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Impact of Government Environmental Regulations on Remanufacturing Supply Chain with Multi-Subject Responsibility for Recycling and Disposal

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Abstract: With the emergence of a large number of waste electronic products and the enhancement of social awareness of environmental protection, the recycling of waste electronic products has become one of the pressing issues of social concern. Government environmental regulation is an important policy to promote the development of the remanufacturing industry. In this paper, we study the government levies recycling and disposal fees on original products for environmental governance and establish two game models based on the perspective of maximizing social welfare with no government regulation and a tripartite liability system. The optimal decisions on wholesale, retail prices and quantity of original and remanufactured products, as well as the recycling and disposal fee are analyzed under both models. Based on the numerical results, the impact of the main parameter (such as the responsibility sharing ratio) on the decisions and profits of the parties is discussed. The results show that (1) the wholesale and retail prices of remanufactured products are not affected by government regulation; (2) the tripartite liability system can increase the output of remanufactured products and reduce the output of original products while cutting the profits of remanufacturing supply chain members, and increasing social welfare; (3) government's optimal recycling and disposal fee is not related to the sharing ratio. The study can provide practitioners with suggestions for ways to develop environmental regulation.

Keywords: recycling and disposal; tripartite liability system; remanufacturing supply chain; government environmental regulations; Stackelberg game

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1. Introduction

Due to the worldwide economy's rapid growth and rising levels of consumption, waste product management has exploded in many industries such as electric vehicles and electronic appliances. As a result, the global trend towards green and low-carbon development has become clearer, and the global race around the green, low-carbon technology, and industry development is more intense. As of April 2022, more than 130 countries and regions, including China, the US, and Europe, have proposed long-term reduction targets to achieve carbon neutrality. In order to promote a green and low-carbon circular economic system, many countries around the world have tried to establish an EPR (extended producer responsibility) system in many areas to accelerate the development of the EOL (end-of-life) product remanufacturing industry and promote comprehensive resource conservation and recycling [1]. For example, in Japan, the Appliance Recycling Law enacted in 1998 stipulates that appliance manufacturers are responsible for recycling. In the United States of America, more than 115 EPR policies have been implemented in

33 states in 2019. The Government of Canada has adopted a CAP-EPR (Canadian National Action Plan for Extended Producer Responsibility) policy, with 90% of provinces setting legislation and restrictions on products under the EPR program. Four European countries have introduced EPR compliance requirements in 2023, mainly by charging operators who produce and sell the relevant goods an environmental recovery fee at different rates to reduce waste, conserve resources, increase recycling rates, and promote the design and use of eco-products.

As a creation of the world's second largest economy, China's remanufacturing enterprise is useful and of interest. With China's economic growth, the market of electrical and electronic products has grown rapidly, and the social holdings of household appliances have ranked first in the world [2]. As the peak end-of-life time for electrical and electronic products approaches in China, efficient disposal of these waste products not only preserves social resources but also lessens environmental pollution. The Chinese government has placed increasing emphasis on promoting a green and low-carbon circular economic system, making "double carbon" an important national strategy and issuing corresponding regulations and strategic guidelines over the past decade. For example, the Circular Economy Promotion Law of the People's Republic of China has been implemented since January 2009, seeking to advance the creation of a circular economy, increase resource utilization efficiency, and achieve sustainable development. The policy of "exchanging old appliances for new ones" was released in the same year. In addition, the Regulations on the Recycling and Disposal of Waste Electrical and Electronic Equipment (WEEE) have been in force since January 2011, and the government levies waste product disposal fees on producers of electrical and electronic products to set up a recycling and disposal fund to subsidize formal recycling and disposal enterprises. In January 2017, the government issued the Implementation Plan for the Extended Producer Responsibility System, proposing that by 2020, an initial policy system related to the extended producer responsibility system would be formed, and the standardized recovery and recycling rate of key species of waste products would reach 40% on average. In 2022, the Chinese government issued the Opinions on Deepening the Reform of the Management System of the Electrical and Electronic Industry, which provide direction for enterprises to build a recycling and disposal system and fulfill their extended producer responsibility. The introduction and implementation of the above policies demonstrates that the Chinese government is paying the electrical and electronics industry's high-quality growth an increasing amount of attention, and the electronic and electrical industry should gradually upgrade to "green—low carbon—intelligent" transformation.

Under the background of relevant laws and regulations issued by governments to promote the recycling and remanufacturing of waste products, many scholars have begun to study the influence of government regulations on the decision-making of remanufacturing supply chain members. The government regulation system considered in the existing research is mainly the EPR system, where the producer is accountable for the whole existence cycle of the product, including the recycling and disposal of the product after use, and the research perspectives mostly consider the producer's contribution to a recycling and disposal fund under the government regulation, which is used to subsidize recyclers. These studies all show that government regulations can increase the incentive for producers to remanufacture and promote the development of the recycling and remanufacturing industry [1,3]. Enterprises also participate in recycling and remanufacturing activities in different ways; for example, Apple, Think Pad, Xiaomi, Jimei furniture and other companies have introduced trade-in operations [4]. However, is it optimal for governments, enterprises, or consumers to place all responsibility for the recycling and disposal of products on the producer? In the practice of developed countries, there are already provisions for subjects other than producers to take responsibility for recycling and disposal. For example, in the United States, to remind consumers of their environmental responsibilities and obligations, legislation has been passed to ensure that consumers have the benefit of using remanufactured products so that the concept of recycling and reuse of resources is transmitted throughout society. The EU requires consumers to pay for disposal and to guarantee the integrity of e-waste when returning it after use. Japan's Specified Household Appliances Recycling Law affirms that "whoever sells, collects" and "whoever consumes, pays", requiring retailers and consumers to assume certain responsibilities for the recycling and disposal of end-of-life products. How will different subject responsibility systems affect enterprises and consumers? In academic circles, there are few research results on the liability system of different subjects in recycling and disposal at present.

This paper attempts to study the tripartite liability system for recycling and disposal of waste products shared by the producer, seller, and consumers, with the government levying certain recycling and disposal fees on the three responsible parties and the three responsible parties paying the recycling and disposal fee according to sharing ratio. We further investigate the impact of the tripartite liability system on the decision-making of remanufacturing supply chain members and analyze the impact of changes in the responsibility-sharing ratio on equilibrium results. We also discuss the relationship between consumer acceptance of remanufactured products, the spillover of environmental benefits from remanufactured products, corporate profits, and total social welfare. The study aims to furnish a reference for the government to formulate applicable legal guidelines and policies and for the operational selections of remanufacturing supply chain participants.

The rest of this study is organized as follows: In Section 2, the relevant literature is reviewed. Section 3 introduces the model and assumptions. The decision models for the remanufacturing supply chain under the no government regulation and the tripartite liability system are provided in Section 4, and the model results are compared and analyzed. In Section 5, we analyze not only the impact of changes in the responsibility-sharing ratio on equilibrium results but also the impact of changes in the main parameter on profits and social welfare through a numerical example. Finally, Section 6 summarizes the main research findings of the article.

2. Literature Review

At present, many countries pay great attention to the remanufacturing industry, and ways to enhance the speedy and healthful improvement of remanufacturing industry is the issue being considered by academia, the business community, and the government. The relevant research can be summarized into the following three aspects, which are described below.

2.1. Research on Recycling and Remanufacturing from the Perspective of Government Financial Subsidy Policy

Studies based on government financial subsidy policies mostly consider special government subsidy funds. Heydari et al. [5] designed a contractual mechanism for new product discounts and reimbursement of recycling costs for used products and discussed the role of different subsidy policies introduced by the government to supply chain member firms to increase firm earnings and promote recycling and remanufacturing. Mitra and Webster [6] constructed a game model between manufacturers and remanufacturers in three scenarios: government subsidies to manufacturers, government subsidies to remanufacturers, and both, and analyzed the role of government subsidies on recycling activities by comparing them. Feng et al. [7] used the Stackelberg and Cournot duopoly game models to analyze the full-remanufacturing and partial-remanufacturing, concurrently considering the remanufacturing subsidy and the market surrounding parameters. Zhang et al. [8] analyzed the impact of government fund policy on the selections of CLSC through four dynamic game models, combining the remanufacturing mode and government fund policy. The subsidies in the above studies were targeted at manufacturers or remanufacturers, while some scholars have also studied government subsidies to recyclers. For example, Zhao and Lin [9] considered not only the case of government subsidies for manufacturers, recyclers, and consumers but also of government subsidies for retailers, and they compared the optimal pricing and profits of sales and recycling channel members under different subsidy targets. Gorji et al. [10] considered an EV recycling supply chain composed of the government, EV recycling center, inspection center, and maintenance center. The influence of government subsidies on the equilibrium value of decision variables of each center in the electric vehicle supply chain under three scenarios was discussed.

The abovementioned study considers a special financial allocation for government subsidy funding sources, while some scholars consider a government subsidy funding source of break-even type waste product disposal fund, where the state levies disposal funds from producers of electrical and electronic products to subsidize recycling and disposal enterprises based on the provisions of the Regulations on the Administration of Recycling and Disposal of Waste Electrical and Electronic Products. For example, Zheng et al. [2] considered a break-even type of subsidy policy based on the context of competition between formal and informal recycling channels, and considered the reward and punishment mechanism for the government to levy recycling and disposal fees from manufacturers and subsidize formal recyclers, and analyzed the design of the extended producer responsibility system under different objectives.

2.2. Research on Recycling and Remanufacturing from the Perspective of Government Rewards and Penalties

Studies based on government rewards and penalties have mostly considered government rewards and penalties for manufacturers, or penalties for manufacturers and rewards for recycling and remanufacturing enterprises. Some scholars have studied the case where the targets of both rewards and penalties are manufacturers. For example, Hammond and Beullens [11] used variational inequalities to construct a closed-loop supply chain model to analyze the impact of the EU Waste Electrical and Electronic Equipment Directive (WEEE Directive) on product pricing and the overall profitability of the closed-loop supply chain under a reward and penalty mechanism; Bansal and Cangopadhyay [12] considered rewards for good environmental performance and penalties for poor environmental performance to analyze the influence of reward and penalty policies on firms' environmental strategies and social welfare. Wang et al. [13] considered a government reward and penalty system for recycling and study the recycling responsibility-sharing mechanism between manufacturers and WEEE recyclers. Sheu and Chen [14] considered a government reward and penalty policy of taxing manufacturers and subsidizing recyclers. They compared the optimal decisions of manufacturers and recyclers under two scenarios: no reward and penalty policy and reward and penalty policy; Li et al. [15] analyzed the impact of the government reward–penalty mechanism on finest selections and ways in which participants in CLSC pick out companions. Huang et al. [16] constructed three different remanufacturing scenarios and utilized the Stackelberg game to derive the equilibrium results of every situation with and without a reward–penalty mechanism. Alev et al. [17] explored ways in which the EPR system affects producer intervention strategies in the secondary market, and provided policy insights for the implementation environment of the EPR system for durable goods that are different from those of non-durable goods.

2.3. Research on Recycling and Remanufacturing from the Perspective of "Trade-In" Policies

Miao and Xia [18] discovered that the implementation of the "trade-in" policy can better connect the recycling side of old products with the sales side of new products. Li and Zhu [19] studied the implementation of "trade-in" strategies by home appliance enterprises under the constraints of the extended producer responsibility system and analyzed the optimal pricing decisions of "trade-in" products under government subsidies and fund levies. Their research shows that government policy constraints have an impact on the number of recycled products, product sales, and profits under the "trade-in" strategy. "Trade-in" is widely available in developed countries and is a good model for practicing EPR. The government must develop further support systems to improve the EPR model. Tang et al. [20] discussed the optimal choice of trade-in supplier in a binary supply chain with only one manufacturer and one retailer. Quan et al. [21] also investigated the trade-in service in CLSC consisting of one manufacturer and one retailer, considering two options and two-period for the trade-in service. Ke et al. [22] studied the influence of second-hand product trade-in value on consumer purchasing behavior and the optimal strategies of original equipment manufacturers (OEMs) and remanufacturers, using a stylized two-period model. Fan et al. [23] created game-theoretic models in a supply chain with traditional retail channels and dual-channel structures to investigate whether and when the manufacturer implements the collection delegation policy and also looked at the best channel to use for trade-ins.

The three types of research mentioned above provide important references for this paper to study the policy of promoting the remanufacturing industry based on the perspective of multi-subject responsibility. However, most of the studies have placed the responsibility for recycling on the producer, but in fact, the healthy and sustainable development of the remanufacturing industry requires the shared responsibility of supply chain members and consumers. Therefore, in addition to the responsibility of the producer, the responsibility for recycling should also be placed on the channel operators and consumers. In this paper, we aim to investigate a tripartite liability system for recycling to provide scientific guidance to the government in formulating policies to promote the sustainable development of the remanufacturing industry. The tripartite liability system designed in this paper is a supplement to the EPR system.

3. Analytical Framework

3.1. Model Overview

Based on the electrical and electronic products industry, this paper considers a remanufacturing supply chain consisting of a manufacturer and a retailer. The model framework of the research problem is shown in Figure 1 below, in which the government introduces relevant regulations for the recycling and disposal of waste products (stipulating that all participants are responsible for the recycling and disposal of waste products from production to use), requiring the manufacturer, retailer, and consumers to share the responsibility for recycling and disposal. The government levies recycling and disposal fees on the three responsible parties for environmental management, and the three responsible parties share the recycling and disposal fees according to a certain ratio.

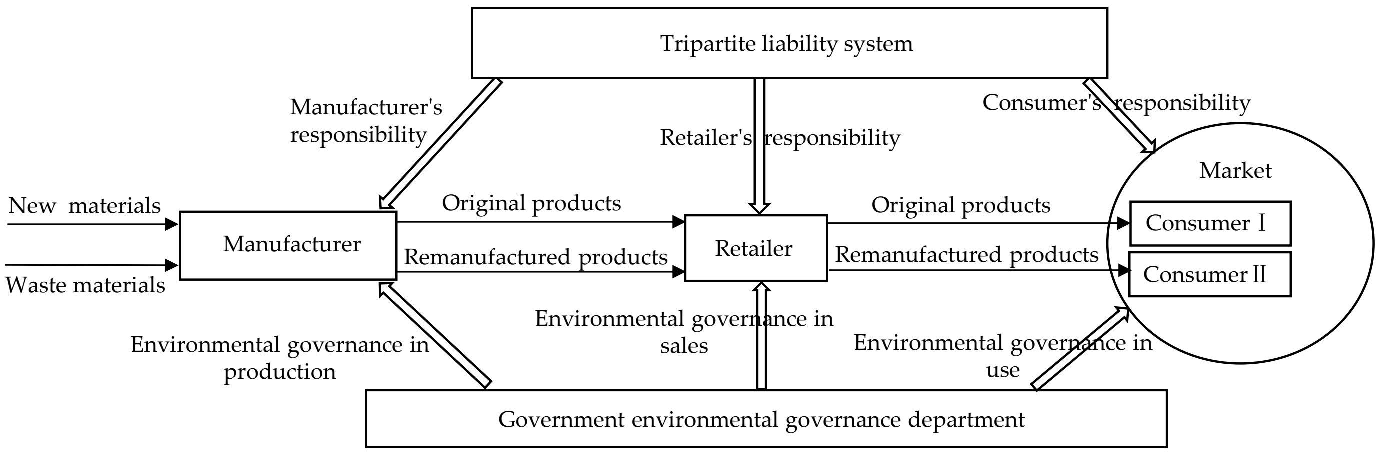

Figure 1. Decision-making model framework of remanufacturing supply chain under tripartite liability system.

The manufacturer is an enterprise that produces electrical and electronic products (such as television sets, and washing machines). The enterprise has two production strategies. One is to purchase new materials for product manufacturing (its products are called original products), and the other is to use waste materials that can be reused after waste products are recycled for product manufacturing (its products are called remanufactured products). Under the tripartite liability system implemented by the government, the manufacturer first determines the wholesale price of the original and remanufactured products sold to the retailer. Due to consumers' doubts about the quality of the remanufactured products in the market, consumers' perceived value of the remanufactured products is lower than that of the original products. In addition, we consider that the production cost of the remanufactured products is lower than the production cost of the original products (literatures [24] and [25] may support this argument). In this case, it is reasonable for this paper to propose the following: the wholesale price of the remanufactured product is lower than the wholesale price of the original product.

The retailer then determines the retail price of the original and remanufactured products sold to the consumer market. According to the consumer utility theory in economics, purchase behavior occurs only when the consumer's perceived value of the product is greater than the price of the product. Therefore, there are some consumers in the market who do not buy any product. The remaining consumers partially purchase the original product (Consumer I) and partially purchase the remanufactured product (Consumer II). The government sets up an environmental governance department, which is responsible for controlling the environmental pollution caused by the production and use of original and remanufactured products. The fees levied by the government to implement the tripartite liability system are used for environmental governance, and the environmental governance costs of each link can be calculated according to the number of products.

Furthermore, to more intuitively analyze the impact of the government's tripartite liability system for recycling and disposal on the decision-making of supply chain members, this paper also considers the option of the absence of government regulation and constructs the game models of the government, manufacturer, and retailer under the no government regulation condition and the tripartite liability system, and then compares and analyzes the implementation effect of government regulation, as well as the impact of changes in the responsibility sharing ratio on equilibrium results.

3.2. Parameters and Variables

i: Remanufacturing supply chain model, i = N, L represents no government regulation model, tripartite liability system.

A: The potential market capacity of original and remanufactured products in a market area.

v: Consumers' perceived value of the original product, that is, consumers' willingness to pay for the purchase of the original product; let v obey uniform distribution, $v \sim U[0, A]$ [25,26].

θ: Consumer acceptance of remanufactured products, that is, the perceived value discount of the remanufactured product relative to the original product, $\theta \in (0, 1)$.

c_n: Unit production cost of the original product; let the marginal production cost of the original product be consistent with the average unit production cost.

c_r: Unit production cost of the remanufactured product; let the marginal production cost of remanufactured products be consistent with the average unit production cost, $c_r < c_n$.

b: The environmental benefit spillover brought by unit remanufactured product of the manufacturer.

d: The environmental governance cost of government disposal unit product (including original and remanufactured products).

α_M: The responsibility sharing ratio of recycling and disposal fees borne by the manufacturer, $\alpha_M \in (0, 1)$.

α_R: The responsibility sharing ratio of recycling and disposal fees borne by the retailer, $\alpha_R \in (0, 1)$.

α_C: The responsibility sharing ratio of recycling and disposal fees borne by the consumer, $\alpha_C \in (0, 1)$, $\alpha_M + \alpha_R + \alpha_C = 1$.

f: The unit original product's recycling and disposal fee levied by the government on the responsible parties (to promote the development of the remanufacturing industry, the government encourages manufacturers to produce remanufactured products, retailers to sell remanufactured products, and consumers to purchase remanufactured products. The tripartite liability system stipulates that the production, sales, and purchase of remanufactured products are exempt from recycling and disposal fees); the government's decision-making variable.

w_n^i: Wholesale price of the original product; the manufacturer's decision variable.
w_r^i: Wholesale price of the remanufactured product; the manufacturer's decision variable.
p_n^i: Retail price of the original product; the retailer's decision variable.
p_r^i: Retail price of the remanufactured product; the retailer's decision variable.
q_n^i: Market demand function of the original product.
q_r^i: Market demand function of the remanufactured product.
π_G^i: Revenue function of the government (social welfare).
π_M^i: Profit function of the manufacturer.
π_R^i: Profit function of the retailer.
u_n^i: Consumers' utility function when purchasing the original product.
u_r^i: Consumers' utility function when purchasing the remanufactured product.

3.3. Model Assumptions

To more clearly describe the research problems, this paper also makes the following assumptions:

(1) The market area is a deterministic demand market. The manufacturer determines the production of original and remanufactured products according to consumer demand, and the retailer determines the wholesale quantity of original and remanufactured products according to consumer demand.
(2) In Model L, the game decision problem among the government, manufacturer, and retailer belongs to the three-stage Stackelberg game. The government decides in the first stage, the manufacturer decides in the second stage, and the retailer decides in the third stage. In Model N, this is a two-stage Stackelberg game, that is, the manufacturer decides in the first stage, and the retailer decides in the second stage.
(3) All game players are completely rational, aiming at maximizing profits.
(4) In Model N, the market demands of original and remanufactured products, respectively, are $q_n^{\mathrm{N}} = [A(1-\theta) - p_n^{\mathrm{N}} + p_r^{\mathrm{N}}]/(1-\theta)$, $q_r^{\mathrm{N}} = (\theta p_n^{\mathrm{N}} - p_r^{\mathrm{N}})/[\theta(1-\theta)]$ [27].
(5) In Model L, the consumer pays $\alpha_C f$ recycling and disposal fee when purchasing a unit of the original product; then, the price can be considered as $(p_n^{\mathrm{L}} + \alpha_C f)$. Therefore, the original and remanufactured product market demand, respectively, is $q_n^{\mathrm{L}} = [A(1-\theta) - (p_n^{\mathrm{L}} + \alpha_C f) + p_r^{\mathrm{L}}]/(1-\theta)$, $q_r^{\mathrm{L}} = [\theta(p_n^{\mathrm{L}} + \alpha_C f) - p_r^{\mathrm{L}}]/[\theta(1-\theta)]$.
(6) Government revenue π_G^i is expressed as social welfare (which has been widely used in the relevant research literature [28–30]), including six elements: (i) Manufacturer's profit π_M^i; (ii) Retailer's profit π_R^i; (iii) The total utility of consumers (u_n^i+u_r^i); (iv) The original product recycling and disposal fee fq_n^i (zero if there is no government regulation) levied on the three parties; (v) The environmental benefits of the manufacturer's production of remanufactured products bq_r^i; (vi) The environmental governance cost $d(q_n^i + q_r^i)$ (the number of products disposed of by the government is the number of products circulating in the supply chain, assuming that the d value of the original product is consistent with that of the remanufactured product).
(7) This paper does not discuss the product life cycle problem, only considers the case of a single-period game. In this single period, the current market has enough old products to meet the remanufacturing production needs.

4. The Model

4.1. No Government Regulation Model (Model N)

In Model N, the government has not issued relevant laws and regulations to clarify the main responsibility of recycling and disposal, and the game behavior between manufacturers and retailers is not subject to government intervention. The decision between the manufacturer and the retailer is a two-stage game, in which the manufacturer determines the wholesale price of the original and remanufactured products in the first stage. In the second stage, the retailer determines the retail price of the original product and the remanufactured product. Based on the backward induction method, the optimization problem for retailers is first given as

$$(\mathrm{P}_R^{\mathrm{N}}): \quad \max_{p_n^{\mathrm{N}}, p_r^{\mathrm{N}}} \pi_R^{\mathrm{N}} = (p_n^{\mathrm{N}} - w_n^{\mathrm{N}}) q_n^{\mathrm{N}} + (p_r^{\mathrm{N}} - w_r^{\mathrm{N}}) q_r^{\mathrm{N}} \\ s.t. \begin{cases} q_n^{\mathrm{N}} = [A(1-\theta) - p_n^{\mathrm{N}} + p_r^{\mathrm{N}}]/(1-\theta) \\ q_r^{\mathrm{N}} = (\theta p_n^{\mathrm{N}} - p_r^{\mathrm{N}})/[\theta(1-\theta)] \end{cases} \tag{1}$$

The Hessian matrix of the retailer's profit function π_R^{N} is obtained from the optimization problem $(\mathrm{P}_R^{\mathrm{N}})$ as

$$\mathrm{H} = \begin{pmatrix} -\frac{2}{1-\theta} & \frac{2}{1-\theta} \\ \frac{2}{1-\theta} & -\frac{2}{\theta(1-\theta)} \end{pmatrix}. \tag{2}$$

From Equation (2), the first-order sequential principal subequation $|\mathrm{H}_1| = -2/(1-\theta) < 0$, and, in addition, $|\mathrm{H}| = 4/[\theta(1-\theta)] > 0$. Therefore, π_R^{N} is a joint concave function with respect to p_n^{N}, p_r^{N}. The optimal decisions ($p_n^{\mathrm{N}*}$, $p_r^{\mathrm{N}*}$) of the retailer can be obtained according to FOC (First Order Condition) as

$$\begin{cases} p_n^{\mathrm{N}*} = \frac{A + w_n^{\mathrm{N}}}{2} \\ p_r^{\mathrm{N}*} = \frac{A\theta + w_r^{\mathrm{N}}}{2} \end{cases}. \tag{3}$$

Next, the manufacturer's optimization problem is given as

$$(\mathrm{P}_M^{\mathrm{N}}): \quad \max_{w_n^{\mathrm{N}}, w_r^{\mathrm{N}}} \pi_M^{\mathrm{N}} = (w_n^{\mathrm{N}} - c_n) q_n^{\mathrm{N}} + (w_r^{\mathrm{N}} - c_r) q_r^{\mathrm{N}} \\ s.t. \begin{cases} q_n^{\mathrm{N}} = [A(1-\theta) - p_n^{\mathrm{N}} + p_r^{\mathrm{N}}]/(1-\theta) \\ q_r^{\mathrm{N}} = (\theta p_n^{\mathrm{N}} - p_r^{\mathrm{N}})/[\theta(1-\theta)] \\ p_n^{\mathrm{N}} \in \max \pi_R^{\mathrm{N}} \\ p_r^{\mathrm{N}} \in \max \pi_R^{\mathrm{N}} \end{cases} \tag{4}$$

Substituting Equation (3) into the optimization problem $(\mathrm{P}_M^{\mathrm{N}})$, the manufacturer's profit function is obtained as

$$\pi_M^{\mathrm{N}} = (w_n^{\mathrm{N}} - c_n)\left[\frac{A}{2} - \frac{w_n^{\mathrm{N}} - w_r^{\mathrm{N}}}{2(1-\theta)}\right] + \frac{(w_r^{\mathrm{N}} - c_r)(\theta w_n^{\mathrm{N}} - w_r^{\mathrm{N}})}{2\theta(1-\theta)}. \tag{5}$$

Similarly, the Hessian matrix of π_M^{N} is used to determine that π_M^{N} is a joint concave function with respect to w_n^{N}, w_r^{N}. The manufacturer's optimal decisions ($w_n^{\mathrm{N}*}$,$w_r^{\mathrm{N}*}$) can be obtained from FOC, see Theorem 1.

Theorem 1. *In the absence of governmental regulation, the wholesale price of the original product is* $w_n^{\mathrm{N}*} = \frac{A + c_n}{2}$ *and the wholesale price of the remanufactured product is* $w_r^{\mathrm{N}*} = \frac{A\theta + c_r}{2}$ *at the equilibrium of the game between the parties.*

Substituting ($w_n^{\mathrm{N}*}$, $w_r^{\mathrm{N}*}$) into Equation (3), we obtain Theorem 2.

Theorem 2. *In the absence of governmental regulation, the retail price of the original product is* $p_n^{N*} = \frac{3A+c_n}{4}$ *and the retail price of the remanufactured product is* $p_r^{N*} = \frac{3A\theta+c_r}{4}$ *at the equilibrium of the game between the parties.*

4.2. Tripartite Liability System Model (Model L)

In Model L, the government introduces relevant laws and regulations to clarify that manufacturers, retailers, and consumers are jointly responsible for recycling and disposal, and the responsibility sharing ratio of recycling and disposal fees borne by each of the three parties is α_M, α_R, and α_C. The decision between the government and the supply chain members is a three-stage game in which the government determines the recycling and disposal fee f in the first stage; the manufacturer determines the wholesale prices w_n^L and w_r^L of the original and remanufactured products in the second stage; and the retailer determines the retail prices p_n^L and p_r^L of the original and remanufactured products in the third stage. Again, based on the backward induction method, the optimization problem for retailers is first given as

$$(\mathrm{P}_R^L): \quad \max_{p_n^L, p_r^L} \pi_R^L = (p_n^L - w_n^L - \alpha_R f)q_n^L + (p_r^L - w_r^L)q_r^L$$
$$s.t. \quad \begin{cases} q_n^L = [A(1-\theta) - (p_n^L + \alpha_C f) + p_r^L]/(1-\theta) \\ q_r^L = [\theta(p_n^L + \alpha_C f) - p_r^L]/[\theta(1-\theta)] \end{cases} \tag{6}$$

From the Hessian matrix of the retailer's profit function π_R^L, it follows that π_R^L is a joint concave function on p_n^L and p_r^L. The optimal decisions (p_n^{L*}, p_r^{L*}) of the retailer can be obtained from FOC as

$$\begin{cases} p_n^{L*} = \frac{A+(\alpha_R-\alpha_C)f+w_n^L}{2} \\ p_r^{L*} = \frac{A\theta+w_r^L}{2} \end{cases}. \tag{7}$$

Furthermore, the optimization problem for the manufacturer is given as

$$(\mathrm{P}_M^L): \quad \max_{w_n^L, w_r^L} \pi_M^L = (w_n^L - c_n - \alpha_M f)q_n^L + (w_r^L - c_r)q_r^L$$
$$s.t. \quad \begin{cases} q_n^L = [A(1-\theta) - (p_n^L + \alpha_C f) + p_r^L]/(1-\theta) \\ q_r^L = [\theta(p_n^L + \alpha_C f) - p_r^L]/[\theta(1-\theta)] \\ p_n^L \in \max \pi_R^L \\ p_r^L \in \max \pi_R^L \end{cases} \tag{8}$$

Substituting Equation (7) into the optimization problem (P_M^L), the manufacturer's profit function can be obtained as

$$\pi_M^L = \frac{1}{2}\left[(w_n^L - c_n - \alpha_M f)(A - \frac{w_n^L + (\alpha_R + \alpha_C)f - w_r^L}{1-\theta}) + (w_r^L - c_r)\frac{\theta[w_n^L + (\alpha_R + \alpha_C)f] - w_r^L}{\theta(1-\theta)}\right]. \tag{9}$$

Similarly, the manufacturer's optimal decisions (w_n^{L*},w_r^{L*}) can be obtained as

$$\begin{cases} w_n^{L*} = \frac{A+(\alpha_M-\alpha_R-\alpha_C)f+c_n}{2} \\ w_r^{L*} = \frac{A\theta+c_r}{2} \end{cases}. \tag{10}$$

Finally, the optimization problem for the government is given as

$$(\mathrm{P}_G^{\mathrm{L}}): \quad \max_f \pi_G^{\mathrm{L}} = \pi_M^{\mathrm{L}} + \pi_R^{\mathrm{L}} + u_n^{\mathrm{L}} + u_r^{\mathrm{L}} + f q_n^{\mathrm{L}} + b q_r^{\mathrm{L}} - d(q_n^{\mathrm{L}} + q_r^{\mathrm{L}})$$
$$s.t. \quad \begin{cases} q_n^{\mathrm{L}} = [A(1-\theta) - (p_n^{\mathrm{L}} + \alpha_C f) + p_r^{\mathrm{L}}]/(1-\theta) \\ q_r^{\mathrm{L}} = [\theta(p_n^{\mathrm{L}} + \alpha_C f) - p_r^{\mathrm{L}}]/[\theta(1-\theta)] \\ p_n^{\mathrm{L}} \in \max \pi_R^{\mathrm{L}} \\ p_r^{\mathrm{L}} \in \max \pi_R^{\mathrm{L}} \\ w_n^{\mathrm{L}} \in \max \pi_M^{\mathrm{L}} \\ w_r^{\mathrm{L}} \in \max \pi_M^{\mathrm{L}} \end{cases} \tag{11}$$

Substituting Equations (7) and (10) into the optimization problem ($\mathrm{P}_G^{\mathrm{L}}$), the government revenue function is obtained (see Appendix A for consumer utility):

$$\pi_G^{\mathrm{L}} = [p_n^{\mathrm{L}} - c_n - (\alpha_M + \alpha_R) f] q_n^{\mathrm{L}} + (p_r^{\mathrm{L}} - c_r + b) q_r^{\mathrm{L}} + \frac{A^2}{2} - (p_n^{\mathrm{L}} + \alpha_C f)A + \frac{(p_n^{\mathrm{L}} + \alpha_C f - p_r^{\mathrm{L}})^2}{2(1-\theta)} + \frac{(p_r^{\mathrm{L}})^2}{2\theta} - d\left(A - \frac{p_r^{\mathrm{L}}}{\theta}\right) \tag{12}$$

From $\frac{d^2 \pi_G^{\mathrm{L}}}{df^2} = -\frac{1}{16(1-\theta)} < 0$, it is determined that π_G^{L} is a concave function on f. The optimal government decision (the optimal recycling and disposal fee levied by the government on a unit of original product) can be obtained from FOC, see Theorem 3.

Theorem 3. *Under the tripartite liability system, the optimal government recycling and disposal fee at the equilibrium of the game between the parties is* $f^* = 4b - 3[A(1-\theta) - (c_n - c_r)]$.

The optimal pricing of the manufacturer and retailer can be obtained by substituting f^* into Equations (7) and (10). For the sake of the layout of the paper, we summarize all equilibrium solutions in the next subsection to compare the model results more closely.

4.3. Comparison of the Two Models

Based on the model solutions in the previous two subsections, the wholesale price, retail price, production volume, recycling and disposal fees, and the revenue of the supply chain member firms and the government under the equilibrium of the two models are summarized in Table 1.

Table 1. The equilibrium results of the two models.

Optimal Solution	Model N	Model L
$w_n^{i\,*}$	$\frac{A+c_n}{2}$	$\frac{A+c_n+(\alpha_M-\alpha_R-\alpha_C)f^*}{2}$
$w_r^{i\,*}$	$\frac{A\theta+c_r}{2}$	$\frac{A\theta+c_r}{2}$
$q_n^{i\,*}$	$\frac{A(1-\theta)-(c_n-c_r)}{4(1-\theta)}$	$\frac{A(1-\theta)-(c_n-c_r)-f^*}{4(1-\theta)}$
$q_r^{i\,*}$	$\frac{\theta c_n-c_r}{4\theta(1-\theta)}$	$\frac{\theta(c_n+f^*)-c_r}{4\theta(1-\theta)}$
$p_n^{i\,*}$	$\frac{3A+c_n}{4}$	$\frac{3A+c_n+(\alpha_M+\alpha_R-3\alpha_C)f^*}{4}$
$p_r^{i\,*}$	$\frac{3A\theta+c_r}{4}$	$\frac{3A\theta+c_r}{4}$
f^*	N/A	$4b-3[A(1-\theta)-(c_n-c_r)]$
π_M^{i*}	$\frac{(A-c_n)^2}{8}+\frac{(\theta c_n-c_r)^2}{8\theta(1-\theta)}$	$\frac{(A-c_n-f^*)^2}{8}+\frac{(\theta c_n+\theta f^*-c_r)^2}{8\theta(1-\theta)}$
π_R^{i*}	$\frac{(A-c_n)^2}{16}+\frac{(\theta c_n-c_r)^2}{16\theta(1-\theta)}$	$\frac{(A-c_n-f^*)^2}{16}+\frac{(\theta c_n+\theta f^*-c_r)^2}{16\theta(1-\theta)}$
π_G^{i*}	$\frac{7(A-c_n)^2}{32}+\frac{7(\theta c_n-c_r)^2}{32\theta(1-\theta)}+ b\cdot\frac{\theta c_n-c_r}{4\theta(1-\theta)}-d\cdot\frac{A\theta-c_r}{4\theta}$	$\frac{7(A-c_n-f^*)^2}{32}+\frac{7(\theta c_n+\theta f^*-c_r)^2}{32\theta(1-\theta)}+ f^*\cdot\frac{A(1-\theta)-(c_n-c_r)-f^*}{4(1-\theta)}+ b\cdot\frac{\theta c_n+\theta f^*-c_r}{4\theta(1-\theta)}-d\cdot\frac{A\theta-c_r}{4\theta}$

By analyzing the optimal decision of the manufacturer's wholesale price of remanufactured products and the optimal decision of the retailer's retail price of remanufactured products under the two models, we obtain Property 1.

Property 1.

(i) $w_r^{N*} = w_r^{L*}$, $p_r^{N*} = p_r^{L*}$;

(ii) $\frac{\partial w_r^{i*}}{\partial c_n} = 0$, $\frac{\partial p_r^{i*}}{\partial c_n} = 0$;

(iii) $\frac{\partial w_r^{i*}}{\partial \theta} > 0$, $\frac{\partial p_r^{i*}}{\partial \theta} > 0$.

Proof of Property 1. (i) It can be proved by comparing the expressions of w_n^{N*} and w_r^{L*} and by comparing the expressions of p_r^{N*} and p_r^{L*}. (ii) By observing the expressions w_r^{i*} and p_r^{i*}, the unit cost c_n of the original product is not included, so the conclusion is established. (iii) According to the first-order partial derivative, $\frac{\partial w_r^{i*}}{\partial \theta} = \frac{A}{2} > 0$ and $\frac{\partial p_r^{i*}}{\partial \theta} = \frac{3A}{4} > 0$ can be obtained. □

Property 1 shows that the wholesale price and retail price of remanufactured products remain unchanged regardless of whether the government system is implemented. Whether the government system is implemented or not, the wholesale price and retailer price of remanufactured products are not related to the unit production cost of original products, and the wholesale price and retail price of remanufactured products are positively correlated with consumer acceptance of remanufactured products.

By analyzing the manufacturer's optimal decision on the wholesale price of the original product under the two models and the retailer's optimal decision on the retail price of the original product, we obtain Proposition 1.

Proposition 1.

(i) *When government regulation is not implemented, the wholesale price and retail price of the original product have nothing to do with the unit production cost of the remanufactured product. When implementing government regulation, the wholesale price and retail price of the original product are related to the unit production cost of the remanufactured product, and the correlation is affected by the responsibility sharing ratio of the three parties.*

(ii) *When government regulation is not implemented, the wholesale price and retail price of the original product are not related to the consumer's acceptance of the remanufactured product. When government regulation is not implemented, the wholesale price and retail price of the original product are related to the consumer's acceptance of the remanufactured product, and the correlation is affected by the responsibility sharing ratio of the three parties.*

(iii) *The wholesale price and retail price of the original products will be affected by government regulation, and the price increase or decrease depends on the responsibility sharing ratio of the three parties.*

Based on Proposition 1, we obtain the following findings: (1) In the absence of government regulation, whether it is an original or remanufactured product, its unit production cost only affects the wholesale price and sales price of the product, but does not affect the wholesale price and sales price of the other product. After the implementation of government regulation, the unit production cost of the original product only affects the wholesale price and retail price of the original product, and the unit production cost of the remanufactured product affects not only the wholesale price and retail price of the remanufactured product but also the wholesale price and retail price of the original product. (2) In the absence of government regulation, consumer acceptance of remanufactured products only affects the wholesale price and retail price of remanufactured products, and does not affect the wholesale price and retail price of original products. After the implementation of government regulation, consumer acceptance of remanufactured products affects the wholesale price and retail price of both products. (3) The tripartite liability system does not affect the wholesale price and retail price of remanufactured products. The different settings of the responsibility sharing ratio increase or decrease the wholesale price and retail price of the original products. When the responsibility sharing ratio satisfies $\alpha_M - \alpha_R - \alpha_C > 0$, there is $w_n^{L*} > w_n^{N*}$, which indicates that the wholesale price of the original product under Model L will increase. Conversely, it will decrease. When the responsibility sharing ratio satisfies $\alpha_M + \alpha_R - 3\alpha_C > 0$, there is $p_n^{L*} > p_n^{N*}$, which indicates that the retail price of the original product under Model L will increase. Conversely, it will decrease.

By analyzing the optimal production of original and remanufactured products under the two models, Property 2 can be obtained.

Property 2.

(i) $q_n^{N*} > q_n^{L*}$, $q_r^{N*} < q_r^{L*}$;

(ii) $\frac{\partial q_n^{L*}}{\partial f} < 0$, $\frac{\partial q_r^{L*}}{\partial f} > 0$.

Proof of Property 2.

(i) $q_n^{N*} - q_n^{L*} = \frac{A(1-\theta)-(c_n-c_r)}{4(1-\theta)} - \frac{A(1-\theta)-(c_n-c_r)-f^*}{4(1-\theta)} = \frac{f^*}{4(1-\theta)} > 0$, thus $q_n^{N*} > q_n^{L*}$. $q_r^{N*} - q_r^{L*} = \frac{\theta c_n - c_r}{4\theta(1-\theta)} - \frac{\theta(c_n+f^*)-c_r}{4\theta(1-\theta)} = -\frac{f^*}{4(1-\theta)} < 0$, thus $q_r^{N*} < q_r^{L*}$.

(ii) $\frac{\partial q_n^{L*}}{\partial f} = -\frac{1}{4(1-\theta)} < 0$, $\frac{\partial q_r^{L*}}{\partial f} = \frac{1}{4(1-\theta)} > 0$. □

Property 2 shows that the government implementation of the tripartite liability system reduces the original product output and increases the remanufactured product output. The higher the recycling and disposal fees, the lower the output of the original products and the higher the output of the remanufactured products. It can be seen that the tripartite liability system is conducive to promoting the development of remanufacturing industry.

Proposition 2 can be obtained by analyzing the positive and negative correlation between the optimal recycling and disposal fee f^* and each parameter.

Proposition 2.

(i) *Given that other parameters are unchanged, the optimal recycling and disposal fee f^* has no relationship with the responsibility sharing ratio of the three parties.*

(ii) *When $\alpha_C \in (0,1)$, there are always $\frac{\partial f^*}{\partial b} > 0$, $\frac{\partial f^*}{\partial A} < 0$, $\frac{\partial f^*}{\partial \theta} > 0$, $\frac{\partial f^*}{\partial c_n} > 0$, $\frac{\partial f^*}{\partial c_r} < 0$.*

Proof of Proposition 2.

(i) Observing the expression of f^* does not include the responsibility sharing ratio of the three parties, so the conclusion is established.

(ii) When $\alpha_C \in (0,1)$, $\frac{\partial f^*}{\partial b} = 4 > 0$, $\frac{\partial f^*}{\partial A} = -3(1-\theta) < 0$, $\frac{\partial f^*}{\partial \theta} = 3A > 0$, $\frac{\partial f^*}{\partial c_n} = 3 > 0$, $\frac{\partial f^*}{\partial c_r} = -3 < 0$. □

It can be seen from Proposition 2 that the government's optimal recycling and disposal fee setting is not affected by the responsibility sharing ratio of the three parties, that is, given that other parameters are unchanged, regardless of the change in the responsibility sharing ratio of the three parties, the government's optimal recycling and disposal fee remains unchanged. The levy standard of recycling and disposal fee is positively correlated with the environmental benefit spillover brought by unit remanufactured products, the acceptance of consumers to remanufactured products, and the unit production cost of original products, but negatively correlated with the potential market capacity of products and the unit production cost of remanufactured products.

By analyzing the optimal profits of the manufacturer and retailer under the two models and the optimal revenue of the government, we can obtain Property 3.

Property 3. $\pi_M^{N*} > \pi_M^{L*}$, $\pi_R^{N*} > \pi_R^{L*}$, $\pi_G^{N*} < \pi_G^{L*}$.

Proof of Property 3. To ensure the existence of the original products on the market, obviously, $q_n^{L*} = \frac{A(1-\theta)-(c_n-c_r)-f^*}{4(1-\theta)} > 0$, thus $A(1-\theta)-(c_n-c_r) > f^*$. Further,

$$\begin{aligned}\pi_M^{N*}-\pi_M^{L*} &= \frac{(A-c_n)^2}{8}+\frac{(\theta c_n-c_r)^2}{8\theta(1-\theta)}-\frac{(A-c_n-f^*)^2}{8}+\frac{(\theta c_n+\theta f^*-c_r)^2}{8\theta(1-\theta)} \\ &= \frac{f^*[2(1-\theta)A-2(c_n-c_r)-f^*]}{8(1-\theta)} > 0\end{aligned}$$

. Therefore, $\pi_M^{N*} > \pi_M^{L*}$ is proved. Since $\pi_R^{N*} = \frac{1}{2}\pi_M^{N*}$, $\pi_R^{L*} = \frac{1}{2}\pi_M^{L*}$ can be proved. Therefore, $\pi_R^{N*}-\pi_R^{L*} = \frac{1}{2}(\pi_M^{N*}-\pi_M^{L*}) > 0$ holds, that is, $\pi_R^{N*} > \pi_R^{L*}$ is proved. Moreover,

$$\begin{aligned}&\pi_G^{L*}-\pi_G^{N*} \\ &= \frac{7(A-c_n-f^*)^2}{32}+\frac{7(\theta c_n+\theta f^*-c_r)^2}{32\theta(1-\theta)}+f^*\cdot\frac{A(1-\theta)-(c_n-c_r)-f^*}{4(1-\theta)}+b\cdot\frac{\theta c_n+\theta f^*-c_r}{4\theta(1-\theta)} \\ &-d\cdot\frac{A\theta-c_r}{4\theta}-\left\{\frac{7(A-c_n)^2}{32}+\frac{7(\theta c_n-c_r)^2}{32\theta(1-\theta)}+b\cdot\frac{\theta c_n-c_r}{4\theta(1-\theta)}-d\cdot\frac{A\theta-c_r}{4\theta}\right\} \\ &= \frac{f^{*2}}{32(1-\theta)} > 0\end{aligned}$$

, therefore, $\pi_G^{L*} > \pi_G^{N*}$ is proved. □

Property 3 shows that compared with the absence of government regulation, although the tripartite liability system reduces the profits of the members of the remanufacturing supply chain, it improves the total social welfare. It can be seen that the tripartite liability system is conducive to promoting the development of the recycling and remanufacturing industry.

5. Numerical Analysis

To better compare the optimal decision-making and profit of the game parties under the two models, to explore the influence of the change in the responsibility sharing ratio of the parties in the tripartite liability system on the decision-making and profit of the game parties, and to obtain the implementation effect of the tripartite liability system more intuitively, this section uses numerical examples for analysis and sets the basic parameter values based on electrical and electronic products. To facilitate numerical analysis, the basic parameters are scaled and preprocessed without affecting the conclusion. It should be emphasized that the values of these parameters are not set against the realistic conditions. The basic parameter values are as follows: potential market capacity $A = 1$, consumer acceptance of remanufactured products $\theta = 0.7$, the unit production cost of original products $c_n = 0.3$, the unit production cost of remanufactured products $c_r = 0.2$, environmental benefit spillover $b = 0.16$, and environmental governance cost $d = 0.05$.

5.1. Impact of the Change in the Responsibility Sharing Ratio on the Results

To analyze the impact of the change in the responsibility sharing ratio on the optimal decision and profits, this section presents a comparative analysis of three sets of numerical examples. Let $\alpha_C = 0.1$, α_M increase by 0.1 from 0 to 0.9 (α_R decrease by 0.1 from 0.9 to 0); the model results are shown in Table 2. Let $\alpha_R = 0.1$, α_M increase by 0.1 from 0 to 0.9 (α_C decrease by 0.1 from 0.9 to 0); the model results are shown in Table 3. Let $\alpha_M = 0.1$, α_R increase by 0.1 from 0 to 0.9 (α_C decrease by 0.1 from 0.9 to 0); the model results are shown in Table 4.

It can be seen from Table 2 that when α_C is fixed at 0.1, as the manufacturer's responsibility sharing ratio gradually increases, the wholesale price of the original product gradually increases, and other decision results and profits remain unchanged. This result verifies Proposition 2; when other parameters are given, the responsibility sharing ratio of the three party responsibility does not affect the f value, and thus does not affect the output of the two products and the income of the game parties. Comparing Model N with Model L, the original product output, manufacturer profit, and retailer profit are lower under Model L, and the values of remanufactured product output, the retail price of the original product and the government revenue are higher. This shows that although the implementation of the tripartite liability system makes the profit of the supply chain member enterprises decline, it is beneficial to promote the development of recycling and remanufacturing from the perspective of increasing the output of remanufactured products and reducing the output of original products. In addition, it can be seen from Table 2 that when α_M is lower than 0.5, the wholesale price of the original product is lower under Model L. When α_M is higher than 0.5, the wholesale price of the original product is lower under Model N. When α_M is equal to 0.5, the wholesale prices of the original product under Model N and Model L are equal.

Table 2. The impact of the change in the responsibility sharing ratio between the manufacturer and retailer when $\alpha_C = 0.1$.

α_C		w_n^{N*}	w_r^{N*}	q_n^{N*}	q_r^{N*}	p_n^{N*}	p_r^{N*}	f^*	π_M^{N*}	π_R^{N*}	π_G^{N*}
0.1		0.65	0.45	0.1667	0.0119	0.825	0.575	N/A	0.0613	0.0307	0.1003
α_M	α_R	w_n^{L*}	w_r^{L*}	q_n^{L*}	q_r^{L*}	p_n^{L*}	p_r^{L*}	f^*	π_M^{L*}	π_R^{L*}	π_G^{L*}
0	0.9	0.63	0.45	0.1333	0.0452	0.831	0.575	0.04	0.0553	0.0277	0.1004
0.1	0.8	0.634									
0.2	0.7	0.638									
0.3	0.6	0.642									
0.4	0.5	0.646									
0.5	0.4	0.65									
0.6	0.3	0.654									
0.7	0.2	0.658									
0.8	0.1	0.662									
0.9	0	0.666									

Table 3. The impact of the change in the responsibility sharing ratio between the manufacturer and consumer when $\alpha_R = 0.1$.

α_R		w_n^{N*}	w_r^{N*}	q_n^{N*}	q_r^{N*}	p_n^{N*}	p_r^{N*}	f^*	π_M^{N*}	π_R^{N*}	π_G^{N*}
0.1		0.65	0.45	0.1667	0.0119	0.825	0.575	N/A	0.0613	0.0307	0.1003
α_M	α_C	w_n^{L*}	w_r^{L*}	q_n^{L*}	q_r^{L*}	p_n^{L*}	p_r^{L*}	f^*	π_M^{L*}	π_R^{L*}	π_G^{L*}
0	0.9	0.63	0.45	0.1333	0.0452	0.799	0.575	0.04	0.0553	0.0277	0.1004
0.1	0.8	0.634				0.803					
0.2	0.7	0.638				0.807					
0.3	0.6	0.642				0.811					
0.4	0.5	0.646				0.815					
0.5	0.4	0.65				0.819					
0.6	0.3	0.654				0.823					
0.7	0.2	0.658				0.827					
0.8	0.1	0.662				0.831					
0.9	0	0.666				0.835					

Table 3 shows that when α_R is fixed at 0.1, as the manufacturer's responsibility sharing ratio gradually increases, the optimal decision and profit of the supply chain member enterprises and government revenue are consistent with Table 2 (except for the retail price of the original product). In addition, it can be seen from Table 3 that when α_C is lower than 0.25, the retail price of the original product is lower under Model N. When α_C is higher than 0.25, the retail price of the original product is lower under Model L. When α_C is equal to 0.25, the retail prices of the original products under Model N and Model L are equal.

According to Table 4, when α_M is fixed at 0.1, as the retailer's responsibility sharing ratio gradually increases, the optimal decision and profit of the supply chain member enterprises and government revenue are consistent with the results of Table 3 (except for the wholesale price of the original product), and the wholesale price remains unchanged.

Table 4. The impact of the change in the responsibility sharing ratio between the retailer and consumer when $\alpha_M = 0.1$.

α_M		w_n^{N*}	w_r^{N*}	q_n^{N*}	q_r^{N*}	p_n^{N*}	p_r^{N*}	f^*	π_M^{N*}	π_R^{N*}	π_G^{N*}
0.1		0.65	0.45	0.1667	0.0119	0.825	0.575	N/A	0.0613	0.0307	0.1003
α_R	α_C	w_n^{L*}	w_r^{L*}	q_n^{L*}	q_r^{L*}	p_n^{L*}	p_r^{L*}	f^*	π_M^{L*}	π_R^{L*}	π_G^{L*}
0	0.9	0.634	0.45	0.1333	0.0452	0.799	0.575	0.04	0.0553	0.0277	0.1004
0.1	0.8					0.803					
0.2	0.7					0.807					
0.3	0.6					0.811					
0.4	0.5					0.815					
0.5	0.4					0.819					
0.6	0.3					0.823					
0.7	0.2					0.827					
0.8	0.1					0.831					
0.9	0					0.835					

Combining Tables 2–4, the main findings are summarized as follows:

(i) Compared with the absence of government regulation, although the tripartite liability system reduces the profits of remanufacturing supply chain members, it increases the output of remanufactured products and government social welfare and reduces the output of original products.

(ii) In the tripartite liability system, when other parameters are fixed, the change in the responsibility sharing ratio among manufacturers, retailers, and consumers only affects the wholesale price and retail price of the original products, and other decisions and profits are not affected.

5.2. Impact of Main Parameters on the Profit of Supply Chain Members and Social Welfare

According to Proposition 2, when given the potential market capacity, the consumer's acceptance of the remanufactured product, the unit production cost of the original product, the unit production cost of the remanufactured product, and the unit environmental benefit spillover of the remanufactured product, then the optimal unit recycling and disposal fee, member profits and social welfare can be determined.

Firstly, the changing trend of member enterprises' profit and social welfare with the spillover of environmental benefits of unit remanufactured products is shown in Figure 2.

Under the tripartite liability system, the profits of the enterprise and the social welfare have a convex function relationship with the b value. Under the given parameter value, as the b value increases from 0.15 to 0.2, the profits of the supply chain member enterprises show a convex negative correlation and the social welfare shows an increasing trend. Compared with Model N and Model L, the profits of supply chain member enterprises under the tripartite liability system are lower than those without government regulation, and the social welfare under the tripartite liability system is higher than that without government regulation.

Based on the same parameter values, the trend of supply chain member profits and social welfare with the environmental benefit spillover of unit-remanufactured products is shown in Figure 3.

Under the tripartite liability system, the relationship between the profit of the enterprise, the social welfare and the θ value is a convex function. Under the given parameter value, as the θ value increases from 0.7 to 0.74, the profits of the supply chain members decrease first and then increase. When $\theta \approx 0.733$, the profits of the supply chain members reach the minimum. However, social welfare has been increasing. Compared with Model N and Model L, the profits of supply chain member enterprises under the tripartite liability system are lower than those without government regulation, and the social welfare under the tripartite liability system is higher than that without government regulation.

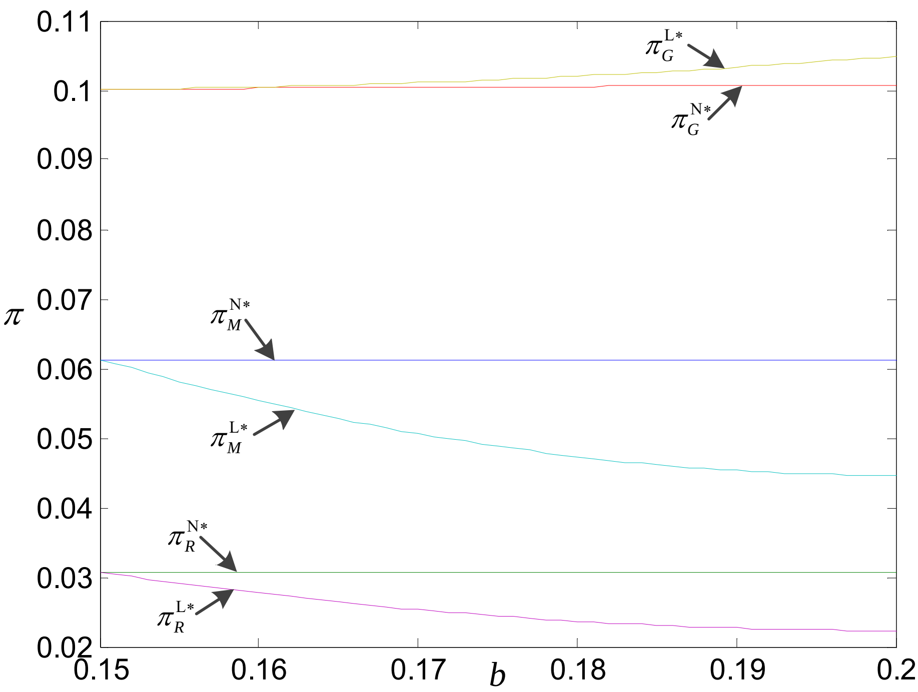

Figure 2. The changing trend of profits and social welfare with b.

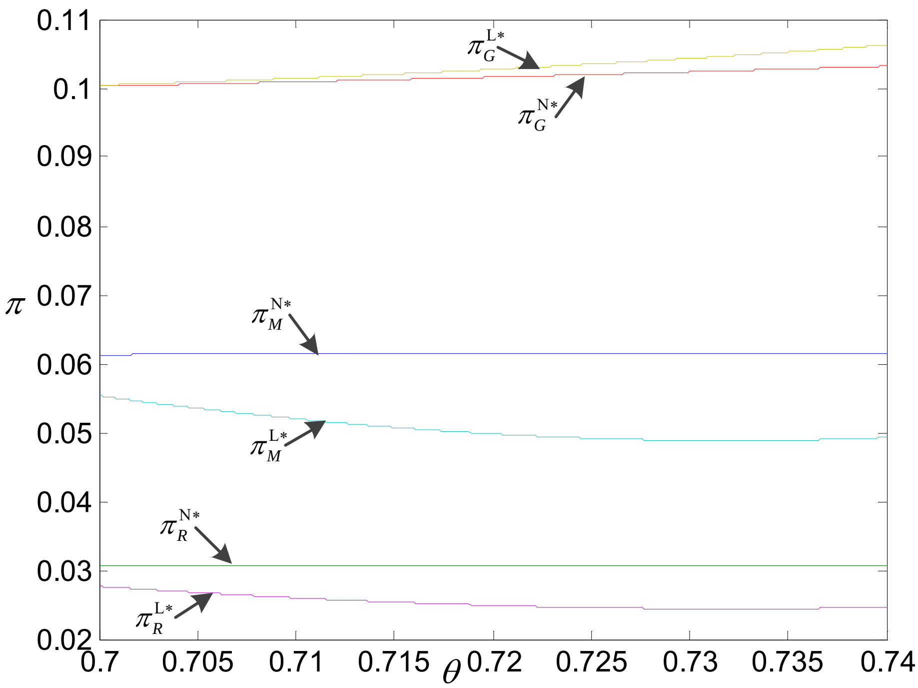

Figure 3. The changing trend of profits and social welfare with θ.

6. Conclusions

In the electrical and electronic products industry, from the production chain to the distribution chain to the consumption chain, each participant has the insufficient motivation to implement recycling and remanufacturing activities of waste products, especially in countries such as China where recycling and remanufacturing are at an early stage of development. The government adopts a scientific and reasonable policy system as an effective measure to motivate members of the remanufacturing supply chain system to carry out recycling and remanufacturing, which is of great significance to promote the development of the remanufacturing industry.

In this paper, we consider the manufacturer, retailer, and consumer as the three responsible parties for recycling and remanufacturing who share the responsibility of recycling and disposal of end-of-life products, and the three parties share the recycling and disposal fees proportionally. By comparing and analyzing the optimal decision of wholesale price, production, and retail price of original products and remanufactured products under the two models, and discussing the influence of relevant parameters on the government's determination of the optimal recycling and disposal fee and the maximum profit of supply chain member enterprises.

The research results indicate that:

(1) Compared with the absence of government regulation, the government's implementation of the tripartite liability system helps to increase the output of remanufactured products while reducing the output of original products and increasing the government's revenue (i.e., total social welfare), thus suggesting that the tripartite liability system is a useful policy to promote the development of the remanufacturing industry.
(2) When the government implements the tripartite liability system, the share of tripartite responsibility only affects the wholesale and retail prices of original products, while other optimal decisions of supply chain members (e.g., production setting, pricing of remanufactured products) are not affected. In other words, given the other parameters remain unchanged, the optimal output of each product, the optimal recycling and disposal fee, the profit of supply chain member enterprises, and the government revenue are also fixed, independent of the apportionment ratio.
(3) The profit of supply chain members under the tripartite liability system is convexly negatively related to the environmental benefit spillover per unit of recycled product, but the total social welfare is convexly positively related to it. This indicates that the stronger the pro-environmental spillover effect of remanufactured products under the implementation of the tripartite principal responsibility system, the higher the total social welfare.
(4) When the government implements the tripartite principal responsibility system, the profit of supply chain member firms tends to decrease and then increase as consumer acceptance of remanufactured products increases, while the total social welfare tends to increase at the margin.

The theoretical contribution of this paper is that we study the decision-making of remanufacturing supply chain under the intervention of governmental environmental regulation, discuss the production decision and sales pricing decision of enterprises' original products and remanufactured products under the recycling and disposal fee sharing mechanism of multiple supply chain members, and better enrich the green supply chain management literature. The main practical implication of this paper is that the research findings can provide a scientific basis for the government to formulate laws and regulations related to the recycling and remanufacturing industries, as well as for the operational decisions of remanufacturing supply chain members.

One limitation of this paper is that we consider a manufacturer producing both original and remanufactured products, while a realistic scenario may be that one manufacturer produces original products while another remanufacturer produces remanufactured products and there is market competition between the two. In the next research work, we will further investigate the competitive supply chain management problem in this scenario.

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Appendix A. Consumer Utility

As shown in Figure A1, consumers' perceived value v of the original product is evenly distributed on $[0, A]$. Consumers in the $[0, x_1]$ interval do not purchase any product, consumers II in the $[x_1, x_2]$ interval purchase remanufactured products, and consumers I in the $[x_2, A]$ interval purchase original products. At x_1, the utility of consumers purchasing remanufactured products is consistent with the utility of the no purchase behavior, so it can be seen that $\theta v - p_r^{\mathrm{L}} = 0$; we obtain $v = p_r^{\mathrm{L}}/\theta$, that is, $x_1 = p_r^{\mathrm{L}}/\theta$. At x_2, the utility of consumers purchasing the original product is consistent with the utility of purchasing the remanufactured product, so $v - (p_n^{\mathrm{L}} + \alpha_C f) = \theta v - p_r^{\mathrm{L}}$; we obtain $v = (p_n^{\mathrm{L}} + \alpha_C f - p_r^{\mathrm{L}})/(1-\theta)$, that is, $x_2 = (p_n^{\mathrm{L}} + \alpha_C f - p_r^{\mathrm{L}})/(1-\theta)$. Therefore, the consumer utility of purchasing the original product is

$$u_n^{\mathrm{L}} = \int_{\frac{p_n^{\mathrm{L}}+\alpha_C f - p_r^{\mathrm{L}}}{1-\theta}}^{A} (v - p_n^{\mathrm{L}} - \alpha_C f)dv. \tag{A1}$$

The consumer utility of purchasing remanufactured products is

$$u_r^{\mathrm{L}} = \int_{\frac{p_r^{\mathrm{L}}}{\theta}}^{\frac{p_n^{\mathrm{L}}+\alpha_C f - p_r^{\mathrm{L}}}{1-\theta}} (\theta v - p_r^{\mathrm{L}})dv. \tag{A2}$$

Therefore, the total utility of consumers is

$$u_n^{\mathrm{L}} + u_r^{\mathrm{L}} = \frac{A^2}{2} - (p_n^{\mathrm{L}} + \alpha_C f)A + \frac{(p_n^{\mathrm{L}} + \alpha_C f - p_r^{\mathrm{L}})^2}{2(1-\theta)} + \frac{(p_r^{\mathrm{L}})^2}{2\theta}. \tag{A3}$$

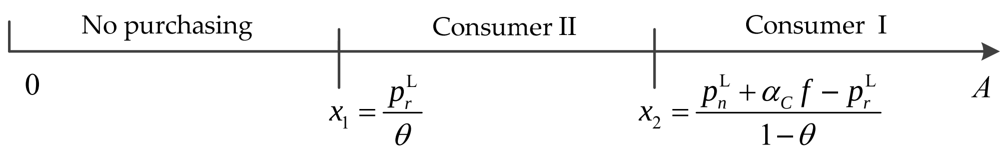

Figure A1. Consumer purchase choice decision diagram.

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