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Research Article

Research on Closed-Loop Supply Chain with Competing Retailers under Government Reward-Penalty Mechanism and Asymmetric Information

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In manufacturer-led closed-loop supply chain (CLSC) with two competing retailers, the retailer-1 recycles WEEE whose fixed recycling cost is asymmetric information. Using dynamics game theory and principal-agent theory, three dynamic game models are built including (1) benchmark model without reward-penalty mechanism (RPM); (2) decentralized model with carbon emission RPM; (3) decentralized model with carbon emission RPM and recovery rate RPM. This paper discusses the influence of RPM and retailers competition on the CLSC and members benefits. The results show that (1) the carbon emission RPM increases retail price, but decreases the WEEE recycling motivation usually. On the contrary, the recovery rate RPM guides WEEE recycling and lowers the retail price effectively. (2) In any case, the retailer-1's profit is higher than that of the retailer-2; apparently it suggests that the retailer recycling WEEE gains competitive advantages. Furthermore, both the recovery rate RPM and retailers competition are beneficial to improve the competitive advantage. The relationship between two retailers' retail price is affected by many complicated factors. (3) The WEEE buyback price and WEEE recovery rate with high fixed recycling cost (H-type) are always higher than that of low fixed recycling cost (L-type), respectively, which means that the H-type fixed recycling cost has scale advantages; the greater the reward-penalty intensity and the fiercer the competition, the more obvious the scale advantages under certain condition. (4) The retailers' competition can not only guide WEEE recycling but also improve retailers' profits. Meanwhile, the impact of competition on the manufacturer is related to RPM, but the fierce competition decreases the manufacturer's profit.

1. Introduction

Due to the development of the economy and technology, the speed of the products upgrading is accelerated; as a result, more and more waste products are produced, particularly, this phenomenon is prominent in the electrical and electronic industry. According to incomplete statistics, by the end of 2017, there were 65 million tons of used electronic products in the world, which increased 33 percent over the 2012 level (http://www.tijinw.com/). Wu et al. showed that the value of recycling has reached about \$286 billion, which accounts for 8.89% of the total sales in the United States, compared to only \$100 billion in 2006 [1]. The Waste Electrical and Electronic Equipment (WEEE) contains more than seven hundreds of chemical materials, and half of them are hazardous to human health. So, if the large number of WEEE is not properly treated and reused, it will not only lead to the waste of reusable resources but also it will cause seriously environmental pollution. Thus, facing with the reality of resource shortage and environmental pollution, the WEEE recycling and remanufacturing has attracted worldwide attention [2–5]. As the world's largest manufacturing country, China is also the largest producer of WEEE, so it is valuable to study the CLSC for Electrical and Electronic products.

Some studies indicate that the profit generated by reverse logistics is not enough to motivate supply chain members to take an active part in recycling and remanufacturing activity [6]; thus, the efficient operation of the CLSC is inseparable from the guidance of the government [5]. On the one hand, the government uses laws and regulations, the Extended Producer Responsibility (EPR) law and WEEE Directive, to force enterprises to recycle WEEE. On the other hand, different kinds of measures are adopted to encourage enterprises to recycle WEEE (subsidies, taxes, penalty, and RPM) [7–10]. For example, the WEEE Recycling Management Regulation" went into effect in China in 2011, which specifies the establishment of a disposal fund for WEEE being used to subsidize the WEEE recovery and treatment; meanwhile, the manufacturer should pay for the WEEE disposal fund, and the manufacturer will be penalized if it fails to meet the WEEE recovery target (recovery rate). In reality, government of Liuyang goverment in Hunan province of China provided a one-time subsidy to motivate enterprises to launch remanufacturing activities that covered 20% of the total investment of remanufacturing construction and equipment. In Liuyang Remanufacturing Industrial Park, Hunan province, China, remanufacturers can get annual production subsidies ranging from ten thousand RMB to one hundred thousand RMB according to their different annual productions. Moreover, the government of Wuhan in Hubei province gave Sevalo Construction Machinery Remanufacturing Co., Ltd. one million RMB as an R&D subsidy.

With the environmental problems increasingly prominent caused by the large amount of greenhouse gas emissions, the controlling greenhouse gas emissions has become the world concern since the 1990s. Thus, the carbon emissions constraint on enterprises established by the government is very essential. For instance, the carbon emission trading and the carbon cap policy [11, 12] are commonly used by countries. The Chinese government pledged to reduce 40%–45% of carbon emissions per unit of GDP by 2020 compared with 2005 at the global climate conference in Copenhagen, which also has been put into the Twelfth Five-Year Plan. The carbon emission reduction policy usually makes enterprise tend to adopt the negative production strategy; as a result, it not only failed to achieve the purpose of carbon emission reduction but also decrease the efficiency of supply chain [13]. So, the government can refer to the RPM [9, 10], which means that the government will reward the enterprise if it emits less carbon; otherwise, the enterprise will be penalized. So, in this way, the enterprise can be motivated to reduce the total carbon emissions.

With the development of economy, the competition has shifted from manufacturing to selling, and the retailers competition are very common in actually, such situations are not rare in reality; for example, according to a recent survey by retail analyst First Insight on Nov. 5, 2019, Walmart is gaining popularity among consumers as it competes with Amazon (http://stock.eastmoney.com). A development and competition analysis report shows that the rapid development of Jingdong has caused a serious impact on Gome and Suning; Jingdong accounts for 56.3% share of the e-commerce market, but the Gome and Suning have less than 10% shares (https://www.taodocs.com). Some researchers have focused on the retailers' competition problem, Savaskan studied the RSC channel design with the competing retailers [14], Shu Guo et al. discussed how retail competition and consumer returns affect green product development in fashion apparel [15], and few discussed the retailers' competition in CLSC with the RPM.

The CLSC usually faces the risk of asymmetric information [10, 16–18], such as the market demand, the recovery effort, and recovery amounts. In such scenarios, some information is only available to one member, and the other members have to make decisions based on limited information, which can result in the adverse selection and moral hazard. In order to make CLSC more effective, an information screening contract should be designed to indentify the real information.

According to the above, we consider a CLSC with one leading manufacturer and two competing retailers; the manufacturer is responsible for producing products and then selling them to retailers; finally, the retailers sell the products to the customers. The manufacturer entrusts the retailer to recycle WEEE; furthermore, in order to discuss the influence of participating in WEEE recycling on the competing retailers, we assumed that only one retailer recycle WEEE, whose fixed recovery cost is private information. For improving the WEEE recovery rate and restricting carbon emissions of CLSC, we introduce the recovery rate RPM and the carbon emissions RPM into the CLSC, respectively. And on the basis, three dynamic game models are built to address the following questions:

(1) For asymmetric information, how does the manufacturer design an information screening contract? And verify the validity of the abovementioned contract.

(2) What is the impacts of carbon emissions RPM and recovery rate RPM on the CLSC decisions (e.g., recovery rate and retail price) and members' profits, respectively? And what is the interaction on the CLSC when the two RPM are implemented at the same time?

(3) Whether WEEE recycling activity affects the two competing retailers under a certain situation (with or without RPM)? Or how does it affect the two competing retailers?

(4) What is the influence of competition coefficient on decision (e.g., recovery rate and retail price) and the members' profits?

(5) For the government, how to design the carbon emissions and recovery rate RPM is not only beneficial to guide WEEE recycling and restrict the carbon emissions but also does not damage the members profits of CLSC?

2. Literature Review

This section mainly introduces the related literatures from the following aspects: government guidance, carbon emissions constrain, and asymmetric information.

A large number of scholars have studied the effectiveness of government guidance on recycling and remanufacturing activities. Webster and Mitra [19] considered the impact of WEEE recycling law on the manufacturing and remanufacturing activity; the results proved that the moderate recovery rate and unit recovery cost were beneficial to manufacturers and remanufacturers. Mitra and Webster [20] studied the influence on recycling and remanufacturing when government subsidies different nodal enterprises under the remanufacturing competition, which showed that the government should subsidy both manufacturers and recyclers. Aksen et al. [21] compared the effect of government supportive policies with legislative policies on system profits. It also concluded that the government's supportive policies were more conducive to the system profits. Rahman and Subramanian [22] found that government legislation is one of the main driving forces to stimulate computer recycling operations. Ma et al. [23] investigated the impact of the government consumption subsidy on dual-channel CLSC. Yu et al. [24] discussed the WEEE recycling and disposal decision-making problem guided by the government, built four recycling decision-making models with recycling subsidy incentive according to different recycling responsibility subjects, and then analyzed the impact of subsidy on each recycling decision using the numerical simulation method. He et al. [25] indicated that the government's environmental policies increase the recycling proportion, but strengthen the reverse supply chain bullwhip effect. However, Zhang et al. [26] found that the old-for-new policy increases the profitability of the CLSC and reduces the bullwhip effect of the retailers and the distributors. Heydari et al. [27] built the models with and without government intervention, respectively, and discussed the effect of government incentives (tax exemptions and subsidies) on improving supply chain coordination. Shimada et al. [28] proved that the extended producer responsibility (EPR) scheme compelled the CLSC to make efforts to recycling the end-of-life home appliance in Japan. Wang et al. [29] investigated strategies for the allocation strategy of government subsidies among the parties in the RSC of e-waste consisting of one collector, one remanufacturer, and two retailers and discussed the impact of government subsidies on pricing strategies in RSC of WEEE. Zhang and Abaid [30] studied green supply chain coordination considering government intervention, green investment, and customer green preferences in the petroleum industry and showed that stronger government intervention may not always lead to higher green improvement and government should switch from taxes to subsidies in the high green investment cost scenario. Moreover, the government can benefit from low-cost green technologies.

Different from the above research studies, some scholars combine government rewards with penalties for recycling and remanufacturing called RPM [9]; for example, Wang et al. [9] discussed the decision-making problem of recycling and remanufacturing under RPM and proved the effectiveness of the government's RPM in guiding recycling activity by comparing the recycling decisions with or without RPM. Wang et al. [31] found that the government's RPM can effectively improve the recovery rate and reduce the new product price in a single collection channel CLSC. Then, Wang et al. [32] built the recycling and remanufacturing decision-making models of the reverse supply chain without government intervention, with government RPM and government tax-subsidy mechanism, respectively, and compared the optimal decisions of the abovementioned models. The results showed that the RPM was more effective in guiding the recycling and remanufacturing activity. Based on the government subsidy policy, Cao et al. [33] introduced the penalty policy and pointed out that it was better to implement both subsidy and penalty measures than to implement subsidy or penalty measures alone. Yi et al. [34] studied the impact of RPM on the optimal decision of CLSC mixed recycling channel and made comparison from the aspects of environmental protection, consumers, and node enterprises.

Being faced with the reality of global warming and air pollution more seriously, it is necessary to introduce the government's carbon emission constraint into the CLSC responding to the development of "low energy consumption and high yield" industry. Researchers have studied the CLSC under different carbon emission constraint policies. For example, the idea of carbon emission trading was first put forward by Montgomery [11]. Fareeduddin et al. [12] studied how carbon cap policy imposes a strict constraint on the carbon emissions amount generated in CLSC operations. Tao et al. [35] founnd that carbon policies in the CLSC network can restrict players' behaviors when the total permitted carbon emissions are so low that the periodic carbon emission policies may be superior to the global carbon emission policies. Thus, based on carbon emission constraint, Nie et al. [36] explored the pricing and recycling decisions of CLSC; the result showed that larger remanufacturing emission reduction efforts can effectively reduce the total carbon emissions and unit carbon emissions; however, it could help to reduce retail price and wholesale price and improve the recovery rate and members' profit. Bazan et al. [37] developed environmentally responsible CLSC models in which a penalty tax is applied when the CLSC exceeds its carbon emissions cap. According to the idea of recycling RPM, Wang et al. [38] considered the reverse supply chain with the carbon emission RPM and recovery rate RPM which consists of two competing manufacturers and a single recycler, and the decision-making problem of reverse supply chain was discussed. De and Gir [39] studied a CLSC focusing on managing, scheduling and routing problems to achieve economical and environmental sustainability, and built CLSC moldes with a heterogeneous fleet under carbon emission reduction policy including four distinct environmental policies viz. cap, carbon tax, cap-and-purchase and cap-and-sale for carbon emission regulations.

All the above studies were carried out under the condition of symmetry information, asymmetric information is a common phenomenon in the supply chain management, the complexity and uncertainty of recycling and remanufacturing make the asymmetry information problem more serious. In the case of asymmetry information of retailers' operating cost, using the principal-agent theory, Gong et al. [40] studied the decision problems under three situations: non-government participation, the government reward manufacturers, and the government reward and penalty the manufacturers respectively. Based on the above research, Gong and Ge [41] studied the coordination mechanism of reverse supply chain under government guidance, assuming that both the retailers' operating cost and demand of remanufactured products are all asymmetric, they discussed the optimal pricing strategies under the situation of government's non-participation, and government reward retailers and manufacturers respectively. Assuming that the recycler's fixed cost is asymmetric information, Wang et al. [10] discussed the RPM of electronic products reverse supply chain. Moreover, they proved the effectiveness of the RPM to guide the recycling of WEEE using principal-agent theory. Wang et al. [16] studied the design problem of RPM under asymmetric information in CLSC. They designed a screening contract to identify the recycling efforts of recyclers based on the principal-agent theory. The result shows that the RPM is conducive to the reduction of retail price and the increase of recycling quantity. Under the situation of asymmetric information and RPM, Wang et al. [17] discussed the dual competitive recycling channels which means both retailer and recycler participate in recycling in CLSC. Such studies on CLSC are limited to single-node enterprises. Zhang et al. [18] discussed the RPM in CLSC with two competing manufacturers and a recycler under asymmetric information. From the above, we can see the research about government RPM under asymmetric information is mostly limited to the case of a single nodal enterprise except for Zhang et al. [18].

3. Assumptions and Notations

In this section, we consider the electronic and electrical products CLSC with one manufacturer, two competing retailers (retailer-1 and retailer-2), and customers (see Figure 1) in a single production cycle [16–18, 31]. The manufacturer is responsible for producing products and then selling them to retailers with the wholesale price p_m; finally, the retailers sell the products to the customers with the retail price p_1 and p_2, respectively. The assumptions and notations of the proposed models can be seen in Sections 3.1 and 3.2.

3.1. Assumptions. The necessary assumptions for the proposed models are presented, even if some of them seem unreasonable. They are set to avoid the complexity of the research, but would not affect the main results and management insights in the paper.

(1) The CLSC consists of a manufacturer, two retailers, and customers and government; the manufacturer acts as the channel leader and the two competing retailers act as the channel follower.

(2) The market demand is assumed to be a linear function of the retail price, which can be expressed as $q_i = a - p_i + \varepsilon p_j\,(i, j = 1, 2;\ i \neq j)$ [14, 42]; the ε expresses the intensity of competition between two retailers. It means that market demand of retailers decreases with the increase of its own retail price, meanwhile increasing with the other retailer's retail price.

(3) Considering that the WEEE recycling awareness of the two retailers is different, and in order to discuss the influence of participating in WEEE recycling on the competition between the two retailers, we assumed that only the retailer-1 recycle WEEE [39] and manufacturer buy it back from retailer-1 with the buyback price w.

(4) To further simplify the study, the retailer-1's unit recovery cost including recovery efforts and recovery promotion is assumed to be zero [18], which would not affect the main results and management insights in the models.

(5) To guarantee the economic significance of the model, we assume that the manufacturing cost with the new material is higher than the remanufacturing cost with the recycled WEEE material, and it can be expressed as $c_m > c_r$ [14, 18, 43]; thus, the manufacturer would not use new material until the recycled WEEE material is used out [16–18, 31]; Furthermore, we assume that the new products and remanufactured products are of the same quality [14, 16–18, 43].

(6) All the WEEE materials recycled can be used for remanufacturing, which can avoid the trivial remanufacturing rate assumption and complex calculation; meanwhile, it would not affect the main results and management insights obtained from the models [31, 36].

(7) The fixed recovery cost of retailer-1 is $I = \beta\tau^2$ [14, 30, 43] including the recovery channel construction costs and advertising costs, where β is the recovery difficulty coefficient and τ is the recovery rate.

(8) The fixed recovery cost of retailer-1 is asymmetric information, but the common information is that it can be divided into the high fixed recovery cost type (H-type) and low fixed recovery cost type (L-type); the corresponding probability is $p(I_H) = \mu$, $p(I_L) = 1 - \mu$, which means that the probability of retailer-1 being H-type is μ and the probability of

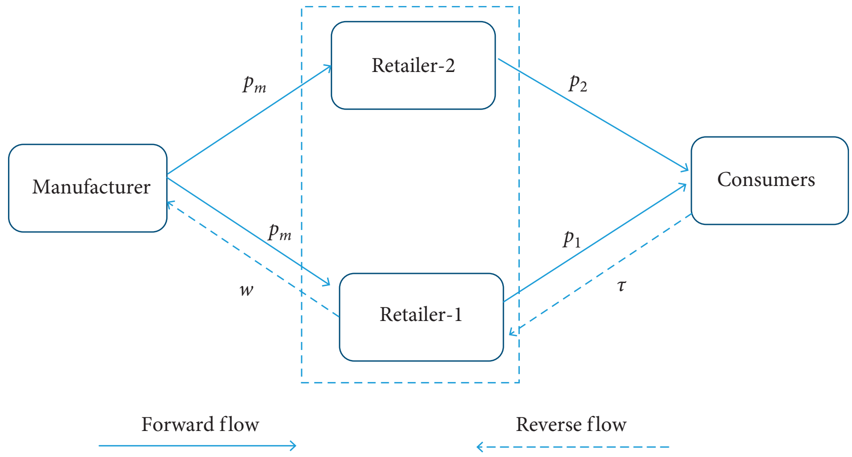

FIGURE 1: CLSC structure with two competing retailers without RPM.

retailer-1 being L-type is $1-\mu$ [10]. To be noted that μ is the fixed value in this paper.

(9) According to assumption (5), we also assume that the unit carbon emission of the new product is the same as the remanufactured ones [38]. The government imposes the carbon emission RPM on the manufacturer, namely, the government sets carbon emissions cap and unit carbon emission reward-penalty intensity, and the manufacturer will be punished economically when its total carbon emission is higher than the carbon emission cap; otherwise, the government will reward the manufacturer [18, 38].

(10) In the same way, the government imposes the recovery rate RPM on the retailers, which means that the government sets a target recovery rate and unit recovery rate reward-penalty intensity, and the retailers will be rewarded when its recovery rate is higher than the target recovery rate; otherwise, the retailers will be punished [18, 32, 38].

(11) We suppose that the government does not take costs of RPM into account.

(12) Assuming that both the manufacturer and the retailers are risk neutral, the risk preference or risk aversion are not taken into account.

3.2. Notation. In this section, the notation used throughout this paper is summarized as follows.

4. CLSC Game Model without the RPM (Case 1)

According to assumptions (3), (4), and (7), the manufacturer entrusts the retailer-1 to collect WEEE (retailer-2 does not) and fixed recovery cost of retailer-1 is asymmetric information; therefore, the basic principal-agent relationship is formed between the manufacturer and retailer-1. The manufacturer entrusts $j-$type retailer-1 to recycle WEEE from customers and buys the WEEE back at buyback price w_j from retailer-1 ($j\in\{H,L\}$) and then uses them in preference to new materials to produce electronic and electrical products owing to the unit cost savings of remanufacturing using recycled WEEE.

The abovementioned asymmetric information in this relationship belongs to the adverse selection problem; it means that the retailer-1 with information advantages will hide the fixed recovery cost information before signing the contract in order to obtain a high buyback price, which may lead the manufacturer to make wrong decisions due to lack of information. For these reasons, enhancing the efficiency of the CLSC, it is very important to design the information screening contract for the manufacturer to acquire the retailer-1's true fixed recovery cost information. In this section, we consider the information screening contract designed by the manufacturer for the retailer-1 expressed as $\{(w_H,\tau_H)(w_L,\tau_L)\}$ based on assumptions and notations, namely, the manufacturer offers high buyback price w_H to H-type retailer-1 because it brings high recovery rate τ_H; otherwise, the manufacturer offers low buyback price w_L to L-type retailer-1.

Figure 1 gives the structure of CLSC without RPM, which consists of one manufacturer, two competing retailers, and consumers. The solid line and the dashed line represent the forward flow direction and the reverse flow direction, respectively. The manufacturer is responsible for producing electronic and electrical products, and then selling them to retailers with the wholesale price p_m; finally, the retailers sell the products to the customers with the retail price p_1 and p_2, respectively. The retailer-1 is responsible for recycling WEEE from customers and then sells WEEE to the manufacturer for remanufacturing electronic and electrical products.

Based on the abovementioned analysis, the expected profit of the manufacturer can be expressed as follows:

$$\pi_M^{(1)}=\left[2a+(1-\varepsilon)\left(p_1+p_2\right)\right]\left(p_m-c_m\right)+\left(a-p_1+\varepsilon p_2\right)\cdot\left[\mu\tau_H\left(\Delta-w_H\right)+(1-\mu)\tau_L\left(\Delta-w_L\right)\right],\tag{1}$$

$$\text{s.t. }\left(a-p_1+\varepsilon p_2\right)\left(p_1-p_m+\tau_H w_H\right)-\beta_H\left(\tau_H\right)^2\geq\pi_{R_0},\tag{2}$$

$$(a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_L w_L) - \beta_L (\tau_L)^2 \geq \pi_{R_0}, \quad (3)$$

$$\begin{aligned}(a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_H w_H) - \beta_H (\tau_H)^2 \\ > (a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_L w_L) - \beta_H (\tau_L)^2,\end{aligned} \quad (4)$$

$$\begin{aligned}(a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_L w_L) - \beta_L (\tau_L)^2 \\ \geq (a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_H w_H) - \beta_L (\tau_H)^2,\end{aligned} \quad (5)$$

where π_{R_0} is called as the conserved profit which is the optimal profits of the retailer-1 without information screening contract. Equations (2) and (3) are participation constraints that can guarantee the retailer-1's profit no less than its conserved profit. Equation (4) indicates that the profit of H-type retailer-1 when it chooses H-type contract is higher than the profit of choosing L-type contract. In the same way, equation (5) shows the profit of L-type retailer-1 when it chooses L-type contract higher than the profit of choosing H-type contract. Equations (4) and (5) are both incentive compatibility constraints to avoid the false information from the retailer-1 which can be used to maximize the retailer-1's profit.

The expected profit of the retailer-1 can be expressed as follows:

$$\begin{aligned}\pi_{R_{1H}}^{(1)} &= (a - p_1 + \varepsilon p_2)[(p_1 - p_m) + \tau_H w_H] - \beta_H (\tau_H)^2, \\ \pi_{R_{1L}}^{(1)} &= (a - p_1 + \varepsilon p_2)[(p_1 - p_m) + \tau_L w_L] - \beta_L (\tau_L)^2.\end{aligned} \quad (6)$$

The expected profit of the retailer-2 can be expressed as follows:

$$\pi_{R_2}^{(1)} = (a - p_2 + \varepsilon p_1)(p_2 - p_m). \quad (7)$$

This game problem includes not only a Stackelberg dynamic game between manufacturer and retailers but also a static game between retailer-1 and retailer-2. The game order is as follows: (1) the manufacturer set buyback price w_H and w_L for WEEE at first; (2) the two retailers decide the retail price p_1 and p_2, respectively, at the same time, retailer-1 determines the WEEE recovery rate τ_H and τ_L according to the manufacturer's buyback price.

Solving the abovementioned game model with the Lagrange multiplier method, we can obtain:

$$\begin{aligned}
w_H^{(1)} &= \frac{p_m + \Delta}{2}, \\
w_L^{(1)} &= \frac{\Delta}{2}, \\
p_1^{(1)} &= \frac{8\beta_H\beta_L (a + p_m)(2 + \varepsilon) - \Delta^2 (a\varepsilon + \varepsilon p_m + 2a)[(1 - \mu)\beta_H + \mu\beta_L]}{8\beta_H\beta_L (4 - \varepsilon^2) + \Delta^2 (2 - \varepsilon^2)[(\mu + 1)\beta_H - \mu\beta_L]}, \\
p_2^{(1)} &= \frac{8\beta_H\beta_L (a + p_m)(2 + \varepsilon) - \Delta^2 (p_m + a\varepsilon + a)[(1 - \mu)\beta_H + \mu\beta_L]}{8\beta_H\beta_L (4 - \varepsilon^2) + \Delta^2 (2 - \varepsilon^2)[(\mu + 1)\beta_H - \mu\beta_L]}, \\
\tau_H^{(1)} &= \frac{(p_m + \Delta)}{4\beta_H}\left[\frac{8\beta_H\beta_L (2 + \varepsilon)(a - p_m + \varepsilon p_m) + 2a\beta_H\Delta^2 (2 - \varepsilon^2)}{8\beta_H\beta_L (4 - \varepsilon^2) + \Delta^2 (2 - \varepsilon^2)[(\mu + 1)\beta_H - \mu\beta_L]}\right], \\
\tau_L^{(1)} &= \frac{\Delta}{4\beta_L}\left[\frac{8\beta_H\beta_L (2 + \varepsilon)(a - p_m + \varepsilon p_m) + 2a\beta_H\Delta^2 (2 - \varepsilon^2)}{8\beta_H\beta_L (4 - \varepsilon^2) + \Delta^2 (2 - \varepsilon^2)[(\mu + 1)\beta_H - \mu\beta_L]}\right].
\end{aligned} \quad (8)$$

5. CLSC Game Model with Carbon Emissions RPM (Case 2)

Facing the crisis of global warming and in order to response to the "low-carbon economy" policy, it is very important to reduce the carbon emissions produced by enterprises. In this section, we mainly discuss that the government imposes carbon emissions RPM on the manufacturer to reduce the carbon emissions. Corresponding to the abovementioned assumptions, as shown in Figure 2, the government sets a cap on carbon emissions e_o and unit carbon emission reward-penalty intensity f for the manufacturer. That is, when the total quantity of carbon emissions of the manufacturer exceeds the carbon emission cap, the government will penalize the manufacturer for the exceeding part; otherwise, the government will reward the manufacturer for the unmet part. Therefore, the carbon emission reward-penalty amount for the manufacture can be represented as $M_f = -f(Qe_m - e_o)$.

Figure 2 shows the CLSC structure with competing retailers with carbon emission RPM. The details of the information screening contract in case 2 are the same as in case 1. According to the abovementioned analysis, the expected profit of the manufacturer adds the carbon emission reward-penalty amount $M_f = -f(Qe_m - e_o)$ based on case 1, which can be expressed as follows:

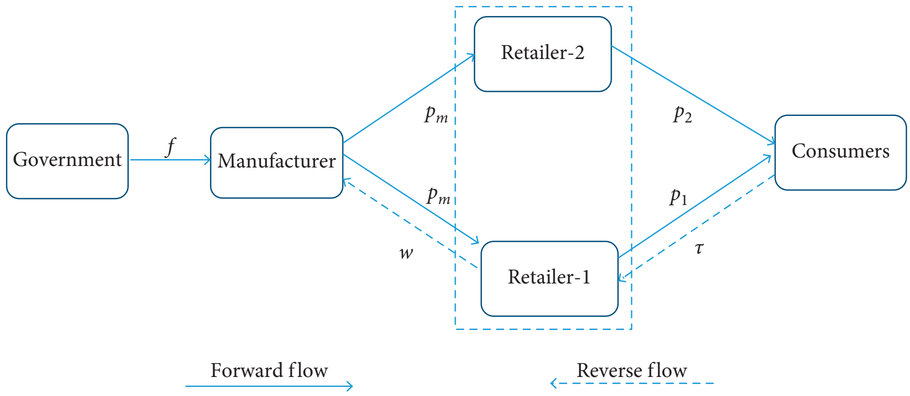

Figure 2: CLSC structure with two competing retailers with carbon emission RPM.

$$\pi_M^{(2)} = [2a + (1-\varepsilon)(p_1+p_2)](p_m - c_m - fe_m) + fe_0 + (a - p_1 + \varepsilon p_2)[\mu\tau_H(\Delta - w_H) + (1-\mu)\tau_L(\Delta - w_L)], \quad (9)$$

$$\text{s.t. } (a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_H w_H) - \beta_H(\tau_H)^2 \geq \pi_{R_0}, \quad (10)$$

$$(a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_L w_L) - \beta_L(\tau_L)^2 \geq \pi_{R_0}, \quad (11)$$

$$(a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_H w_H) - \beta_H(\tau_H)^2 \geq (a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_L w_L) - \beta_H(\tau_L)^2, \quad (12)$$

$$(a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_L w_L) - \beta_L(\tau_L)^2 \geq (a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_H w_H) - \beta_L(\tau_H)^2. \quad (13)$$

Since the expected profit of the retailers' are the same as in case 1, the abovementioned constraints are similar to case 1, where π_{R_0} is called as conserved profit which is the optimal profits of the retailer-1 without information screening contract. Equations (10) and (11) are participation constraints that can guarantee the retailer-1's profit no less than its conserved profit. Equations (12) and (13) are both incentive compatibility constraints to avoid the false information from the retailer-1 which can be used to maximize the retailer-1's profit. Equation (12) indicates that the profit of H-type retailer-1 choosing H-type contract is higher than the profit of choosing L-type contract. On the contrary, equation (13) shows the profit of L-type retailer-1 when choosing L-type contract higher than the profit of choosing H-type contract.

The expected profit of the retailer-1 can be expressed as follows:

$$\pi_{R_{1H}}^{(2)} = \left((a - p_1 + \varepsilon p_2)[(p_1 - p_m) + \tau_H w_H] - \beta_H(\tau_H)^2\right),$$
$$\pi_{R_{1L}}^{(2)} = \left((a - p_1 + \varepsilon p_2)[(p_1 - p_m) + \tau_L w_L] - \beta_L(\tau_L)^2\right). \quad (14)$$

The expected profit of the retailer-2 can be expressed as follows:

$$\pi_{R_2}^{(2)} = (a - p_2 + \varepsilon p_1)(p_2 - p_m). \quad (15)$$

The CLSC game order in case 2 is the same as the case 1. Solving the abovementioned programming model with the Lagrange multiplier method. To simplify the computational complexity, we assume that $A = f[(1-\varepsilon)(e_m+u) + (2-\varepsilon)e_0]\Delta^2 + \varepsilon u\beta_H\beta_L\Delta^2/8\beta_H\beta_L(4-\varepsilon^2) + \Delta^2(2-\varepsilon^2)((\mu+1)\beta_H - \mu\beta_L)$, and $A > 0$ is known to us; thus, there holds $q_1^{(2)} = q_1^{(1)} - A$. We can obtain that

$$w_H^{(2)} = \frac{p_m + \Delta + f(2e_m - e_0)}{2},$$

$$w_H^{(2)} = \frac{\Delta + f(2e_m - e_0)}{2},$$

$$p_1^{(2)} = p_1^{(1)} + \frac{f(e_m + 2e_0 + \mu)\Delta^2}{8\beta_H\beta_L(4-\varepsilon^2) + \Delta^2(2-\varepsilon^2)[(\mu+1)\beta_H - \mu\beta_L]},$$

$$p_2^{(2)} = p_2^{(1)} + \frac{f(e_m + e_0 + c_m\mu)\Delta^2 - \beta_H\beta_L\mu\Delta^2}{8\beta_H\beta_L(4-\varepsilon^2) + \Delta^2(2-\varepsilon^2)[(\mu+1)\beta_H - \mu\beta_L]},$$

$$\tau_H^{(2)} = \tau_H^{(1)} + \frac{1}{2\beta_H}\left(\frac{f(2e_m - e_0)}{2}q_1^{(1)} - w_H^2 A\right),$$

$$\tau_L^{(2)} = \tau_L^{(1)} + \frac{1}{2\beta_L}\left(\frac{f(e_m - e_0)}{2}q_1^{(1)} - w_L^2 A\right). \quad (16)$$

6. CLSC Game Model with Carbon Emissions RPM and Recovery Rate RPM (Case 3)

In this section, on the one hand, the government imposes carbon emissions RPM on the manufacturer to constraint its carbon emissions, which is the same as case 2. On the other hand, the government implements recovery rate RPM for retailers to promote WEEE recycling.

As shown in Figure 3, on the one hand, the government sets a cap on carbon emissions e_o and unit carbon emission reward-penalty intensity f for the manufacturer. That is, when the total quantity of carbon emissions of the manufacturer exceeds the carbon emission cap e_o, the government

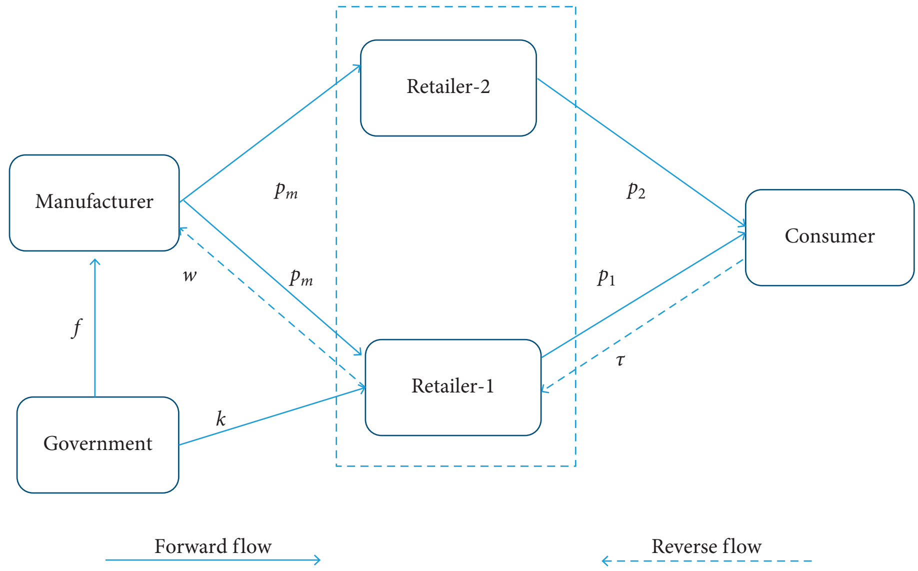

FIGURE 3: CLSC structure with two competing retailers with carbon emission RPM and recovery rate RPM.

will penalize the manufacturer for the exceeding part; otherwise, the government will reward the manufacturer for the unmet part. The carbon emission reward-penalty amount for the manufacturer can be represented as $M_f = -f(Qe_m - e_o)$. On the other hand, the government sets a target recovery rate τ_0 and unit recovery rate reward-penalty intensity k for retailers. Only the retailer-1 participates in recycling WEEE based on the assumptions, namely, when the recovery rate of retailer-1 exceeds the target recovery rate τ_0, the government will reward it for the exceeding part; otherwise, the government will penalize the retailer-1 for the unmet part. Therefore, the recovery rate reward-penalty amount of retailer-1 is $M_k = k[\tau - \tau_0]$. The reward-penalty amount of retailer-2 is $-k\tau_0$ because it does not participate in recycling WEEE, which results in zero recovery rate.

Figure 3 shows the CLSC structure with two competing retailers under carbon emission RPM and recovery rate RPM. In this section, we consider the information screening contract for the manufacturer to obtain the retailer-1's private information is the same as case 1 and case 2, which can also be expressed as $\{(w_H, \tau_H)(w_L, \tau_L)\}$, respectively.

Based on the abovementioned analysis, the expected profit of the manufacturer can be expressed as follows:

$$\begin{aligned}\pi_M^{(3)} &= [2a + (1-\varepsilon)(p_1 + p_2)](p_m - c_m - fe_m) + fe_0 \\ &\quad + (a - p_1 + \varepsilon p_2)[\mu\tau_H(\Delta - w_H) \\ &\quad + (1-\mu)\tau_L(\Delta - w_L)],\end{aligned} \tag{17}$$

$$\text{s.t. } (a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_H w_H) - \beta_H(\tau_H)^2 + k(\tau_H - \tau_0) \ge \pi_{R_0}, \tag{18}$$

$$(a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_L w_L) - \beta_L(\tau_L)^2 + k(\tau_L - \tau_0) \ge \pi_{R_0}, \tag{19}$$

$$\begin{aligned}&(a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_H w_H) - \beta_H(\tau_H)^2 + k\tau_H \\ &\quad > (a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_L w_L) - \beta_H(\tau_L)^2 + k\tau_L,\end{aligned} \tag{20}$$

$$\begin{aligned}&(a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_L w_L) - \beta_L(\tau_L)^2 + k\tau_L \\ &\quad > (a - p_1 + \varepsilon p_2)(p_1 - p_m + \tau_H w_H) - \beta_L(\tau_H)^2 + k\tau_H.\end{aligned} \tag{21}$$

The profit of retailer-1 is different from case 1 and case 2 because the government impose recovery rate RPM on it, that is, the recovery rate reward-penalty amount $M_k = k[\tau - \tau_0]$ is added to the retailer-1's profit function, which lead to the abovementioned constraints change accordingly, where π_{R_0} is called as conserved profit of retailer-1. Equations (18) and (19) are participation constraints that can guarantee the retailer-1's profit recycling WEEE no less than its conserved profit. Equations (20) and (21) are both incentive compatibility constraints to avoid the false information from the retailer-1 which can be used to maximize the retailer-1's profit. Equation (20) indicates that the profit of H-type retailer-1 choosing H-type contract is higher than the profit of choosing L-type contract. Meanwhile, equation (21) shows the profit of L-type retailer-1 choosing L-type contract higher than the profit of choosing H-type contract.

Referring to abovementioned the analysis, the recovery rate reward-penalty amount $M_k = k[\tau - \tau_0]$ will be added to the retailer-1's profit function, so it can be expressed as follows:

$$\begin{aligned}\pi_{R_{1H}}^{(3)} &= ((a - p_1 + \varepsilon p_2)[(p_1 - p_m) + \tau_H w_H] \\ &\quad - \beta_H(\tau_H)^2) + k(\tau_H - \tau_0), \\ \pi_{R_{1L}}^{(3)} &= ((a - p_1 + \varepsilon p_2)[(p_1 - p_m) + \tau_L w_L] \\ &\quad - \beta_L(\tau_L)^2) + k(\tau_L - \tau_0).\end{aligned} \tag{22}$$

In the same way, the reward-penalty amount $-k\tau_0$ will be added to the expected profit of the retailer-2 in this case, which can be expressed as follows:

$$\pi_{R_2}^{(3)} = (a - p_2 + \varepsilon p_1)(p_2 - p_m) - k\tau_0. \quad (23)$$

The decision process of the CLSC game model in case 3 is similar to those of the case 1 and case 2. Solving the above-mentioned programming model with the Lagrange multiplier method, in order to make the result simpler, we assume $B = [(2\Delta c_m + 2\mu c_m + 2\Delta^2) + \varepsilon(\Delta c_m + \beta_H \mu c_m + \beta_L \mu)]/8\beta_H\beta_L(4 - \varepsilon^2) + \Delta^2(2-\varepsilon^2)((\mu+1)\beta_H - \mu\beta_L)$ again; thus, $q_1^{(3)} = q_1^{(2)} + Bk$. So, we can obtain

$$\begin{aligned}
w_H^{(3)} &= \frac{(p_m + \Delta) + f(2e_m - e_0) + k\varepsilon(2\beta_H + \beta_L)}{2}, \\
w_L^{(3)} &= \frac{\Delta + f(e_m - e_0) + k\varepsilon(\beta_H + \beta_L)}{2}, \\
p_1^{(3)} &= p_1^{(2)} - \frac{2k(\Delta c_m + \mu c_m + \Delta^2)}{8\beta_H\beta_L(4-\varepsilon^2) + \Delta^2(2-\varepsilon^2)[(\mu+1)\beta_H - \mu\beta_L]}, \\
p_2^{(3)} &= p_2^{(2)} - \frac{k(\Delta c_m + \beta_H \mu c_m + \mu\beta_L)}{8\beta_H\beta_L(4-\varepsilon^2) + \Delta^2(2-\varepsilon^2)[(\mu+1)\beta_H - \mu\beta_L]}, \\
\tau_L^{(3)} &= \tau_L^{(2)} + \frac{k}{2\beta_L}\left[1 + w_L^{(2)}B + \frac{\varepsilon(\beta_H + \beta_L)q_1^{(3)}}{2}\right], \\
\tau_H^{(3)} &= \tau_H^{(2)} + \frac{k}{2\beta_H}\left[1 + w_H^{(2)}B + \frac{\varepsilon(2\beta_H + \beta_L)q_1^{(3)}}{2}\right].
\end{aligned} \quad (24)$$

7. Result Analysis

In this section, we compare the decision-making results under different situations, and we can get the following conclusions:

Proposition 1. *Comparing buyback price, the recovery rate of WEEE, respectively, in case 1 with case 2.*

(1) When the retailer-1 is H-type, if the manufacturers' per unit carbon emission satisfy $0 < e_m < e_0/2$; thus, $w_H^{(2)} < w_H^{(1)}, \tau_H^{(2)} < \tau_H^{(1)}$; if the $e_0/2 < e_m < e_0$, there holds $w_H^{(2)} < w_H^{(1)}$; however, the recovery rate τ_H is impacted by reward-penalty intensity f, per unit carbon emission e_m, the recovery difficulty coefficient β_H and β_L, and the competition coefficient ε, and so on.

(2) When the retailer-1 is L-type, we can get $w_L^{(2)} < w_L^{(1)}$ and $\tau_L^{(2)} < \tau_L^{(1)}$, the buyback price and the recovery rate in case 2 are all lower than that in case 1. In other words, the carbon emission RPM is not conducive to guiding WEEE recycling.

Proof. Based on the optimal decisions of case 1 and case 2, we can obtain

$$\begin{aligned}
w_H^{(2)} - w_H^{(1)} &= \frac{f(2e_m - e_0)}{2}, \\
\tau_H^{(2)} - \tau_H^{(1)} &= \frac{1}{2\beta_H}\left(\frac{f(2e_m - e_0)}{2}q_1^{(1)} - w_H^{(2)}A\right), \\
w_L^{(2)} - w_L^{(1)} &= \frac{f(e_m - e_0)}{2} < 0, \\
\tau_H^{(2)} - \tau_H^{(1)} &= \frac{1}{2\beta_L}\left(\frac{f(e_m - e_0)}{2}q_1^{(1)} - w_L^{(2)}A\right).
\end{aligned} \quad (25)$$

Based on the reality, the manufacturer's per unit carbon emission is lower than the carbon emission cap set by government, that is, $0 < e_m < e_0$. When $0 < e_m < e_0/2$, we have $w^{(2)} < w^{(1)}$ and $\tau^{(2)} < \tau^{(1)}$, the higher the carbon emission reward-penalty intensity f, the lower the buyback price and the recovery rate with other conditions unchanged. When $e_0/2 < e_m < e_0$, we have $w_H^{(2)} > w_H^{(1)}, w_L^{(2)} < w_L^{(1)}$, and $\tau_L^{(2)} < \tau_L^{(1)}$; however, $\tau_H^{(2)} - \tau_H^{(1)}$ is influenced by so many factors that their relationship is uncertain.

Proposition 1 suggested that the carbon emission RPM can reduce the buyback price and recovery rate of WEEE when retailer-1 is L-type. When the retailer-1 is H-type, the change of buyback price and recovery rate of WEEE are related to other factors, for example, when the unit carbon emission meets $0 < e_m < e_0/2$ with carbon emission RPM, the manufacturer will reduce the buyback price of WEEE in order to reduce the production cost, which lead to the recovery rate go down lastly. However, given the carbon emissions cap is certain, the carbon emission RPM influences manufacturer's profit greatly if $e_0/2 < e_m < e_0$; therefore, the manufacturer will improve the buyback price of WEEE to induce retailer-1 to increase recovery rates of WEEE, which will reduce the total production cost of the manufacturer. □

Proposition 2. *Comparing the retail price in case 1 with case 2.*

(1) The retailer-1's retail price in case 2 is always higher than that in case 1, that is, $p_1^{(2)} > p_1^{(1)}$. Moreover, with the increase of the reward-penalty intensity f and the per unit carbon emission e_m, the $p_1^{(2)} - p_1^{(1)}$ increases gradually.

(2) For the retailer-2, only when the reward-penalty intensity f is lower than a certain value, the retailer-2's retail price in case 2 is lower than that in case 1, that is, $p_2^{(2)} < p_2^{(1)}$; otherwise, there is $p_2^{(2)} > p_2^{(1)}$.

Proof. Based on the optimal decisions of case 1 and case 2, we can obtain

$$p_1^{(2)} - p_1^{(1)} = \frac{f(e_m + 2e_0 + \mu)\Delta^2}{8\beta_H\beta_L(4-\varepsilon^2) + \Delta^2(2-\varepsilon^2)[(\mu+1)\beta_H - \mu\beta_L]},$$

$$p_2^{(2)} - p_2^{(1)} = \frac{f(e_m + e_0 + c_m\mu)\Delta^2 - \beta_H\beta_L\mu\Delta^2}{8\beta_H\beta_L(4-\varepsilon^2) + \Delta^2(2-\varepsilon^2)[(\mu+1)\beta_H - \mu\beta_L]}. \tag{26}$$

It is well known to us that $\tau_L^{(1)} = (\Delta/4\beta_L)[8\beta_H\beta_L(2+\varepsilon)(a - p_m + \varepsilon p_m) + 2a\beta_H\Delta^2(2-\varepsilon^2)/8\beta_H\beta_L(4-\varepsilon^2) + \Delta^2(2-\varepsilon^2)[(\mu+1)\beta_H - \mu\beta_L]] > 0$ and there holds $8\beta_H\beta_L(2+\varepsilon)(a - p_m + \varepsilon p_m) + 2a\beta_H\Delta^2(2-\varepsilon^2) > 0$, so we can deduce that $8\beta_H\beta_L(4-\varepsilon^2) + \Delta^2(2-\varepsilon^2)[(\mu+1)\beta_H - \mu\beta_L] > 0$. According to the abovementioned analysis, we can easily get $p_1^{(2)} - p_1^{(1)} > 0$. When $0 < f < \beta_H\beta_L\mu/(e_m + e_0 + c_m\mu)$, there is $f(e_m + e_0 + c_m\mu)\Delta^2 - \beta_H\beta_L\mu\Delta^2 < 0$, so we can get that $p_2^{(2)} - p_2^{(1)} < 0$; otherwise, when $f > (\beta_H\beta_L\mu/(e_m + e_0 + c_m\mu))$, we can get that $p_2^{(2)} - p_2^{(1)} > 0$.

Proposition 2 suggested that the carbon emission RPM raises the retailer-1's retail price, but the retailer-2's retail price is impacted by f, e_m, β_H, β_L, and other factors. However, under certain conditions, the greater the reward-penalty intensity f or the larger the unit carbon emission e_m, the higher the retail price of retailer-1 and retailer-2.

Case 1 suggest that the carbon emission RPM usually reduces the buyback price of WEEE, which will cause the income from recovery transfer payment for WEEE of retailer-1 decrease, so the retailer-1 will raise the retail price to maximize its profit. Meanwhile, the retailer-2's retail price is not directly affected by the buyback price of WEEE because it does not participate in recycling WEEE, but it is indirectly affected by the manufacturer and retailer-1 under carbon emission RPM, such as vertical competition relationship and upstream and downstream supply relationship, as a result, the retailer-2's retail price change unclearly comparing to retailer-1's retail price. □

Proposition 3. *Comparing the WEEE buyback price of case 2 with case 3. Regardless of the type of retailer-1's fixed recovery cost, the buyback price in case 3 is always higher than that in case 2. With the increase of the recovery rate reward-penalty intensity k and the competition coefficient ε, the WEEE buyback price also increases.*

Proof. Based on the optimal decision in case 2 and case 3, we can obtain

$$\begin{aligned} w_H^{(3)} - w_H^{(2)} &= \frac{k\varepsilon(2\beta_H + \beta_L)}{2} > 0, \\ w_L^{(3)} - w_L^{(2)} &= \frac{k\varepsilon(\beta_H + \beta_L)}{2} > 0, \\ \frac{\partial\left(w_H^{(3)} - w_H^{(2)}\right)}{\partial(k\varepsilon)} &= \frac{2\beta_H + \beta_L}{2} > 0, \\ \frac{\partial\left(w_L^{(3)} - w_L^{(2)}\right)}{\partial(k\varepsilon)} &= \frac{\beta_H + \beta_L}{2} > 0. \end{aligned} \tag{27}$$

Proposition 3 has been proved by the abovementioned proof results easily, which shows that the recovery rate RPM and the competition between two retailers are all conducive to increasing the WEEE buyback price; the greater the recovery rate RPM intensity k and the more the competition ε, the higher the buyback price. At the same time, we can also obtain from $(\partial(w_H^{(3)} - w_H^{(2)})/\partial(k\varepsilon)) - (\partial(w_L^{(3)} - w_L^{(2)})/\partial(k\varepsilon)) = (\beta_H/2) > 0$ that the H-type buyback price is more sensitive to the recovery rate RPM and the competition than that of L-type; in other words, the H-type retailer-1 has more advantage compared to L-type in this situation. □

Proposition 4. *Comparing the WEEE recovery rate of case 2 with case 3. No matter what type of retailer-1's fixed recovery cost is, the recovery rate $\tau_H^{(3)}$ and $\tau_L^{(3)}$ in case 3 is always higher than the recovery rate $\tau_H^{(2)}$ and $\tau_L^{(2)}$ in case 2. The WEEE recovery rate increases with the increase of recovery rate RPM intensity.*

Proof. Based on the optimal decisions of case 2 and case 3, we can obtain

$$\begin{aligned} \tau_H^{(3)} - \tau_H^{(2)} &= \frac{k\left(2 + \varepsilon(2\beta_H + \beta_L)q_1^{(3)} + 2w_H^{(2)}B\right)}{4\beta_H} > 0, \\ \tau_L^{(3)} - \tau_L^{(2)} &= \frac{k\left(2 + \varepsilon(\beta_H + \beta_L)q_1^{(3)} + 2w_L^{(2)}B\right)}{4\beta_L} > 0, \\ \frac{\partial\left(\tau_H^{(3)} - \tau_H^{(2)}\right)}{\partial k} &= \frac{2 + \varepsilon(2\beta_H + \beta_L)q_1^{(3)} + 2w_H^{(2)}B}{4\beta_H} > 0, \\ \frac{\partial\left(\tau_L^{(3)} - \tau_L^{(2)}\right)}{\partial k} &= \frac{2 + \varepsilon(\beta_H + \beta_L)q_1^{(3)} + 2w_L^{(2)}B}{4\beta_L} > 0. \end{aligned} \tag{28}$$

The $8\beta_H\beta_L(2+\varepsilon)(a - p_m + \varepsilon p_m) + 2a\beta_H\Delta^2(2-\varepsilon^2) > 0$ has been proved in Proposition 2; it is easy to prove $B = [(2\Delta c_m + 2\mu c_m + 2\Delta^2) + \varepsilon(\Delta c_m + \beta_H\mu c_m + \beta_L\mu)]/8\beta_H\beta_L(4-\varepsilon^2) + \Delta^2(2-\varepsilon^2)((\mu+1)\beta_H - \mu\beta_L) > 0$, so we can get that $\tau^{(3)} - \tau^{(2)} > 0$ and $\partial(\tau^{(3)} - \tau^{(2)})/\partial k > 0$. Furthermore, there is $(\partial(\tau_H^{(3)} - \tau_H^{(2)})/\partial k) > (\partial(\tau_L^{(3)} - \tau_L^{(2)})/\partial k)$ because $\beta_H < \beta_L$ and $w_H > w_L$, which means that the H-type buyback price is more sensitive to the recovery rate RPM. Proposition 4 is proved to be true.

Proposition 4 shows that the recovery rate RPM is beneficial to improve the WEEE recovery rate, and the WEEE recovery rate increases with the increasing of the recovery rate reward-penalty intensity, but the H-type recovery rate is more sensitive to the recovery rate reward-penalty intensity than that of L-type. Because the direct incentive object of recovery rate RPM is retailer-1, the greater the recovery rate reward-penalty intensity, the harder the retailer-1 try to recycle WEEE. We also know from Proposition 3 that the H-type buyback price is more sensitive to the recovery rate RPM, so it is easy to understand the change of the recovery rate with H-type and L-type. □

Proposition 5. *Comparing two retailer's retail price of case 2 with case 3, two retailer's retail price in case 3 are all lower than that in case 2, and the greater the reward-penalty intensity, the lower the retail price of retailer-1 and retailer-2. It shows that the recovery rate RPM can effectively reduce the retail price of retailers, and it is more beneficial to retailer-1.*

Proof. Based on the optimal decisions in case 2 and case 3, we can obtain

$$\begin{aligned} p_1^{(3)} - p_1^{(2)} &= \frac{-2k\left(\Delta c_m + \mu c_m + \Delta^2\right)}{8\beta_H\beta_L\left(4-\varepsilon^2\right) + \Delta^2\left(2-\varepsilon^2\right)\left[(\mu+1)\beta_H - \mu\beta_L\right]} < 0, \\ p_2^{(3)} - p_2^{(2)} &= \frac{-k\left(\Delta c_m + \beta_H\mu c_m + \mu\beta_L\right)}{8\beta_H\beta_L\left(4-\varepsilon^2\right) + \Delta^2\left(2-\varepsilon^2\right)\left[(\mu+1)\beta_H - \mu\beta_L\right]} < 0. \end{aligned} \tag{29}$$

Referring to proof of Proposition 2 $8\beta_H\beta_L(2+\varepsilon)(a - p_m + \varepsilon p_m) + 2a\beta_H\Delta^2(2-\varepsilon^2) > 0$, it is easy to prove that $p_1^{(3)} - p_1^{(2)} < 0$, $p_2^{(3)} - p_2^{(2)} < 0$, and we also get $p_1^{(3)} - p_1^{(2)}/p_2^{(3)} - p_2^{(2)} = 2$ according to the abovementioned proof, which means that the retail price of retailer-1 falls even more sharply than that of retailer-2. Because the recovery rate RPM increases the WEEE buyback price and WEEE recovery rate, which means that retailer-1 gets more recycling transfer payments income and recovery rate reward, therefore, retailer-1 will be able to reduce its retail price. However, because of the competitive relationship between the two retailers, the reduction of the retailer-1's retail price will indirectly promote the retailer-2 to reduce its retail price. □

Proposition 6. *Comparing the WEEE buyback price of case 1 with case 3.*

(1) When the retailer-1 is H-type, as long as any one of the following conditions is satisfied, we can get that $w_H^{(3)} \geq w_H^{(1)}$; otherwise, there is $w_H^{(3)} < w_H^{(1)}$:

$$\begin{aligned} &\frac{e_0}{2} \leq e_m < e_0, \\ &0 < e_m < \frac{e_0}{2}, \\ &k\varepsilon \geq \frac{f\left(e_0 - 2e_m\right)}{\left(2\beta_H + \beta_L\right)}. \end{aligned} \tag{30}$$

(2) When the retailer-1 is L-type and the condition $k\varepsilon \geq \left(f\left(e_0 - e_m\right)/\left(\beta_H + \beta_L\right)\right)$ is met, we can get that $w_L^{(3)} \geq w_L^{(1)}$; otherwise, we can get that $w_L^{(3)} < w_L^{(1)}$.

Proof. Based on the optimal decision variables made by case 1 and case 3, we can obtain

$$\begin{aligned} w_H^{(3)} - w_H^{(1)} &= \frac{k\varepsilon\left(2\beta_H + \beta_L\right) + f\left(2e_m - e_0\right)}{2}, \\ w_L^{(3)} - w_L^{(1)} &= \frac{k\varepsilon\left(\beta_H + \beta_L\right) + f\left(e_m - e_0\right)}{2}. \end{aligned} \tag{31}$$

On the one hand, we can see from Proposition 1 that the carbon emission RPM improves the H-type WEEE buyback price only when $e_0/2 \leq e_m < e_0$; or else, it can reduce the H-type WEEE buyback price. On the other, according to Proposition 3 we can get that the recovery rate RPM can improve the buyback price. Thus, when the government implements both carbon emission RPM and recovery rate RPM, the WEEE buyback price will be affected by the interaction of reward-penalty intensity f and k, which means only if the recovery rate reward-penalty intensity k is larger than a certain value or the carbon emission reward-penalty intensity f is lower than a certain value, the WEEE buyback price will improve; the greater the recovery rate reward-penalty intensity k, or the smaller the carbon emission reward-penalty intensity f, the higher the WEEE buyback price. □

Proposition 7. *Comparing two retailers' retail price of case 1 with case 3, we discuss the impact of the carbon emission RPM and the recovery rate RPM on the retail price.*

(1) Retailer-1's retail price can be affected by the interaction behavior of carbon emission RPM and recovery rate RPM. Only the condition $2k\left(\Delta c_m + \mu c_m + \Delta^2\right) > f\left(e_m + 2e_0 + \mu\right)\Delta^2$ is satisfied, and we can get that $p_1^{(3)} < p_1^{(1)}$; otherwise, we can get that $p_1^{(3)} \geq p_1^{(1)}$.

(2) For retailer-2, as long as any one of the following conditions is satisfied, we can get that $p_2^{(3)} < p_2^{(1)}$; otherwise, we can get that $p_2^{(3)} \geq p_2^{(1)}$:

$$\begin{aligned} &f\left(e_m + e_0 + \mu c_m\right) \leq \mu\beta_H\beta_L, \\ &f\left(e_m + e_0 + \mu c_m\right) > \mu\beta_H\beta_L, \\ &k\left(\Delta c_m + \mu\beta_H c_m + \mu\beta_L\right) > f\left(e_m + e_0 + \mu c_m\right)\Delta^2 - \mu\beta_H\beta_L\Delta^2. \end{aligned} \tag{32}$$

Proof. Based on the optimal decision variables of case 1 and case 3, we can obtain

Table 1: The comparison of existing work with our paper.

Reference	Recovery regulations/policy	Carbon constraints	Recovery RPM	Carbon emissions RPM	Asymmetric information	Retailer's competition
Webster and Mitra [20, 21],						
Aksen et al. [22], Rahman and Subramanian [23],						
Ma et al. [24],	√					
Heydari et al. [28], Shimada and Van Wassenhove [19]						
Montgomery [11], Fareeduddin et al. [12],						
Tao et al. [35],		√				
Bazan et al. [37]						
Wang et al. [9, 31, 32],						
Cao and Sha [33],			√			
Yi and Liang [34]						
Nie et al. [36]				√		
Wang et al. [38]			√	√		
Gong et al. [40, 41]					√	
Wang et al. [10, 16, 17]			√		√	
Zhang et al. [18]			√	√	√	
Our paper			√	√	√	√

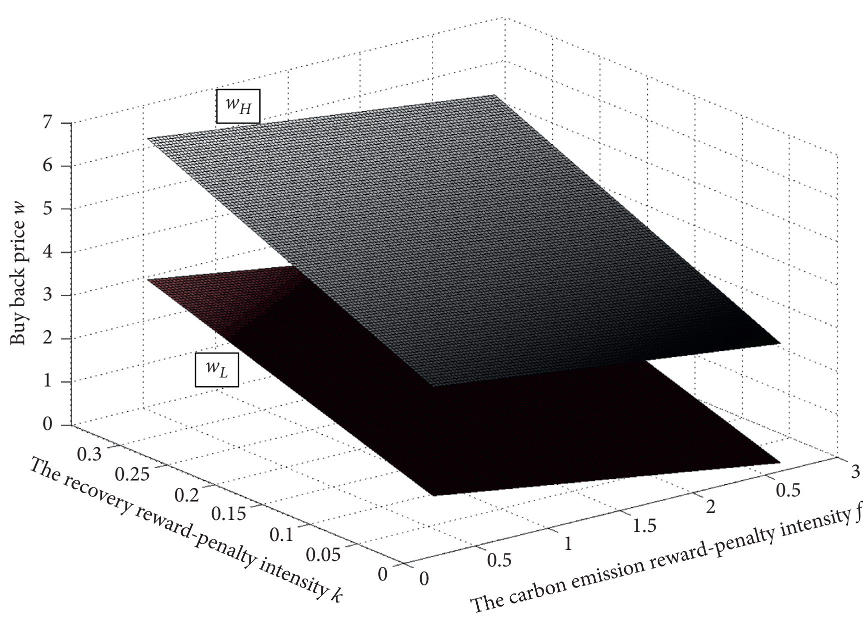

Figure 4: WEEE buyback price w_H and w_L vs. f and k.

$$p_1^{(3)} - p_1^{(1)} = \frac{f\left(e_m + 2e_0 + \mu\right)\Delta^2 - 2k\left(\Delta c_m + \mu c_m + \Delta^2\right)}{8\beta_H\beta_L\left(4-\varepsilon^2\right) + \Delta^2\left(2-\varepsilon^2\right)\left[(\mu+1)\beta_H - \mu\beta_L\right]},$$
$$p_2^{(3)} - p_2^{(1)} = \frac{\left[f\left(e_m + e_0 + c_m\mu\right) - \beta_H\beta_L\mu\right]\Delta^2 - k\left(\Delta c_m + \beta_H\mu c_m + \beta_L\mu\right)}{8\beta_H\beta_L\left(4-\varepsilon^2\right) + \Delta^2\left(2-\varepsilon^2\right)\left[(\mu+1)\beta_H - \mu\beta_L\right]}. \tag{33}$$

According to Proposition 2, the carbon emission RPM improve the retailer-1's retail price and the carbon emission RPM can reduce the retailer-2's retail price under certain condition. At the same time, Proposition 5 shows that the recovery rate RPM helps lower the two retailers' retail price. So, like the WEEE buyback price, the two retailers' retail

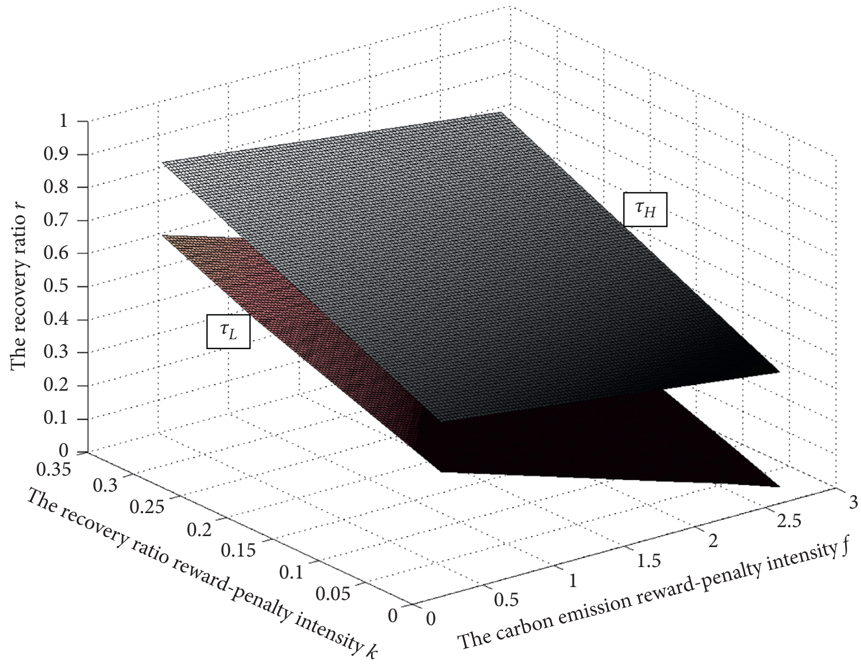

Figure 5: WEEE recovery rate τ_H and τ_L vs. f and k.

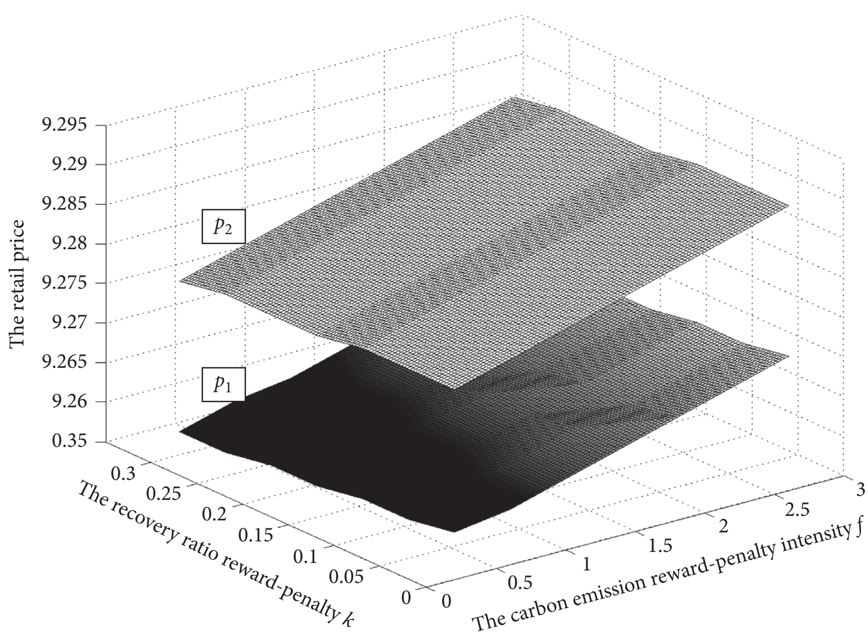

Figure 6: The retail price p_1 and p_2 vs. f and k.

price will be affected by the interaction of carbon emission reward-penalty and recovery rate reward-penalty, that is, only when the reward-penalty intensities f and k meet certain conditions, which can help reduce the retailers' retail price. In a word, Proposition 7 shows that the lower the amount of carbon emission reward-penalty fe_m, or the larger the recovery rate reward-penalty intensity k, it is better to reduce the retailers' retail price; moreover, it is better for consumers. $\square$

Proposition 8. *Comparing the different types of WEEE buyback price, the WEEE recovery rate of case 1 and case 2* *with case 3, respectively. In any conditions, we have* $w_H > w_L$ *and* $\tau_H > \tau_L$.

Proof. Based on the optimal decision variables in case 1, case 2, and case 3, we can obtain

$$\begin{aligned}
w_H^{(1)} - w_L^{(1)} &= \frac{p_m}{2};\\
w_H^{(2)} - w_L^{(2)} &= \frac{p_m + fe_m}{2},\\
w_H^{(3)} - w_L^{(3)} &= \frac{p_m + fe_m + \varepsilon\beta_H k}{2},\\
\tau_H^{(1)} - \tau_L^{(1)} &= \frac{\left(w_H^{(1)}\beta_L - w_L^{(1)}\beta_H\right)q_1^{(1)}}{2\beta_H\beta_L},\\
\tau_H^{(2)} - \tau_L^{(2)} &= \frac{\left(w_H^{(2)}\beta_L - w_L^{(2)}\beta_H\right)q_1^{(2)}}{2\beta_H\beta_L},\\
\tau_H^{(3)} - \tau_L^{(3)} &= \frac{\left(w_H^{(3)}\beta_L - w_L^{(3)}\beta_H\right)q_1^{(3)}}{2\beta_H\beta_L}.
\end{aligned} \tag{34}$$

It is so easy to get that $w_H > w_L$ from the abovementioned results, and because of the $w_H > w_L$ and $\beta_H < \beta_L$, the $\tau_H > \tau_L$ has been proved. Proposition 8 shows that the WEEE buyback price and the WEEE recovery rate with H-type are larger than L-type. In other words, the H-type fixed recovery cost means the high recovery ability and the advantages of scale; therefore, it is beneficial to obtain high recovery rate.

Due to the complex results of three cases, the comparative analysis between two retailers' retail price is not involved in the abovementioned research, nor does the impact of competition among retailers on system decisions and members' profits, which will be supplemented in Section 8. □

8. Numerical Analysis

In this section, we assume that $a = 10$, $c_m = 4$, $\Delta = 3$, $\beta_H = 10$, $\beta_L = 20$, $\mu = 0.5$, $\tau_0 = 0.5$, $e_0 = 1.2$, $e_m = 0.1$, $p_m = 5$, $f \in [0, 2.6]$, and $k \in [0, 0.35]$. Firstly, based on Table 1 in Appendix A, we discuss the impact of carbon emission reward-penalty and recovery rate reward-penalty on the system decisions and members benefits with the retailers' competition coefficient fixed, $\varepsilon = 0.5$ (from Figures 4–7). We can find that

(1) It can be shown from Figures 4, 5, and 7 that the WEEE buyback price w_H and w_L, the WEEE recovery rate τ_H and τ_L, and the retailers' profit reduce with the increasing of the carbon emission reward-penalty intensity f; however, they are all increasing with the increase of the recovery rate reward-penalty intensity k. This reflects that the carbon emission RPM cannot guide the system recycling; on the contrary, the recovery rate RPM can effectively stimulate system recycling initiative. Those are consistent with Proposition 1, Proposition 3, and Proposition 4.

(2) From Figures 6 and 7 we can see, with the increasing of the carbon emission reward-penalty intensity f, two retailers' retail price p_1 and p_2 increase too; however, they all decrease as the recovery rate reward-penalty intensity k increases, which are consistent with Proposition 2 and Proposition 5. We can also see that the retailer-1's retail price p_1 is always lower than that of retailer-2, but the retailer-1's profit is always higher than that of retailer-2. These reflect that the recovery rate RPM is good for the consumers. Moreover, the retailer who plays an active part in the WEEE recycling can get the competitive advantage compared to the retailer that does not participate in WEEE recycling.

(3) No matter how change in reward-penalty intensity k and f, the H-type WEEE buyback price w_H and WEEE recovery rate τ_H are higher than that of the L-type, respectively. When the other conditions remain the same, the larger the reward-penalty intensity f and k, the more obvious the scale advantage of the H-type retailer-1, which is consistent with Proposition 8.

Based on Table 2 in Appendix A, the impact of competition among retailers on system decisions and members benefits will be discussed in the following sections under the fixed carbon emission reward-penalty intensity ($f = 2$), we can find that

(4) According to Figures 8–10, the WEEE buyback price w_H and w_L, the WEEE recovery rate τ_H and τ_L, and the retailers' profit π_{R1} and π_{R2} gradually rise as the recovery rate reward-penalty intensity k and the retailers' competition increase. The fiercer the competition, the faster the rising speed. This suggests that retailers' competition not only can guide the WEEE recycling in addition to the recovery rate RPM but also benefits the retailers themselves.

(5) From Figure 11 we can see that it is different from (2) that there is $p_1 > p_2$ only when competition coefficient is lower than a certain value; otherwise, there is always $p_1 < p_2$. According to Figure 10, the $\pi_{R1} > \pi_{R2}$ is always true. These reflect retailer-1's competitive advantage; the fiercer the competition is, the more obvious the competitive advantage of retail-1 is.

(6) The manufacturer's profit changing shown in Figure 12 is different from the retailers' profit changing that retailers' competition is conducive to increase the manufacturer's profit when the reward-penalty intensity k is lower than a certain value; however, when the reward-penalty intensity k exceeds a certain value, the fierce retailers' competition damages the manufacturer's profit. Because the WEEE buyback price is a cost to the manufacturer and goes up

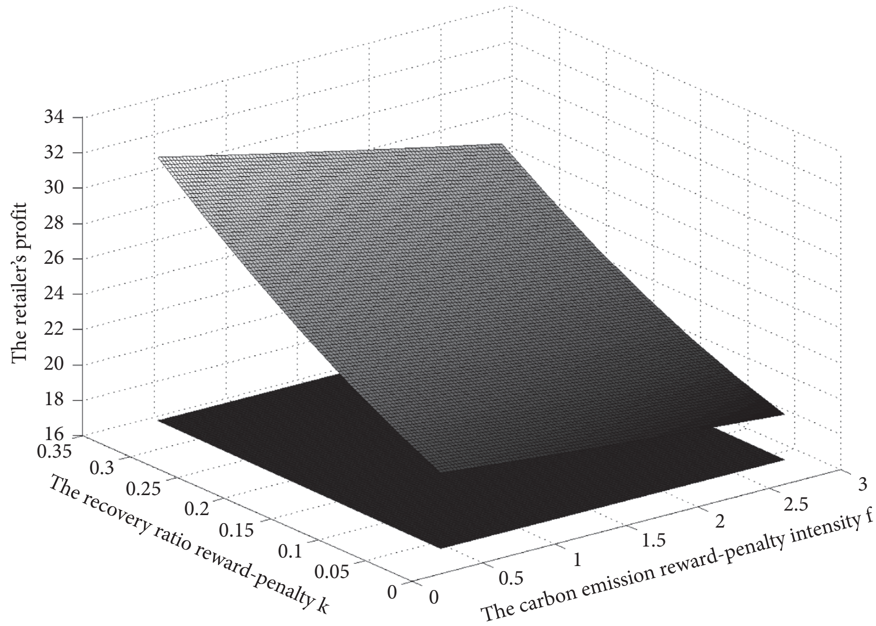

Figure 7: The retailers' profit π_{R1} and π_{R2} vs. f and k.

Table 2: Notation.

Symbol	Description
β_j	The recovery difficulty coefficient when the retailer-1's fixed recovery cost is j type, where $j \in \{H, L\}$, and there holds $\beta_H < \beta_L$. Under certain circumstances, the higher the fixed recovery cost, the larger the recycling scale, the better for recycling, that is, the lower the recovery difficulty
τ_j	The recovery rate when the retailer-1's fixed recovery cost is j type, which is the retailer-1's decision variable, where $j \in \{H, L\}$, and $\tau_j \in (0,1)$; the higher the fixed recovery cost is with a certain β, the higher the recycling rate is
I_j	The retailer-1's fixed recovery cost is j type, where $j \in \{H, L\}$
μ	The probability of retailer-1's fixed recovery cost is H-type
c_r	The manufacturer's unit remanufacturing cost using recycled WEEE
c_m	The manufacturer's unit manufacturing cost using new material
Δ	The unit cost savings of remanufacturing using recycled WEEE instead of new material, which can be expressed as $\Delta = c_m - c_r$
w_j	The buyback price of WEEE when the retailer-1's fixed recovery cost is j type, which is paid by the manufacturer when buying back WEEE from retailer-1, and it is also manufacturer's decision variable, where $j \in \{H, L\}$
p_m	The wholesale price of electronic products, which is paid by the retailers to manufacturer
p_i	The retail price of retailer-i when selling products to customers, where $i \in \{1, 2\}$, which is the retailers' decision variable
q_i	The market demand of the retailer-i, where $q_i = a - p_i + \varepsilon p_j\,(i, j = 1, 2)$ and $Q = q_i + q_j$
a	The potential market demand of retailers
ε	The competition coefficient, that is the intensity of competition between retailers, where $\varepsilon \in (0,1)$
e_0	The carbon emission cap set by the government
τ_0	The target recovery rate set by the government, where $\tau_0 \in (0,1)$
e_m	The unit carbon emission of the manufacturer
f	The unit carbon emission reward-penalty intensity established by the government
k	The unit recovery rate reward-penalty intensity established by the government
π_M	The manufacturer's profit
π_{Ri}	The retailer's profit $(i = 1, 2)$

Note: the decision variable and members' profit in Section 4 (Case 1)–Section 6 (Case 3).

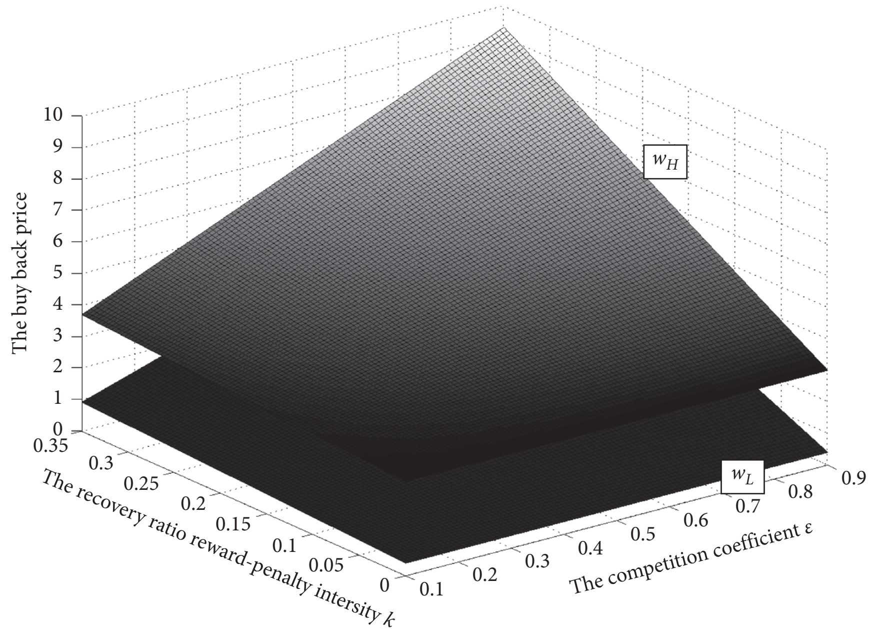

Figure 8: WEEE buyback price w_H and w_L vs. ε and k.

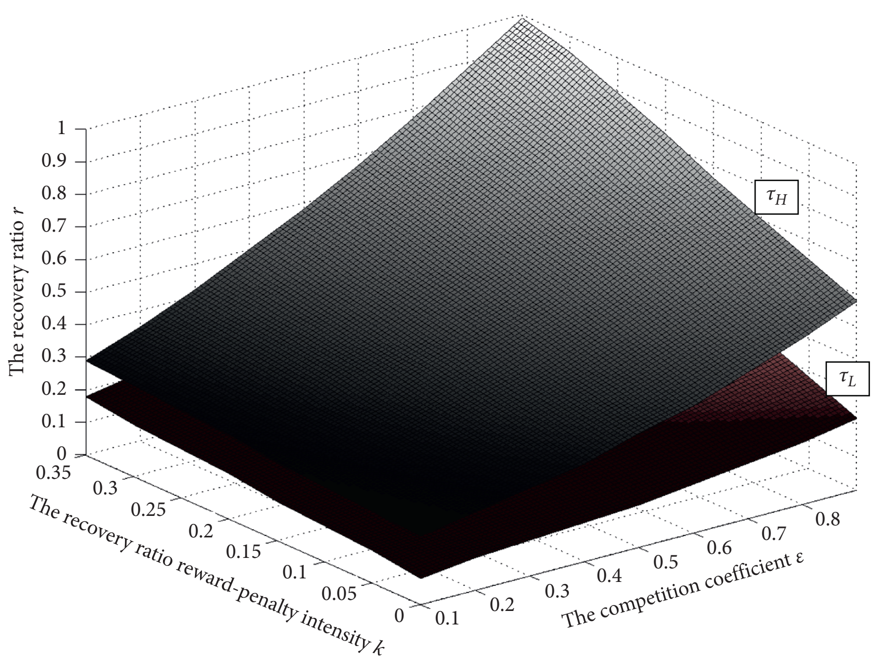

Figure 9: WEEE recovery rate τ_H and τ_L vs. ε and k.

with reward-penalty intensity k and the retailers' competition increases according to (4) or Figure 8, it would not hurt the manufacturer's profit until it exceeds a certain limits.

From (4), (5), and (6) we can find that the retailer's competition can not only effectively guide WEEE recycling activity but also improve the retailers' profit income. However, from the whole point of

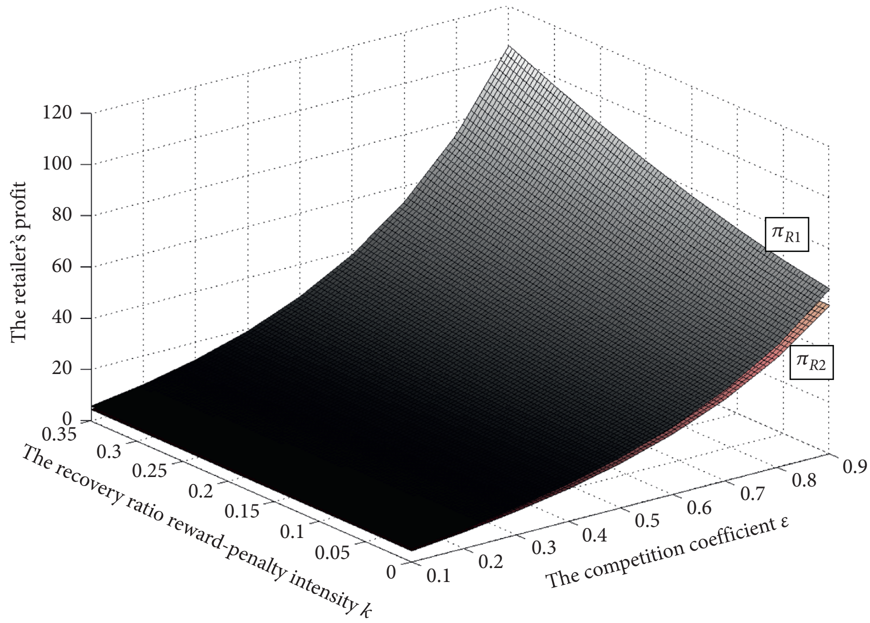

FIGURE 10: The retailer's profit π_{R_1} and π_{R_2} vs. ε and k.

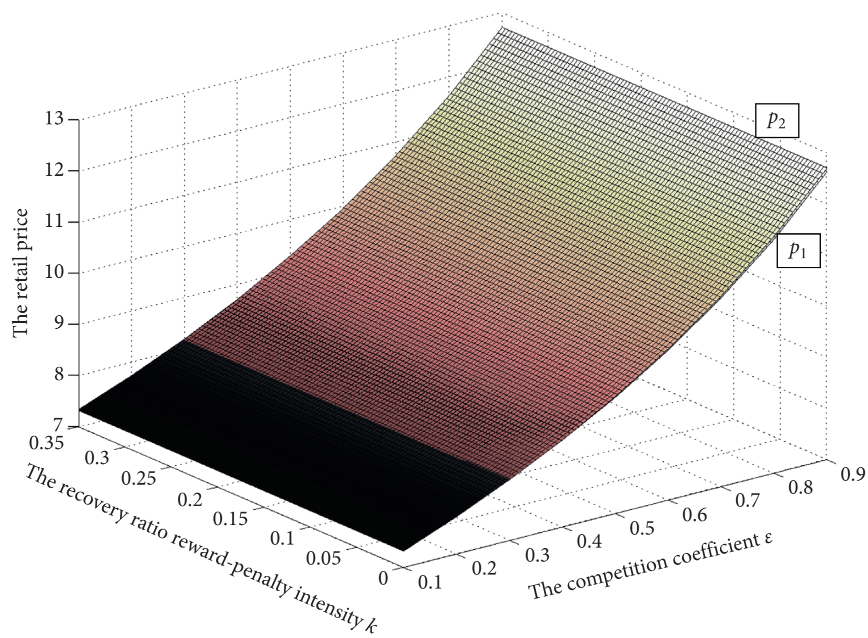

FIGURE 11: The retail price p_1 and p_2 vs. ε and k.

view, the moderate competition is optimal for the CLSC system.

(7) We also obtain from Figures 8 and 9 that no matter how competitive it is, there is always $w_H > w_L$ and $\tau_H > \tau_L$. When other things stay the same, the greater the competition, the more obvious the H-type scale advantage. This indicates that H-type retailer-1 is more suitable for the competitive environment with RPM.

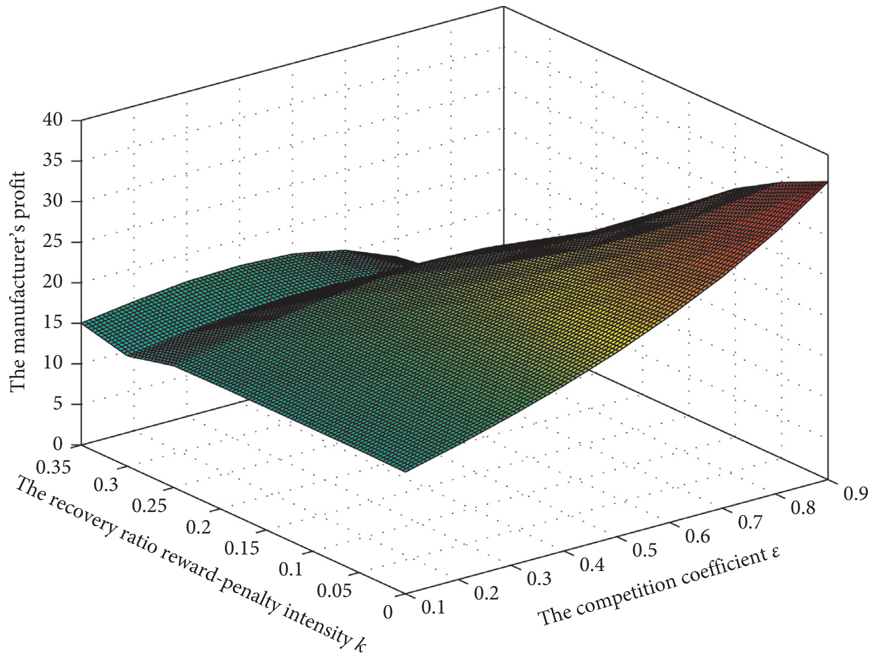

Figure 12: The manufacturer's profit π_M vs. ε and k.

9. Conclusion and Future Research

Based on the asymmetric information situation, this paper research CLSC with competing retailers and the RPM, and the dynamics game model with or without RPM has been built. We can get the following conclusions:

(1) Usually, the carbon emission RPM cannot guide the WEEE recycling; meanwhile, it is bad for consumers. On the contrary, the recovery rate RPM can effectively guide the WEEE recycling, and it can reduce the retail price.

(2) In any case, the retailer-1's profit is always higher than of the retailer-2. Namely, taking an active part in WEEE recycling is helpful to gain the competitive advantage for the retailer-1; moreover, the greater the recovery rate reward-penalty intensity, or the fiercer the competition, the more competitive advantage the retailer-1 can gain.

(3) Whatever the situation, the WEEE buyback price and the recovery rate with H-type is always larger than that of L-type. When other things stay the same, the fiercer the competition and the greater the recovery rate reward-penalty intensity, the more obvious the H-type scale advantage.

(4) The retailers' competition not only is beneficial to guide the WEEE recycling but also benefits the retailers themselves. However, from the whole point of view, the moderate competition is optimal for the CLSC system.

In order to achieve the coordinated development of CLSC in terms of economy, environment, and society, we come up with some managerial suggestions: (1) firstly, for the manufacturer, it has better increased investment in scientific research to reduce per unit carbon emission under carbon RPM; only in this way can the manufacturer expand production and enjoy returns on scale; secondly, the manufacturer should entrust the H-type retailer to recover WEEE for getting high recovery rate and decreasing total cost; thirdly, in order to protect the profits, the manufacturer can raise the wholesale price when facing the fierce retailers competition and the strong intensity of government RPM. (2) For the competing retailers, recycling WEEE can gain competitive advantage. In the case of a certain carbon emission RPM, the greater the recovery rate RPM intensity or the fiercer the retailer competition, the retailer which undertakes the WEEE recycling can further expand scale advantages and competitive advantage through increasing investment in fixed recovery costs. (3) For the government, how to reconcile the contradiction which resulted from the carbon emission RPM and recovery rate RPM in terms of the WEEE recovery rate, retail price, and members profits is the most important. The government needs to balance the intensity of carbon emission RPM and the recovery rate RPM; only in this way can the RPM is not only optimal to environment but also does not damage the members profits of CLSC. Moreover, the government should make macroeconomic regulation on retailer competition to prevent excessive competition from hurting the manufacturers' profits under government RPM.

Only a single production cycle is considered in this paper, but two or multiple production cycles may be more realistic. Some of the assumptions are too simple to be realistic (e.g., unit recycling cost, unit carbon emissions, and remanufacturing rate). Some assumptions are too strict to be realistic. Meanwhile, the impact of change of carbon emission cap and WEEE target recovery rate made by the government on system decisions and members benefits were not taken into account in the numerical analysis. The defect mentioned above can be taken as one of the research directions of CLSC in the future so that it can make theoretical research conform to practices.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

X. Q. Zhang conducted the study design, performed the simulation analysis, and drafted the manuscript; X. G. Yuan organized this paper and contributed to design the model.

Acknowledgments

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Supplementary Materials

Appendix A is the result of the numerical analysis in section 8, which contains two parts. First, in Table 1 in Appendix A, we discuss the impact of carbon emission reward-penalty and recovery rate reward-penalty on the system decisions, and member benefits with the retailers' competition coefficient is fixed ($e = 0.5$); the carbon emission reward-penalty intensity ranges from 0.2 to 2.6, and the recovery rate reward-penalty intensity ranges from 0.05 to 0.3. Corresponding figure in the paper are Fig.4–Fig.7. Secondly, in Table 2 in Appendix A, we mainly discuss the impact of competition among retailers on system decisions and member benefits under the fixed carbon emission reward-penalty intensity ($f = 2$) and the recovery rate reward-penalty intensity ranges from 0.05 to 0.3 and the competition coefficient ranges from 0 to 1. Corresponding figure in the paper are Fig.8–Fig.12. (*Supplementary Materials*)

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