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Research on an Enterprise Remanufacturing Strategy Based on Government Intervention

Jian Cao , Jiayun Zeng *, Yuting Yan and Xihui Chen

School of Management, Zhejiang University of Technology, Hangzhou 310023, China; jcao@zjut.edu.cn (J.C.); ytyan@zjut.edu.cn (Y.Y.); jerrychen0526@zjut.edu.cn (X.C.)

* Correspondence: 2111804057@zjut.edu.cn; Tel.: +86-138-1912-1623; Fax: +86-0571-8529-0284

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Abstract: Due to rapid economic development and population growth, environmental pollution problems such as urban pollution and depletion of natural resources have become increasingly prominent. Municipal solid waste is part of these problems. However, waste is actually an improperly placed resource. As a part of green supply chain management, remanufacturing can turn waste products into remanufactured products for resale. Based on the development status of China's remanufacturing industry, this paper establishes three Stackelberg game models, namely the free recycling model (model N), the government regulation model based on the reward–penalty mechanism (model G), and the government dual-intervention model (model GF). In this study, the standard solution method for the Stackelberg game method, namely the backward induction method, is applied to solve the dynamic game equilibrium. For comparison, a further numerical analysis is also carried. The research results show that: (1) in the closed-loop supply chain based on remanufacturing, the strengthening of cooperation between manufacturers and remanufacturers is beneficial in terms of maximizing supply chain profits; (2) in order to maximize social benefits, the government needs to intervene in green supply chain management; (3) government regulation is particularly important when the remanufacturing industry is in the initial stage of development; (4) government intervention needs to be based on the development level of the remanufacturing industry; (5) in order to maximize social benefits, it is recommended that the government consider the ratio between the green consumption subsidies and the taxes on new products.

Keywords: green supply chain management; remanufacturing; government intervention; extended producer responsibility

1. Introduction

Due to rapid economic development and population growth, environmental pollution problems such as urban pollution and depletion of natural resources have become increasingly prominent. Municipal solid waste is a byproduct of these issues, with data showing that globally each person generated 1.2 kg of municipal solid waste per day in 2016. [1]. Hoornweg and Bhada-Tata [2] predict that this number will increase to 1.42 kg/day by 2025. This unprecedented volume and variety of waste contaminates the air, soil, and water, thereby affecting human health [3,4].

Nevertheless, waste products are hailed as hidden urban resources. Compared with conventional supply chain management, the green supply chain management (GSCM) approach not only focuses on increasing business profits, but also on creating environmental benefits [5,6]. As part of GSCM, remanufacturing activities can give new life to waste products. In the remanufacturing process, waste products are collected from end-users, then the value of these waste products is recovered, enabling them to be sold as new products [7]. Remanufacturing reduces both the natural resources needed and the waste produced.

Obviously, corporate operations are mainly driven by business profits rather than environmental protection [5,6], even though sustainable development is part of corporate social responsibility (CSR). The development of a nation's remanufacturing industry often requires government intervention, especially in the initial stage. Due to the conflict between economic growth and environmental protection, the extended producer responsibility (EPR) principles were formulated by Lindhqvist in 1990. Lindhqvist defined it as a policy strategy to make manufacturers responsible for the entire life-cycle of their products [8], particularly the end-of-life period. Many developed countries have applied the EPR principles. The EPR principles are mandatory for vehicles and waste electrical and electronic equipment (WEEE) according to the end-of-life Vehicles Directive (Directive 2000/53/EC—the "ELV Directive") [9] and WEEE Directive (Directive 2002/96/EC) [10]. The Packaging Directive (Directive 2004/12/EC) [11] also indirectly elicits the EPR principles by requiring EU Members to act to ensure the collection and recycling of packaging waste. These bills have been continuously revised and are still in use. Even though no federal-level legislation has been embraced by federal lawmakers, individual US states have enacted more than 70 EPR laws since 1991 [12]. The Packaging Recycling Law, passed in 1995, was the first piece of EPR legislation in Japan directly dealing with waste containers and wrapping [13].

Data from the World Bank show that China, as the most populous country in the world, surpassed the United States to produce the largest volume of global municipal solid waste in 2004 [14]. To tackle this serious problem and its deteriorating effects on the environment, the Chinese government introduced a variety of EPR policies in the home appliance market during 2009–2012. According to the replacement subsidy, consumers receive a subsidy worth 10% of the price of five kinds of new appliances [15]. In 2019, Beijing, as a pilot city, launched a new round of 3-year energy-saving product consumption subsidy policies. Based on the energy savings level, subsidies at 8–20% of the purchase price are provided to consumers [16]. Additionally, China is entering into a new era of waste sorting revolving around waste recycling. Since 1 July 2019, Shanghai, the first pilot city in China, has enforced mandatory legal provisions on waste classification, whereby residents who do not separate waste properly are fined. Since then, other major cities in China have followed suit [17].

In practice, companies worldwide have become more concerned with environmental problems because of influences from regulations, customers, and stakeholders [5,18], meaning manufacturers often act as recyclers to recycle used products from consumers. Manufacturers often cooperate with professional remanufacturers in order to optimize costs and reduce competition. The Chinese remanufacturing industry is currently in its infancy and has limited capacity to handle all used products. Hence, both manufacturers and remanufacturers have production lines dedicated to remanufacturing waste products. However, the uncertainty surrounding the actual effects is relatively high. In order to maximize the environmental and social benefits, government involvement is very important. To promote sustainable development, a critical issue that beleaguers the government is whether and how to intervene. This research attempts to study the following two issues: (1) to figure out the optimal decisions for manufacturers and remanufacturers with and without government intervention; (2) to compare the impacts of different government interventions.

In order to address these two issues, this article examines theoretical foundations, relevant research, and the current Chinese remanufacturing scenario in order to construct three Stackelberg models. These are the free recycling model, government regulation model (based on a reward–penalty mechanism), and the government dual-intervention model. After these model are established, they are solved by the inverse solution method. This paper compares the enterprise strategies and profits for the different models and obtains different propositions. Finally, this paper analyzes calculation examples and draws further conclusions. The contributions of this article are mainly reflected by the following aspects:

(1) Based on the development of China's remanufacturing industry, a practical context has arisen, whereby manufacturers outsource part of their remanufacturing business to remanufacturers;
(2) Many existing studies take the ratio between a government's green subsidies for remanufactured products and green taxes on new products as exogenous variables. This article regards this

ratio as an endogenous variable, which helps to provide the government with more practical legal policies. The analysis of the calculation examples in this study strongly proves that the government should consider the optimal ratio between government subsidies and tax policies.

2. Literature Review

Since the 1990s, the optimization of green supply chain management (GSCM) in the literature has been paid increasing attention [6]. The importance of GSCM is related to gaining and maintaining the corporate competitive advantage [19,20], improving performance [21–23], and integrating GSCM processes with green human resource management [24,25]. Meanwhile, the GSCM research boom is prevalent in both developed countries and emerging economies. Luthra el et investigated the Indian automobile industry [26], while Khan et al. analyzed data from 218 Pakistan firms in the manufacturing industry [27]. Suryanto et al. studied GSCM in Malaysian firms [28]. Economic models and mathematical programming approaches have been widely used in the previous studies on green supply chain operations involving remanufacturing. Li et al. used the Stackelberg game model to examine pricing policies in a dual-channel green supply chain [29]. By comparing manufacturer remanufacturing and supplier remanufacturing models, Xiong and Zhao found out that both manufacturers and suppliers are more likely to engage in remanufacturing as the per unit remanufacturing cost decreases [30]. Heydari et al. analyzed a two-stage reverse supply chain to find the optimal paid reward for customers for used products [31].

The reward–penalty mechanisms (RPMs) and policies have been discussed in many documents as a government intervention method in GSCM. Tang et al. showed that an intensive reward–penalty mechanism is more likely to achieve maximum social welfare benefits compared to the use of a higher recycling rate using a Stackelberg game theory-based model [32]. Wang et al. showed that reward–penalty mechanisms can increase the collection quantity effectively while lowering both the wholesale and retail prices.Regarding the developed game theory models, Wang et al. indicated the same result as Wang et al., in addition to showing that RPMs boosted the sales quantity and total profits in a closed-loop supply chain (CLSC) [33–37]. It has been found in previous studies that green subsidy schemes are also potential intervention methods. Sheu and Chen pointed out that social welfare improves by 27.8% compared to without green taxation and subsidization [35]. Cao studied green subsidy and tax quotas through a two-stage model and discussed the production and recycling decisions for each member in the supply chain [36]. Ma et al. suggested that government consumption subsidies are beneficial to consumers, manufacturers, and retailers [37]. Yu et al. proved that an elaborate green subsidy scheme can not only lead to higher profits for manufacturers and incentivize manufacturers to be more "green", but also reduce the initial government investment [38]. Bigerna et al. suggested that policymakers constantly change the level of green subsidies based on market development levels [39]. Similarly, government green subsidies were viewed as exogenous variables in the study by Li [40].

The research gaps between our research and the previous studies cover three points. The first point is that based on the current status in China, we believe that manufacturers will cooperate with professional remanufacturers to outsource some of the remanufacturing. The second point is that many related studies in the past have only considered one method of government intervention, while our study takes into account the two policies that have been implemented in China and compares the two policies to determine whether they should be combined. Third, in the past models of government subsidies in GSCM, many scholars have viewed the ratio between subsidies and taxes as an external variable, ignoring how the government implements the optimal ratio scheme. In our study, the ratio is regarded as an exogenous variable.

3. Model Formulation

3.1. Model Framework

First, we discuss the traditional Stackelberg game model comprising manufacturers (M) and remanufacturers (R) without government regulations. The supply chain is deemed to be where the manufacturers produce new products and recycle used products with a certain level effort. In this model, the manufacturers perform part of the remanufacturing, while some remanufacturing business is outsourced to remanufacturers. The manufacturers are in charge of all of the sales, marked in Figure 1 as model N (free recycling model). Second, we consider a scenario whereby the government envisions the achievement of a targeted recycling rate and implements a reward–penalty mechanism, named model G (government regulation model based on reward–penalty mechanism) in Figure 1. Third, considering an alternative reward–penalty mechanism, we consider a scenario whereby the government provides green consumers with a green purchasing subsidy and charges manufacturers a green production tax on new products, shown in Figure 1 as model GF (government dual-intervention model).

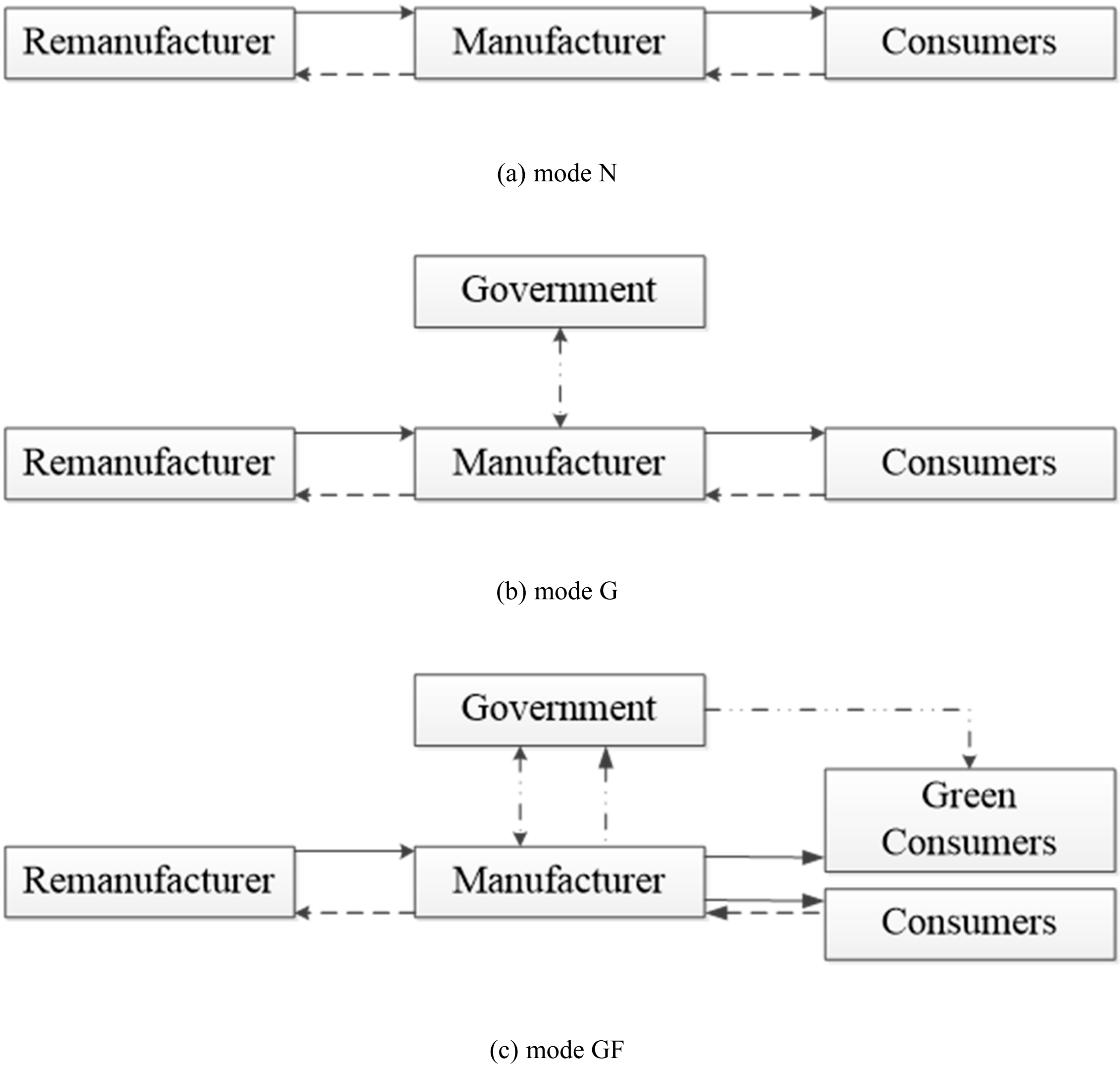


Figure 1. Three Stackelberg game models involving remanufacturing. (**a**) mode N; (**b**) mode G; (**c**) mode GF.

Furthermore, we assume that both manufacturers and remanufacturers are rational decision -makers aiming to maximize their own profits, that their capacity can meet the market demand, and that all recycled products are used for remanufacturing. For convenience and cost reduction purposes, manufacturers outsource part of their remanufacturing business to remanufacturers. The prices of new products and remanufactured products are determined by the market. As the Stackelberg game leaders, manufacturers makes the first move, then the remanufacturers observe the leaders' strategy and react to determine the corresponding outsourcing ratio. Then, on this basis, the government sets the reward–penalty mechanism to encourage recycling. Under this scenario, if the recycling rate is higher than the benchmark recycling rate, the manufacturers will be rewarded with certain incentives, otherwise they will be penalized. Finally, under the reward-penalty mechanism, the government, as a decision-making entity, comprehensively considers the environmental management costs from the waste and environmental benefits brought about by remanufacturing. Based on the EPR principles, the government issues an elaborate green subsidy scheme to pursue maximum social welfare benefits across the entire supply chain. The green taxes collected from manufacturers are later transferred into green subsidies for green customers who buy remanufactured products. By comparing and analyzing these three models, we can determine the impacts of the reward-penalty mechanism and green consumption subsidy mechanism on corporate decision-making and social welfare, helping provide policy-makers to adjust interventions to achieve policy targets.

3.2. Notations and Descriptions

The parameters and variables and their descriptions are shown in Table 1.

Table 1. Parameters and variables.

Notations	Descriptions
i	i = N, G, and GF respectively represent three models, namely model N (free recycling mode), model G (government regulation model based on reward–penalty mechanism), model GF (government dual-intervention mode).
$c_{M,n}$,$c_{M,r}$,c_R	$c_{M,n}$: the cost for the manufacturers to produce new products; $c_{M,r}$: the cost for the manufacturers to produce remanufactured products; c_R: the cost for the remanufacturers to produce remanufactured products
w	as unit outsourcing cost
δ	public acceptance of remanufactured products, $\delta \in (0,1)$
τ_0	benchmark recycling rate set by the government
η	reward–penalty intensity established by the government
z	ratio between unit subsidy for green consumers and tax on new products, $z = s/f$
e^i	manufacturers' recycling effort level, where ke^i is the cost of recycling, k is the coefficient between the recycling effort and the recycling cost. $R = \varphi e^i$, i.e., the quantities of used products recycled by manufacturers, as well as the quantities of remanufactured products; φ is the coefficient between the manufacturers' recycling effort and recycling amount.
τ^i	actual recycling rate, i.e., $t^i = R/Q_n$, $\tau^i \in [0,1]$
α^i	the ratio of outsourcing, $\alpha^i \in (0,1)$; $\alpha^i R^i$ is the quantity of remanufactured products produced by the remanufacturers; $\xi(\alpha^i R^i)/2$ are investment costs for the technology, equipment, etc.; ξ is the coefficient between quantities of used products and costs; $d((1-\alpha)R^N)^2/2$ are investment costs for technology, equipment, etc.; d is the coefficient between quantities of used products and costs
p_n, p_r	new unit, remanufactured product price
$Q^i_{M,n}$, $Q^i_{M,r}$, Q^i_M	$Q^i_{M,n}$: quantities of new products produced by manufacturer; $Q^i_{M,r}$: quantities of remanufactured products produced by manufacturer; Q^i_M: manufacturers' total output, $Q^i_M = Q^i_{M,r} + Q^i_{M,n}$
Q^i_R	Remanufacturers' output
f	Government tax on new products
s	Government subsidies for green consumers to purchase remanufactured products; $s = zf, (z = z_1, z_2)$ respectively represent the ratio between the unit subsidies for green consumers and the government taxes on new products when the manufacturers partially or fully recycle the wasted products
π^i_M, π^i_R, π^{FG}_G	the objective functions of the manufacturers, remanufacturers, and government

3.3. Assumption

In order to simplify the supply chain, this research makes the following assumptions:

(1) Considering the wear and tear of products during the remanufacturing process, this study assumes that the remanufactured products will be scrapped after consumers have finished using them, and will no longer flow into the supply chain;

(2) Waste products are derived from wasted products, so the recycling volume of wasted products is less than or equal to the output of new products in the previous period, namely $R \le Q_{M,n}$;

(3) In models N, G, and GF, the remanufacturers determine their remanufacturing outsourcing proportion, denoted as α, while the outsourcing business volume is αR. Based on the principle of the extended producer responsibility, the manufacturers are responsible for the remanufacturing of the remaining waste products, $(1-\alpha)R$;

(4) Since waste products can be used in the production of remanufactured products, the resources required to produce remanufactured products are lower than those required to produce new products, and remanufacturers are more specialized in the remanufacturing industry, therein $0 < c_R < c_{M,r} < c_{M,n} < 1$;

(5) Based on the fact that Chinese consumers have low acceptance of remanufactured products, we set the consumers' acceptance of remanufactured products as $\delta < 1$;

(6) We assume that the market size is 1 and consumers' willingness to pay for new products is θ, which is evenly distributed within [0, 1]. The consumers' willingness to pay for remanufactured goods is $\delta\theta$. Therefore, the net utility available to consumers when purchasing new products is $U_n = \theta - p_n$, while the net utility available to consumers when purchasing recycled products is $U_r = \delta\theta - p_r$. We view the demand function for new products as $Q_{M,n} = Q - \frac{p_n - p_r}{1-\delta}$ and for remanufactured products as $R = \frac{\delta p_n - p_r}{\delta(1-\delta)}$ without the government subsidy. With the government green product subsidy, the demand functions are $Q_{M,n} = Q - \frac{p_n - p_r + s}{1-\delta}$, $R = \frac{\delta p_n - p_r + s}{\delta(1-\delta)}$.

(7) The reward and punishment function for the government is: $L = \eta(\tau - \tau_0)Q_{M,n}$. When $\tau \ge \tau_0$, L represents the government recycling reward; when $\tau \le \tau_0$, L represents the recycling penalty;

(8) Based on the EPR principles, government subsidies for green consumers will encourage consumers to purchase remanufactured products. In order to better fulfill the EPR principles, the government should provide green consumption subsidies to consumers who purchase remanufactured products. The government should also levy green taxes on manufacturers that produce new products. The ratio between green subsidies and green taxes is greater than 1, which is $\lambda \ge 1$.

4. Stackelberg Game Models

4.1. Model N (Free Recycling Mode)

In this model, the manufacturers first decide both the quantity of new products $Q_{M,n}$ and the level of recycling effort e simultaneously, and then the remanufacturers determine the ratio of outsourcing α. The specific decision functions are shown below.

The manufacturers' recycling decision and new product output decision are:

$$\max \pi_M^N\left(Q_{M,n}^N\right) = (p_n - c_{M,n})Q_{M,n}^N + (p_r - c_{M,r})R^N + (c_{M,r} - w)Q_R^N - ke^N - \frac{d\left((1-\alpha)R^N\right)^2}{2}, s.t. R^N \le Q_{M,n}^N \quad (1)$$

$$\max \pi_M^N\left(e^N\right) = (p_n - c_n)Q_{M,n}^N + (p_r - c_{M,r})R^N + (c_{M,r} - w)Q_R^N - ke^N - \frac{d\left((1-\alpha)R^N\right)^2}{2}, s.t. R^N \le Q_{M,n}^N \quad (2)$$

The decision for the ratio of outsourcing is:

$$\max \pi_R^N\left(\alpha^N\right) = (w - c_R)Q_R^N - \frac{\xi\left(Q_R^N\right)^2}{2} \quad (3)$$

These problems are typical of the Cournot duopoly and Stackelberg game model. We solve (1) and (2) according to the backward induction method. The optimal solutions under mode N are shown in Table 2. By analyzing the above results, the relationships between each decision variable and the main parameters are obtained, as shown in Table 3. See Appendix A for the solution process.

Table 2. The optimal solutions under model N.

c_R	(N-1) $(c_{R1}, c_{M,n})$	(N-2) $(0, c_{R1})$
$Q_{M,n}^{N*}$	$\frac{N_2-2\varphi\delta\xi c_{M,n}}{2\varphi\xi(d+2\delta-2\delta^2)}$	$\frac{\varphi dw-N_4}{\varphi\xi(6\delta+2+d)}$
e^{N*}	$\frac{-N_1}{\varphi^2\xi(d+2\delta-2\delta^2)}$	$\frac{\varphi dw-N_4}{\varphi^2\xi(6\delta+2+d)}$
α^{N*}	$\frac{\varphi(c_R-w)\left(d+2\delta-2\delta^2\right)}{N_1}$	$\frac{\varphi(c_R-w)(d+6\delta+2)}{N_4-\varphi dw}$
R^{N*}	$\frac{-N_1}{\varphi\xi(d+2\delta-2\delta^2)}$	$\frac{\varphi dw-N_4}{\varphi\xi(6\delta+2+d)}$
Q_R^*	$\frac{w-c_R}{\xi}$	$\frac{w-c_R}{\xi}$
$Q_{M,r}^{N*}$	$\frac{\varphi\delta\xi c_n-N_3}{\varphi\xi(d+2\delta-2\delta^2)}$	$\frac{-(N_4+N_5)}{\varphi\xi(6\delta+2+d)}$
Q_M^{N*}	$\frac{N_2-2N_3}{2\varphi\xi(d+2\delta-2\delta^2)}$	$\frac{\varphi dw-(2N_4+N_5)}{\varphi\xi(6\delta+2+d)}$
τ^{N*}	$\frac{2N_1}{2\varphi\delta\xi c_{M,n}-N_2}$	1

Table 3. Relationships between variables and parameters in model N.

Interval	N-1			N-2		
Parameters/Variables	$c_{M,n}$	$c_{M,r}$	c_R	$c_{M,n}$	$c_{M,r}$	c_R
e^{G*}, R^{G*}	+	−	−	−	−	−
α^{N*}	−	+	−	+	+	−
$Q_{M,n}^{N*}$	−	+	+	−	−	−
Q_R^{N*}	/	/	−	/	/	−
$Q_{M,r}^{N*}$	+	−	+	−	−	+
Q_M^{N*}	−	−	+	−	−	−
τ^{N*}	+	−	−	/	/	/

Note: "+", "−", "± ", "/" indicate that the variable is positively, negatively, non-linearly, or not related to the parameter, respectively.

According to the recycling rate, the development of the remanufacturing industry can be classified into the germination and mature periods. The larger τ is, the more developed the remanufacturing industry is. In this paper, the development of the remanufacturing industry is based on the per unit production cost for the remanufacturers. The lower c_R is, the higher the development level is. In addition, in order to facilitate reading and understanding, the costs of remanufacturing in the (N-1) and (N-2) intervals in this article are sequentially reduced. When c_R is in the (N-1), it means the remanufacturer's capability to produce remanufactured products is strong. When c_R is in the (N-2), it means the remanufacturer's capability is weak.

$$c_{R1} = \frac{2k\xi(\delta-1)+2\varphi(1+\delta)\left(dw-\xi c_{M,r}\right)-\varphi\xi Qd-2\varphi\xi Q\delta(1-\delta)+\varphi\xi dc_{M,n}+4\varphi\xi\delta c_{M,n}}{2\varphi d(1+\delta)}$$
$$N_1 = k\xi + \varphi d(c_R - w) + \varphi\xi(c_{M,r} - \delta c_{M,n})$$
$$N_2 = \varphi\xi d + 2\varphi\xi\delta(1-\delta) + 2k\xi\delta - \varphi\xi dc_{M,n} + 2\varphi\xi\delta c_{M,r} - 2\varphi\delta d(w - c_R)$$
$$N_3 = k\xi + \varphi\xi c_{M,r} - 2\varphi\delta(1-\delta)(c_R - w), N_4 = \varphi\xi(c_{M,r} + c_{M,n}) - \varphi\xi(1+\delta) + k\xi + \varphi dc_R$$
$$N_5 = 2\varphi(w - c_R) - \varphi dc_R + 6\varphi\delta(w - c_R)$$

Proposition 1. *$e^{N*}, R^{N*}, Q_R^{N*}, \alpha^{N*}$ are negatively related to c_R, while $Q_{M,r}^{N*}$ is positively related to c_R. When $c_R > c_{R1}$, τ^{N*} is negatively related to c_R, $Q_{M,n}^{N*}$, Q_M^{N*} is positively related to c_R; when $c_R < c_{R1}$, $Q_{M,n}^{N*}$ is negatively related to c_R, $\tau^{N*} = 1$.*

Proposition 1 shows that as the remanufacturers' ability continues to increase, the remanufacturers adopts a strategy of using a greater amount outsourcing to produce remanufactured products.

At the same time, the manufacturers adopt a strategy of recycling more waste products and producing fewer remanufactured products. When the remanufacturers are in the development period, the recycling rate continues to increase as the c_R decreases and the manufacturers choose to produce fewer new products. Based on the aforementioned assumption that the manufacturers choose to produce fewer remanufactured and new products, the manufacturers' total output is reduced. Hence, the remanufacturers' increased output means that the market share for the manufacturers is reduced and their leading status is weakened; when the remanufacturing cost for the remanufacturers is in the range of (N-2) (that is, the remanufacturing industry enters a mature period), the recycling volume of waste products is equal to the volume of new products, whereby the recycling volume of waste products and the output of new products are both increasing while c_R is declining.

Proposition 2. *$Q_{M,n}^{N*}, Q_M^{N*}$ are negatively related to $c_{M,n}$. When $c_R > c_{R1}$, $e^{N*}, R^{N*}, Q_{M,r}^{N*}, \tau^{N*}$ are positively related to $c_{M,n}$. When $c_R < c_{R1}$, $e^{N*}, R^{N*}, Q_{M,r}^{N*}$ are negatively related to $c_{M,n}$.*

Proposition 2 shows that as $c_{M,n}$ continues to increase, the manufacturers apply a strategy to lower their output of both new products and total products. The remanufacturers' output remains stable, leading to the market share and leading status of the manufacturers declining. When c_R is in the range of (N-1), whereby the manufacturers' per unit cost for new products increases, the manufacturers would focus on their remanufacturing business and improving their recycling efforts. The manufacturers would adopt strategies to increase their own output of remanufactured products, hence the recycling rate would increase accordingly. When c_R is in the range of (N-2), as the manufacturers' per unit cost for new products increases, the remanufacturers will increase the amount of outsourcing. In the range of (N-2), the manufacturers apply a strategy to fully recycle all used products, so the output for recycling products is equal to the output for new products. When the output of new product declines, the manufacturers' recycling activities and output of remanufactured products also decline.

Proposition 3. *$e^{N*}, R^{N*}, Q_{M,r}^{N*}, Q_M^{N*}$ are negatively related to $c_{M,r}$. When $c_R > c_{R1}$, $Q_{M,n}^{N*}$ and $c_{M,r}$ are positively correlated. When $c_R < c_{R1}$, $Q_{M,n}^{N*}$ and $c_{M,r}$ are negatively correlated.*

Proposition 3 shows that as $c_{M,r}$ decreases, the manufacturers tend to increase their recycling efforts, thereby recycling more waste products. The amount of remanufactured products and the total capacity increase, along with the manufacturers' market share and dominance. When c_R is in the interval range of (N-1), as $c_{M,r}$ continues to decrease, the manufacturers produce fewer new products. When c_R is in the interval range of (N-2), the recycling rate is maintained at 100% and the recycle amount is equal to the output of new products. The output of new products and the amount of recycling increase while $c_{M,r}$ decreases.

4.2. Model G (Government Regulation Model Based on Reward–Penalty Mechanism)

In real-life operations, when the remanufacturing industry is in its initial period, if there is a lack of external incentives, manufacturers are often reluctant to be involved in recycling activities. Hence, government regulation and intervention are important. To promote the implementation of the EPR system, the government needs to take certain measures to encourage manufacturers to recycle waste products. In this model, by setting up the reward–penalty mechanism based on the benchmark recycling rate, the government regulates the recycling activities.

The manufacturers' recycling decision and new product output decision are:

$$\max\pi_M^G\left(Q_{M,n}^G\right) = (p_n - c_n)Q_{M,n}^G + (p_r - c_{M,r})R^G + (c_{M,r} - w)Q_R^N - ke^G - \frac{d\left((1-\alpha)R^G\right)^2}{2} + \eta\left(\tau^G - \tau_0\right)Q_{M,n}^G,\ s.t. R^G \leq Q_{M,n}^{G*} \tag{4}$$

$$\max\pi_M^G\left(e^G\right) = (p_n - c_n)Q_{M,n}^G + (p_r - c_{M,r})R^G + (c_{M,r} - w)Q_R^G - ke^G - \frac{d\left((1-\alpha)R^G\right)^2}{2} + \eta\left(\tau^G - \tau_0\right)Q_{M,n}^{G*} \tag{5}$$

The decision for the ratio of outsourced business is:

$$\max \pi_R^G\left(\alpha^G\right) = (w - c_R)Q_R^G - \frac{\xi\left(Q_R^G\right)^2}{2} \tag{6}$$

According to the backward induction method used to solve the problems expressed in (3) and (4), when C_R is in different ranges, we can derive the optimal decisions for model G, as shown in Table 4. By analyzing the solution results, the relationships between each decision variable and the main parameters are obtained. The results are shown in Table 5. The solution process is the same as for model N, and so will not be described in detail here.

$$C_{R3} = \frac{2k\xi(\delta-1)+2\varphi(1+\delta)\left(dw-\xi c_{M,r}\right)-\varphi\xi Qd-2\varphi\xi Q\delta(1-\delta)+\varphi\xi dc_{M,n}+4\varphi\xi\delta c_{M,n}+\varphi\xi d\eta\tau_o+2\varphi\xi\eta(1+\delta\tau_o)}{2\varphi d(1+\delta)}$$

$$G_1 = k\xi + \varphi d(c_R - w) + \varphi\xi(c_{M,r} - \delta c_{M,n})$$

$$G_2 = \varphi\xi d + 2\varphi\xi\delta(1 - \delta) + 2k\xi\delta - \varphi\xi dc_{M,n} + 2\varphi\xi\delta c_{M,r} + 2\varphi\delta d(c_R - w)$$

$$G_3 = k\xi + \varphi\xi c_{M,r} - 2\varphi\delta(1 - \delta)(c_R - w)$$

$$G_4 = k\xi - \varphi\xi(1 + \eta) + \varphi\xi(c_{M,r} + c_{M,n}) - \varphi\xi\delta$$

$$G_5 = 2\varphi(w - c_R) + 6\varphi\delta(w - c_R)$$

Table 4. Solution results for model G.

c_R	**(G-1)**	**(G-2)**
	$(c_{R2}, c_{M,n})$	$(0, c_{R2})$
$Q_{M,n}^{G*}$	$\frac{G_2-2\varphi\delta\xi c_{M,n}-2\varphi\xi\eta\delta(1+t_o)+\varphi\xi d\eta\tau_o}{2\varphi\xi(d+2\delta-2\delta^2)}$	$\frac{\varphi d(w-c_R)-G_4-\varphi\xi\eta t_o}{\varphi\xi(d+2+6\delta)}$
e^{G*}	$\frac{\varphi\xi\eta(1+\eta\tau_o)-G_1}{\varphi^2\xi(d+2\delta-2\delta^2)}$	$\frac{\varphi d(w-c_R)-G_4-\varphi\xi\eta t_o}{\varphi^2\xi(d+2+6\delta)}$
α^{G*}	$\frac{\varphi(c_R-w)\left(d+2\delta-2\delta^2\right)}{G_1-\varphi\xi\eta(1+\delta\tau_o)}$	$\frac{\varphi(c_R-w)(d+6\delta+2)}{G_4+\varphi d(c_R-w)+\varphi\xi\eta t_o}$
R^{G*}	$\frac{\varphi\xi\eta(1+\eta\tau_o)-G_1}{\varphi\xi(d+2\delta-2\delta^2)}$	$\frac{\varphi d(w-c_R)-G_4-\varphi\xi\eta t_o}{\varphi\xi(d+2+6\delta)}$
Q_R^{G*}	$\frac{w-c_R}{\xi}$	$\frac{w-c_R}{\xi}$
$Q_{M,r}^{G*}$	$\frac{\varphi\delta\xi c_{M,n}+\varphi\xi\eta(1+\delta\tau_o)-G_3}{\varphi\xi(d+2\delta-2\delta^2)}$	$\frac{\varphi d(w-c_R)-2G_4-G_5-2\varphi\xi\eta\tau_o}{\varphi\xi(d+6\delta+2)}$
Q_M^{G*}	$\frac{G_2-2G_3+2\varphi\xi\eta(1-\delta)-\varphi\xi d\eta\tau_o}{2\varphi\xi(d+2\delta-2\delta^2)}$	$\frac{-G_2-G_5-\varphi\xi\eta t_o}{\varphi\xi(d+6\delta+2)}$
τ^{G*}	$\frac{2\varphi\xi\eta(1+\eta\tau_o)-2G_1}{G_2-2\varphi\delta\xi c_{M,n}-2\varphi\xi\eta\delta(1+t_o)+\varphi\xi d\eta\tau_o}$	1

Table 5. Relationships between variables and parameters in model G.

Interval	**G-1**					**G-2**				
Parameters/Variables	$c_{M,n}$	$c_{M,r}$	c_R	η	τ_o	$c_{M,n}$	$c_{M,r}$	c_R	η	τ_o
e^{G*}, R^{G*}	+	−	−	+	+	−	−	−	+	−
α^{G*}	−	+	−	−	−	+	+	−	−	+
$Q_{M,n}^{G*}$	−	+	+	−	−	−	−	−	+	−
Q_R^{G*}	/	/	−	/	/	/	/	−	/	/
$Q_{M,r}^{G*}$	+	−	+	+	+	−	−	+	+	−
Q_M^{G*}	−	−	+	±	−	−	−	±	+	−
τ^{G*}	+	−	−	+	+	/	/	/	/	/

Obviously, the relationship between the optimal solution and the parameters $c_{M,n}, c_{M,r}, c_R$ under model G is basically the same as that under model N. Therefore, the following proposition mainly analyzes the relationships between variables and parameters η, τ_0 in model G.

Proposition 4. *When $c_R > c_{R2}$, $e^{G*}, R^{G*}, Q_{M,r}^{G*}, \tau^{G*}$ and η, τ_0 are positively related; $\alpha^{G*}, Q_{M,n}^{G*}$ and η, τ_0 are negatively related; Q_M^{G*} is negatively related with τ_0; and the relationship between Q_M^{G*} and η is uncertain.*

Proposition 4 shows that when the remanufacturing industry is in the germination period, the more intensive the reward–penalty mechanism is and the higher the recycling rate is, the more likely the manufacturers will be to increase their recycling efforts, recycling volume, and output of remanufactured products while reducing the output of new products. During this period, these two regulatory measures can incentivize the manufacturers to increase their recycling rate. The remanufacturers will lower their outsource ratio to maintain their output.

Proposition 5. *When $c_R < c_{R2}$, $e^{G*}, R^{G*}, Q_{M,r}^{G*}, Q_M^{G*}$, and η are positively related, while all are negatively related with τ_0; α is negatively related with η and positively related with τ_0.*

Proposition 5 shows that when the remanufacturing industry is in the mature period, the manufacturers will recycle all waste products, so the number of waste products will be equal to the number of new products. When the government increases the regulation intensity, the manufacturers will increase their recycling efforts, producing more new products and more remanufactured products (increasing the total output). The remanufacturers will outsource less of their remanufacturing business, while their own remanufactured product output will remain unchanged, so the manufacturers' market share and market dominance will increase accordingly. When the government increases the basic recycling rate, the manufacturers reduce their output of new products and remanufactured products (reducing the total output). At this time, the remanufacturers increase the contracting share of the remanufacturing business so that its output is unchanged, meaning the manufacturers' market share and market dominance decline accordingly.

4.3. Model GF (Government Dual-Intervention Mode)

The environmental pollution and energy consumption caused by manufacturing activities can be partially alleviated by remanufacturing. In reality, the market is composed of two types of consumers: normal consumers, who prefer to purchase new products, and green consumers, who view remanufactured products as a cost-effective choice. Therefore, the government is motivated to adopt certain incentives based on the EPR principles to encourage consumers to purchase remanufactured products. This study discusses the government's development of a green subsidy scheme to motivate green customers to fulfill the EPR principles, which were originally developed for manufacturers. In this scenario, the government aims for maximum social benefits. The manufacturers indirectly fulfill the EPR principles by paying taxes on new products to the government, while green consumers qualify for a certain purchasing subsidy on remanufactured products provided by the government.

In this model, we present a three-layer game model, which incorporates the government, manufacturers, remanufacturers, and green and non-green consumers. The government as a leader determines the tax per unit on new products to maximize overall social welfare. On this basis, according to this tax amount, the manufacturers determine their output of new products and their recycling efforts so as to maximize profits. The remanufacturers thereafter determine their level of outsourcing based on their own profit maximization.

The social welfare component consists of four parts: the manufacturers' profits, remanufacturers' profits, consumer surplus, and government expenditure.

The government's tax decision for new products is:

$$\max \pi_G^{GF}(f) = \pi_M^{GF} + \pi_R^{GF} + \pi_C^{GF} - \eta(t - t_0)Q_{M,n}^{GF} + fQ_{M,n}^{GF} - sR^{GF} \tag{7}$$

Among these:

$$\pi_M = (p_n - c_n)Q_{M,n} + (p_r - c_{M,r})R + (c_{M,r} - w + b)Q_R - ke + \eta\left(\tau^{GF} - \tau_0\right)Q_n - fQ_{M,n}^{GF}$$
$$\pi_R = (w - c_r - b)\alpha R - \frac{\xi(\alpha R)^2}{2}$$
$$\pi_c = \int_{\frac{p_n - p_r + s}{1-\delta}}^{1} (\theta - p_n)d\theta + \int_{\frac{p_r - s}{\delta}}^{\frac{p_n - p_r + s}{1-\delta}} (\delta\theta - p_r + s)d\theta = \frac{\varphi^2 e^2 + \delta\varphi e^2 Q_n + \delta Q_n^2}{2\delta}$$

The manufacturers' recycling decisions and new product decisions are:

$$\max\pi_M^{GF}\left(Q_{M,n}^{GF}\right) = (p_n - c_n)Q_{M,n}^{GF} + (p_r - c_{M,r})R^{GF} + (c_{M,r} - w)Q_R{}^{GF} - ke^{GF} - \frac{d\left((1-\alpha)R^{GF}\right)^2}{2} + \eta\left(\tau^{GF} - \tau_0\right)Q_{M,n}^{GF} - fQ_{M,n}^{GF},\ s.t. Q_{M,n}^{GF} \geq R^{GF} \quad (8)$$

$$\max\pi_M^{GF}\left(e^{GF}\right) = (p_n - c_n)Q_{M,n}^{GF} + (p_r - c_{M,r})R^{GF} + (c_{M,r} - w)Q_R^{GF} - ke^{GF} - \frac{d\left((1-\alpha)R^{GF}\right)^2}{2} + \eta\left(\tau^{GF} - \tau_0\right)Q_{M,n}^{GF} - fQ_{M,n}^{GF}$$

The decision for the ratio of outsourcing is:

$$\max\pi_R^{GF}\left(\alpha^{GF}\right) = (w - c_r)\alpha^{GF}R^{GF} - \frac{\xi\left(\alpha^{GF}R^{GF}\right)^2}{2} \quad (9)$$

The backward induction method is still applied here. For c_R in different ranges, the relations between the optimal government tax level and the parameters are shown in Table 6. (In the stage of incomplete manufacturer recycling, the tax expression f is more complicated, so f is not substituted in Table 7**.** For the value of f, see Appendix B.) The optimal decisions for the GF model are shown in Table 7**.** By analyzing the solution results, the relationships between each decision variable and the parameters are obtained. The results are shown in Table 8.

$$c_{R3} = \frac{2k\xi(\delta-1) + 2\varphi(1+\delta)\left(dw - \xi c_{M,r}\right) - \varphi\xi Qd - 2\varphi\xi Q\delta(1-\delta) + \varphi\xi dc_{M,n} + 4\varphi\xi\delta c_{M,n} + \varphi\xi d\eta\tau_o + 2\varphi\xi\eta(1+\delta\tau_o) + \varphi\xi f(d + 4\delta + 2z + 2z\delta)}{2\varphi d(1+\delta)}$$
$$GF_1 = k\xi + \varphi d(c_R - w) + \varphi\xi(c_{M,r} - \delta c_n)$$
$$GF_2 = \varphi\xi d + 2\varphi\xi\delta(1-\delta) + 2k\xi\delta - \varphi\xi dc_{M,n} + 2\varphi\xi\delta c_{M,r} + 2\varphi\delta d(c_R - w)$$
$$GF_4 = 5\varphi\xi(1+\delta) - 2\varphi\xi(c_{M,r} + c_{M,n}) - 2k\xi$$
$$GF_3 = k\xi + \varphi\xi c_{M,r} - 2\varphi\delta(1-\delta)(c_R - w)$$

Table 6. Relationships between government unit tax and parameters for GF model.

Interval	**GF-1**					**GF-2**				
Parameters/Variables	$c_{M,n}$	$c_{M,r}$	c_R	η	τ_o	$c_{M,n}$	$c_{M,r}$	c_R	η	τ_o
f^{GF*}	+	−	−	−	−	/	/	/	+	−

Table 7. The optimal solutions for the GF model.

c_R	**(GF-1)**	**(GF-2)**
	(c_{R3}, $c_{M,n}$)	**(0, c_{R3})**
$Q_{M,n}^{GF*}$	$\frac{GF_2 - 2\varphi\delta\xi c_{M,n} - 2\varphi\xi\eta\delta(1+t_o) + \varphi\xi d\eta\tau_o - \varphi\xi f(d+\delta+2z\delta)}{2\varphi\xi(d+2\delta-2\delta^2)}$	$\frac{GF_4 - 2\varphi d(c_R - w)}{2\varphi\xi(d+6\delta+2)}$
e^{GF*}	$\frac{\varphi\xi\eta(1+\eta\tau_o) - GF_1 + \varphi\xi f(\delta+z)}{\varphi^2\xi(d+2\delta-2\delta^2)}$	$\frac{GF_4 - 2\varphi d(c_R - w)}{2\varphi^2\xi(d+6\delta+2)}$
α^{GF*}	$\frac{\varphi\xi\eta(1+\eta\tau_o) - GF_1 + \varphi\xi f(\delta+z)}{\varphi^2\xi(d+2\delta-2\delta^2)}$	$\frac{2\varphi(c_R - w)(d+6\delta+2)}{GF_4 - 2\varphi d(c_R - w)}$
R^{GF*}	$\frac{\varphi\xi\eta(1+\eta\tau_o) - GF_1 + \varphi\xi f(\delta+z)}{\varphi\xi(d+2\delta-2\delta^2)}$	$\frac{GF_4 - 2\varphi d(c_R - w)}{2\varphi\xi(d+6\delta+2)}$
Q_R^{GF*}	$\frac{w - c_R}{\xi}$	$\frac{w - c_R}{\xi}$
$Q_{M,r}^{GF*}$	$\frac{GF_2 - 2GF_3 + 2\varphi\xi\eta(1-\delta) - \varphi\xi d\eta\tau_o + \varphi\xi f(\delta+z)}{2\varphi\xi(d+2\delta-2\delta^2)}$	$\frac{4\varphi(1+3\delta(c_R - w)) + GF_4}{2\varphi\xi(d+6\delta+2)}$
Q_M^{GF*}	$\frac{2\varphi\xi\eta(1+\eta\tau_o) - 2GF_1 - \varphi\xi f(d-2z+2\delta z)}{GF_2 - 2\varphi\delta\xi c_n - 2\varphi\xi\eta\delta(1+t_o) + \varphi\xi d\eta\tau_o}$	$\frac{2\varphi(1-3\delta)(c_R - w) + GF_4 - \varphi d(c_R - w)}{\varphi\xi(d+6\delta+2)}$
τ^{G*}	$\frac{2\left[\varphi\xi\eta(1+\eta\tau_o) - GF_1 + \varphi\xi f(\delta+z)\right]}{GF_2 - 2\varphi\delta\xi c_{M,n} - 2\varphi\xi\eta\delta(1+t_o) + \varphi\xi d\eta\tau_o - \varphi\xi f(d+\delta+2z\delta)}$	1

Table 8. Relationships between variables and parameters in the GF model.

Interval	GF-I					GF-II				
Parameters/Variables	$c_{M,n}$	$c_{M,r}$	$c_{M,r}$	η	τ_O	$c_{M,n}$	$c_{M,r}$	c_R	η	τ_O
e^{G*}, R^{G*}	+	−	−	±	−	−	−	−	/	/
α^{G*}	−	+	±	±	+	+	+	±	/	/
$Q_{M,n}^{GF*}$	±	+	+	±	±	−	−	−	/	/
Q_R^{G*}	/	/	−	/	/	/	/	−	/	/
$Q_{M,r}^{G*}$	+	−	±	±	−	−	−	+	/	/
Q_M^{G*}	±	±	±	±	±	−	−	±	/	/
τ^{G*}	±	−	−	±	±	/	/	/	/	/

Proposition 6. *When $c_R > c_{R3}$, f^{GF*} is positively related to $c_{M,n}$, and negatively related to $c_{M,r}, c_R, \eta, \tau_0$.*

Proposition 6 shows that when the remanufacturing industry is in the development period, when the manufacturers' new product cost increases, in order to achieve the goal of maximizing social benefits, the government should increase the tax on new products; while the remanufacturer or manufacturers' remanufactured product cost decreases, in order to maximize social benefits, the government should reduce taxes. When the government increases the benchmark recycling rate or intensity, the government should reduce taxes.

Proposition 7. *When $c_R < c_{R3}$, f^{GF*} is positively related to η, and negatively related to τ_O. And f^{GF*} has no relationship with $c_{M,r}, c_{M,r}, c_R$.*

Proposition 7 shows that when the remanufacturing industry is at the mature stage, when the government adopts a greater level of intensity for the reward and punishment mechanism, the government should increase taxes, while if the government increases the benchmark recycling rate, the government should reduce the taxes.

Proposition 8. *When $c_R > c_{R3}$, α^{G*} is positively related with τ_0, $e^{G*}, R^{G*}, Q_{M,r}^{G*}$ is negatively related with τ_0.*

Proposition 8 shows that when the remanufacturing industry is in the development period, under the dual regulations, as the government increases the benchmark recycling rate, the manufacturers adopt a lower level of recycling effort and the remanufacturers increase their proportion of outsourcing, so the number of remanufactured products produced by the manufacturers is also reduced.

Proposition 9. *When $c_R > c_{R3}$, $e^{G*}, R^{G*}, \alpha^{G*}, Q_n^{G*}, Q_R^{G*}, Q_{M,r}^{G*}, Q_M^{G*}, \tau^{G*}$ are not related with η, τ_0.*

Proposition 9 shows that when the remanufacturing industry is at the mature stage, under the dual regulations, the government reward–penalty mechanism does not work.

4.4. Comparison of the Three Modes

In Sections 4.1–4.3, we analyzed and found solutions for the three models in sequence, but did not compare the different models. In this section, by further comparing and analyzing the optimal decision-making processes for the three models, the following propositions were obtained.

Proposition 10. *When manufacuterer recycles part of the waste products $e^{N*} < e^{G*} < e^{GF*}$, when the manufacturer recycles all the waste, $e^{N*} < e^{G*}$. And $c_{R1} < c_{R2} < c_{R3}$.*

Proposition 10 shows that when the remanufacturing industry is in the early stage of development, government regulation can effectively enhance the manufacturers' recycling activity, and among the two government regulation models, the government's dual-regulation model is better in terms of environmental performance. When the remanufacturing industry is at the mature stage, the government's implementation of rewards and punishments based on the recycling rate can encourage the manufacturers to recycle waste products. Under models GF, G, and N, the cost threshold for complete recycling of waste products is successively reduced, showing that even if the remanufacturering industry is in the development period, government regulations can effectively encourage the manufacturers to fully recycle.

Proposition 11. $Q_{M,r}^{N*} < Q_{M,r}^{G*} < Q_{M,r}^{GF*}$, *when the manufacturer recycles all the waste products,* $Q_M^{N*} < Q_M^{G*}$.

Proposition 11 shows that when the manufacturers partially recycle, under models G and GF, the output of remanufactured products is higher than under model N. This shows that government regulations can effectively guide the manufacturers to pay attention to their own remanufacturing business and produce more remanufactured products, and that the effects of dual interventions are more obvious. In the case of full recycling, the total output from the manufacturers in model G is higher than the total output of the manufacturers in model N, indicating that government regulation based on the reward and punishment model of recycle can encourage the manufacturers to increase their output.

5. Numerical Analysis

In Section 4, we separately found the optimal solutions for the manufacturers and remanufacturers under the three models, as well as the optimal solution for the government under the third model. We analyzed the relationships between the optimal solutions and some key parameters, and made a preliminary comparative analysis of the three models in Section 4.4. However, due to the relatively complicated solution results, it was not possible to directly analyze the profits, recycling rates, and other factors. In order to more clearly and intuitively judge the recycling of waste products and corporate profits in each model and to better understand the impacts of government regulations on closed-loop supply chain operations, we conducted a numerical analysis. We set the basic parameters as follows: $c_{M,n} = 0.99$, $c_{M,r} = 0.35$, $w = 0.35$, $\delta = 0.68$, $\varphi = 2$, $k = 0.2$, $\xi = 0.78$, $d = 1$, $\tau_0 = 0.3$, $\eta = 0.04$, $z_1 = 1.5$, $z_2 = 0.7$, $Q = 2.5$, $A = 0.05$ The basis for setting the basic parameters came from actual data accumulated by Chinese remanufacturing companies that we visited and interviewed and the academic results of related papers. For example, based on the results of our field research and the research results of Chen, Cao, and Kumar [41], we found that in the current development stage of the Chinese remanufacturing industry, the cost of remanufactured products is 30–40% of the cost of new products. We assigned the unit costs for new products and remanufactured products for manufacturers as follows: $c_{M,n} = 0.99$, $c_{M,r} = 0.35$. Based on our field research and the results in results [42,43], we found that when $\tau_0 = 0.3$, $\eta = 0.04$ in the current development stage of China's remanufacturing industry, manufacturers can better promote the recycling of waste products, so we assigned the values $\tau_0 = 0.3$, $\eta = 0.04$.

5.1. Environmental Performance Perspective

Using c_R as the horizontal axis, the recycling rates under the three models can be clearly viewed in Figure 2.

The analysis concludes as follows:

(1) The recycling rates under models G and GF are greater than those under model N, indicating that government regulations can effectively guide manufacturers to improve their recycling rates and achieve greater environmental performance;

(2) Comparing the remanufacturing cost ranges for 100% recycling under the three models, model GF has the longest range, model G is second, and model N has the shortest range. This shows that under model GF (the government dual-intervention mode) full recycling can easily be achieved,

model N (Free Recycling mode) is the most difficult to achieve full recycling, and model G (government regulation model based on a reward–penalty mechanism) is somewhere in between. Figure 2 shows that the reward–penalty mechanism and green subsidy and tax regulations can effectively encourage manufacturers to recycle all waste products, even when the remanufacturing industry is immature. The intervention of the government is very important in the early stage of the development of the remanufacturing industry.

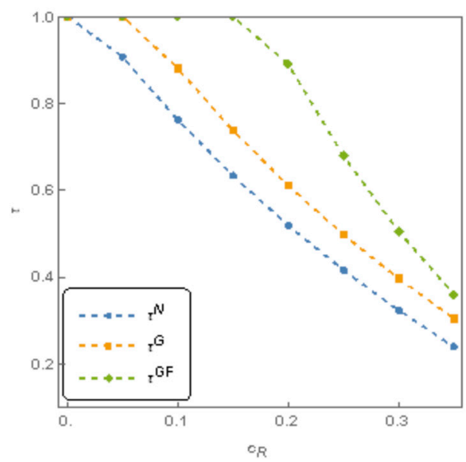


Figure 2. The recycling rates under different development models.

5.2. *Business Cooperation Perspective*

Using c_R as the horizontal axis, the outsourcing ratio under the three models can be clearly viewed in Figure 3.

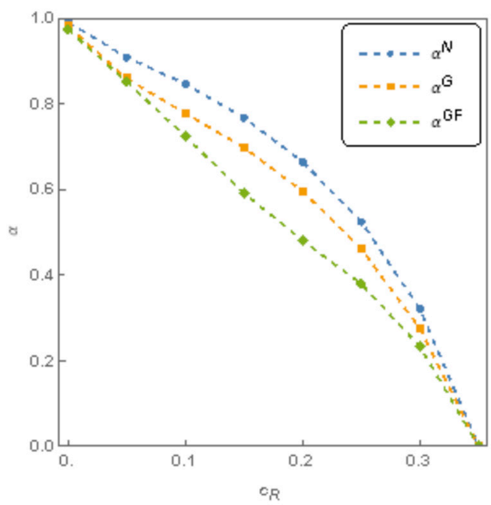


Figure 3. Outsourcing ratio analysis for different development models.

Under models N, G, and GF, manufacturers recycle wasted products through self-built recycling channels. Manufacturers also manufacture both new products and remanufactured products. In addition, the manufacturers take into account the fact that the remanufacturers are professionals in the remanufacturing business. In order to optimize costs and reduce competition, manufacturers outsource part of the remanufacturing business to remanufacturers. As the remanufacturing costs for remanufacturers increase, the outsourcing profit margins decrease, manufacturers and remanufacturers tend to not cooperate, and the closeness of the cooperation decreases. The analysis shows that the remanufacturers and manufacturers cooperate most closely when there is no government intervention.

When the remanufacturing industry is in the development period between the beginning stage and maturity, the cooperation under the reward and punishment mechanism model would be closer than under the government dual-intervention model.

5.3. Economic Benefit Perspective

Using c_R as the horizontal axis and the manufacturers' profit π_M, the remanufacturers' profit π_R, and the total supply chain profit π_T as the vertical axis, the profit graphs for different models are obtained, as shown in Figure 4.

It can be seen from Figure 4 that under the three models, as the remanufacturing industry gradually matures, the remanufacturers' total profits and the supply chain profits both increase. Among these, the remanufacturers' profits under models N, G, and GF are the same, and increase as c_R decreases. Further analysis leads to the following conclusions:

(1) When the remanufacturing industry is in the early stage of development, as shown in Figure 4a,c, the manufacturers' profits and the total supply chain profits are significantly lower than with model G or model GF. This shows that when the remanufacturing industry is in a relatively immature period, government intervention will obviously increase manufacturers' profits and the total supply chain profits. Therefore, the government plays an important role in guiding the transformation of the remanufacturing industry from the primary stage to the mature stage;

(2) Under the GF model, the manufacturers' profits basically increase as the remanufacturing industry gradually matures; that is, the unit cost for remanufactured products produced by remanufacturers decreases. The reason for the turning point in the manufacturers' profit curve lies in the changes in government regulations. It can be seen from the figure that the dual government regulations have a more significant impact on profits than a single government regulation. When the manufacturers do not fully recycle, the government will sacrifice its profits in order to maximize the total social welfare benefits; when the manufacturers fully recycle, the government will maintain its own profit margins;

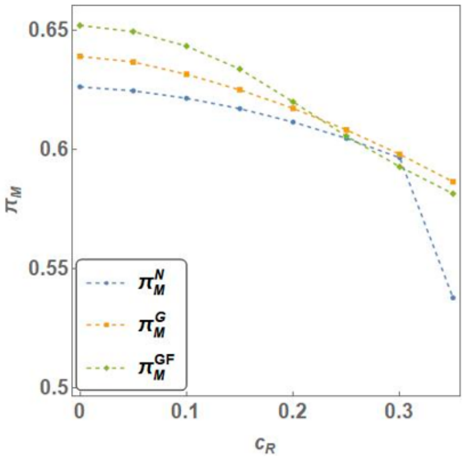
(3) When the remanufacturing industry is at the early stage of development, there is no significant difference in the manufacturers' profits between model G and model GF, however the total supply chain profits under the model G are significantly higher than the total supply chain profits under model GF. This shows that when the remanufacturing industry is in the early stages of development, dual interventions have an obvious effect on promoting recycling among manufacturers, however this essentially occurs in exchange for some of the profits from the entire supply chain. At this time, the government scheme involving reward and punishment regulations based on the recycling rate is better and more effective in terms of maximizing social profits;

(4) When the remanufacturing industry is relatively mature, the profits for manufacturers under model GF and model N are significantly lower than under model G. Under the three models, there is no significant difference in the manufacturers' profit. This shows that when the remanufacturers are relatively mature, the government scheme involving reward and punishment regulations based on the recycling rate is better and more effective in terms of maximizing the manufacturers' profits.

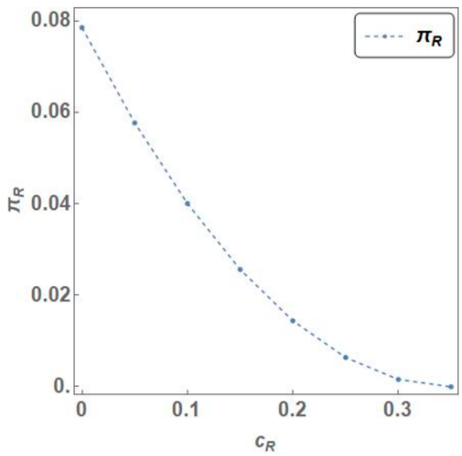
5.4. Government Strategy Perspective

In this section, based on the perspective of government regulation, by setting the parameter values for different government regulations, we can analyze the influence of government regulations on the supply chain and propose flexible strategies that are contingent on the development period and maturity of the remanufacturing industry.

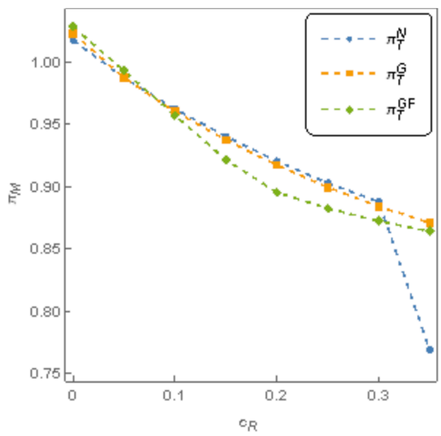
In order to analyze the impacts of the specific government regulation model based on the reward–penalty mechanism, this study sets four groups of values for the basic recycling rates and reward–penalty intensity as follows: $\eta = 0.01, \tau_0 = 0.3$; $\eta = 0.01, \tau_0 = 0.6$; $\eta = 0.04, \tau_0 = 0.3$; $\eta = 0.04, \tau_0 = 0.6$. The impacts of the government regulations are shown in Figure 5, whereby Figure 5a shows the manufacturers' recycling rate, Figure 5b shows the manufacturers' profits, and Figure 5c shows the remanufacturers' profits.



a. Manufacturer's profit figure

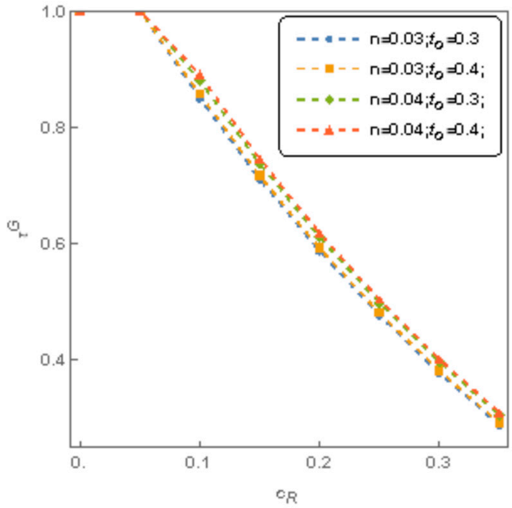


b. Remanufacturer's profit figure

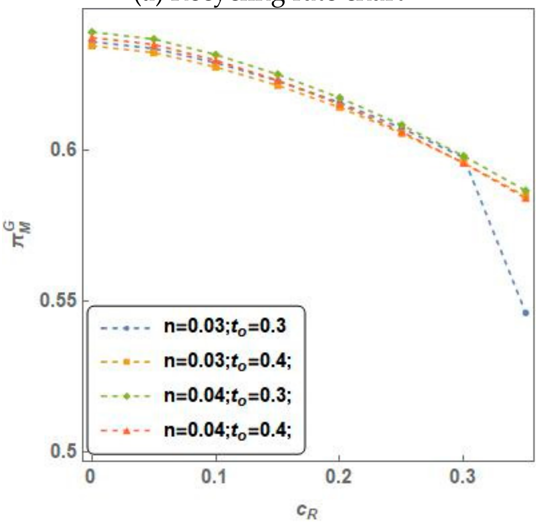


(c) Profit analysis chart under different modes

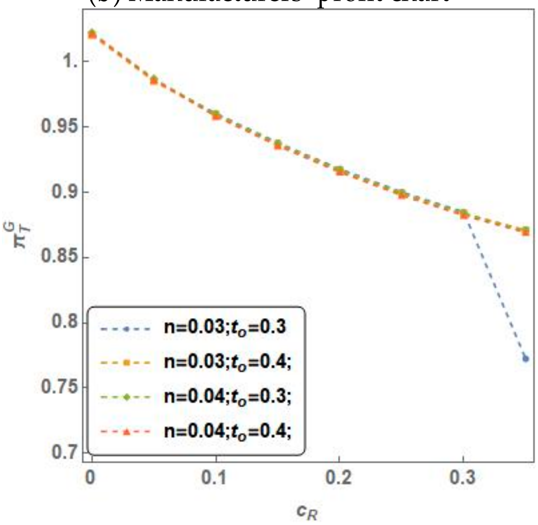
Figure 4. Profit figures under different models. (**a**) Manufacturer's profit figure; (**b**)Remanufacturer's profit figure; (**c**) Profit analysis chart under different modes.



(**a**) Recycling rate chart



(**b**) Manufacturers' profit chart

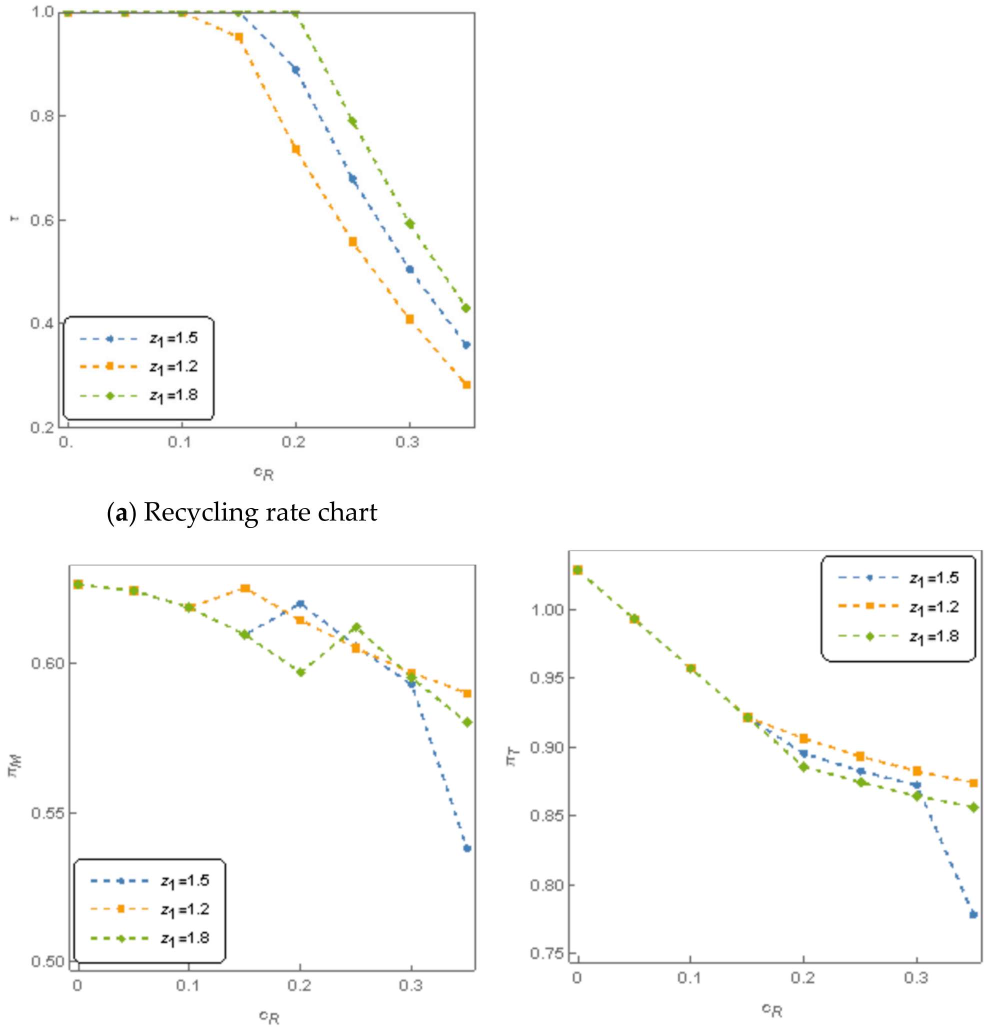


(**c**) Supply chain total profit chart

Figure 5. Impact of η, τ_0. (**a**) Recycling rate chart; (**b**) Manufacturer's profit chart; (**c**) Supply chain total profit chart.

It can be seen from Figure 5a that when the government increases the basic recycling rate or increases the reward–penalty intensity, the recycling rate in the supply chain increases. From Figure 5b,c, it can be seen that under government regulations, the increases in the reward–penalty intensity and benchmark recycling rates do not significantly affect the manufacturers' profits or the total supply chain profits. When the remanufacturing industry is in the early stages of development, increasing the reward–penalty intensity can effectively increase the manufacturers' profits and the total supply chain profits, while manufacturers also increase their recycling efforts and recycling rate.

In order to further analyze the effects of dual government regulations, this study sets three group value ratios for government green consumption subsidies and green taxes on new products: $z_1 = 1.5$; $z_2 = 1.2$; $z_3 = 1.8$; ($z = s/f$). For the influence analysis of parameter z, see Figure 6.



(**a**) Recycling rate chart

(**b**) Manufacturers' profit chart

(**c**) Supply chain total profit chart

Figure 6. Influence analysis of parameter z. (**a**) Recycling rate chart; (**b**) Manufacturer's profit chart; (**c**) Supply chain total profit chart.

It can be seen from Figure 6a that the increase in z is helpful in encouraging the manufacturers to completely recycle waste products. It can be seen from Figure 6b that the manufacturers' profits generally increase with the reduction of remanufacturing costs, but when the remanufacturers enter the mature period (i.e., the manufacturers' complete recycling process), their profits trend downward. When the manufacturers enters the state of complete recycling, their profits increase with the reduction of remanufacturing costs. Under the three different green consumption subsidies and green tax ratios, when the manufacturers enter the state of complete recycling, their profits remain the same. When the remanufacturing industry is still in its infancy, the manufacturers' profits under $z_1 = 1.5$ are significantly lower than when $z_1 = 1.2$; $z_1 = 1.8$. This shows that regarding the manufacturers' development, it is not as simple as a smaller or larger ratio being better, rather it requires the government to formulate a tailored approach. It can be seen from Figure 6c that the total supply chain profits increase as the cost of remanufactured products decreases, and after the manufacturers begin to fully recycle all wasted products, the total supply chain profits are the same under different z parameter settings. When the remanufacturing industry is still in its infancy, the total supply chain profits under $z_1 = 1.5$ are significantly lower than for $z_1 = 1.2$; $z_1 = 1.8$; this also shows that regarding the manufacturers' development, the government should formulate a tailored approach.

Overall, when manufacturers do not fully recycle, the government increases the ratio between the green consumption subsidy and green taxes on new products, which encourages manufacturers to engage in recycling activities. This shows that government should consider the optimal ratio and formulate a tailored scheme.

6. Summary

This paper analyzes the strategic choices for manufacturers and remanufacturers under the three models, as well as the optimal choices for the government under one model (model GF), assessing the impacts of different government regulations on business operation and environmental performance. The main conclusions are as follows:

(1) When the manufacturers and the remanufacturers cooperate, the manufacturers take into account the remanufacturer is professional at producing remanufacturered products. Based on the status of China's remanufacturing industry, this research assumes that manufacturers collect waste products via self-built channels. For the sake of cost optimization and to reduce competition, manufacturers outsource some of the remanufacturing business to remanufacturers. At this time, the government's reward–penalty mechanism based on the recycling rate has a positive effect on manufacturers' recycling activities. Increasing the basic recycling rate setting or improving the intensity of the reward–penalty mechanism can increase the recycling rate. When the remanufacturing industry is in the early stages of development, increasing the intensity can effectively increase the manufacturers' profits and the total supply chain profits. It is worth noting that when manufacturers and remanufacturers cooperate, most of the profits go to the manufacturers, while remanufacturers make stable but meagre profits and the manufacturers occupy a dominant market position. The remanufacturers can try to create revenue sharing contracts with the manufacturers;

(2) The government dual-regulation approach can encourage manufacturers to increase their recycling rate and enter the state of full recycling. To a certain extent, the dual regulations can motivate manufacturers to increase their recycling rate and increase their output of remanufactured products. However, essentially some of the manufacturers' profits and the entire supply chain profits are sacrificed, meaning this is not a good long-term strategy for promoting the development of the remanufacturing industry;

(3) The government dual-regulation approach can better encourage manufacturers to increase their recycling rates compared with the single reward–penalty mechanism. When manufacturers enter the state of complete recycling, the dual-regulation model can to a certain extent encourage manufacturers to increase the amount of recycling of waste products and increase the output of their own remanufactured products;

(4) Government regulations are more important when the remanufacturing industry is at the beginning of its development. When the remanufacturing industry reaches a mature stage, manufacturers can voluntarily achieve a higher recovery rate in order to maximize their own profits. Therefore, the government should flexibly formulate corresponding regulatory measures according to the development of the remanufacturing industry;

(5) In the state of incomplete recycling by manufacturers, the government increases the ratio between green consumption subsidies and green taxes on new products, helping to increase manufacturers' recycling rates and the cost range for complete recycling; more importantly, this approach does not necessarily harm the manufacturers' profits and the total supply chain profits. This shows that the government should figure out the optimal ratio between government subsidies and tax policies.

Based on the relevant conclusions from these three models, the government should introduce the following policies to promote the development of the remanufacturing industry: (1) the effects of dual-regulation approach are better, whereby the government can simultaneously levy taxes and introduce subsidies; (2) the government policies should be specific to different companies, rather than taking a "one size fits all" approach; (3) the government, manufacturers, and remanufacturers need to strengthen their cooperation; (4) the remanufacturing industry is still in its infancy in China, meaning guidance from the government can promote the development of the remanufacturing industry.

The following ideas should be considered in future related research: (1) the cooperative effects of different enterprises and governments; (2) the superimposed effects of different regulations; (3) the optimal ratio between government subsidies and tax policies.

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Appendix A. Solution Process for Model N

This model has two stages, whereby the standard solution is the backward induction method; that is, the analysis starts from the second stage, and so on until the first stage.

(1) Second stage analysis

$$\max \pi_R^N\left(\alpha^N\right) = (w - c_R)Q_R^N - \frac{\xi\left(Q_R^N\right)^2}{2}$$

By solving the optimal first-order conditions $\partial\pi_R^N/\partial\alpha^N = 0$, we get:

$$\alpha^N = \frac{(w - c_R)}{\varphi\xi e^N} \tag{A1}$$

(2) The first stage analysis

For the new product quantity decision problem in (1), the Lagrange function is constructed as follows:

$$L(Q_{M,n}^N, e^N, \lambda) = \pi_M^N(Q_{M,n}^N, e^N) + \lambda_1(Q_{M,n}^N - R^N)$$

$$\begin{cases} \frac{\partial L}{\partial Q_{M,n}^N} = 0 \\ \frac{\partial L}{\partial e_{M,n}^N} = 0 \\ \lambda(Q_{M,n}^N - R^N) = 0 \\ Q_{M,n}^N - R^N \geq 0 \end{cases} \tag{A2}$$

We substitute (A1) into the manufacturers' profit function π_M^N and solve (A2).

a. When $\lambda_1 = 0, Q_{M,n} > R$, the optimal response function obtained was:

$$Q_{M,n}^{N*} = \frac{\varphi\xi d(1 - c_{M,n}) + 2\varphi\xi\delta(1 - \delta + c_{M,r} - c_{M,n}) + 2k\delta\xi + 2\varphi\delta d(c_R - w)}{2\varphi\xi(d + 2\delta - 2\delta^2)} \tag{A3}$$

$$e^{N*} = \frac{\varphi d(w - c_R) + \varphi\xi(\delta c_{M,n} - c_{M,r}) - k\xi}{\varphi^2\xi(d + 2\delta - 2\delta^2)} \tag{A4}$$

We substitute (A3) and (A4) into formula (A1) to obtain:

$$\alpha^N = \frac{\varphi(c_R - w)\left(d + 2\delta - 2\delta^2\right)}{k\xi + \varphi\xi(c_{M,r} - \delta c_{M,n}) + \varphi d(c_R - w)} \tag{A5}$$

According to the condition $Q_{M,n} > R$, the value c_{R1} that satisfies its establishment can be further obtained:

$$c_R < \frac{2k\xi(1+\delta)+2\varphi\xi c_{M,r}(1+\delta)+\varphi\xi d\left(1-c_{M,n}\right)+2\varphi\xi\delta(1-\delta)-2\varphi dw(1+\delta)-4\varphi\delta\xi c_{M,n}}{2\varphi d(1+\delta)} = c_{R_1} \tag{A6}$$

b. When $\partial\pi_R^{GF}/\partial\alpha^{GF} = 0$. $\lambda_1 \neq 0, Q_{M,n} = R$, we get:

$$e^N = -\frac{(k\xi - \varphi\xi + \varphi\xi c_{M,r} + \varphi\xi c_{M,n} - \varphi\xi\delta + \varphi d c_{M,r} - \varphi d w)}{\varphi^2\xi(d + 6\delta + 2)} \tag{A7}$$

$$Q_{M,n}^N = -\frac{(k\xi - \varphi\xi + \varphi\xi c_{M,r} + \varphi\xi c_{M,n} - \varphi\xi\delta + \varphi d c_{M,r} - \varphi d w)}{\varphi\xi(d + 6\delta + 2)} \tag{A8}$$

Appendix B. Solution Process for Model GF

This model has three stages, whereby the standard solution is the backward induction method; that is, the analysis starts from the third stage, and so on until the first stage.

(1) Third stage analysis.

$$\max\pi_R^{GF}\left(\alpha^{GF}\right) = (w - c_R)Q_R^{GF} - \frac{\xi\left(Q_R^{GF}\right)^2}{2}$$

We optimize the first-order conditions by solving $\partial\pi_R^{GF}/\partial\alpha^{GF} = 0$, and we get:

$$\alpha^{GF} = \frac{(w - c_R)}{\varphi\xi e^{GF}} \tag{A9}$$

(2) Second stage analysis

For the new product quantity decision problem in (6), the Lagrange function is constructed as follows:

$$L(Q_{M,n}^{GF}, \lambda) = \pi_M^{GF} + \lambda(Q_{M,n}^{GF} - R^{GF})$$

$$\begin{cases} \frac{\partial L}{\partial Q_{M,n}^{GF}} = 0 \\ \lambda(Q_{M,n}^{GF} - R^{GF}) = 0 \\ Q_{M,n}^{GF} - R^{GF} \geq 0 \end{cases} \tag{A10}$$

We substitute (A9) into the manufacturers' profit function π_M^{GF} and solve (A10) at the same time:

a. When $\lambda_3 = 0, Q_{M,n} > R$:

$$Q_{M,n}^{GF} = \frac{2\varphi\delta\xi Q(1-\delta)-\varphi\xi d\left(c_{M,n}-Q+f+n*t_o\right)+2\varphi\xi\delta\left(c_{M,n}-c_{M,r}+f+n+nt_o+zf\right)-2\varphi d\delta\left(w-c_R\right)-2k\delta\xi}{2\varphi\xi(d+2\delta-2\delta^2)} \tag{A11}$$

$$e^{GF} = \frac{\varphi d(w - c_R) + \varphi\xi(\delta c_n - c_{mr}) - k\xi + \varphi\xi\eta(1 + \delta\tau_o) + \varphi\xi f(\delta + z)}{\varphi^2\xi(d + 2\delta - 2\delta^2)} \quad \text{(A12)}$$

b. When $\lambda_3 \neq 0, Q_{M,n} = R$:

$$e^{GF} = \frac{\varphi d(w - c_{M,r}) - k\xi - \varphi\xi(c_{M,n} + c_{M,r}) + \varphi\xi Q(1 + \delta) + \varphi\xi\eta(1 - t_o)}{\varphi^2\xi(d + 6\delta + 2)} \quad \text{(A13)}$$

$$Q^{GF} = \frac{\varphi d(w - c_{M,r}) - k\xi - \varphi\xi(c_{M,n} + c_{M,r}) + \varphi\xi Q(1 + \delta) + \varphi\xi\eta(1 - t_o)}{\varphi\xi(d + 6\delta + 2)} \quad \text{(A14)}$$

(3) First-stage analysis

The government aims for maximum social benefits. In order to promote the manufacturers' recycling activity when manufacturer recycles partial of the wasted products, the ratio is greater than 1; when the manufacturer recycles all the wasted products, the ratio is less than 1.

(3.1) When the manufacturers do not fully recycle, the governments tax regulations are as follows below.

We substitute (A9), (A11), and (A12) into the government's profit function π_G^{GF}.

a. When $\lambda_2 = 0, -\eta(t - t_0)Q_{M,n}^{GF} + fQ_{M,n}^{GF} - sR^{GF} < 0$:

$$f_1 = \frac{4k\delta\xi(\delta-1)(\delta+z_1) - \varphi\xi d^2\left(Q - c_{M,n} + \eta\tau_o\right) - 4\varphi\xi\left(\eta + c_{M,r} - c_{M,n} + Q\delta^2(1-\delta)\right)}{\varphi\xi\left((d+2\delta)^2 + 4{z_1}^2(d+\delta) + 4\delta^2(2z_1 - z^2) - 4\delta^3(1+2z_1) + 8\delta d z_1\right)} + \frac{+4\varphi d\delta^2(w - c_R)(1-\delta-z_1) + 4\varphi z_1\xi\eta\delta^2 - 4\varphi\xi d z_1\eta\delta\tau_o}{\varphi\xi\left((d+2\delta)^2 + 4{z_1}^2(d+\delta) + 4\delta^2(2z_1 - z^2) - 4\delta^3(1+2z_1) + 8\delta d z_1\right)} \quad \text{(A15)}$$

(3.2) When the manufacturers fully recycle, the government's tax regulations are as follows below.

According to the condition $-\eta(t - t_0)Q_{M,n}^{GF} + fQ_{M,n}^{GF} - sR^{GF} = 0$:

$$f_2 = \frac{\eta - \eta t_o}{1 - z} \quad \text{(A16)}$$

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