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Research Article

Optimal Decisions and Implementation Efficiency of the Extended Producer Responsibility System for E-Waste under Take-Back Legislations

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The collection and reuse of the e-wastes have attracted increasing attention all over the world. In order to incentivize the producer to collect and recover the e-waste, more and more countries have formulated the take-back legislation with the economic or administrative instruments based on the spirit of extended producer responsibility (EPR). Facing two different types of policy instruments (economic or administrative instrument), how the take-back legislation affects the collection and reuse of the e-waste and how to ensure the efficiencies of the two types of take-back legislation have attracted the public's attention. Therefore, this paper establishes a stylized model consisting of a monopoly manufacturer who is responsible for collection and remanufacturing under two different types of the take-back legislation. The manufacturer's optimal production, collection, remanufacturing decisions, and optimal profit are derived using Karush–Kuhn–Tucker (KKT) conditions. Sensitivity analysis shows that stricter mandated collection rate hurts the manufacturer's profit, but the effects of the government's subsidy and tax on the manufacturer's optimal decisions rely on the cost of the new product. The firm needs to adjust the cost of the new products corresponding to the specific subsidy and tax. Finally, a neutral fiscal policy is proposed to determine the government's optimal subsidy and tax in order to ensure the consistency of the efficiencies of the two types of take-back legislation. The government should set that the ratio of the optimal tax and subsidy under the neutral fiscal policy is exactly consistent with the mandatory collection target. This policy aims to guide the manufacturer's voluntary collection rate to meet the government's mandated collection target and thus change the mandatory collection mode to the voluntary collection mode.

1. Introduction

The intense growth of the economy and technology and the increase in the consumer's demand have greatly accelerated the speed of product upgrading [1]. In 2019, 53.6 million metric tons of e-waste are produced all over the world, and this figure will reach 120 million metric tons in 2050 (https://www.itu.int/en/ITU-D/Environment/Pages/Spotlight/Global-Ewaste-Monitor-2020.aspx). The rapid increase of the e-waste not only pollutes the environment heavily, but also leads to a serious waste of resources, thereby attracting lots of attention from the firms and the government.

To scientifically deal with the e-wastes and fulfill the goals of protecting the environment and utilizing the resources, the extended producer responsibility (EPR) comes into being. EPR shows that producers should be responsible for the product's environmental impact of the whole lifecycle, especially during the collection, recycling, and final disposal stage [2]. As EPR takes root in the practice, product recovery of the collected used products is very essential [3]. Remanufacturing is the most popular product recovery option [4, 5]. It restores the quality and function of the used product to the standards of the new product [6, 7]. However, the producer's voluntary collection behavior entirely driven by the remanufacturing profit cannot meet the environmental requirement of the society and the government. Therefore, increasing countries and regions have enacted different take-back legislations based on EPR to incentivize the producer to engage in the collection and reuse of the used products.

The current take-back legislations include the administrative and economic instruments [8, 9]. The administrative instrument usually sets the mandated collection target and requires that the producer must meet the reuse target set by the government [10]. In fact, the European Waste Electrical and Electronic Equipment (WEEE) Directive with the administrative instrument points out that the collection rate of the used product should increase from 45% to 65% in 2019 [11]. Under the take-back legislation with the administrative instrument, the producer is forced to accomplish the mandated collection target, which is referred to as the mandatory collection mode. However, in an alternative manner, an economic instrument usually induces the producer to achieve environmental goals through the subsidy and tax [12]. For example, the Chinese WEEE fund policy that focuses on the economic instrument imposes 10 CNY on each new computer produced by the manufacturer and provides a subsidy 80 CNY for each collected computer [13]. In fact, the Chinese WEEE fund policy affects the producer's cost and benefit by imposing a tax on the new product and subsidizing the collection of the used product, thereby incentivizing the producer to voluntarily participate in the collection of the used product [14]. Under the take-back legislation with the economic instrument, the producer needs to achieve the certain collection target voluntarily, which is also referred to as the voluntary collection mode. Facing two different instruments, the first objective is to exploit the producer's optimal response mechanism under different instruments and the effects of different instruments on the producer's optimal response mechanism.

Regardless of the economic instrument or the administrative instrument, the aim of the take-back legislation is to promote the producer to transfer the quantity of the landfill and improve the collection quantity of the used product, thereby improving the environmental performance. But the difference between the two instruments is that the administrative instrument directly affects the producer's collection behavior, whereas the economic instrument indirectly influences the producer's collection behavior. Extant scholars mostly stress the influences of the two instruments on the producer's collection behavior [15, 16] but ignore the consistency of the legislation efficiencies with different instruments, that is how the government establishes the economic instrument to meet the collection target regulated by the administrative instrument. In the same economic market, if the legislation efficiencies of the two instruments are not consistent, the collection market will fall into chaos and the government's resources will be wasted. Therefore, our second research goal is to design a neutral fiscal policy to solve the consistency of the legislation efficiencies of the two instruments and realize the transformation from the producer's mandatory collection to the producer's voluntary collection.

Focusing on the above research goals, this paper raises the following four research questions: (1) Under the take-back legislation with the administrative instrument (abbreviated as RP), what are the monopoly manufacturer's optimal decisions and profit? (2) Under the take-back legislation with the economic instrument (abbreviated as FP), what are the monopoly manufacturer's optimal decisions and profit? (3) How do the administrative and economic instruments affect the manufacturer's optimal decisions and profit? (4) How does the government set the appropriate subsidy and tax to improve the manufacturer's voluntary collection rate to meet the government's mandated collection target?

In order to solve the above research questions, a stylized model with a monopoly manufacturer is established. First, under two take-back legislations, the manufacturer's optimal production, collection, remanufacturing decisions, and profit are derived via the Karush–Kuhn–Tucker (KKT) conditions. Then, the impacts of these two take-back legislations on the manufacturer's optimal decisions and profit are investigated using sensitivity analysis. Finally, a neutral fiscal policy is proposed to determine the optimal subsidy and tax to improve the manufacturer's voluntary collection rate to meet the mandated collection target, which does good to transforming the mandatory collection to the voluntary collection. The research results regarding these two take-back legislations expect to provide managerial insights for optimizing and improving the EPR policy.

The main contributions of this paper are as follows: First, the optimal manufacturer's decisions are determined under two take-back legislations, and the effects of the two take-back legislations on the manufacturer's decisions are affected by the cost advantage of the new or remanufactured product. When the remanufacturing cost advantage dominates, the take-back legislations with the administrative and economic instruments affect not only the manufacturer's collection behavior but also the remanufacturing and production. When the remanufacturing cost advantage is not obvious, the take-back legislation with the administrative instrument only affects the manufacturer's collection and has nothing to do with the remanufacturing and production. But, the take-back legislation with the economic instrument affects collection by the subsidy and the production and remanufacturing by the tax. Then, from the perspective of the consistency of the legislation efficiency, a neutral fiscal policy is put forward and the optimal tax and subsidy are decided to make the manufacturer transform from the mandatory collection to the voluntary collection, which can ensure the consistency of the legislation efficiencies of the two types of take-back legislations. Meanwhile, we find that a higher mandated collection target is not only motivated by higher collection subsidy but also adjusted by higher tax.

The rest of the study is organized as follows: The related literature is reviewed in Section 2. Section 3 depicts the model framework and establishes a stylized model with a monopoly manufacturer. In Section 4, the manufacturer's optimal production, collection and remanufacturing decisions, and profit are identified under two types of take-back legislation, and the impacts of these two types of take-back legislation on the manufacturer's optimal decisions and profit are investigated, respectively. Section 5 designs a neutral fiscal policy to guarantee the consistency of the efficiencies of the two types of take-back legislation and avoid confusion in the market due to the inconsistent efficiency of the legislation. Section 6 shows the numerical analysis of the main parameters of the take-back legislation. In the end, the main findings of this paper are summarized and some policy optimization suggestions are provided in Section 7.

2. Literature Review

The literature regarding this paper is divided into two streams: one stream is the operation management of the EPR system, and the other is related to the impacts of the take-back legislations with the administrative and economic instruments on the operations management of the EPR system.

2.1. Operation Management of the EPR System. The EPR system is an operations framework of the extended producer responsibility with a closed-loop cyclic process consisting of extracting raw materials, producing, selling, collecting, and recovering [17]. The EPR system gains profits from not only selling products but also recovering collected cores, thereby benefiting both the economic and environmental performances [18, 19]. It is a hot spot for scholars to study the production and operation activities of enterprises from the perspective of operation and management [20–22]. Therefore, the operations management of the EPR system has attracted more scholars' attention.

The operations management of the EPR system related to this study mainly covers the recovery of used products and collection decisions. The manners of product recovery mainly include remanufacturing, disassembling, recycling, refurbishing, repair, etc. Remanufacturing is recognized as the most effective product recovery option and studied by many scholars. Some scholars focus on introducing remanufacturing market [23], optimizing remanufacturing cost [7], the consumer's perceived value of the remanufactured product [24], the production and pricing of the remanufactured product [25, 26], and economic profit [27–29]. Wang et al. [3] found that the manufacturer disposes the used products by recycling, remanufacturing, and innocent treatment and determines the optimal portfolio of product recovery options and environmental impacts of different portfolios. Based on the above literature, both remanufacturing and innocent treatment are considered in this study. The producer's product recovery behavior depends on the collection decision of the used products, especially the choice of the collection channel of the used products. Savaskan et al. [30] studied the choice of reverse collection channel of the used product and found that the retailer is the most suitable for collection because she is closer to the consumer. Modak et al. [31] compared the impacts of the manufacturer-led collection, retailer-led collection, and third party-led collection on the optimal pricing, product quality, and collection effort decision and found that the third party-led collection is always disadvantageous, but the choice between the manufacturer-led and the retailer-led collection depends on the threshold of the collection effort. Wu et al. [32] compared the optimal environmental responsibility investment, pricing, and collection decision under the above three kinds of collection channels and also revealed that the third party-led collection is always disadvantageous, but the choice between the manufacturer-led and the retailer-led collection depends on the transferring price. Similar to the existing literature emphasizing the manufacturer-led collection [33, 34], this study focuses on the manufacturer-led collection. The above studies only focus on the operations management of the EPR system driven by the economic profit but ignore the impact of the take-back legislation on the operations management of the EPR system.

2.2. The Impacts of the Take-Back Legislations on the EPR System. To better advance the extended producer responsibility, many countries have established related legislations. The existing take-back legislations mainly include administrative and economic instruments.

2.2.1. The Impacts of Administrative Instrument on the EPR System. Many scholars investigate the impact of the administrative instrument of the take-back legislation with the required rate (such as the European WEEE Directive) on the operation management of the EPR system. Zheng and Hong [35] explored the effects of the mandated collection rate on the collection decisions of the closed-loop supply chain with different channel structures but ignored the influence of the compulsory rate on product recovery. Esenduran et al. [36] decided on the monopoly manufacturer's production and remanufacturing strategies in the context of the mandated collection rate and showed that a higher collection rate cannot necessarily achieve the desired goal. Based on the above study, Esenduran et al. [11] further explored the effects of the mandated collection and reuse targets on the production and remanufacturing decisions of the closed-loop supply chain in a competitive environment. They demonstrate a stricter mandated target is not necessarily beneficial to remanufacturing. Xu et al. [37] took the manufacturer's collection rate as an endogenous variable; exploited the impact of the required collection target on the manufacturer's production, collection rate, and remanufacturing decisions; and manifested that the required collection rate does not necessarily hurt the manufacturer's economic profit. Chen et al. [38] examined the operation and economic performance of the closed-loop supply chain considering the mandated collection and reuse rates and declared that the higher the collection and reuse rates, the more efficient the collection and reuse. Mazahir et al. [39] improved the existing take-back legislation and pointed out that the reuse target of the used product can be realized by recycling and/or remanufacturing. They also compared the manufacturer's production and remanufacturing strategies considering the existing and modified take-back legislation.

2.2.2. The Impacts of Economic Instrument on the EPR System. Lots of scholars studied the economic instrument of the take-back legislation with the subsidy and tax (such as the Chinese WEEE fund policy) on the operation management of the EPR system. Chang et al. [40] discussed the production, collection, and recycling decisions of the closed-loop supply chain in the context of the joint tax-subsidy policy and found that this policy can motivate the manufacturer to collect and recycle. Zhang et al. [41] investigated the impact of the Chinese WEEE fund policy on the remanufacturing mode of the closed-loop supply chain and revealed that without fund policy, the manufacturer should remanufacture by himself, and with fund policy, the manufacturer should authorize the retailer to remanufacture. The above studies only consider the single product recovery method, that is recycling or remanufacturing. But Liu et al. [42] assumed that the monopoly manufacturer can remanufacture and recycle simultaneously and investigated the monopoly manufacturer's production, remanufacturing, and recycling decisions considering the fund policy. Li et al. [43] took the competition among the manufacturer, remanufacturer, and recycler into account and determined the closed-loop supply chain's optimal strategies under three conditions, namely no subsidy, the government providing subsidy, and the government providing subsidy and imposing tax simultaneously. They also analyze the impacts of the government's subsidy and tax on the decisions of the closed-loop supply chain.

Different from the above studies, this study assumes the monopoly manufacturer can innocently dispose of the remaining used products in the process of remanufacturing and explores the effects of the take-back legislation with the economic instrument on the monopoly manufacturer's production, collection, remanufacturing, and innocent disposal decisions.

2.2.3. Comparison between the Two Types of Take-Back Legislation. The above studies respectively studied the impact of the certain type of take-back legislation on the operation management of the EPR system and ignored the comparison of the efficiencies of the two types of take-back legislation. Therefore, Atasu et al. [15] compared the economic instrument and the administrative instrument of the take-back legislation, analyzed the preferences of different stakeholders for the two types of legislations, and identified that the preference depends on the collection cost and environmental externality. Aflaki and Mazahir [16] compared three types of the take-back legislation, that is the mandated target, tax/subsidy policy, and the above two policies, and studied the impacts of different policies on the manufacturer's remanufacturing decision. Some other scholars simultaneously investigate the impacts of the administrative and economic instrument of the take-back legislation on the operation management of the closed-loop supply chain. Liu et al. [14] examined the closed-loop supply chain's optimal operation management when both the mandated collection rate and the fund policy exist. But the above studies ignore the consistency of the efficiencies of different take-back legislations.

2.3. Research Gap. As the take-back legislation improves, distinguished instruments of the take-back legislation exist in the same economic market and they achieve the same environmental goals. However, the current literature lacks a discussion on the consistency of the efficiencies of different take-back legislations. In the same market economy, the inconsistency of the efficiencies of different take-back legislations can make the legislations not work. For example, the inappropriate tax and subsidy make the mandated target ineffective. The possibility of ineffective policy motivates this study. Table 1 shows the research gap between the existing literature and this study. This study contributes to the extant literature as follows: (1) Different from the previous studies on the operation management of the EPR system, this study considers that the collection cost of the monopoly manufacturer is diseconomies of scale. The monopoly manufacturer not only remanufactures the collected cores, but also innocently disposes of the remaining collected cores. (2) In contrast to the current literature on the take-back legislation, this study simultaneously introduces the economic and administrative instrument of the take-back legislation and explores the impact mechanisms of the take-back legislation. (3) Compared with those studies focusing on the comparison of the efficiencies of the two take-back legislations, this study emphasizes the consistency of the efficiencies of the two types of take-back legislation and examines how the government establishes the take-back legislation with the economic instrument in order to realize the mandated collection target under the take-back legislation with the administrative instrument and avoid the inconsistency of the legislation efficiency.

3. Model Framework

In this section, we first display the impact of the take-back legislation on the manufacturer's operation management, then introduce market segmentation and main cost parameters, and, finally, the stylized model framework of a monopoly manufacturer is formulated. The main parameters and decision variables used in the whole study are summarized in Table 2.

As shown in Figure 1, the impacts of the two types of take-back legislation on the manufacturer's operation management are displayed. Figure 1(a) represents the take-back legislation with the administrative instrument (RP), namely the government sets a mandated collection rate τ on the manufacturer. In other words, if the manufacturer sells q_n units of new products, the government the requires manufacturer's collection quantity must reach τq_n. Figure 1(b) represents the take-back legislation with economic instrument (FP), namely the government sets a subsidy s on collection activity and a tax t on the production activity of the manufacturer. In other words, if the manufacturer sells q_n units of new products and collects q_c units of

Table 1: Summary of the literature review.

Authors	Operation management of the EPR system				The impacts of the take-back legislations		
	Remanufacturing	Collection quantity	Economic profit	Environmental impact	Economic instrument	Administrative instrument	Comparison of two legislations
Abbey et al. (2019)	✓		✓				
Reimann et al. (2019)	✓		✓	✓			
Zhou et al. (2019)	✓		✓	✓			
Chen and Chen (2019)	✓		✓	✓			
Xu and Wang (2018)	✓		✓				
Wang et al. (2021)	✓	✓	✓	✓			
Savaskan et al.(2004)	✓		✓				
Modak et al.(2018)	✓	✓	✓				
Wu et al.(2020)	✓	✓	✓				
Zheng and Hong (2021)	✓		✓			✓	
Esenduran et al. (2016)	✓	✓	✓	✓		✓	
Esenduran et al. (2017)	✓	✓	✓	✓		✓	
Xu et al. (2021)	✓		✓	✓		✓	
Chen et al. (2021)	✓	✓	✓	✓		✓	
Mazahir et al. (2019)	✓		✓	✓		✓	
Chang et al. (2019)	✓		✓	✓	✓		
Zhang et al.(2021)	✓		✓	✓	✓		
Liu et al. .(2017)	✓	✓	✓	✓	✓		
Li et al. (2018)	✓		✓	✓	✓		
Atasu et al. (2013)			✓	✓	✓	✓	✓
Aflaki and Mazahir (2015)	✓		✓	✓	✓	✓	✓
Liu et al. (2021)	✓	✓	✓	✓	✓	✓	
This study	✓	✓	✓	✓	✓	✓	✓

cores, the government provides the corresponding subsidy sq_c and levies the corresponding tax tq_n.

Under the effect of take-back legislation, the manufacturer produces and sells a new product, and at the same time is responsible for collecting, remanufacturing, and innocently disposing of the after-sale products.

After remanufacturing, the used products can be sold on the market as remanufactured products. This study assumes that the products are at the maturity stage of the lifecycle [44]. All the prices, collection rate, and remanufacturing rate are stable, and thus this study focuses on the single period static problem [45, 46]. The manufacturer determines the quantities of the new product (q_n), the collected product (q_c), and the remanufactured product (q_r).

Then, market segmentation is introduced. The manufacturer can choose to remanufacture by himself or outsource to a third party and then sell remanufactured products with its own brand. Therefore, both new and remanufactured products are available in the market. Consumers decide to buy the new product or the remanufactured product depending on the utility maximization. In a single period, the market size is stable and the potential consumer quantity can be normalized to 1 [47]. Similar to the related remanufacturing literature [48, 49], the consumer's perceived value of the new product ν is uniformly distributed in the interval (0, 1), and the consumer's value discount for the remanufactured product is α. The price and quantity of the new and remanufactured products are

Table 2: Parameters and decision variables used in this study.

Decision variables	Descriptions
p_n	The price of the new product ($/unit)
q_n	The quantity of the new product (unit)
p_r	The price of the remanufactured product ($/unit)
q_r	The quantity of the remanufactured product (unit)
q_c	The collection quantity (unit)
Parameters	
c_n	The unit production cost of the new product ($/unit)
c_r	The unit remanufacturing cost of the remanufactured product ($/unit)
c_d	The unit innocent treatment cost of the used product ($/unit)
$C_c = \kappa q_c^2$	The collection cost of the used product ($)
τ	The mandated collection target
s	The unit subsidy on the collected product ($)
t	The unit environmental tax on the new product ($)
α	The consumer value discount for the remanufactured product
Π^i	The manufacturer's profit, $i \in \{RP, FP\}$ ($)

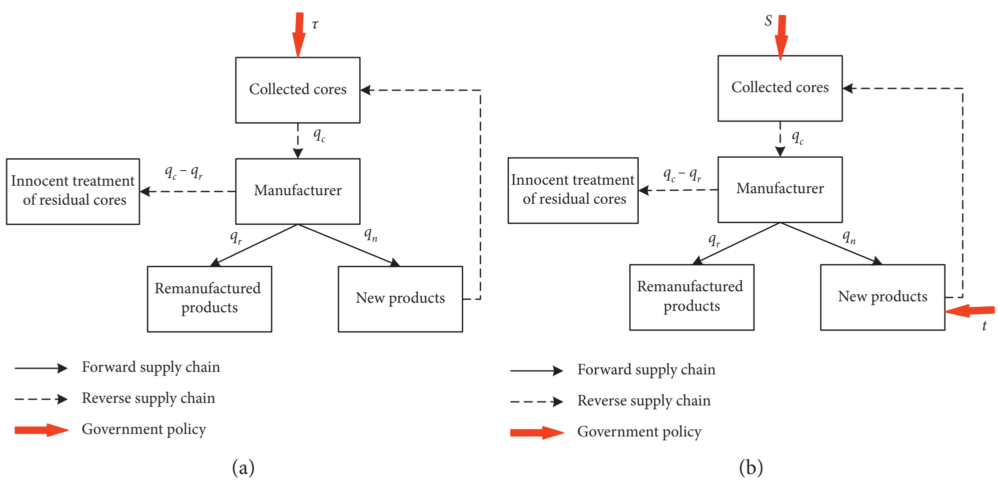

Figure 1: EPR system under the take-back legislation. (a) RP and (b) FP.

denoted by p_n, q_n, p_r, and q_r, respectively. The consumer's utility from buying a new product is $U_n = \nu - p_n$, and the consumer's utility from buying a remanufactured product is $U_r = \alpha\nu - p_r$. When $U_n > U_r$ and $U_n > 0$, the consumer chooses to buy the new product. When $U_r > U_n$ and $U_r > 0$, the consumer chooses to buy the remanufactured product. To ensure that there are remanufactured products sold in the market, the low pricing strategy of the remanufactured product is adopted, that is $p_r < \alpha p_n$ [50, 51]. In terms of the utility function, the inverse demand functions of the new and remanufactured products are given by $p_n = 1 - q_n - \alpha q_r$ and $p_r = \alpha(1 - q_n - q_r)$, respectively.

Furthermore, the main cost parameters are displayed. The production cost of the new product and the remanufacturing cost are linear and denoted by c_n and c_r, respectively. The collected cores can only be remanufactured once. Similar to the literature [52, 53], the collection cost of the used product C_c is a convex increasing function of the collection quantity q_c and is denoted by $C_c = \kappa q_c^2$. The manufacturer needs to innocently dispose of the collected cores that are not remanufactured. The innocent treatment cost of the collected cores is c_d.

At last, the impacts of the two take-back legislations on the manufacturer's operations management are considered.

When the government implements administrative instrument, the manufacturer must follow the mandated collection target τ set by the government. Under the case of the mandated mode, the manufacturer's profit can be represented as follows:

$$\max_{\{q_n, q_r, q_c\}} \Pi^{RP} = (p_n - c_n)q_n + (p_r - c_r)q_r - (q_c - q_r)c_d - \kappa q_c^2, \tag{1}$$

$$\text{s.t.} \quad 0 < q_r \le q_c, \tag{2}$$

$$0 < \tau q_n \le q_c < q_n. \tag{3}$$

In equation (1), the first term is the profit of selling new products, the second term is the profit of selling remanufactured products, the third term is the disposal cost of unremanufactured cores, and the fourth term is the collection cost. Equation (2) ensures the quantity of the remanufactured product is not more than the quantity of the collection. Equation (3) shows that the collection quantity is not less than the minimum collection quantity set by the government, but less than the quantity of new product.

When the government adopts an economic instrument, the government imposes an environmental tax t on each new product produced by the manufacturer and provides a subsidy s per core. In the voluntary mode, the manufacturer's profit can be calculated as shown in the following equations, and among them, q_n, q_r, and q_c are the decision variables.

$$\max_{\{q_n, q_r, q_c\}} \Pi^{FP} = (p_n - c_n - t)q_n + (p_r - c_r)q_r - (q_c - q_r)c_d - \kappa q_c^2 + sq_c, \tag{4}$$

$$\text{s.t.} \quad 0 < q_r \leq q_c < q_n. \tag{5}$$

In equation (4), the first term is the profit of selling new products deducting the tax, the second term is the profit of selling remanufactured products, the third term is the disposal cost of unremanufactured cores, the fourth term is the collection cost, and the last term is the government subsidy expenditure. Equation (5) indicates that the collection quantity is not less than the quantity of the remanufactured product but less than the quantity of the new product.

4. Model Analysis

This section uses KKT conditions to solve the optimization problem of the monopoly manufacturer's decisions considering different types of the take-back legislation. First, the optimal decisions of the monopoly manufacturer under the two instruments of the take-back legislation are derived. Then, we investigate the impacts of the two instruments of the take-back legislation on the manufacturer's optimal decisions.

4.1. The Manufacturer's Optimal Decisions under the Take-Back Legislation with the Administrative Instrument. Under the take-back legislation with the administrative instrument, this section explores the effect of the mandated collection rate on the manufacturer's production decisions and whether the administrative instrument is effective or not. Thus, we have the following proposition.

Proposition 1. *When the take-back legislation with the administrative instrument is effective, the manufacturer's optimal equilibrium decisions are as follows.*

4.1.1. Scenario RP-A. When $c_{n1} < c_n \leq c_{n2}$, $q_r^{RP-A*} = (\alpha\kappa\phi^2 + (1 + \phi(\alpha + \kappa\phi))c_d + \alpha c_n - (1 + \kappa\phi^2)c_r / 2\alpha(1 - \alpha + \kappa\phi^2))$, $q_c^{RP-A*} = \tau q_n^{RP-A*}$ and $q_n^{RP-A*} = (1 - \alpha - c_d - \phi c_d - c_n + c_r / 2(1 - \alpha + \kappa\phi^2))$.

4.1.2. Scenario RP-B. When $c_{n2} < c_n < c_{n3}$, $q_n^{RP-B*} = (1 + \alpha\tau - c_n - \tau c_r / 2(1 + 2\alpha\tau + \alpha\tau^2 + \kappa\tau^2))$ and $q_c^{RP-B*} = q_r^{RP-B*} = \tau q_n^{RP-B*}$. Here,

$$\begin{aligned} c_{n1} &= \frac{\left(1 + \kappa\tau^2\right)c_r - \alpha\kappa\tau^2 - (1 + \tau(\alpha + \kappa\tau))c_d}{\alpha}, \\ c_{n2} &= \frac{\alpha\tau(1 - \alpha - \kappa\tau) - \left(1 + \kappa\tau^2 + \alpha\tau(2 + \tau)\right)c_d + (1 + \tau(\alpha + \kappa\tau))c_r}{\alpha(1 + \tau)}, \\ c_{n3} &= \frac{\alpha\tau - \alpha^2\tau + \kappa\tau + c_r + \alpha\tau c_r}{\alpha + \alpha\tau + \kappa\tau}. \end{aligned} \tag{6}$$

See the proof in Appendix.

Proposition 1 shows that when the take-back legislation with the administrative instrument is effective, the manufacturer only collects at the mandated collection rate given by the government. When the cost of the new product is relatively low, namely scenario RP-A, the manufacturer collects τ times of the new product, some of which are remanufactured and the remaining are innocently disposed of. When the cost of the new product is relatively high, namely scenario RP-B, the manufacturer still collects τ times of the new product, but all the collected cores are remanufactured. Higher cost of the new product demonstrates the advantage of the remanufacturing is more obvious. Therefore, the manufacturer prefers to remanufacturing all collected cores when the cost of the new product is high.

Figure 2(a) explains Proposition 1 more visually. Figure 2(a) illustrates when the government implements the take-back legislation with the administrative instrument and the mandated collection rate is effective, the manufacturer has two different feasible decision areas (corresponding to

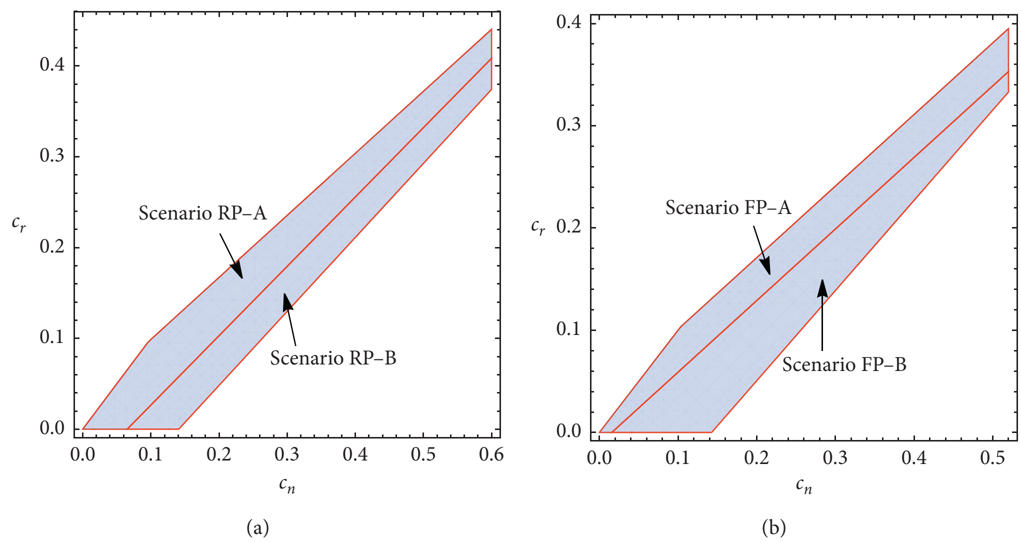

Figure 2: The optimal strategy under two distinct instruments of take-back legislation. (a) The administrative instrument and (b) the economic instrument.

scenario RP-A and RP-B, respectively) according to the corresponding production cost range (c_n and c_r). Here, according to the cost range $c_{n1} < c_n \le c_{n2}$ or $c_{n2} < c_n < c_{n3}$, we get the scenario RP-A or scenario RP-B.

Based on Proposition 1, we investigate the impacts of the mandated collection rate on the manufacturer's optimal decisions under the take-back legislation with the administrative instrument as indicated in the following proposition.

Proposition 2. *The impacts of the mandated collection rate on the manufacturer's optimal decisions are shown in Table 3, where the notations "+" and "−" represent monotonic increase and decrease, respectively.*

See the proof in Appendix.

Proposition 2 demonstrates that, regardless of the cost of the new product, the impacts of the mandated collection rate on the manufacturer's optimal decisions are the same. The higher the mandated collection rate, the lower the quantity of the new product and the manufacturer's profit. Simultaneously, the quantity of the collection and the remanufactured product will increase with the mandated collection rate τ.

4.2. The Manufacturer's Optimal Decisions under the Take-Back Legislation with the Economic Instrument. Under the take-back legislation with the economic instrument, the government imposes an environmental tax on the new product and provides a subsidy for the collection. The manufacturer's optimal decisions with the profit maximization are shown in the following proposition.

Proposition 3. *Under the take-back legislation with the economic instrument, the manufacturer's optimal decisions are given as follows.*

Table 3: The impacts of the mandated collection rate τ on the manufacturer's optimal decisions.

	Optimal decisions			
Scenario	q_n^{RP*}	q_c^{RP*}	q_r^{RP*}	Π^{RP*}
RP-A	−	+	+	−
RP-B	−	+	+	−

4.2.1. Scenario FP-A. When $(c_r - t\alpha - c_d/\alpha) < c_n \le c_{n4}$, $q_n^{FP-A*} = (1 - t - \alpha - c_n + c_r - c_d/2(1-\alpha))$, $q_r^{FP-A*} = (t\alpha + \alpha c_n - c_r + c_d/2(1-\alpha)\alpha)$, and $q_c^{FP-A*} = (s - c_d/2\kappa)$.

4.2.2. Scenario FP-B. When $c_{n4} < c_n < c_{n5}$, $q_n^{FP-B*} = \alpha(1 - s - t - \alpha) + (1-t)\kappa - (\alpha+\kappa)c_n + \alpha c_r/2(\alpha - \alpha^2 + \kappa)$ and $q_c^{FP-B*} = q_r^{FP-B*} = (s + t\alpha + \alpha c_n - c_r/2(\alpha - \alpha^2 + \kappa))$.

Here,

$$c_{n4} = \frac{\alpha(s - s\alpha - t\kappa) - ((1-\alpha)\alpha + \kappa)c_d + \kappa c_r}{\alpha\kappa},$$
$$c_{n5} = \frac{\alpha - s(1+\alpha) - \alpha(2t+\alpha) + \kappa - t\kappa + (1+\alpha)c_r}{2\alpha + \kappa}. \quad (7)$$

See the proof in Appendix.

As is shown in Proposition 3, when the cost of the new product is relatively low, namely scenario FP-A, the manufacturer collects part of the used product. Among the collected cores, some are remanufactured and the remaining are innocently disposed of. When the cost of the new product is relatively high, namely scenario FP-B, the manufacturer still collects part of the used product, but all of them are remanufactured. Higher cost of the new product means more benefits from the remanufacturing. Said differently, the manufacturer prefers to remanufacturing all collected cores when the cost of the new product is high. In addition, in order to ensure the scenario FP-A exists under

Table 4: The impacts of the subsidy s and the tax t on the manufacturer's optimal decisions.

Scenario		Optimal decisions			
		q_n^{FP*}	q_c^{FP*}	q_r^{FP*}	Π^{FP*}
FP-A	s	Ni	+	Ni	+
	t	−	Ni	+	−
FP-B	s	−	+	+	+
	t	−	+	+	−

the take-back legislation with the economic instrument, there is a lower threshold for the government subsidy, that is $\underline{s} = c_d$, and the government subsidy must meet the condition of $s > \underline{s}$. Only when the subsidy covers the innocent treatment cost of the used product can the manufacturer actively collect more used products in the voluntary mode. Similarly, to ensure the existence of the scenario FP-B under the take-back legislation with the economic instrument, there is a higher threshold of the government subsidy, that is $\overline{s} = \alpha\kappa + 2\alpha c_d + \kappa c_d - \kappa c_r/2\alpha$, and the subsidy should meet the condition: $s < \overline{s}$.

Figure 2(b) explains Proposition 3 more visually and illustrates when the government implements the take-back legislation with the economic instrument, the manufacturer has two different feasible decision areas (corresponding to scenario FP-A and FP-B, respectively) according to the corresponding production cost range (c_n and c_r). Here, according to the cost range $(c_r - t\alpha - c_d/\alpha) < c_n \leq c_{n4}$ or $c_{n4} < c_n < c_{n5}$, we get the scenario FP-A or scenario FP-B.

Next, the impacts of the subsidy s and the tax t on the manufacturer's optimal decisions under the take-back legislation with the economic instrument are indicated in the following proposition.

Proposition 4. *The impacts of the subsidy s and the tax t on the manufacturer's optimal decisions under the take-back legislation with the economic instrument are shown in Table 4. The symbols "+" and "−" represent monotonic increase and decrease, respectively.*

See the proof in Appendix.

Proposition 4 reveals that the impacts of the subsidy s and the tax t on the manufacturer's optimal decisions are different under different scenario environments. Under scenario FP-A, as the subsidy increases, both the quantity of collection and the manufacturer's profit increase, but the quantities of the new and the remanufactured products remain unchanged. Since the cost of the new product is low, the remanufacturing cost advantage is not obvious, and the collected cores are partly remanufactured. Therefore, the collection subsidy has no effect on the producing and remanufacturing decisions and only influences the collection quantity and profit. As the tax increases, both the quantity of the new product and the manufacturer's profit decrease but the quantity of the remanufactured product increases. The tax has nothing to do with the quantity of the collection. In this case, the tax increases the cost of the new product and lowers the market competitiveness of the new product, which results in the decline in the quantity of the new product and the increase in that of the remanufactured product. Consequently, the resulted manufacturer's profit decreases accordingly. Because the collected cores are partly remanufactured, the tax has no effect on the collection decision.

Under scenario FP-B, with the increases of the subsidy s and the tax t, the quantity of the new product decreases but both the quantities of collection and the remanufactured products increase. In addition, the increase in the subsidy leads to higher manufacturer's profit, but more tax decreases the manufacturer's profit. Since the cost of the new product is high enough, the remanufacturing cost advantage is more obvious, which leads all the collected cores to be remanufactured. In this setting, more subsidies can increase not only the quantity of the collection but also that of the remanufactured product, thereby improving the manufacturer's profit. Similarly, more tax increases the cost of the new product, so both the quantity of the new product and the manufacturer's profit tends to decrease.

5. The Consistency of the Take-Back Legislation Efficiency of the Two Instruments

Under the take-back legislation with the administrative instrument, the manufacturer is forced to collect used products by establishing the mandated collection target. But the take-back legislation with the economic instrument induces the manufacturer to voluntarily collect the used products by the tax and subsidy. Although these two types of take-back legislation are essentially distinguishable, their aims are to reduce the unscientifical disposal of the used products as much as possible and to achieve the same environmental performance. The previous studies [15, 39] mostly focus on the horizontal comparison of the two types of take-back legislation and analyze which type of the take-back legislation is more effective, but ignore the consistency of the efficiencies of the two types of take-back legislation. Therefore, this section investigates how the government sets the specific subsidy and tax to make the voluntary collection rate achieve the mandated collection target anticipated by the government. This can change the manufacturer's collection from the mandatory to the voluntary on the premise that the two types of take-back legislation have the same efficiency.

To answer the above research questions, a neutral fiscal policy based on the economic instrument is proposed. When the government sets the mandated collection target, the neutral fiscal policy is able to urge the manufacturer's collection from the mandatory to the voluntary under the following two conditions: (1) the voluntary collection rate should meet the government's mandated collection target under the neutral fiscal policy and (2) the government's tax should be equal to the subsidy under the neutral fiscal policy, and the government does not need extra capital investments to achieve complete self-sufficiency. The above two conditions embody the advantages of a neutral fiscal policy. This policy can not only achieve the government's environmental requirement, but also does not need the government to provide additional funds and can realize the capital turnover of the system itself.

Therefore, based on the decision analysis in Section 4, this section first explores how to change the mandatory to the voluntary between the scenario RP-A under the administrative instrument and the scenario FP-A under the economic instrument. With the neutral fiscal policy, the following two conditions should be satisfied when the manufacturer's collection transfers from the mandatory to the voluntary:

$$\begin{cases} \dfrac{q_c^{FP-A*}(s,t)}{q_n^{FP-A*}(s,t)} = \tau, \\ \\ s q_c^{FP-A*}(s,t) = t q_n^{FP-A*}(s,t). \end{cases} \quad (8)$$

Solving it yields $s^{FP-A*} = (\kappa\tau(1-\alpha-c_n+c_r) + (1-\alpha-\kappa\tau)c_d/1-\alpha+\kappa\tau^2)$ and $t^{FP-A*} = \tau(\kappa\tau(1-\alpha-c_n+c_r) + (1-\alpha-\kappa\tau)c_d/\ 1-\alpha+\kappa\tau^2)$.

Substituting s^{FP-A*} and t^{FP-A*} into $q_c^{FP-A*}(s,t)$, $q_r^{FP-A*}(s,t)$, and $q_n^{FP-A*}(s,t)$, we have $q_n^{FP-A*}(\tau) = (1-\alpha-c_d-\tau c_d-c_n+c_r/2(1-\alpha+\kappa\tau^2))$, $q_r^{FP-A*} = (\alpha\kappa\tau^2 + \alpha c_n - (1+\kappa\tau^2)c_r + (1+\tau\quad(\alpha+\kappa\tau))c_d/2\alpha(1-\alpha+\kappa\tau^2))$, and $q_c^{FP-A*}(\tau) = \tau(1-\alpha-c_d-\tau c_d-c_n+c_r/2(1-\alpha+\kappa\tau^2))$.

Compared with the optimal decisions under scenario RP-A, it follows that $q_n^{FP-A*}(\tau) = q_n^{RP-A*}(\tau)$, $q_c^{FP-A*}(\tau) = q_c^{RP-A*}(\tau)$, and $q_r^{FP-A*}(\tau) = q_r^{RP-A*}(\tau)$.

Substituting s^{FP-A*} and t^{FP-A*} into the interval range of the cost of the new product under scenario FP-A in the Proposition 3 reveals that $c_{n1} < c_n \le c_{n2}$. This resulted interval range is exactly consistent with the interval range of the cost of the new product under scenario RP-A in Proposition 1.

In summary, when the tax and subsidy under the neutral fiscal policy are t^{FP-A*} and s^{FP-A*}, respectively, the scenario FP-A achieves both the same mandated collection target and economic performance under the scenario RP-A. Therefore, when the government implements the neutral fiscal policy and respectively sets the tax and subsidy as t^{FP-A*} and s^{FP-A*}, the manufacturer's collection changing from the mandatory to the voluntary can be achieved between the scenarios RP-A and FP-A.

Now, we attempt to study how to transfer the manufacturer's collection from the mandatory to the voluntary between the scenario RP-B under the administrative instrument and the scenario FP-B under the economic instrument.

Adopting the neutral fiscal policy, the following two conditions should be met when the manufacturer's collection transfers from the mandatory to the voluntary:

$$\begin{cases} \dfrac{q_c^{FP-B*}(s,t)}{q_n^{FP-B*}(s,t)} = \tau, \\ \\ s q_c^{FP-B*}(s,t) = t q_n^{FP-B*}(s,t). \end{cases} \quad (9)$$

Solving this problem yields $s^{FP-B*} = ((\alpha-\alpha^2+\kappa)\tau - (\alpha+(\alpha+\kappa)\tau)c_n + (1+\alpha\tau)c_r/1+\kappa\tau^2+\alpha\tau(2+\tau))$ and

$$t^{FP-B*} = \tau\frac{(\alpha-\alpha^2+\kappa)\tau - (\alpha+(\alpha+\kappa)\tau)c_n + (1+\alpha\tau)c_r}{1+\kappa\tau^2+\alpha\tau(2+\tau)}. \quad (10)$$

Substituting s^{FP-B*} and t^{FP-B*} into $q_c^{FP-B*}(s,t)$, $q_r^{FP-B*}(s,t)$, and $q_n^{FP-B*}(s,t)$, we know $q_n^{FP-B*}(\tau) = (1+\alpha\tau-c_n-\tau c_r/2+4\alpha\tau+2(\alpha+\kappa)\tau^2)$ and $q_c^{FP-B*}(\tau) = q_r^{FP-B*}(\tau) = \tau(1+\alpha\tau-c_n-\tau c_r/\ 2+4\alpha\tau+2(\alpha+\kappa)\tau^2)$.

Compared with the optimal decisions under scenario RP-B, we obtain $q_n^{FP-B*}(\tau) = q_n^{RP-B*}(\tau)$, $q_c^{FP-B*}(\tau) = q_c^{RP-B*}(\tau)$, and $q_r^{FP-B*}(\tau) = q_r^{RP-B*}(\tau)$.

Substituting s^{FP-B*} and t^{FP-B*} into the interval range of the cost of the new product under scenario FP-B in Proposition 3 yields that $(\alpha\tau(1-\alpha-\kappa\tau) - (1+\kappa\tau^2+\alpha\tau\ (2+\tau))c_d + (1+\tau(\alpha+\kappa\tau))c_r/\alpha(1+\tau)) < c_n < 1+\tau\alpha-\tau c_r$.

This above-obtained interval range completely covers the interval range of the cost of the new product under scenario RP-B in Proposition 1. This implies that when the tax and subsidy under the neutral fiscal policy are t^{FP-B*} and s^{FP-B*}, respectively, the scenario FP-B can simultaneously reach the same mandated collection target and economic performance under the scenario RP-B. Therefore, when the government adopts the neutral fiscal policy and respectively sets the tax and subsidy as t^{FP-B*} and s^{FP-B*}, the manufacturer's collection changing from the mandatory to the voluntary can be achieved between the scenarios RP-B and FP-B as confirmed in the following proposition.

Proposition 5. *In order to meet the mandated collection target τ set by the government, the government's optimal subsidy and tax under the scenario FP-A are $s^{FP-A*} = (\kappa\tau(1-\alpha-c_n+c_r) + (1-\alpha-\kappa\tau)c_d/1-\alpha+\kappa\tau^2)$ and $t^{FP-A*} = \tau s^{FP-A*}$, respectively. Under the scenario FP-B, these values are $s^{FP-B*} = ((\alpha-\alpha^2+\kappa)\tau - (\alpha+(\alpha+\kappa)\tau)c_n + (1+\alpha\tau)c_r/1+\kappa\tau^2+\alpha\tau(2+\tau))$ and $t^{FP-B*} = \tau s^{FP-B*}$, respectively. Under the neutral fiscal policy, the government's tax t is τ times of the subsidy s, that is $s^{FP*} = \tau t^{FP*}$. Both the optimal subsidy s and tax t are the increasing functions of the government's mandated collection target τ.*

See the proof in Appendix.

Proposition 5 shows that the government can determine the optimal tax and subsidy under the neutral fiscal policy to realize the anticipated collection goal. The ratio of the unit tax and the unit subsidy exactly equals the government's mandated collection target. Note that the higher mandated collection rate, the higher the subsidy and the tax. Higher tax can inhibit the production of the new product, whereas higher subsidy can improve collection and remanufacturing, thereby improving the collection target.

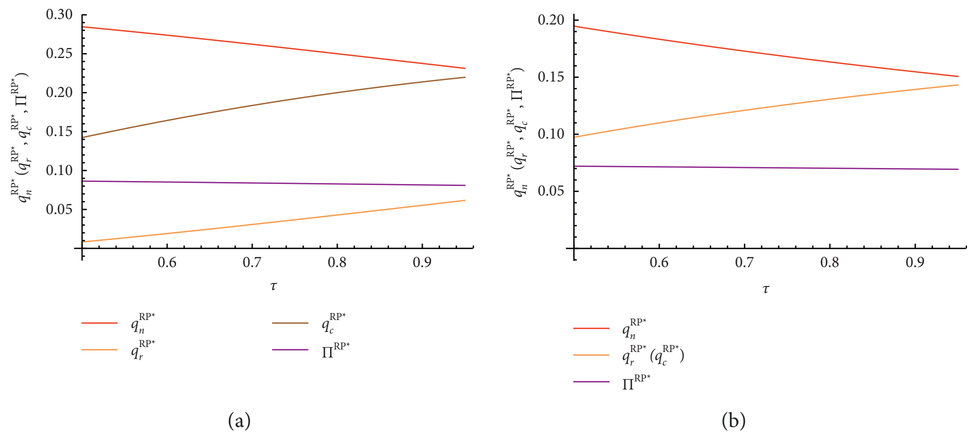

FIGURE 3: The impacts of the mandated collection rate on the manufacturer's optimal decisions. (a) Scenario RP-A and (b) scenario RP-B.

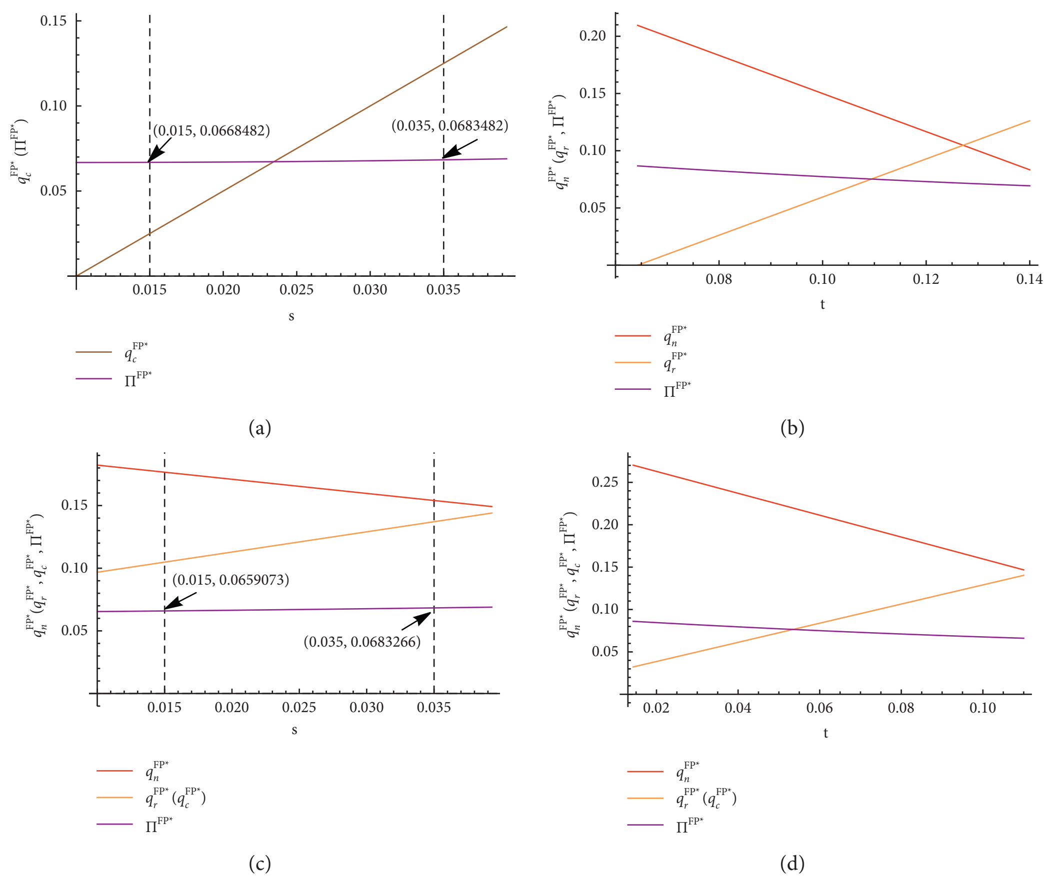

FIGURE 4: The impacts of s and t on the manufacturer's optimal decisions. (a) The impacts of s under scenario FP-A, (b) the impacts of t under scenario FP-A, (c) the impacts of s under scenario FP-B, and (d) the impacts of t under scenario FP-B.

6. Numerical Analysis

In order to intuitively illustrate the impacts of the mandated collection rate on the manufacturer's optimal decisions in Proposition 2, Figure 3 is drawn (the values of the parameters refer to the literature [3, 42], let $\alpha = 0.7$, $c_r = 0.3$, $c_d = 0.01$, $\kappa = 0.1$, $\tau = 0.5$, and $c_n = 0.4\,(0.46)$). It can be seen that as the government improves the mandated collection responsibility, the quantity of the new product continuously decreases and the quantities of the remanufactured products and the collected cores increase, but the manufacturer's whole profit decreases.

In order to intuitively illustrate the impacts of the subsidy s and the tax t on the manufacturer's optimal decisions in Proposition 4, Figure 4 is drawn (the values of the parameters refer to the literature [3, 42]' let $\alpha = 0.7$, $c_r = 0.3$, $c_d = 0.01$, $\kappa = 0.1$, $t = 0.1$, $s = 0.03$, and $c_n = 0.35\,(0.4)$). It can be seen that under scenario FP-A, the increase in the subsidy can promote the collection and improve the manufacturer's profit. But the increase in the tax can lower the quantity of the new product, increase the quantity of the remanufactured product, but finally lower the manufacturer's profit. Under scenario FP-B, the increase in the subsidy can promote the collection and remanufacturing, lower the quantity of the new product, but finally improve the manufacturer's profit. However, the increase in the tax can lower the quantity of the new product, increase the quantity of the collected core and that of the remanufactured product, but finally lower the manufacturer's profit.

7. Conclusions

The mechanism of the extended producer responsibility provides a theoretical basis for scientifically dealing with the issues of collecting and reusing the e-waste. To incentivize the producer to improve the collection and reuse of the used product and protect the environment and fully utilize the resources, the government as a regulator designs the take-back legislations with the economic and administrative instruments based on the extended producer responsibility. How the two types of take-back legislation affect the producer's collection behavior has not been well studied. Meanwhile, although the two types of take-back legislation implement different instruments, they both aim to improve the collection rate of the used product. In the same market, the issue of whether the efficiencies of the two types of take-back legislation are consistent does not seem to be addressed in literature.

Therefore, to fill these research gaps, we establish a stylized model with a monopoly manufacturer aiming to maximize the profit. First, the manufacturer's optimal production, collection, remanufacturing decisions, and optimal profit under two types of take-back legislation are respectively determined. Then, the impacts of the two types of take-back legislation on the manufacturer's optimal decisions are respectively investigated. Finally, the consistency of the efficiencies of the two types of take-back legislation is evaluated, and a neutral fiscal policy is designed to set certain subsidy and tax to make the manufacturer's voluntary collection rate meet the government's mandated collection target.

The main results and observations obtained in this study are as follows:

(1) First, when the take-back legislation with the administrative instrument is effective, the manufacturer only collects the used product at the mandated collection target. But, whether the collected cores are partially or fully remanufactured depends on the production cost of the new product or the remanufacturing cost advantage.

(2) Second, when the government implements the take-back legislation with the administrative instrument, a stricter mandated collection goal can improve the manufacturer's optimal collection and remanufacturing quantities regardless of the cost of the new product, but may hurt the production of the new product and the manufacturer's profit.

(3) Third, when the take-back legislation with the economic instrument is effective, the government's subsidy should be controlled in an appropriate interval. In this case, the manufacturer's optimal quantities of the collection and the remanufactured products extremely depend on the cost of the new product. As the cost of the new product increases, the manufacturer tends to change from partially remanufacturing to fully remanufacturing.

(4) Fourth, when the government enacts the take-back legislation with the economic instrument, the effects of the government's subsidy and tax on the manufacturer's optimal decisions rely on the cost of the new product. When the cost of the new product is relatively low, more subsidies can increase the number of collected cores but the tax has no effect on the collection quantity. The increasing tax can enhance the quantity of the remanufactured products but the subsidy has no effect on it. When the cost of the new product is relatively high, the improvement in the subsidy and tax can lead to more quantities of the collection and the remanufactured products.

(5) Fifth, in terms of different costs of the new product, the government can determine the optimal tax and subsidy via a neutral fiscal policy to achieve the mandated collection goal. Moreover, the ratios of the optimal tax and subsidy are exactly equal to those with the mandated collection rate.

From the aforementioned results, the following managerial insights and implications can be provided for the government and firms:

(1) For the government, first, in terms of the take-back legislation with the administrative instrument, the government can improve the mandated collection rate to increase the manufacturer's collection rate. Second, under the take-back legislation with the economic instrument, the government should classify the catalogue of the products according to the cost of the new product and adjust the corresponding subsidy and tax for each category of the products to achieve the goal of improving collection and remanufacturing rate. Finally, the ratio of the optimal tax and subsidy under the neutral fiscal policy is exactly consistent with the mandatory collection target. Therefore, when the government formulates the two types of take-back legislation, the tax, subsidy, and mandated collection target should be fully considered.

(2) From the view of the firms, first of all, the firm's manager can actively respond to the government's subsidy to increase the economic profit. Then, the manager needs to always pay attention to the subsidy and tax and adjusts the cost of the new products corresponding to the specific subsidy and tax.

There are still some limitations to be explored in the future. First of all, this study only considers the government's mandated collection target and ignores the mandated reuse target. Next, it does not discuss the interactions among the manufacturer, the upstream, and downstream of the supply chain. Finally, it does not fully consider the complex competition in the market. Therefore, in the future, diversified policies and the competition and cooperation from the upstream and downstream of the supply chain will be incorporated into the research.

Appendix

Proof of Proposition 1. The Hessian matrix of Π^{RP} is negative definite and the profit function of Π^{RP} is concave of q_n, q_r, and q_c.

The Lagrangian is $L = \Pi_M + \gamma_1 (q_n - q_c) + \gamma_2 (q_c - \tau q_n) + \gamma_3 (q_c - q_r) + \gamma_4 q_r$ with $(\partial L/\partial q_n) = 1 - c_n - 2q_n - 2\alpha q_r + \gamma_1 - \tau\gamma_2$, $(\partial L/\partial q_r) = c_d - c_r - \alpha q_n + \alpha(1 - q_n - q_r) - \alpha q_r - \gamma_3 + \gamma_4$, and $(\partial L/\partial q_c) = -c_d - 2\kappa q_c - \gamma_1 + \gamma_2 + \gamma_3$. Because the profit function is concave, necessary conditions and sufficient conditions for optimality are $(\partial L/\partial q_n) = 0$, $(\partial L/\partial q_r) = 0$, and $(\partial L/\partial q_c) = 0$, whereas $\gamma_1 (q_n - q_c) = 0$, $\gamma_2 (q_c - \tau q_n) = 0$, $\gamma_3 (q_c - q_r) = 0$, and $\gamma_4 q_r = 0$. In terms of $\gamma_2 (q_c - \tau q_n) = 0$, when the quantity of the collected cores exceeds the government's mandated collection target, the mandated collection target is ineffective. Since this study focuses on the conditions where the mandated collection target is effective, $q_c - \tau q_n > 0$ is not considered. At this time, only when $\gamma_2 > 0$, $q_c - \tau q_n = 0$ denotes that the mandated collection target is effective. In terms of $\gamma_4 q_r = 0$, since $q_r > 0$, $\gamma_4 = 0$ according to the complementary slackness theorem. In terms of $\gamma_1 (q_n - q_c) = 0$, since it cannot be guaranteed that all used products can be collected in the reality, namely $q_n > q_c$, $\gamma_1 = 0$ according to the complementary slackness theorem. Based on the above analysis, we finally get the following two feasible strategies. □

A. Scenario RP-A: $\gamma_1 = = 0$, $\gamma_2 > 0$, $\gamma_3 = = 0$, and $\gamma_4 = = 0$

Solving the first-order conditions yields q_n^{RP-A*}, q_r^{RP-A*}, and q_c^{RP-A*}. Using $\gamma_2 > 0$, $q_c - q_r \geq 0$, $q_n^{RP-A*} > 0$, and $q_r^{RP-A*} > 0$, we have $((1 + \kappa\tau^2)c_r - \alpha\kappa\tau^2 - (1 + \tau(\alpha + \kappa\tau))c_d/\alpha) = c_{n1} < c_n \leq c_{n2} = (\alpha\tau(1 - \alpha - \kappa\tau) - (1 + \kappa\tau^2 + \alpha\tau(2 + \tau))c_d + (1 + \tau(\alpha + \kappa\tau))c_r/\alpha(1 + \tau))$.

B. Scenario RP-B: $\gamma_1 = = 0$, $\gamma_2 > 0$, $\gamma_3 > 0$, and $\gamma_4 = = 0$

Solving the first-order conditions yields q_n^{RP-B*}, q_r^{RP-B*}, and q_c^{RP-B*}. In terms of $\gamma_2 > 0$ and $\gamma_3 > 0$, we know $(\alpha\tau(1 - \alpha - \kappa\tau) - (1 + \kappa\tau^2 + \alpha\tau(2 + \tau)) c_d + (1 + \tau(\alpha + \kappa\tau)) c_r/\alpha(1 + \tau)) = c_{n2} < c_n < c_{n3} = (\alpha\tau - \alpha^2\tau + \kappa\tau + c_r + \alpha\tau c_r /\alpha + \alpha\tau + \kappa\tau)$.

Proof of Proposition 2. $(\partial q_n^{RP-A*}/\partial\tau) < 0$, $(\partial q_n^{RP-B*}/\partial\tau) < 0$, $(\partial q_c^{RP-A*}/\partial\tau) > 0$, $(\partial q_c^{RP-B*}/\partial\tau) > 0$, $(\partial q_r^{RP-A*}/\partial\tau) > 0$, $(\partial q_r^{RP-B*}/\partial\tau) > 0$, $(\partial\Pi^{RP-A*}/\partial\tau) < 0$, and $(\partial\Pi^{RP-B*}/\partial\tau) < 0$. □

Proof of Proposition 3. The Hessian matrix of Π^{FP} is negative definite and the profit function of Π^{FP} is concave of q_n, q_r, and q_c. The Lagrangian is $L = \Pi_M + \lambda_1 (q_n - q_c) + \lambda_2 (q_c - q_r) + \lambda_3 q_r$ with $(\partial L/\partial q_n) = 1 - t - c_n - 2q_n - 2\alpha q_r + \lambda_1$, $(\partial L/\partial q_r) = c_d - c_r - \alpha q_n + \alpha(1 - q_n - q_r) - \alpha q_r - \lambda_2 + \lambda_3$, and $(\partial L/\partial q_c) = s - c_d - 2\kappa q_c - \lambda_1 + \lambda_2$. Because the profit function is concave, the necessary conditions and sufficient conditions for optimality are $(\partial L/\partial q_n) = 0$, $(\partial L/\partial q_r) = 0$, and $(\partial L/\partial q_c) = 0$, whereas $\lambda_1 (q_n - q_c) = 0$, $\lambda_2 (q_c - q_r) = 0$, and $\lambda_3 q_r = 0$. In terms of $\lambda_3 q_r = 0$, since $q_r > 0$, $\lambda_3 = 0$ according to the complementary slackness theorem. In terms of $\lambda_1 (q_n - q_c) = 0$, since it cannot be guaranteed that all used products can be collected in the reality, namely $q_n - q_c > 0, \lambda_1 = 0$ according to the complementary slackness theorem. Based on the above analysis, we finally get the following two feasible strategies. □

C. Scenario FP-A: $\lambda_1 = = 0$, $\lambda_2 = = 0$, and $\lambda_3 = = 0$

Solving the first-order conditions gives q_n^{FP-A*}, q_r^{FP-A*}, and q_c^{FP-A*}. From $q_n - q_c > 0$, $q_r > 0$, and $q_c - q_r \geq 0$, we have $(-t\alpha - c_d + c_r/\alpha) < c_n \leq c_{n4} = (\alpha(s - s\alpha - t\kappa) - ((1 - \alpha)\alpha + \kappa)c_d + \kappa c_r/\alpha\kappa)$. According to $q_c > 0$, we get $s > c_d$.

D. Scenario FP-B: $\lambda_1 = = 0$, $\lambda_2 > 0$, and $\lambda_3 = = 0$

Solving the first-order conditions gives q_n^{FP-B*}, q_r^{FP-B*}, and q_c^{FP-B*}. From $\lambda_2 > 0$ and $q_n - q_c > 0$, it can be seen that $(\alpha(s - s\alpha - t\kappa) - ((1 - \alpha)\alpha + \kappa)c_d + \kappa c_r/ \alpha\kappa) = c_{n4} < c_n < c_{n5} = (\alpha - s(1 + \alpha) - \alpha(2t + \alpha) + \kappa - t\kappa + (1 + \alpha)c_r/ \ 2\alpha + \kappa)$. According to $c_{n5} > c_{n4}$, we get $s < ((2\alpha + \kappa)c_d + \kappa(\alpha - c_r)/2\alpha)$.

Proof of Proposition 4. $(\partial q_n^{FP-A*}/\partial t) < 0$, $(\partial q_c^{FP-A*}/\partial s) > 0$, $(\partial q_r^{FP-A*}/\partial t) > 0$, $(\partial\Pi^{FP-A*}/\partial s) > 0$, $(\partial\Pi^{FP-A*}/\partial t) < 0$, $(\partial q_n^{FP-B*}/\partial s) < 0$, $(\partial q_n^{FP-B*}/\partial t) < 0$, $(\partial q_c^{FP-B*}/\partial s) > 0$, $(\partial q_c^{FP-B*}/\partial t) > 0$, $(\partial q_r^{FP-B*}/\partial s) > 0$, $(\partial q_r^{FP-B*}/\partial t) > 0$, $(\partial\Pi^{FP-B*}/\partial s) > 0$, and $(\partial\Pi^{FP-A*}/\partial t) < 0$. □

Proof of Proposition 5. The above analysis process shows the proof of optimal solutions on s and t. In addition, by calculating the first derivative of τ for the optimal s and t, we can obtain that $(\partial s^{FP-B*}/\partial\tau) > 0$, $(\partial t^{FP-B*}/\partial\tau) > 0$, $(\partial s^{FP-A*}/\partial\tau) > 0$, and $(\partial t^{FP-A*}/\partial\tau) > 0$. □

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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