and functional valuation satisfy the parameter boundaries $p_r - \beta_r \lambda > 0$ and $p_r \leq \delta p_n + \beta_r \lambda$.

This boundary assumption enforces structural feasibility and prevents trivial mathematical outcomes. In a completely indifferent market where consumer valuation or green preference drops below these survival thresholds, the demand function collapse would eliminate any economic incentive for a firm to establish a reverse logistics network. Consequently, defining this parameter space ensures a robust environment for studying the strategic tensions and coordination mechanisms between OEMs and third-party remanufacturers (Atasu et al., 2008; Örsdemir et al., 2014).

Assumption 4. The market operates across a two-period horizon. In the first stage, the manufacturer acts as a monopolist producing only new products. In the second stage, the 3PR collects and recycles the discarded items from the first stage, incurring a quadratic scaling collection cost of $\eta \lambda^2 / 2$, while the manufacturer concurrently supplies both new and remanufactured products to segmented consumer markets.

The two-stage framework establishes the necessary temporal sequence to model reverse supply chain dynamics (Atasu and Souza, 2013). The quadratic cost structure ($\eta\lambda^2/2$) reflects the real-world law of diminishing marginal returns in reverse logistics, where expanding collection rates from initial clean streams is inexpensive, but reclaiming deeply diluted waste streams requires exponentially higher capital outlays. This multi-period setup allows for a realistic simulation of how manufacturing firms transition from traditional linear systems into active, ESG-driven closed-loop manufacturing structures (Örşdemir et al., 2014; Zou et al., 2016).

Assumption 5. The unit carbon emission generated during the production of a new product is e , while the unit carbon emission of producing a remanufactured product is φe , φ represents the carbon emission discount rate of remanufactured products relative to new products (Ghosh et al., 2020).

Assumption 5 indicates that consumers can tell the differences between the new and remanufactured products, which can be justified and observed in practice. Additionally, applying interviews with consumers, van Weelden (2016) identified that consumers have obvious preferences for new and remanufactured products. This assumption also reflects the environmental benefits of remanufacturing and integrates ESG factors, where lower emissions from remanufactured products can reduce the overall carbon footprint of the supply chain.

Assumption 6. The supply chain operates under a top-down carbon cap-and-trade policy design. The government sets fixed baseline carbon quotas for new and remanufactured products as G_n and G_r respectively. Any carbon deficit incurred during the physical manufacturing process must be resolved by purchasing credits from the external carbon market at a unit trading price P_e , while surplus quotas can be liquidated for market revenue.

This assumption integrates the institutional regulatory environment into the corporate decision-making core (Huang et al., 2023; Wang et al., 2018). Rather than treating environmental policy as a flat tax or a simple operational barrier, modeling the cap-and-trade framework as a dynamic market index (P_e) transforms regulatory parameters into internal financial mechanisms. This allows the game-theoretic equations to capture how top-down government constraints shift the economic balance of power between supply chain entities, explicitly mapping how carbon market volatility shapes corporate ESG strategy.

Utility and demand function

According to Feng et al. (2021) and Jiang and Tian (2018), and considering the computation of utility and demand, along with assumptions 1-3, the utility of consumers purchasing new products in the first stage is given by $U_1 = \theta q - p_1$, and the demand function is given by: $D_1 = 1 - p_1/q$.

In stage 2, when $U_n \geq U_r$ and $U_n > 0$, where $(p_n - p_r + \beta_r \lambda)/[(1 - \delta)q] = \theta_1 \leq \theta \leq 1$, consumers only purchase new products. When $U_n < U_r$ and $U_r > 0$, where $(p_r - \beta_r \lambda)/(\delta q) < \theta < \theta_1$, consumers only purchase remanufactured products. Otherwise, consumers do not purchase any products. Referring to Ferguson and Toktay (2006), the demand functions for new and remanufactured products in the second stage are respectively:

$D_n = 1 - \frac{p_n - p_r + \beta_r \lambda}{(1 - \delta)q}$ and $D_r = \frac{\delta p_n - p_r + \beta_r \lambda}{(1 - \delta)\delta q}$, where $\beta_r \lambda$ represent the increase in utility resulting from consumers' preference for remanufactured products.

Decision sequences

To operationalize the game-theoretic framework and clarify how the objective functions and constraints interact, the decision-making process is structured as a multi-stage Stackelberg game. Following the sequential modeling approach established by Feng et al. (2021), the game unfolds over two primary stages depending on the chosen remanufacturing regime, where the dynamic constraints of the players are governed by their respective information sets. In stage 1, manufacturers decide the retail price for new product p_1 and quality q . In stage 2,

- 1) the sequence under outsourcing model is: first, 3PR determines outsourcing fees t^O ; then, retail prices for new and remanufactured products are determined by the manufacturers as p_n and p_r ; finally, 3PR determines the recycling rate of used products λ ;
- 2) the sequence under the authorization model is: first, manufacturers determine the retail prices for new product p_n

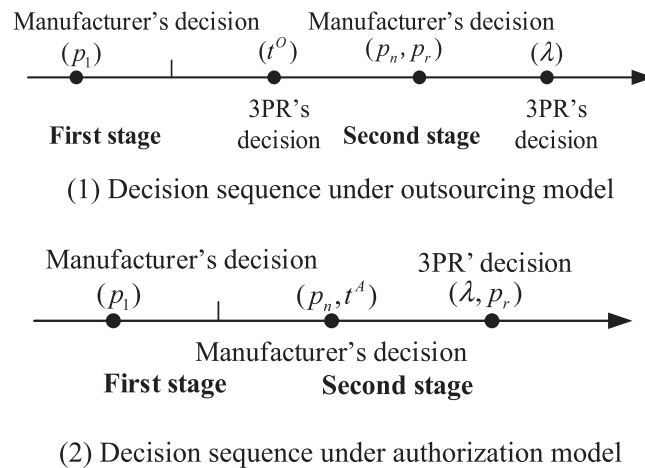


Fig. 2 The decision sequences under two third-party remanufacturing models.

and the authorization fees per unit t^A ; then, 3PR determines the prices for remanufactured product p_r and the recycling rate of used product λ .

Figure 2 shows the decision sequences under two third-party remanufacturing models.

The profit and social welfare functions under two third-party remanufacturing models

Scenario 1: Outsourcing

Based on the above assumptions and the decision sequences, the profit function for the manufacturer in the first stage is as follows:

$$\pi_{M1} = (p_1 - \alpha q^2) \cdot D_1 \quad (1)$$

where $(p_1 - \alpha q^2) \cdot D_1$ represents the profit from new products in the first stage for the manufacturer. In the second stage, under the outsourcing model, the profit functions for the manufacturer and the 3PR are as follows:

$$\pi_M^O = (p_n - \alpha q^2) \cdot D_n + (p_r - t^O) \cdot D_r - P_e[(D_n + \varphi D_r) \cdot e - G_n - G_r] \quad (2)$$

where $(p_n - \alpha q^2) \cdot D_n$ and $(p_r - t^O) \cdot D_r$ represent the profits from new products and remanufactured products in the second stage for the manufacturer, respectively. $P_e[(D_n + \varphi D_r) \cdot e - G_n - G_r]$ refers to the carbon tax paid to the government.

$$\pi_{3PR}^O = (t^O - \gamma \alpha q^2) \cdot D_r - \eta \lambda^2 / 2 \quad (3)$$

where $(t^O - \delta \alpha q^2) \cdot D_r$ represents the outsourcing profit for 3PR from remanufactured products in the second stage. $\eta \lambda^2 / 2$ is the recycling profit for 3PR, the constraint for remanufactured products is $D_r = \lambda \cdot D_1$.

Scenario 2: Authorization

Similarly, under the authorization model, the profit functions for the manufacturer and the 3PR are as follows:

$$\pi_M^A = (p_n - \alpha q^2) \cdot D_n + t^A \cdot D_r - P_e \cdot (D_n \cdot e - G_n) \quad (4)$$

$$\pi_{3PR}^A = (p_r - \gamma \alpha q^2 - t^A) \cdot D_r - \eta \lambda^2 / 2 - P_e(\varphi D_r \cdot e - G_r) \quad (5)$$

where $D_r = \lambda \cdot D_1$.

Further, in line with Örsdemir et al. (2014), we also consider the consumer surplus and the social welfare function:

$$CS^j = \int_{1-D_n-D_r}^{1-D_n} (\delta\theta q - p_r + \beta_r\lambda) d\theta + \int_{1-D_n}^1 (\theta q - p_n) d\theta \quad (6)$$

$$SW^j = \pi_M^j + \pi_{3PR}^j + CS^j + P_e \cdot [(D_n + \varphi D_r) \cdot e - G_n - G_r] \quad (7)$$

where $j = \{O, A\}$, $\int_{1-D_n-D_r}^{1-D_n} (\delta\theta q - p_r + \beta_r\lambda) d\theta$ and $\int_{1-D_n}^1 (\theta q - p_n) d\theta$ represent the consumer surplus regarding new and remanufactured products, respectively. $P_e \cdot [(D_n + \varphi D_r) \cdot e - G_n - G_r]$ refers to the revenue from carbon quotas collected by the government.

Equilibrium solution and analysis

Based on the demand and profit functions, as well as the decision sequences, the equilibrium solution for the first stage is shown in Lemma 1.

Lemma 1 *In the first stage, the manufacturer's equilibrium decision is $p_1^* = 2/(9\alpha)$ and $q^* = 1/(3\alpha)$, based on this, the equilibrium demand and profit are $D_1^* = 1/3$ and $\pi_{M1}^* = 1/(27\alpha)$.*

The equilibrium solution under the outsourcing model in the second stage is presented in Lemma 2.

Lemma 2 *when $\eta > \hat{\eta}_1$, $\alpha < \hat{\alpha}_1$ and $\beta_r < \hat{\beta}_{r1}$, the equilibrium decisions are $t^{O*} = \frac{3\eta N_1}{2M_1} + \frac{\delta+\gamma}{18\alpha} + \frac{eP_e(\delta-\varphi)}{2}$, $p_n^{O*} = \frac{eP_e}{2} + \frac{2}{9\alpha}$, $p_r^{O*} = \frac{3\alpha(t^{O*}+eP_e\varphi)+\delta}{6\alpha}$, $\lambda^{O*} = \frac{N_1}{M_1}$. Further, the equilibrium demand and profit, as well as social welfare, are D_n^{O*} , D_r^{O*} , π_M^{O*} , π_{3PR}^{O*} and SW^{O*} , respectively, where $N_1 = 9\alpha e P_e (\delta - \varphi) + (\delta - \gamma) > 0$, $M_1 = 4(1 - \delta)\delta + 9\alpha(3\eta - 4\beta_r) > 0$.*

All proofs can be found in the appendix

Assuming $\eta > \hat{\eta}_1$, $\alpha < \hat{\alpha}_1$, and $\beta_r < \hat{\beta}_{r1}$ can guarantee the non-negativity and uniqueness of the variables, and $\lambda^{O*} < 1$. We have removed the scenario that $D_r < \lambda \cdot D_1$ because it does not satisfy the non-negativity requirement for 3PR's profit, which means there is a lack of motivation for 3PR to participate in remanufacturing. Hence, we only consider the situation of $D_r = \lambda \cdot D_1$, given in the reality, there are sufficient raw materials or components that can meet the standards for remanufacturing. Further, the green preference of consumers for remanufactured products β_r has a positive effect on the demand for remanufactured products and the profits of 3PR ($\partial D_r^{O*}/\partial \beta_r > 0$, $\partial \pi_{3PR}^{O*}/\partial \beta_r > 0$). This means that the higher the environmental awareness or preferences of consumers, the more the reverse logistics or closed-loop supply chain will benefit.

The equilibrium solution under the licensing model in the second stage is presented in Lemma 3.

Lemma 3 *assume $\eta > \hat{\eta}_1/2$ and $\beta_r < \hat{\beta}_{r2}$, the equilibrium decision is: $t^{A*} = \frac{3\delta-\gamma}{18\alpha} - \frac{eP_e\varphi}{2}$, $p_n^{A*} = \frac{eP_e}{2} + \frac{2}{9\alpha}$, $p_r^{A*} = \delta p_n^{A*} - \frac{O\lambda^{A*}}{9\alpha}$, $\lambda^{A*} = \frac{N_2}{2M_2}$. Further, the equilibrium demand and profit, as well as social welfare, are: D_n^{A*} , D_r^{A*} , π_M^{A*} , π_{3PR}^{A*} , and SW^{A*} , where $N_2 = \delta(1 - \delta) - 9\alpha\beta_r > 0$, $M_2 = 2(1 - \delta)\delta + 9\alpha(3\eta - 2\beta_r) > 0$.*

Similarly, assuming $\eta > \hat{\eta}_1/2$ and $\beta_r < \hat{\beta}_{r2}$ can ensure the non-negativity and uniqueness of the equilibrium solution, and $\lambda^{A*} < 1$. The conclusion that consumers' green preference for remanufactured products β_r positively influences the demand for remanufacturing and the profits of 3PR remains robust under the authorization model (i.e., $\partial D_r^{A*}/\partial \beta_r > 0$, $\partial \pi_{3PR}^{A*}/\partial \beta_r > 0$). By comparing Lemmas 2 and 3, we can identify the trade-offs between outsourcing and authorization models, as outlined in Propositions 1 and 2.

Proposition 1 $p_n^{O*} = p_n^{A*}$, $D_n^{O*} < D_n^{A*}$; $\lambda^{O*} < \lambda^{A*}$, $p_r^{O*} < p_r^{A*}$, $D_r^{O*} > D_r^{A*}$.

Under the licensing model relative to the outsourcing model, there are higher prices for remanufactured products, higher recycling rates, lower demand for remanufactured products (i.e., $\lambda^{O*} < \lambda^{A*}$, $p_r^{O*} < p_r^{A*}$, and $D_r^{O*} > D_r^{A*}$), but higher demand for new products (i.e., $D_n^{O*} < D_n^{A*}$).

Proposition 1 suggests that if the manufacturer prioritizes new products, they can opt for the authorization model to delegate all recycling, remanufacturing, and resale operations to the 3PR without worrying about competition between remanufactured products and new ones. This approach is particularly advantageous for products with strong

core competitiveness or high quality, where the new product's market position is secure enough to not be threatened by remanufactured alternatives.

For instance, Apple, with its strong brand and innovative edge, may choose to authorize Foxconn to handle all recycling, remanufacturing, and resale of older iPhone and iPad models. Since the demand for new Apple products is driven by their advanced features, design, and brand loyalty, Apple would have minimal concerns about the impact of these remanufactured products on the sales of new models. In this case, the manufacturer's focus on maintaining a premium market for new products allows for a seamless integration of remanufacturing operations, which could be more cost-effective and environmentally sustainable.

From an ESG perspective, this model also allows the manufacturer to focus on environmental responsibility by outsourcing the remanufacturing process to a 3PR that can optimize recycling and reduce waste. Additionally, the manufacturer's adherence to ESG principles is enhanced by aligning with consumers who are increasingly concerned with sustainability. By enabling the 3PR to manage these operations, the manufacturer contributes to a circular economy, reducing the overall carbon footprint and supporting green consumer preferences.

This approach also ties into ESG goals in terms of governance, as it ensures that the remanufacturing process follows strict environmental standards, quality control measures, and fair labor practices. Therefore, by adopting the authorization model, the manufacturer not only maintains its competitive edge with new products but also bolsters its ESG commitments in both environmental and social dimensions.

To formally characterize how environmental regulatory boundaries dictate corporate governance decisions, we establish the following proposition regarding the impacts of the government's carbon-quota allocations.

Proposition 2 Under the government's carbon cap-and-trade policy, the strategic alignment and model preferences of the supply chain entities are bounded by the relative threshold of carbon allocations, such that: *when $G_n > \hat{G}_n$ and $G_r < \hat{G}_r$, $\pi_M^{O*} > \pi_M^{A*}$, $\pi_{3PR}^{O*} > \pi_{3PR}^{A*}$; when $G_n < \hat{G}_n$ and $G_r > \hat{G}_r$, $\pi_M^{O*} < \pi_M^{A*}$, $\pi_{3PR}^{O*} < \pi_{3PR}^{A*}$; otherwise, the manufacturer and 3PR may not be able to reach a consensus on selecting the same third-party remanufacturing model.*

The strategic trade-offs and underlying economic incentives between the manufacturer and the 3PR within these two distinct regimes are heavily dependent on the structural distribution of the carbon quotas assigned to new and remanufactured products. Specifically, when a regulatory environment features a high carbon allocation for new products alongside a stringent, low allocation for remanufactured products, both corporate entities gravitate naturally toward the outsourcing model. Under these parametric boundaries, the manufacturer leverages its Stackelberg leadership to retain pricing control, while the 3PR mitigates its regulatory compliance risks through fixed operational outsourcing fees.

Conversely, when the policy paradigm shifts to penalize traditional manufacturing via low-carbon quotas while incentivizing circular operations with high remanufacturing quotas, the supply chain's economic center of gravity pivots. In this scenario, both parties find it mutually optimal to adopt the authorization model. Here, the generous quota allocation allows the 3PR to absorb the carbon-market benefits directly, generating a substantial green premium that can be shared back with the leader via the unit authorization fee. If the government sets these policy instruments within intermediate or balanced zones outside of these distinct intervals, the strategic objectives of the leader and follower clash, creating institutional friction where one party's preferred structure cannibalizes the other's returns.

Proposition 2 yields a vital managerial insight: a "win-win" operational consensus and structural alignment are highly achievable when there is a significant, clear structural asymmetry between the regulatory carbon boundaries of new and remanufactured sectors. By strategically engineering this quota disparity, environmental authorities can predictably steer decentralized closed-loop supply chains toward a unified structural paradigm without triggering costly inter-firm conflict.

Numerical analysis

To offer deeper, multidimensional insights into how single-parameter fluctuations or complex dual-parameter interactions affect the strategic choices and model preferences of both manufacturers and 3PRs, as well as the overarching implications for aggregate social welfare, we conduct a comprehensive numerical analysis.

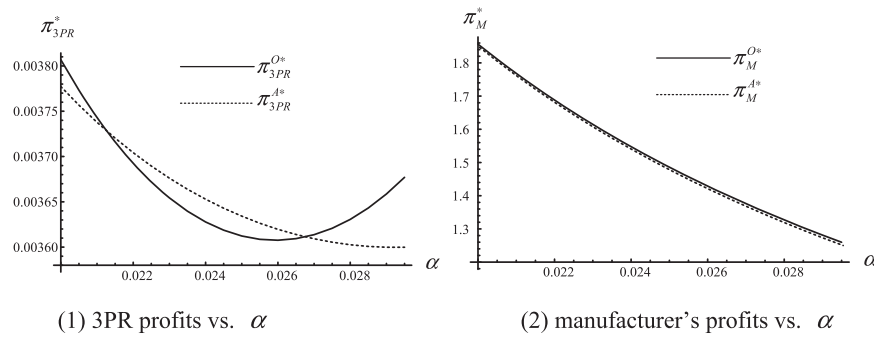


Fig. 3 The profits for the 3PR and the manufacturer versus the ratio parameter of new products production cost.

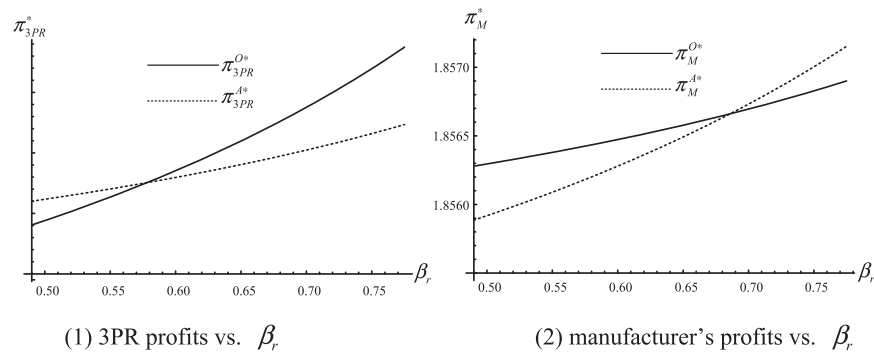


Fig. 4 The profits for the 3PR and the manufacturers versus consumer preference for remanufactured products.

Rather than utilizing arbitrarily isolated data points, the selection baseline and exact continuous intervals of our operational parameter values are established based on a rigorous dual rationale. First, the parameter configurations are mathematically parameterized to strictly satisfy all foundational model assumptions, ensuring that the non-negativity constraints of all decision variables, the mathematical concavity of the profit functions, and the absolute uniqueness of the game-theoretic equilibrium solutions are permanently maintained across the entire simulation space.

Second, the parameters are strategically calibrated to construct an analytical boundary landscape characterized by meaningful intersection thresholds. By deliberately selecting parameter intervals where the profit and welfare curves cross, we can visibly capture and isolate the precise trade-off points where the strategic preferences of supply chain entities shift. This deliberate calibration visually enriches the sensitivity analysis by illustrating how multiple parameters concurrently shift the systemic balance of power, effectively filling the analytical gaps left by purely isolated mathematical proofs and uncovering the joint mechanism driving corporate equilibrium profits and top-down social welfare trajectories.

Under this dual rationale, the baseline parameter configuration is set as follows: $\eta = 0.08$, $\alpha \in [0.02, 0.03]$, $\varphi = 0.3$, $\gamma = 0.4$, $e = 0.01$, $P_e = [0.03, 0.05, 0.07]$, $G_n = 0.02$, $G_r \in [0.02, 0.06]$, $\delta \in [0.4, 0.6]$, $\beta_r \in [0.5, 0.8]$. Figures 3–8 illustrate the mechanism by which parameters influence the equilibrium profits of manufacturers and 3PR, as well as the impact on governmental social welfare.

Figure 3 reveals that as the proportional coefficient of new product production costs, denoted by α (i.e., the cost of new products), increases, the profit of manufacturers under the outsourcing model consistently exceeds that under the authorization model (that is, $\pi_M^{O*} > \pi_M^{A*}$). Otherwise, the profits decrease accordingly (that is, $\partial \pi_M^{j*} / \partial \alpha < 0$, $j = \{O, A\}$). In addition, 3PR prefers the outsourcing model only when the proportional coefficient of new product production costs is either low or high (that is, when $\alpha < 0.0215$ or $\alpha > 0.0265$, $\pi_{3PR}^{O*} > \pi_{3PR}^{A*}$; otherwise, $\pi_{3PR}^{O*} \leq \pi_{3PR}^{A*}$). This indicates that an increase in the cost of new products is not favorable for either manufacturers or 3PR, and that the outsourcing model becomes the unanimous choice or preference for both manufacturers and 3PR when the production costs of new products are either low or high.

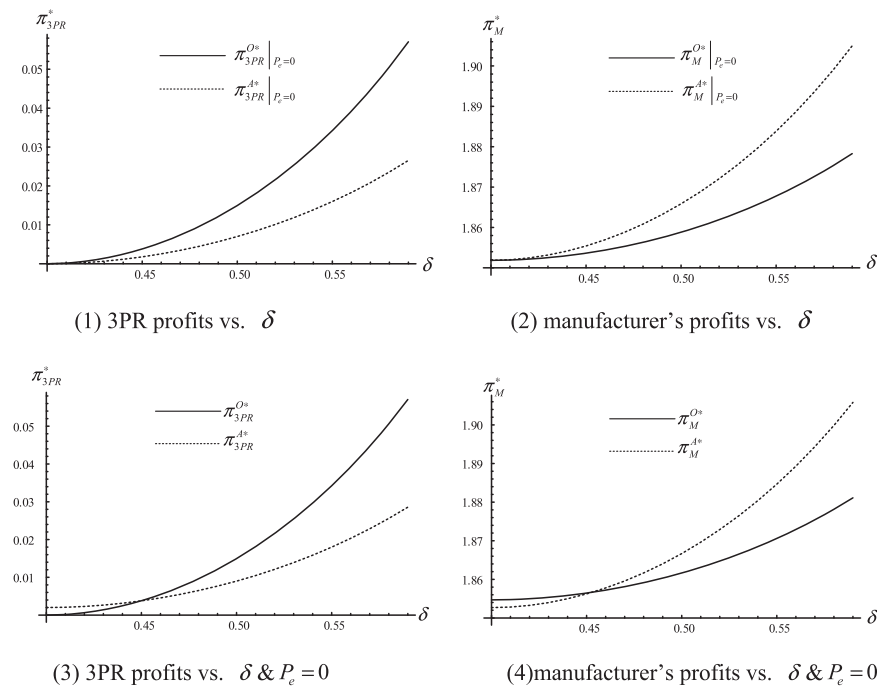


Fig. 5 Profits for the 3PR and manufacturers versus the discount rate of WTP for remanufactured products and the carbon trading price per unit.

Figure 4 illustrates that when consumer green preference for remanufactured products, denoted β_r is high (low), 3PR prefers the outsourcing (authorization) model (that is, when $\beta_r > 0.58$, $\pi_{3PR}^{O*} > \pi_{3PR}^{A*}$; otherwise, $\pi_{3PR}^{O*} \leq \pi_{3PR}^{A*}$); the choice of third-party remanufacturing model by manufacturers is exactly opposite to the preference of 3PR. However, within a certain range, manufacturers and 3PR can converge on a unanimous choice or preference for the outsourcing model (that is, when $0.58 < \beta_r < 0.68$, $\pi_M^{O*} > \pi_M^{A*}$ and $\pi_{3PR}^{O*} > \pi_{3PR}^{A*}$). Furthermore, regardless of the third-party remanufacturing model adopted, consumer preference for remanufactured products is favorable to both manufacturers and 3PR (that is, $\partial \pi_M^{j*} / \partial \beta_r > 0$ and $\partial \pi_{3PR}^{j*} / \partial \beta_r > 0$, $j = \{O, A\}$).

From an ESG perspective, the ability of businesses and 3PRs to align their preferences with consumer green preferences is crucial. Enhanced consumer demand for remanufactured products, driven by environmental consciousness, increases both manufacturers and 3PRs' revenues, which is beneficial for long-term sustainability and profitability. In this context, government intervention through policy incentives, advertising campaigns, and education can play a pivotal role in shaping consumer attitudes toward remanufactured goods. By fostering a culture of sustainability and promoting the benefits of remanufactured products, both economic and environmental gains can be achieved.

This finding contrasts with the conclusions of Feng et al. (2021), who suggested that when there is a significant gap between consumer preferences for new and remanufactured products, both manufacturers and 3PRs prefer the authorization model. This divergence in results could stem from the incorporation of green preferences for new products into their analysis. Our analysis, however, emphasizes that consumer green preferences can shift the dynamics toward outsourcing, which has positive environmental implications.

As consumer preference for remanufactured products increases, businesses can further align with ESG goals by contributing to the circular economy and meeting decarbonization targets. The continuous development of emerging remanufacturing technologies will further support the growth of the remanufactured product market, thereby promoting sustainability and encouraging consumer preferences for green products. In the future, these trends will likely accelerate the shift toward more sustainable consumption patterns and business practices.

The findings of Fig. 5 (1) and (2) align with Feng et al. (2021), which states that “when the discount rate of WTP for remanufactured products is low, manufacturers opt for the outsourcing model; otherwise, they choose the

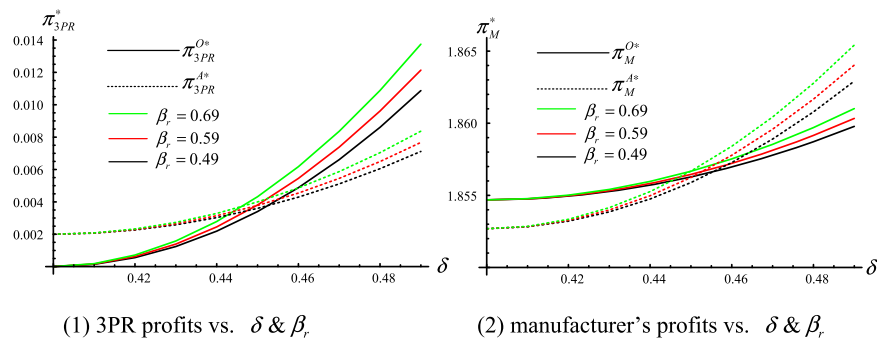


Fig. 6 The profits for the 3PR and manufacturers versus the discount rate of WTP for remanufactured products and consumer preference.

authorization model. Meanwhile, 3PR's preference is opposite to the manufacturer's choice (when $\delta < 0.45$, $\pi_M^{O*} > \pi_M^{A*}$ and $\pi_{3PR}^{O*} < \pi_{3PR}^{A*}$; otherwise, $\pi_M^{O*} \leq \pi_M^{A*}$ and $\pi_{3PR}^{O*} \geq \pi_{3PR}^{A*}$). This is because when the WTP discount rate is low, depressed consumer demand limits remanufacturing profitability. As δ increases, remanufactured products compete directly with new ones, significantly boosting circular revenue potential. Under these high-valuation conditions, the substantial unit authorization fees collected by the manufacturer allow the authorization model to outperform the outsourcing alternative. Comparing Fig. 5 panels reveals that excluding the carbon cap-and-trade policy ($P_e = 0$) significantly amplifies this divergence, entirely preventing the manufacturer and 3PR from reaching an operational consensus.

Consequently, Fig. 5 yields a vital decision rule: when consumer valuation or preference for remanufactured goods resides within a lower interval, the manufacturer should utilize the outsourcing model to preserve downstream market control. Conversely, when consumer valuation shifts into a higher interval, the manufacturer should decisively transition to the authorization model to maximize licensing revenue.

Figure 6, through a sensitivity analysis of dual parameters (δ and β_r) supports the findings in Figs. 4 and 5. Specifically, regardless of the third-party remanufacturing model adopted, consumer preference for remanufactured products is favorable for both manufacturers and 3PR. Furthermore, when the discount rate of WTP for remanufactured products is low, manufacturers opt for the outsourcing model; otherwise, they choose the authorization model. The preferences of 3PR are opposite to the choices of manufacturers.

As illustrated in Fig. 7, a continuous increase in the unit carbon trading price P_e leads to a simultaneous upward trajectory in the equilibrium profits of both the manufacturer and the 3PR across both operational regimes (that is, $\pi_{3PR}^{j*}|_{P_e=0.07} > \pi_{3PR}^{j*}|_{P_e=0.05} > \pi_{3PR}^{j*}|_{P_e=0.03}$ and $\pi_M^{j*}|_{P_e=0.07} \geq \pi_M^{j*}|_{P_e=0.05} \geq \pi_M^{j*}|_{P_e=0.03}$, $j = \{O, A\}$). At first glance, this upward profit trajectory appears to contradict traditional economic intuition, which suggests that a higher carbon trading price should act as a stringent operational penalty, escalating compliance costs and suppressing corporate profitability.

However, this phenomenon uncovers a deeper structural mechanism tied to the design of the regulatory parameters. This positive correlation occurs because the baseline carbon quotas allocated to both new and remanufactured products reside within a relatively generous interval, while the empirical unit carbon emissions of production are optimized at a comparatively low level. Under these specific parametric conditions, the initial free carbon allocation exceeds the actual emissions generated by the supply chain entities. Consequently, the carbon cap-and-trade policy transforms from a traditional cost center into an active regulatory asset-creation mechanism. A rising carbon trading price expands the market value of these surplus quotas, allowing both the manufacturer and the 3PR to generate substantial windfall profits by trading excess allowances in the carbon market. This wealth-creation effect completely offsets and supersedes the marginal cost pressures of manufacturing.

Figure 7 yields a vital policy design insight regarding the strategic sequencing of environmental regulations. In the early stages of implementing carbon-quota trading systems, establishing relatively high baseline quotas for both new and circular sectors creates an economically beneficial environment that secures the survival and financial viability of decentralized supply chain entities. This low-friction entry threshold is particularly critical for the third-party

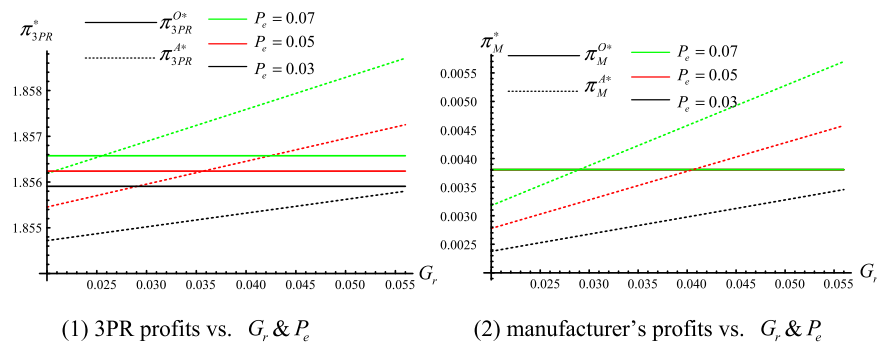


Fig. 7 The profits for the 3PR and manufacturers versus the carbon quota for remanufactured products and the carbon trading price per unit of new products.

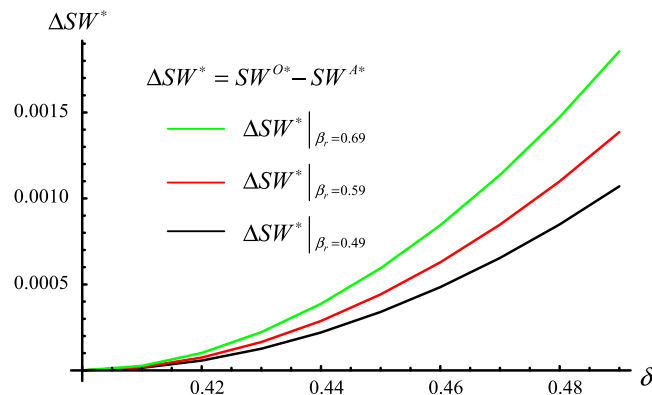


Fig. 8 Government social welfare versus the discount rate of WTP for remanufactured products and consumer preference.

remanufacturer, as its financial returns exhibit a significantly higher sensitivity to carbon policy variations than those of the original manufacturer. By allocating a generous carbon-quota buffer to the remanufacturing sector, environmental authorities can drastically mitigate the early-stage compliance costs of circular operations. This structural incentive motivates the 3PR to aggressively expand its collection and remanufacturing capacity, avoiding situations where early-stage capital is diverted away from infrastructure development to purchase additional carbon credits.

From an ESG perspective, this phased quota framework bridges short-term economic feasibility with long-term ecological stewardship. By deliberately over-allocating carbon quotas to circular activities during the system's infancy, regulators artificially boost the economic viability of remanufacturing. This green premium encourages corporate entities to restructure their supply chain portfolios, reduce their aggregate carbon footprints, and actively promote a circular economy. Such a strategy aligns directly with broader ESG objectives, including industrial waste minimization, lifecycle emissions reduction, and the establishment of sustainable production paradigms. Furthermore, initiating carbon trading policies with a high-quota cushion provides a vital transitional buffer for capital-intensive industries. This smooth operational glide path allows companies to gradually adapt their internal production technologies to carbon constraints over time, ensuring they remain resilient against stricter future reduction targets without compromising their foundational profitability. This dynamic synergy optimizes both financial and environmental outcomes, demonstrating the powerful potential of strategically parameterized cap-and-trade mechanisms to drive meaningful sustainability transitions in the remanufacturing sector.

Figure 8 indicates that government social welfare is always higher under the outsourcing model than under the authorization model, and the difference in social welfare between them increases with the rise in the discount rate of WTP δ for remanufactured products and the increase in consumer preference β_r for remanufactured products (that is, $\Delta SW^* = SW^{O*} - SW^{A*} > 0$, and $\partial \Delta SW^* / \partial \delta > 0$ & $\partial \Delta SW^* / \partial \beta_r > 0$). This occurs because government social welfare under the outsourcing model can gain more from consumer surplus and carbon-quota trading benefits.

Figure 8 further proves that as leaders, when remanufactured products become more popular, choosing the authorization model may benefit manufacturers more, but 3PR and the government have a stronger preference for the outsourcing model, leading to potential divergence. In the future, the government can adopt policies such as subsidies and tax reductions to guide manufacturers from the authorization model to the outsourcing model, thereby ensuring the highest social welfare.

Conclusion

Key findings

Rather than simply reporting numerical equilibrium results, this study reveals the structural governance mechanisms through which closed-loop supply chains balance environmental compliance and market performance. By comparing outsourcing and authorization remanufacturing structures, the game-theoretic framework shows that the choice of remanufacturing model is not merely an operational arrangement, but a strategic governance decision shaped by game sequences, green consumer preferences, and carbon regulatory constraints.

The results indicate that the authorization model is more effective in promoting higher product recycling rates and supporting premium pricing for remanufactured products. However, this model may also generate market friction by restricting total remanufacturing demand. In contrast, the outsourcing model is more conducive to maximizing aggregate social welfare, but its effectiveness depends on specific parameter conditions that align the economic incentives of both the manufacturer and the 3PR.

Another important finding is that environmental regulation should not be viewed simply as a static cost or operational penalty. The carbon cap-and-trade mechanism functions as a dynamic coordinator within the closed-loop supply chain. When carbon quotas are asymmetric or binding, they reshape the strategic relationship between the manufacturer and the 3PR, either promoting coordination or intensifying misalignment. This finding suggests that policy stringency directly influences the governance boundaries and strategic choices of firms engaged in remanufacturing.

Theoretical contributions and practical implications

This study contributes to the literature on closed-loop supply chain governance by showing how remanufacturing structure, market power, consumer preferences, and carbon regulation interact within a unified analytical framework. It extends existing research by moving beyond the isolated analysis of operational efficiency or environmental regulation and instead demonstrating how sustainability outcomes are jointly determined by firm-level governance choices and policy design. The study also enriches the understanding of remanufacturing strategy by distinguishing between outsourcing and authorization as two structurally different governance models with distinct implications for pricing, recycling, demand, profitability, and social welfare. Methodologically, the paper's key novelty is a Stackelberg game framework that endogenizes the manufacturer's choice between outsourcing and authorization while simultaneously representing heterogeneous consumer green preferences, model-specific carbon quotas and trading, and government social welfare. In contrast to prior studies that typically examine remanufacturing governance, green demand, or carbon regulation in isolation, this integrated structure makes it possible to identify the parameter thresholds at which private model preferences converge or conflict and to trace those choices to welfare outcomes. The framework therefore provides a transferable analytical approach for evaluating governance-mode selection when market demand and environmental policy interact.

The findings also offer practical implications for firms. In global technology and electronics sectors, the authorization model resembles the strategy adopted by firms such as Apple, which protect brand equity and primary market share while allowing authorized partners to collect, remanufacture, and resell certified pre-owned products under strict licensing arrangements. This structure enables original equipment manufacturers to serve green consumers

while reducing direct operational risks. By contrast, the outsourcing model is more consistent with practices in automotive and heavy machinery industries, where manufacturers retain control over downstream marketing and pricing while contracting 3PRs to undertake reverse logistics and refurbishing activities.

For managers, the decision to outsource or authorize should be aligned with the firm's market positioning and core competitive advantage. If the main objective is to protect the market share of new products and reduce cannibalization from remanufactured alternatives, the authorization model can serve as a structural shield. By delegating the remanufacturing lifecycle to a 3PR and controlling market entry through authorization fees, manufacturers can protect their brand and pricing power. However, when consumer willingness to pay for remanufactured products remains relatively low, outsourcing may be preferable because it allows the manufacturer to retain downstream pricing control. As green consumer preference increases, firms may benefit from shifting toward authorization to capture the green premium.

For policymakers, the findings provide guidance for designing carbon regulation that supports circular economy development without undermining industrial profitability. At the initial stage of carbon cap-and-trade implementation, regulators should avoid excessively strict penalty regimes. Instead, relatively generous carbon quotas for both new and remanufactured products can create a stable compliance environment and encourage 3PR participation. As closed-loop supply chain infrastructure matures, policymakers can gradually tighten quotas for new product manufacturing while introducing targeted green subsidies. Such a phased regulatory approach can guide firms toward more welfare-enhancing remanufacturing structures and help decouple industrial growth from carbon emissions.

Implementing the proposed ESG-based remanufacturing framework nevertheless involves several practical challenges. Firms may lack reliable product-level data on carbon intensity, recovery yields, and consumers' willingness to pay, while differences in measurement standards can make ESG and carbon-quota comparisons difficult. Authorization and outsourcing also require clear contracts governing quality assurance, brand protection, intellectual-property use, carbon-credit ownership, information sharing, and responsibility for collection and after-sales service. In addition, 3PRs may face capability and financing constraints, and demand, return volumes, carbon prices, and regulatory requirements may vary across regions and over time. Managers should therefore begin with pilot programs, establish shared traceability and auditing systems, define verifiable environmental and service-level indicators, and use adaptable contracts with periodic review. Policymakers can support implementation by harmonizing carbon-accounting standards, facilitating data verification, and offering transitional finance or targeted incentives for qualified 3PRs.

Limitations and future directions

This study has several limitations that provide opportunities for future research. First, the analysis is based on a stylized game-theoretic model rather than an empirical case study. Therefore, the findings mainly capture directional structural trends and governance mechanisms rather than localized emission quantities, exact carbon intensities, or industry-specific operational data. Future research could test the model's applicability using empirical data from specific industries and regulatory contexts.

Second, the current framework considers a monopoly structure involving one manufacturer and one 3PR. In practice, closed-loop supply chains often operate under more complex competitive conditions. Future studies could incorporate horizontal competition among manufacturers, competition among multiple 3PRs, or platform-based remanufacturing channels to examine how market competition affects the stability and performance of outsourcing and authorization strategies.

Third, future research could examine how digital technologies reshape remanufacturing governance. Technologies such as big data analytics, blockchain traceability, digital product passports, and automated robotic recycling systems may reduce transaction costs, improve product recovery efficiency, lower remanufacturing emission intensity, and increase recycling rates. Incorporating these technological factors into the model would generate deeper insights into how digitalization changes the relative advantages of outsourcing and authorization.

Finally, future studies could consider more complex consumer and institutional settings. For example, the coexistence of green and traditional consumer segments may alter demand structures and strategic equilibrium outcomes. In addition, explicit corporate social responsibility mandates may reconfigure the trade-offs between sustainability performance and firm profitability. Addressing these issues would further enrich the understanding of governance design in closed-loop supply chains.

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Author contributions Feng, Z wrote the first draft of the manuscript; Luo, N reviewed and revised the manuscript; Nguyen, T organized the figures and tables and checked the calculations; and Li, G cross-checked the content of the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Ethical approval and informed consent This article does not contain any studies with human participants performed by any of the authors.

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Authors and Affiliations

Zhangwei Feng¹ · Na Luo² · Thuy-Tien Nguyen³ · Guiping Li¹

¹ School of Business, Ningbo University, Ningbo, China

² Dongbei University of Finance and Economics, Dalian, China

³ Business School, Auckland University of Technology, Auckland, New Zealand