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Determining Recycling Fees and Subsidies in China's WEEE Disposal Fund with Formal and Informal Sectors

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Abstract: At present, most of China's waste electrical and electronic equipment (hereafter referred to as WEEE) flow into the informal recycling sector, which has no official disassembly certification. To regulate the WEEE recycling industry, the policy of the WEEE disposal fund has been implemented to levy recycling fees from producers and subsidize the formal recycling sector. This paper aims to solve the challenging problem of how to optimize recycling fees and subsidies. We first study the competition between the formal and informal sectors, and construct the game models of the dismantling and refurbishing processes. Based on the equilibrium outcomes, we then examine the impact of the disposal fund on producers, as well as the formal and informal recycling sectors. With the goal of maximizing social welfare and maintaining a balanced budget for the disposal fund, we study the optimal recycling fee levied on producers and the corresponding subsidy provided to the formal sector. Social welfare is a function of producer and formal-recycler profits, consumer surplus, and the negative externality caused by informal dismantling and refurbishing, such as environmental pollution and safety problems. Results show that the use of subsidy can increase the acquisition quantity of used products in the formal sector, but the increase will slow down with higher subsidy. If the recycling fee that producers are charged is small, social welfare will be improved. In addition, as the fee is increased, social welfare will rise first and then fall. As such, any excessive increase in recycling fees should be avoided.

Keywords: waste electrical and electronic equipment (WEEE); disposal fund; formal sector; informal sector; producers; subsidy; recycling fee

1. Introduction

With the increasing awareness of sustainable development, recycling and reusing have become an important social concern [1,2]. In recent years, huge quantities of waste electrical and electronic equipment (WEEE) have been generated worldwide. In 2009, the amount of global e-waste reached 40 million tons [3] and was estimated to grow at an annual rate of 4% [4]. In China, the number of products scrapped was 3.62 million tons in 2011 [5], and has been growing year by year. For example, China's computer waste is forecasted to quadruple and mobile phone scrap will grow six-fold by 2020, compared with 2007 [6]. WEEEs contain a wide range of substances, some of which are economically valuable, and some are toxic or hazardous [7], and unregulated disposal processes will cause severe environmental pollution.

At present, China has not yet established a complete e-products-recycling system, and most collection and recycling activities have not been done in an environmentally friendly way [8]. According to China's WEEE regulations, dismantling e-products must be strictly audited by environmental protection authorities and issued a disassembly qualification certificate. In reality, only a small percentage of WEEEs flow into the formal recycling sector, which has an official disassembly certification (hereinafter referred to as formal sector). In Beijing, for example, a survey [9] showed that about 63% of waste household appliances entered the informal recycling sector without an official disassembly certification (hereinafter referred to as informal sector). The disassembling methods, such as acid soaking and firing, used in the informal sector are very crude. The toxic waste liquid and residues generated in the processes are discharged directly to the surrounding environment.

As an industry that affects public welfare, the WEEE recycling industry cannot exist without government support. In the issue of WEEE recovery, many developed countries have introduced the principle of extended product responsibility (EPR) [10]. Electronic manufacturers and importers are mandated to take back used products and assume responsibility in the whole life cycle of products. Based on the EPR principle, China has implemented WEEE recycling management regulations since 1 January 2011. The WEEE disposal fund was then established to provide subsidies to formal recyclers and impose recycling fees on electronics producers. In 2017, the State council emphasized the shifts of responsibility from the consumers to producers and set goals of EPR implementation by 2025 [8,11]. The WEEE disposal fund has already achieved some success in promoting the standardized development of the recycling industry. By the end of 2016, 109 recyclers have had official certification in dismantling WEEE. These official recyclers' annual disposal capacity exceeded 150 million units with the actual disposal amount exceeding 75 million units. The green recovery rate, which is the ratio of formally recycled products to the total scrapped products, has grown to about 60% in 2015, compared with about 34% in 2012 [12].

The question of what reasonable recycling fees and subsidies are remains unanswered. Currently, inappropriate subsidy standards have resulted in an unbalanced recovery structure. In 2015, the green recovery rates of products in the first recovery catalog are as follows: TVs 180%, refrigerators 17%, washing machines 38%, air conditioners 0.25%, and microcomputers 27%. The subsidy level for TVs is so high that a large number of products have been scrapped, which leads to a situation where the volume of dismantled products is far higher than the amount theoretically scrapped. For air conditioners, however, the situation is reversed. The subsidy level is too low to offset disposal costs, resulting in an inactive participation of formal recyclers and a low recovery amount. Unreasonable standards of fund subsidies have hindered the healthy development of the recycling industry [13]. In addition, there exists a serious imbalance between receipts and payment of the disposal fund. The growth rate of the production and imports lagged behind the growth rate of waste disposal, and the total recycling fees were not enough to pay the dismantling subsidies, which led to a fund deficit in some periods [13]. For example, in 2016, the disposal fund levied 2610 million RMB and allocated 4714 million RMB, which resulted in a funding gap of more than 2000 million RMB. This deficit caused tremendous pressures on the viability of the disposal fund [14]. Under this scenario, there is an urgent need to set reasonable recycling fees and subsidy standards to effectively support the formal sector and further promote the sustainable development of WEEE recycling industry.

To solve the above problem, we first study the competition between formal and informal sectors. There are two main processing approaches to recycle WEEE, including dismantling and refurbishing. Correspondingly, we built the dismantling and refurbishing subgame models to characterize how the two sectors compete with each other. Refurbishing, which is a kind of reusing, differs from dismantling in two aspects. The formal sector will not receive subsidies from refurbishing according to the disposal fund regulations. Producers will be involved due to the fact that new and refurbished products are substitutive and compete with each other. After obtaining the equilibrium outcomes of the two subgame models, we examine the impact of the disposal fund on the producers and two recycling sectors. With the goal of maximizing social welfare and maintaining a balanced disposal fund, we next discuss the optimal levels of the recycling fee levied on producers and the subsidy provided to the formal sector. Social welfare is a function of producer and formal-recycler profits, consumer surplus, and the negative externality caused by informal dismantling and refurbishing, such as environmental pollution and safety problems. Details of the social-welfare function will be provided in the section "Government's decisions on recycling fees and subsidies." Finally, policy suggestions are provided to assist the government in regulating the recycling industry. In summary, the paper aims to answer the following questions:

(1) What is the level of competition between the formal and informal sectors?
(2) To what degree will the fund policy enhance the competitiveness of the formal sector?
(3) How to determine the optimal recycling fee and subsidy to maximize social welfare and maintain a balanced budget for the disposal fund?

This paper is organized as follows. In Section 2, we provide a summary of the literature related to recycling and subsidy policies. Model setting is shown in Section 3. This is followed by the development of dismantling and refurbishing subgame models in Sections 4 and 5. The impact of recycling fees and subsidies on the two sectors and producers are also discussed. Next, we study the government's decisions on recycling fees and subsidies in Section 6 by carrying out numerical simulations that describe the optimization graphically. Finally, we summarize our main conclusions and provide managerial and policy implications in Sections 7 and 8.

2. Literature Review

With respect to recycling policies, several studies examine the impact of environmental protection policies on the recycling industry and introduce the recovery experiences of foreign countries [10,15,16]. Abdulrahman, Gunasekaran, and Subramanian [17] indicate that a lack of supportive government economic policies is one of the barriers for Chinese reverse logistics. Salhofer, Steuer, and Ramusch [18] compare the waste management between Europe and China and point out that China's formal sector cannot beat the formal one without government subsidies. An imbalance between levies and subsidies may cause a low recycling rate and an unsustainable WEEE funding policy [19].

As to the subsidy policies, many related studies focus on the game between recyclers and the government [20–23]. Aksen, Aras, and Karaarslan [22] divide the subsidy policies into supportive and legislative modes; the former regulates the minimum recovery rate, and the latter does not. Results show that, given the same recovery rate and completion probability, in supportive mode the government pays higher subsidies. In the distribution of subsides, Reference [23] finds that an appropriate allocation ratio can effectively promote the collection of old products and remanufacturing activities in the reverse logistics. Wang et al. [24] prove that a reward–penalty mechanism for government will motivate industry's recycling efforts and improve WEEE collection.

A few studies examine quantitatively the fund-subsidy policy implemented in China. Li [25] uses the method of system dynamics to simulate the recycling mode based on the WEEE disposal fund. Zhao et al. [26] explore the effects of consumers' environmental preference and government subsidy policy on remanufacturing. Shu et al. [27] study the effect of government subsidies for remanufacturing in a supply chain consisting of a local and nonlocal remanufacturer. From the perspective of the whole product life cycle, Chang et al. [28] study the impact of Chinese recycling subsidy policy on environmental pollution and social welfare. Liu et al. [29] build a game model between the formal and informal recycling sectors, and study the impact of government subsidies on improving the formal sector's competitiveness under different competitive scenarios. The above research does not involve producers and the recycling fees. Mu [30] constructs a Stackelberg game model consisting of the government, two producers, and one recycler to determine the levels of recycling fees and subsidies, but does not consider the informal recycling sector.

In view of the competition between the formal and informal sectors, related research focuses mainly on the comparison of policies between different countries [31], status quo of recycling [32], as well as qualitative analysis of the informal sector [8,33,34]. Many studies indicate that the informal sector has become a major recycling force [33] due to incomplete environmental management, high demand for second-hand electronic appliances, and the norm of selling WEEE to individual collectors [32]. A field survey on the recycling industry finds that there are several advantages in the acquisition of old products in the informal sector compared with the formal sector, including a large number of scattered recycling points and door-to-door collection service [33]. Wang et al. [34] analyze the effect of residents' perceptions towards informal recycling on their recycling behavior intentions. Using the system dynamics approach, Besiou et al. [35] examines the impact of informal recycling scavengers on the formal sector. Thus far, the quantitative literature on the competition between the formal and informal sectors is still lacking. Li [36] quantitatively studies the formal and informal recyclers and discusses the reason why informal recyclers' profits are far greater than those of the formal recyclers. But the specific recycling competition between these two is not characterized. By establishing a game model, Liu et al. [37] examine the competition in acquisition prices between the formal and informal sectors. Their research explores the role of the trade-in strategy in supporting formal recyclers from the perspective of a supply chain, but does not involve any fund subsidy policy.

Only a few literatures have studied quantitatively the WEEE disposal fund, but do not involve the investigation of the informal sector and EEE producers. In China, the coexistence and competition between the formal and informal sectors is a common phenomenon that needs to be considered when studying the disposal fund. In accordance with the EPR principle, EEE producers are contributors to the disposal fund and the recycling fee levied on them is directly associated with the operation of the recycling system. Therefore, the role of producers cannot be ignored.

Our research is distinguished from earlier studies as follows: (1) incorporating the roles of government, producers, formal, and informal recycling sectors into the game model; and (2) exploring the optimal recycling fees and subsidy levels to maximize social welfare. Our study is expected to provide a feasible analytic framework for quantitatively studying the informal recycling sector and supporting policies of the recycling industry.

3. Model Setting

In China's recycling industry, there exist two main processing approaches to recycle WEEE. One is dismantling, which means used products are broken down into raw materials and will not return to market circulation in the form of complete products. The other is refurbishing, where used products are reworked so that they can re-enter the market and compete with new products. These two processing approaches differ in several aspects. First, the formal sector is subsidized for the dismantling process, but not for the refurbishing process. According to the WEEE disposal fund regulation, only the dismantling process belongs to recycling and can be subsidized. Second, the relationships with producers are different for the two approaches. Dismantling is indirectly connected with producers through the fund subsidy, while refurbishing is directly associated with producers, because refurbished products compete with new products in the market. Third, the social and environmental impact of these two processing approaches is different. Dismantling can exert a direct influence on the surrounding environment. For instance, the informal sector abandons waste parts containing toxic materials directly after dismantling, which severely pollutes the environment. Refurbishing mainly affects social welfare. For example, by selling inferior refurbished products, most informal recyclers cannot ensure the safety of product usage and risk infringement of patents.

For the above reasons, we consider these two processing approaches respectively, and establish the corresponding models to characterize the competition between formal and informal sectors. We then combine these two subgames and examine the government's decision in setting optimal recycling fees and subsidies.

The basic procedures of the subsidy policy are as follows. Producers pay the disposal fund with recycling fees, which are calculated as the sales quantity of new products multiplied by a per-unit recycling fee. The disposal fund supports the formal sector with subsidies that equal the dismantling amount multiplying a per-unit subsidy. The informal sector will not be subsidized due to the generation of environmental pollution during the process of dismantling and refurbishing.

This paper establishes the Stackelberg game models, including government, producers, and formal and informal recycling sectors. The government is the leader in the game, taking the first step to decide the recycling fees collected from producers and subsidies paid to the formal sector. Next, the producers and two sectors will make their own decisions in the subgames. Depending on different processing procedures and game players involved, we build up game models of dismantling and refurbishing respectively. We solve the models by using the method of backward induction. Based on the equilibrium outcomes of subgames, we then consider the government's decision. We examine the optimal recycling-fee and subsidy levels with the aim of maximizing social welfare and maintaining the disposal fund to be balanced.

4. Subgame of Dismantling Process

As shown in Figure 1 below, the formal and informal sectors compete in the acquisition of used products and gain profits from the dismantling process. We define a firm with disassembly certificate as a formal recycler and a firm without disassembly certificate as an informal recycler.

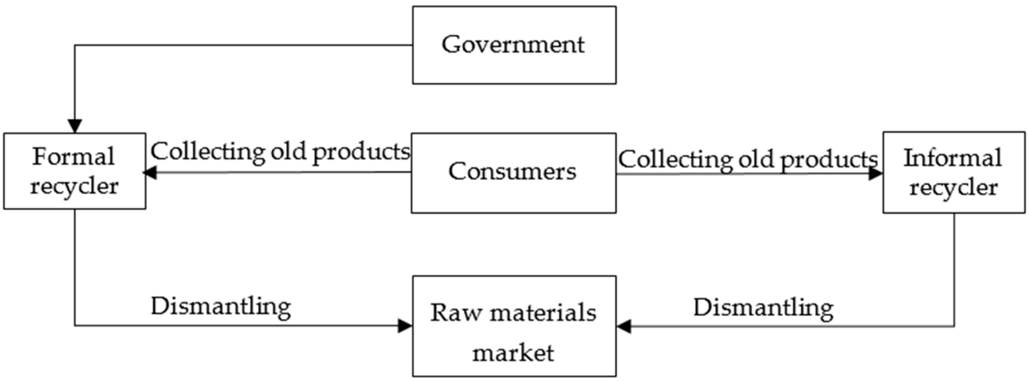

Figure 1. Competition in the dismantling process.

Recyclers dismantle used products to draw valuable materials such as metals and sell them at the price v in the raw-material market. Assume that the dismantling costs for formal and informal recyclers are c_{d1} and c_{d2}, respectively. Considering that the formal recycler needs to invest in environmentally friendly disposal technology, its cost is higher than the informal recycler. As such we have $v > c_{d1} > c_{d2}$. For each unit of dismantled product, the formal recycler obtains a subsidy s from the disposal fund. To facilitate an understanding, we provide the symbols used and their corresponding meanings in Table 1.

Table 1. Definition of symbols.

Symbol	Definition
v	Sale price for materials dismantled from each product
c_{d1}	Dismantling cost for the formal recycler
c_{d2}	Dismantling cost for the informal recycler
s	Subsidy to each dismantled product by formal recycler
q_{1d}	Acquisition quantity of the formal recycler
q_{2d}	Acquisition quantity of the informal recycler
p_{1d}	Acquisition prices of the formal recyclers
p_{2d}	Acquisition prices of the informal recyclers
Q	Basic recycling amount, the amount when acquisition prices are zero
a	Self-price sensitivity on acquisition quantity
b	Cross-price sensitivity on acquisition quantity
π_{1d}	Profit of the formal recycler in dismantling process
π_{2d}	Profit of the informal recycler in dismantling process
QZ	Market share of the formal recycler in acquisition quantity

Table 1. *Cont.*

Symbol	Definition
t	Recycling fee that producers pay for each unit of new product
c_N	Production cost of new products
c_{1r}	Refurbishing costs of the formal recycler
c_{2r}	Refurbishing costs of the informal recycler
α	Consumer preference degree towards refurbished products
θ	Consumers' willingness to purchase
p_N	Sales price of new products
p_R	Sales price of refurbished products
q_N	Demand for new products
q_R	Demand for refurbished products
q_{1r}	Refurbishing quantity of the formal recycler
q_{2r}	Refurbishing quantity of the informal recycler
π_{1r}	Profit of the formal recycler in refurbishing process
π_{2r}	Profit of the informal recycler in refurbishing process
π_m	Profit of producers
SW	Social welfare
w_1	Weight of forward supply chain in calculating social welfare
w_2	Weight of reverse supply chain in calculating social welfare
E_c	Environment cost of informal dismantling
E_r	Safety and environment cost of informal refurbishing

In the game of dismantling process, the formal and informal sectors make decisions simultaneously on the acquisition prices of old products, to maximize their own profits. We assume the acquisition quantities of old products are linear functions of acquisition prices [29].

The acquisition quantity of the formal recycler is $q_{1d} = Q + ap_{1d} - bp_{2d}$.

The acquisition quantity of the informal recycler is $q_{2d} = Q + ap_{2d} - bp_{1d}$.

Here, Q is the basic recycling volume, the amount when the acquisition prices are zero. p_{1d} and p_{2d} are acquisition prices of the formal and informal recyclers. Assume a to be self-price sensitivity on acquisition quantity and b to be cross-price sensitivity on acquisition quantity. Here $a > b > 0$.

The profit function of the formal recycler is:

$$\pi_{1d} = (v - c_{1d} - p_{1d} + s)q_{1d} = (v - c_{1d} - p_{1d} + s)(Q + ap_{1d} - bp_{2d}) \tag{1}$$

The profit function of the informal recycler is:

$$\pi_{2d} = (v - c_{2d} - p_{2d})q_{2d} = (v - c_{2d} - p_{2d})(Q + ap_{2d} - bp_{1d}) \tag{2}$$

By taking the derivatives of π_{1d} and π_{2d} with respect to p_{1d} and p_{2d}, we combine the two first-order conditions and obtain the only equilibrium outcome.

Proposition 1. *In the model of dismantling process, the equilibrium prices and corresponding sales quantities can be summarized as follows:*

$$p_{1d}^* = \frac{2a^2(s + v - c_{1d}) + ab(v - c_{2d}) - Q(2a + b)}{4a^2 - b^2} \tag{3}$$

$$p_{2d}^* = \frac{2a^2(v - c_{2d}) + ab(s + v - c_{d1}) - Q(2a + b)}{4a^2 - b^2} \tag{4}$$

$$q_{1d}^* = \frac{a\big(a(2Q + b(v - c_{2d})) + b(Q - b(s + v - c_{1d})) + 2a^2(s + v - c_{1d})\big)}{4a^2 - b^2} \tag{5}$$

$$q_{2d}^* = \frac{a\big(b(Q + b(v - c_{2d})) + a(2Q - b(s + v - c_{1d})) + 2a^2(v - c_{2d})\big)}{4a^2 - b^2} \tag{6}$$

Corollary 1.

(1) $\frac{\partial p_{1d}^*}{\partial s} = \frac{2a^2}{4a^2-b^2} > 0$, $\frac{\partial p_{2d}^*}{\partial s} = \frac{ab}{4a^2-b^2} > 0$, $\frac{\partial q_{1d}^*}{\partial s} = \frac{2a^3-ab^2}{4a^2-b^2} > 0$, $\frac{\partial q_{2d}^*}{\partial s} = \frac{-a^2b}{4a^2-b^2} < 0$. *As the subsidy increases, the acquisition prices of both sectors will go up. More old products flow into the formal recycler, but less for the informal sector.*

(2) *If* $s = 0$, *then* $q_{1d}^* - q_{2d}^* < 0$ *and* $p_{1d}^* - p_{2d}^* < 0$. *Without any fund subsidy, the formal recycler fails in the competition with the informal recycler, in both the acquisition price and acquisition quantities of old products.*

(3) $q_{2d}^* = 0$ *only if s has to be above* $\frac{a(2Q-b(v-c_{1d}))+b(Q-b(v-c_{2d}))+2a^2(v-c_{2d})}{ab}$. *To eliminate the informal sector, the subsidy has to be very high such that the formal sector is sufficiently competitive.*

Corollary 2. *The market share of the formal recycler in acquisition quantity is defined as QZ.* $QZ = \frac{q_{1d}^*}{q_{1d}^*+q_{2d}^*} = \frac{2a^2(s+v-c_{1d})+a(2Q-b(v-c_{2d}))+b(Q-b(s+v-c_{1d}))}{(2a+b)(2Q+(a-b)(s+2v-c_{1d}-c_{2d}))}$, $\frac{\partial QZ}{\partial s} > 0$ *and* $\frac{\partial^2 QZ}{\partial s^2} < 0$. *As the subsidy level goes up, the market share of the informal sector will increase, but the growth rate decreases, indicating the marginal effect of government subsidy is declining.*

According to Corollary 1 and 2, without subsidy, the formal sector is at a disadvantage in the competition because its cost is higher than the informal sector. This result proves the necessity of implementing the subsidy policy. The use of subsidies can improve the market share of the formal sector in acquisition quantity of used products, but the increase slows down as the subsidy goes up. Only when the subsidy is high enough, can the formal sector have absolute competitive advantage; otherwise, it will be very difficult to suppress the growth of the informal sector.

5. Subgame of Refurbishing Process

The refurbishing model, which is different from the dismantling model, involves e-product producers, as well as the formal and informal recycling sectors. As Figure 2 shows, producers pay a recycling fee to the disposal fund based on each product sold. Both the formal and informal recyclers collect used products and decide the refurbishing quantities. After the refurbishing process, refurbished products are sold in the market.

Consumers have access to both the new and refurbished products, which are heterogeneous and can mutually substitute each other to some degree. Assume that there exists price competition between these two kinds of products. Refurbished products are assumed to be homogeneous, and the formal and informal sectors compete in quantity. In the refurbishing model, we introduce the role of producers, and examine the market competition with three game players and two kinds of heterogeneous goods.

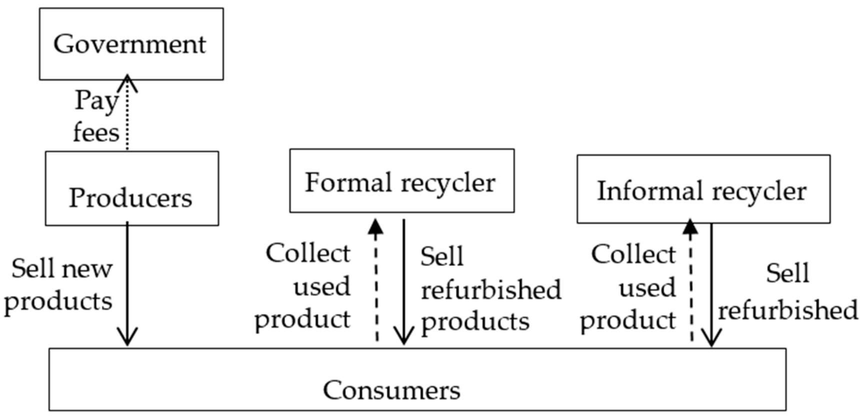

Figure 2. Competition in refurbishing process.

In the refurbishing process, the subgame is divided into two stages. In the first stage, producers decide the sale price of new products and pay a recycling fee t to the disposal fund for each unit of new product. In the second stage, the formal and informal recyclers collect used products and then decide the refurbishing quantities simultaneously. Refurbished products flow into the electrical and electronic equipment market and compete with new products.

Assume the production cost of new products is c_N, and the refurbishing costs of the formal and informal recyclers are c_{1r} and c_{2r}. Generally, remanufacturing will bring a reduction in production cost [38,39], so we have $c_N > c_{1r} > c_{2r}$. New and refurbished products compete against each other as heterogeneous products. Disregarding the price factor, market observation indicates that there is a consumer-preference difference towards new and refurbished products. If consumers' preference degree towards new products is 1, then the preference degree towards refurbished products is assumed to be $(\alpha < 1)$, which means that with the same price level, consumers prefer new products. α can be considered as the consumer-perceived quality factors, which include attributes such as warranty period, physical appearance, and technical specification.

We assume that consumers' willingness to purchase θ has a uniform distribution, i.e., $\theta \sim U[0,1]$ [40]. If consumers buy new products, the utility that they obtain is $U_N = \theta - p_N$, and if consumers choose refurbished products, the utility is $U_R = \alpha\theta - p_R$. Here, p_N and p_R are sale prices of new and refurbished products. With $U_N = U_R$, we can obtain the consumers' indifference point $\theta^* = (p_N - p_R)/(1-\alpha)$. Our paper discusses the situation where both new and refurbished products exist, and their sale quantities are positive, which requires $\alpha \in (p_R/p_N, p_R - p_N + 1)$. The demand for new and refurbished products is

$$q_N = 1 - \theta^* = 1 - \frac{p_N - p_R}{1-\alpha}$$

$$q_R = \theta^* - \frac{p_R}{\alpha} = \frac{p_N - p_R}{1-\alpha} - \frac{p_R}{\alpha} = \frac{p_N}{1-\alpha} - \frac{p_R}{\alpha(1-\alpha)}$$

Given the price of new products p_N, the relationship between the price and sale quantity of refurbished products is

$$p_R = \alpha\, p_N - \alpha(1-\alpha)q_R \tag{7}$$

Assume the refurbishing quantities of the formal and informal recyclers are q_{1r} and q_{2r}, respectively. The total amount of refurbished products in the market equals to the sum of refurbishing quantities in two sectors, i.e., $q_R = q_{1r} + q_{2r}$. Equation (7) can be rewritten as

$$p_R = \alpha\, p_N - \alpha(1-\alpha)(q_{1r} + q_{2r}) \tag{8}$$

The formal recycler's profit in the refurbishing process is

$$\pi_{1r} = (p_R - c_{1r})q_{1r} = (\alpha\, p_N - \alpha(1-\alpha)(q_{1r} + q_{2r}))q_{1r} \tag{9}$$

The informal recycler's profit in the refurbishing process is

$$\pi_{2r} = (p_R - c_{2r})q_{2r} = (\alpha\, p_N - \alpha(1-\alpha)(q_{1r} + q_{2r}))q_{2r} \tag{10}$$

By taking the derivative of π_{1r} and π_{2r} with respect to q_{1r} and q_{2r}, we combine the two first-order conditions and obtain the two recyclers' best response below.

$$q_{1r}^* = \frac{-2c_{1r} + c_{2r} + p_N\alpha}{3(1-\alpha)\alpha},\ q_{2r}^* = \frac{c_{1r} - 2c_{2r} + p_N\alpha}{3(1-\alpha)\alpha},\ p_R{}^* = \frac{1}{3}(c_{1r} + c_{2r} + p_N\alpha) \tag{11}$$

The producers' profit is shown below.

$$\pi_m = (p_N - c_N - t)q_N \tag{12}$$

Substitute Equation (11) with Equation (12), and take the derivative of π_m with respect to p_N, and we obtain the only equilibrium outcome as follows.

Proposition 2. *In the model of the refurbishing process, the equilibrium prices and corresponding sales quantities can be summarized as follows:*

$$p_N{}^* = \frac{3 + c_{1r} + c_{2r} + 3c_N + 3t - 3\alpha - c_N\alpha - t\alpha}{6 - 2\alpha} \tag{13}$$

$$q_N{}^* = \frac{3 + c_{1r} + c_{2r} - 3c_N - 3t - 3\alpha + c_N\alpha + t\alpha}{6 - 6\alpha} \tag{14}$$

$$p_R{}^* = \frac{(c_{1r} + c_{2r})(6 - \alpha) + (c_N + t)(3 - \alpha)\alpha + 3(1 - \alpha)\alpha}{6(3 - \alpha)} \tag{15}$$

$$q_R{}^* = \frac{-(c_{1r} + c_{2r})(3 - 2\alpha) + (c_N + t)(3 - \alpha)\alpha + 3(1 - \alpha)\alpha}{3\alpha(3 - \alpha)(1 - \alpha)} \tag{16}$$

$$q_{1R}{}^* = \frac{-c_{1r}(12 - 5\alpha) + c_{2r}(6 - \alpha) + (c_N + t)(3 - \alpha)\alpha + 3(1 - \alpha)\alpha}{6\alpha(3 - \alpha)(1 - \alpha)} \tag{17}$$

$$q_{2R}{}^* = \frac{-c_{2r}(12 - 5\alpha) + c_{1r}(6 - \alpha) + (c_N + t)(3 - \alpha)\alpha + 3(1 - \alpha)\alpha}{6\alpha(3 - \alpha)(1 - \alpha)} \tag{18}$$

Corollary 3.

(1) $\frac{\partial p_N}{\partial t} = \frac{1}{2}$, $\frac{\partial(p_N - c_N - t)}{\partial t} = -\frac{1}{2}$, $\frac{\partial q_N}{\partial t} = \frac{-3+\alpha}{6-6\alpha} < -\frac{1}{2}$. $\frac{\partial \pi_m}{\partial t} < 0$.
(2) $\frac{\partial p_R}{\partial t} = \frac{\alpha}{6}$, $\frac{\partial q_{1r}}{\partial t} = \frac{1}{6-6\alpha}$, $\frac{\partial q_{2r}}{\partial t} = \frac{1}{6-6\alpha}$. $\frac{\partial \pi_{1r}}{\partial t} > 0$ *and* $\frac{\partial \pi_{2r}}{\partial t} > 0$.

According to Corollary 3, if the recycling fee that producers pay increases by one unit, then the price of new products increases by half, and the sales quantity decreases by more than half. After implementing the policy of the disposal fund, producers will raise the price of new products and transfer part of the recycling fee to consumers. Producers' profit drops due to the decreases in both marginal profit and sales quantity. If the recycling fee that producers pay increases by one unit, then the price of refurbished products rises by $\alpha/6$, which is much less than the proportion that the price of new products increases by. In effect, the sales quantities of refurbished products increase in both the formal and informal sectors. After being levied a recycling fee, producers have to raise the price of new products. This, in turn, leads to an increase in the price of refurbished products. Even with a rising price, the sales quantities of refurbished products will still go up for both recyclers, thus contributing to an increase in their profits. Therefore, charging producers a recycling fee will also benefit the informal sector, because the price competition between new and refurbished products is weakened.

Remark 1. *$q_N t$ is a quadratic concave function of t. There exists a $\bar{t} \in [0, +\infty)$, such that when $t > \bar{t}$, $q_N t$ decreases with t. And $q_N t$ is a decreasing function with respect to α, i.e., $\frac{\partial(q_N t)}{\partial \alpha} < 0$.*

According to Remark 1, the total recycling fees that producers pay follow a quadratic concave function with respect to the unit recycling fee t. When t is high enough, the total recycling fees decrease with t. Therefore, a higher recycling fee does not necessarily enhance the total recycling fees, due to a decrease in producers' new products sales. If the consumers' preference towards refurbished products α is high, the total recycling fee will tend to be lower. That's to say, when the competition between new and refurbished products intensifies, producers suffer from lower sales of new products, which leads to a drop in the total recycling fees.

6. Government's Decisions on Recycling Fees and Subsidies

Based on the above equilibrium outcomes in dismantling and refurbishing subgame models, we next discuss the decisions of government on recycling fees and subsidies. The government's objective is to maximize social welfare, involving profits of producers and formal sector, consumer surplus, and the negative externality caused by informal dismantling and refurbishing, such as the environment pollution and safety problems.

Social welfare = (Weight of forward supply chain) times (profit of producers + consumer surplus of purchasing new products) + (Weight of reverse supply chain) times (profit of the formal sector + consumer surplus of recycling old products in the formal dismantling process − negative externality caused by the informal dismantling − negative externality caused by informal refurbishing). Consequently, we have the following social welfare function:

$$\begin{aligned} \text{MaxSW} = w_1\big((p_N - c_N - t)q_N + \tfrac{3-3\alpha}{6-2\alpha}q_N^2\big) + w_2(v - c_{1d} - p_{1d} + s)q_{1d} \\ +(p_R - C_{1r})q_{1r} + (p_{1d}q_{1d} - \tfrac{1}{2}ap_{1d}^2) - q_{2d}E_d - q_{2r}E_r) \end{aligned} \quad (19)$$

Equation (19) can be expressed as $SW = H(t) + G(s)$. Here E_c is the environmental cost of informal dismantling and E_r is the safety and environment cost of informal refurbishing. w_1 and w_2 are weights of forward and reverse supply chain in calculating the social welfare of implementing the WEEE disposal fund. After substituting the equilibrium outcomes of dismantling and refurbishing subgame models into Equation (19), social welfare is a quadratic function with respect to recycling fee s and subsidy t.

To maintain a balance between recycling fees and subsidies, we add an equation:

$$tq_N = sq_{1d} \quad (20)$$

Define $tq_N = sq_{1d}$ as $f(t) = g(s)$. The right-hand side of Equation (20) is the total recycling fees and the left-hand side is the total subsidies provided to the formal sector's dismantling process. The left-hand side is an increasing function with respect to subsidy.

Remark 2. *$g(s)$ is a strictly increasing and convex function with respect to s. For every t, there exists only one s^* such that $f(t) = g(s)$. Then $s^* = g^{-1}(f(t))$.*

The Equation (19) can be rewritten as $SW = H(t) + G(s^*) = \mathrm{H}(t) + G\big(g^{-1}(f(t))\big)$. Here $\mathrm{H}(t) = w_1((p_N - c_N - t)q_N + \frac{3-3\alpha}{6-2\alpha}q_N^2) + w_2((p_R - c_{1r})q_{1r} - q_{2r}E_r)$, and $G(s) = w_2((v - c_{1d} - p_{1d} + s)q_{1d} + (p_{1d}q_{1d} - \frac{1}{2}ap_{1d}^2) - q_{2d}E_d)$.

Proposition 3. *SW is a concave function with respect to the recycling fee t. There exists a $\hat{t} \in [0, +\infty)$, such that when $t > \hat{t}$, SW decreases with t. And $\hat{t}$ is the optimal recycling fee and $s^* = g^{-1}(f(\hat{t}))$ is the corresponding subsidy. (Please see the Appendix A for proof.)*

According to Proposition 3, social welfare does not necessarily increase as the recycling fee t rises. If t is high enough, social welfare will decrease with t. Therefore, an excessive recycling fee is not a wise choice for the disposal fund. To visualize the results, we use numerical simulation to examine the effect of changing recycling fee on social welfare. Numerical simulations are carried out under the following parameter combination of $Q = 0.1$, $a = 1.2$, $b = 0.6$, $c_{1d} = 0.4$, $c_{2d} = 0.2$, $v = 0.5$, $c_N = 1$, $c_{1r} = 0.8$, $c_{2r} = 0.7$, $E_d = 0.3$, $E_r = 0.1$, $w_1 = 0.2$, $w_2 = 0.8$.

Figure 3 provides the level of social welfare and total recycling fees under different t and α. Figure 3a shows that social welfare first rises and then falls as recycling fee t increases. There exists an optimal recycling fee to maximize the level of social welfare. Consumer preference towards refurbished products α exerts a sensitive influence on social welfare. As α increases, the level of social welfare decreases, due to more intensified competition between new and refurbished products. Figure 3b shows that total recycling fees also first increase and then decrease with respect to recycling fee t. An excessive recycling fee will hurt producers by reducing both their profit margin and sales quantity. As a result, total recycling fees decrease, although the unit recycling fee is raised.

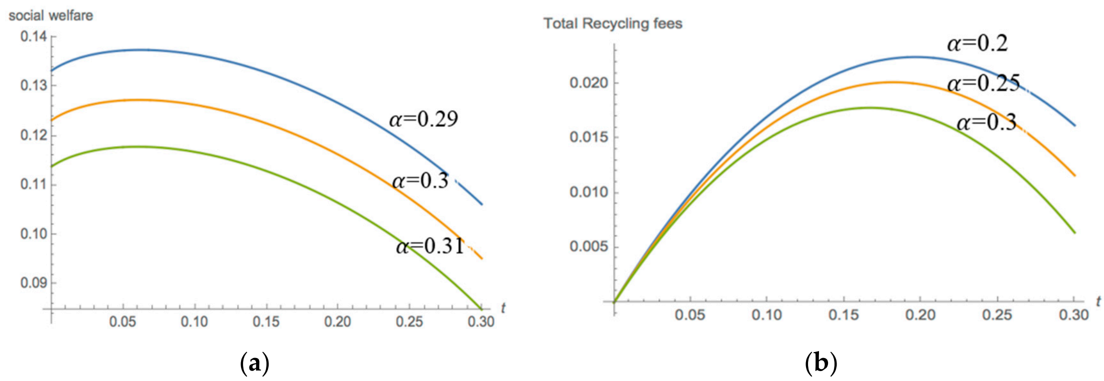

Figure 3. The social welfare and total recycling fees with different values of t and α; (**a**) t = 0.1, 0.2 and 0.3, $s \in [0, 1]$; (**b**) s = 0.2, 0.5 and 1, $t \in [0, 1]$.

If the recycling fee that producers are charged is small, an increase in its value will lead to a higher subsidy level, which effectively supports the development of the formal sector and also improves social welfare. However, the relationship between recycling fees and subsidies is not monotonically increasing, and so is the relationship between recycling fees and social welfare. If the recycling fee is quite large, an increase in its value will cause a decline in new product sales, which lowers the total recycling fees. As a result, subsidy will be smaller for the formal sector. Producers' profit is weakened due to a decrease in both the profit margin and sales quantity. In addition, the informal sector will benefit from the high recycling fee, which leads to an increase in informal refurbishing. Therefore, the combined effect on social welfare will be a decrease. A higher recycling fee will not certainly lead to better social welfare.

7. Summary of Findings

Our results show that, due to the higher cost in disassembling, the formal sector is always at a disadvantage in the competition with the informal sector if there is no subsidy support from the disposal fund. As the subsidy level goes up, the market share of the informal sector will increase; however, the growth rate is slowed down with the increase of subsidies, which shows a decreasing marginal effect of subsidies in supporting the formal sector. To eliminate the informal sector, the subsidy has to be very high; otherwise, it will be very difficult for the formal sector to suppress the informal sector.

After being levied a recycling fee for each new product, producers will raise the sales price and transfer a part of the fee to consumers. The marginal profit of selling new products will decline and the sales volume will fall too, which leads to a decrease in the producers' profit. Influenced by producers' price-raising behavior, the price of refurbished products will also go up, which will weaken price competition between new and refurbished products. Both the formal and informal recyclers will increase the quantities of refurbished products, resulting in higher profits for both sectors. It can be seen that charging producers a recycling fee will also benefit the informal sector, which exerts a negative influence on the level of social welfare.

With an increase in recycling fees, the social welfare level will rise first and then fall, which shows that a higher recycling fee does not necessarily bring about an increase in social welfare. There exists an optimal recycling fee and corresponding subsidy to maximize social welfare and maintain the disposal fund at break even. If the fee that producers are charged is small, the subsidy amount and social welfare will increase with the recycling fee, which promotes the development of the formal sector and improves the level of social welfare. Excessive fees, however, will play the opposite role. If the recycling fee is quite large, an increase in its value will decrease the sales quantity of new products, total recycling fee, the corresponding subsidy level, and social welfare. Therefore, an excessive recycling fee may weaken social welfare and should be avoided.

8. Conclusions

Currently in China, there exist both formal and informal sectors in recycling WEEE, with the informal sector being the dominant one. To regulate the recycling market, China has set up a recycling disposal fund to levy fees on producers and provide subsidies to the formal sector. The current literature rarely studies the fee design of the disposal fund from a quantitative perspective and does not collectively investigate both the informal sector and producers. In China, the coexistence and competition between the formal and informal recycling sectors is a common phenomenon that needs to be taken into consideration when studying the disposal fund policy. Based on the recycling practice, this paper uses game theory to examine the competition between the formal and informal sectors, establishes the models of disassembling and refurbishing processing, and then discusses the impacts of the disposal fund policy on producers and the two sectors. To maximize social welfare and to balance the receipts and payment of the disposal fund, our paper studies the optimal recycling fee and the corresponding subsidy level, which is expected to provide guidance for the government.

Our research conclusions can provide significant practical implications. The disposal fund can help improve the competitiveness of the formal sector, but there are caveats. As the subsidy level goes up, the marginal effect of government subsidy is declining. Therefore, an excessive subsidy level may not be a wise decision for the government. To mitigate the overdependence on government support, a market-oriented operation is suggested for the formal sector to make profit-boosting moves and obtain a sustainable development. As to the recycling fees, our study finds that a higher recycling fee does not necessarily enhance the total recycling fees, due to a decrease in producers' new product sales. An excessive charge on recycling fees will put great pressure on the producers' business, and should be avoided because China is currently in a macroeconomic downturn and the e-products industry is facing severe competition with low profit margins. Therefore, we suggest that the government should consider both the maximization of social welfare and the balance of the disposal fund in setting the appropriate recycling-fee and subsidy levels. Only proper levels of recycling fees and subsidies can improve social welfare in an efficient way. In addition, policymakers should continuously work on raising social awareness of the importance of e-waste recycling. The public should be educated on the proper disposal of old products to the formal recycling sector. In addition, stringent penalties should be assessed when dealing with the informal recycling sector to discourage further environmental degradation.

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Appendix A

Proof of Proposition 3. Since $g(s)$ is a strictly increasing and convex function with respect to s, $g^{-1}(\cdot)$ is an increasing and concave function. According to Remark (1), $f(t)$ is a concave function. Therefore,

$g^{-1}(f(t))$ is a concave function with respect to t. Since $\frac{\partial^2(H(t))}{\partial t^2} = -\frac{9-5\alpha}{36(1-\alpha)} < 0$ and $\frac{\partial^2(G(s))}{\partial s^2} = -\frac{4a^5}{(4a^2-b^2)^2} < 0$, so both $H(\cdot)$ and $G(\cdot)$ are concave functions. Plus, $G(s)$ is an increasing function of s. So $G(g^{-1}(f(t)))$ is also a concave function with respect to t. Then $SW = H(t) + G(g^{-1}(f(t)))$ is a concave function of t. □

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