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Pricing and Collecting Decision of a Closed-Loop Supply Chain Under Market Segmentation With Reward-Penalty Mechanism

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ABSTRACT This paper examines the impact of reward-penalty mechanism (RPM) on the decision-making of a closed-loop supply chain (CLSC) under the framework of market segmentation. Decentralized dynamic game models are developed to obtain and compare the pricing and collecting decision of the CLSC with and without RPM. We find that: (i) RPM improves the actual collection rate and the profit of the recycler, while it decreases the prices of new and remanufactured products in market segments in response to higher consumer preferences; (ii) a higher buyback price guarantees that the manufacturer becomes more profitable when the government imposes low or high intensity of reward-penalty. Otherwise, the manufacturer should set a lower buyback price when the government imposes moderate intensity of reward-penalty; (iii) higher intensity of reward-penalty can not only effectively improve the environmental sustainability of CLSC, but also obtain higher social welfare; (iv) the mechanism that reward equals penalty is optimal, in which case the same intensity maximizes the actual collection rate as well as the profits of the manufacturer and the recycler. Our analysis discusses the parameters which have significant impacts on the pricing and collecting decision of the closed-loop supply chain and gains managerial insights that are both environmentally and economically beneficial.

INDEX TERMS Closed-loop supply chain, reward-penalty mechanism, market segmentation.

I. INTRODUCTION

The remanufacturing strategy aims to excavate the residual value of waste products, that is, to remanufacture the components of waste products that are still functioning well, so as to obtain remanufactured products with functions no less than new products. However, findings form the Global E-waste Monitoring 2020 report released by the United Nations point out that a total of 53.6 million tons of e-waste was generated globally in 2019, of which only 17.4% was recycled and reused. The residual value of e-waste in 2019 is as high as $57 billion. The report also predicts that the total amount of global e-waste will increase to 74.7 million tons in the next ten years [1]. The rapid increase in e-waste is worrisome and poses a huge threat to the environment. The recycling and reuse of waste products becomes top priority. To this end, different countries actively establish recycling policies based on extended producer responsibility (EPR), the purpose of which is to extend manufacturers' responsibility to the whole life cycle of products, especially the recycling and reuse stage of waste products. For instance, EU's Waste Electrical and Electronic Equipment (WEEE) Directive sets mandatory recycling targets and punishment rules for WEEE and requires original manufacturers to be responsible for the recycling of waste products in order to reduce environmental damage caused by such products [2], [3]. In addition to punitive measures, China's Regulations on the Management of the Recycling and Disposal of WEEE (Amended in 2019) set up certain subsidies to encourage manufacturers and recyclers to recycle and centrally dispose WEEE.

In this paper, we focus on the recycling and remanufacturing of WEEE and determine a mechanism that combines reward and penalty, i.e., reward-penalty mechanism (RPM). Specifically, the government implements reward or penalty based on the extent to which the collection rate deviates from the target collection rate [4]. RPM is regarded as a performance-based supervision. By evaluating the collecting status of WEEE in the CLSC, the government

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impose appropriate reward and penalty for improvement so it can maintain those unrecycled WEEE within an acceptable range [5]. The purpose of this paper is not only to evaluate the role of RPM in promoting the recycling and remanufacturing of WEEE, but also to analyze its impact on the collecting decision of WEEE in the CLSC.

Remanufacturing is beneficial because it can reduce manufacturing costs by 40% to 60% [6]. That is to say, remanufacturing is able to create opportunity to sell products to low-end consumers at less cost. But this also poses follow-up issues. One is the pricing decision of new and remanufactured products, which is related to the feasibility of the manufacturer's remanufacturing strategy. It is estimated that for every four remanufactured products sold, the sale of one new product is lost [7]. Thus, making a reasonable pricing decision to maximize its own profit is the key for the manufacturer to consider in remanufacturing activities. Furthermore, although remanufactured products are functionally the same as new products, consumers have different valuations for new and remanufactured products, which directly affects consumers' willingness to pay [1]. Consumers believe that remanufactured products are lower than new products and are unwilling to pay higher prices for remanufactured products than the original price of new products. Therefore, the segmentation of new products and remanufactured products according to consumers' valuations of the products is considered by scholars. It is concluded that consumers' different valuations of products will make the optimal prices of new products and remanufactured products significantly different [8], [9]. This paper gives the optimal pricing decision for new products and remanufactured products in the market segment and further explains under what circumstances the manufacturer's profit will increase.

In this paper, the market is segmented according to consumers' willingness to pay, and then the product demand of each market segment is determined from the theory of consumer utility, so that our model can adapt to price differences and market segmentation. On this basic, we are interested in discussing the following questions:

(i) What pricing and collecting decision best fit the target market under market segmentation?

(ii) How does RPM affect CLSC's pricing and collecting decision, the profits of both supply chain members as well as the environment and social welfare?

(iii) Can RPM improve the profitability of a product portfolio consisting of new and remanufactured products under market segmentation?

To analyze the research questions discussed above, we formulate a decentralized manufacturer-led game model, where the manufacturer segments the market and sets prices for new and remanufactured products while the recycler determines the collection rate of WEEE. In this set up, we compare two contexts under market segmentation: one where the government imposes an RPM and second, where the government does not consider imposing an RPM. Through the two contexts, different equilibrium solutions and profits are obtained, and thus we aim to analyze the impact of RPM on decision variables and profits of the manufacturer and the recycler under market segmentation. Our analysis helps the two players make corresponding decisions and provides RPM-based managerial insights.

The remainder of the paper is distributed as follows. We provide a literature review in Section II. Section III gives the problem description, notations and assumptions. In Section IV, the game model of CLSC without RPM is proposed as the base case, followed by the case with RPM. Section V gives the comparison of both cases, which is supplemented by numerical studies. Then, an extensional research is given in Section VI. Finally, we summarize main findings, propose managerial implications, and present the direction for future work in Section VII.

II. LITERATURE REVIEW

The closed-loop supply chain has attracted considerable attention during the past decades, resulting in a variety of analytical models [10]. Souza [11] provides a basic framework for the modelling of a CLSC from three aspects of strategy, tactics and operation. Our work focuses on the remanufacturing strategy in a CLSC and traces three streams of the literature on pricing decision, market segmentation and government guidance.

A. PRICING DECISION IN A CLOSED-LOOP SUPPLY CHAIN

The closed-loop supply chain that considers the remanufacturing strategy is much more complicated than a forward supply chain, because remanufacturing considers costs, including recycling and production costs, as well as the impact of price on demand and returns [12]–[16]. To this end, a large amount of literature focuses on determining the optimal pricing of new products and remanufactured products in a different setting. Maiti and Giri [17] establish a CLSC model with price-dependent demand and focus on optimal reference price effects on remanufacturing strategy. Gan *et al.* [18] consider the direct sales channel for remanufactured products in identifying the optimal pricing decision and product decision, indicating that the implementation of a separate channel can increase the total profit of the supply chain. Liu *et al.* [7] argue that the quality level of remanufactured products cannot be restored to that of new products, the manufacturer's optimal pricing decision can be derived by solving the convex programming model. Structurally, CLSC includes both forward and reverse supply chains, the focus of some researchers is on selling prices and product recycling/remanufacturing. In some cases, there is no difference between new and remanufactured products, so they are sold at the same price. Savaskan and Van Wassenhove [19] examine the remanufacturing channel of the reverse supply chain and discuss collection efforts surrounding the price decision. Miao *et al.* [20] explore the decision about collection of CLSC under three categories: no collection, partial collection, and full collection, and determine the conditions for these three types according to their economic performance, including profit and price. Hasanov *et al.* [21] comprehensively consider collection costs and environmental factors, indicating that manufacturer favors a hybrid strategy since a higher collection rate can reduce supply chain costs and improve the environmental efficiency of the supply chain. Similarly, Ravi *et al.* [22] develop a decision model to optimize CLSC network of end-of-life vehicles. The results show that as the collection rate increases, the total cost of the supply chain can be reduced by up to 20%.

Although abovementioned literature focuses on the price and collection decisions of CLSC, it ignores the distinction between new and remanufactured products, even if they are as good in product functionality. Some researchers begin to focus on studying the differentiated price decision. For instance, Ferrer and Swaminathan [23] argue that when the profitability of remanufacturing is high, manufacturers are more willing to sell remanufactured products at lower prices to cope with the increased threat of competition. Following this, they characterize manufacturers' differentiated strategies for remanufacturing and pricing, showing that the optimal strategy is not necessarily monotonic remanufacturing savings [24]. Zhang [25] *et al.* and He and Yuan [26] further reveal that different manufacturing costs directly affect manufacturers' product prices, and differentiated prices help solve the problem of cannibalization of remanufactured products.

Most of the pricing models in the literature above are designed to determine products' optimal prices but overlook the cost advantage of remanufacturing. This paper differs from above literature in that we not only implement differential pricing for new and remanufactured products, but also consider the supply of remanufactured products. As shown in the Introduction that remanufacturing can reduce production costs, which may be more attractive in the low-end consumer market. Thus, it is necessary to consider the supply of remanufactured products. The corresponding price decision should also include the decision of the recycler.

B. MARKET SEGMENTATION IN A CLOSED-LOOP SUPPLY CHAIN

The CLSC literature on market segmentation focuses on price and quality of new and remanufactured products that are differentiated by perceived value in a market of heterogeneous consumers whose willingness-to-pay varies [27]–[29]. Seifbarghy *et al.* [30] investigate a market segmentation situation where customers are divided into two types: quality oriented and price oriented and determine the threshold of the percentage of potential quality-oriented consumers. Ferrer and Swaminathan [24] argue that the market is better served through differentiated pricing when consumers are able to distinguish between new and remanufactured products. Raza and Turiac [31] propose an optimal framework for joint determination of pricing, production quantity and market segmentation using differentiated pricing. They further state that allowing consumers to choose products can produce greater utility. When consumers prefer quality, Yang *et al.* [9] incorporate perceived value on quality into consumers' valuations of products, but do not take consumer preferences into account when segmenting the market. Xue *et al.* [32] find the market segmentation strategy and conditions for remanufacturing for firms through remanufacturing competition in a duopoly market with consumer quality preferences. In our models, not only the differentiated pricing of new and remanufactured products is considered, but also consumer preferences are taken into consideration. On the contrary, consumers who only buy one of the products are not considered. Therefore, in the market segment, each consumer can freely choose whether to buy a new product or a remanufactured product according to his own net utility, that is, the consumer's valuation of the product minus the actual price of the product.

C. GOVERNMENT GUIDANCE IN A CLOSED-LOOP SUPPLY CHAIN

As an important part of promoting the development of a closed-loop supply chain, the government's policy guidance has an important impact on the decision-making of the CLSC. In terms of subsidy mechanism, many scholars regard it as a pure reward policy and pay attention to its influence on CLSC [33]–[37]. For instance, Saha *et al.* [38] focus on the pricing decision of remanufacturing in the CLSC by designing a reward-driven policy and then adopt a three-way discount price mechanism to achieve the dual-channel equilibrium of the CLSC in a non-cooperative environment. Han *et al.* [39] examine the impact of subsidies on the remanufacturing pricing decision from the perspective of product acceptability and durability. Zhang *et al.* [40] develop four dynamic models to examine the impact of government subsidies on the decision-making of CLSC. The results show that an appropriate subsidy parameter is beneficial to supply chain members and the environment. Furthermore, Nielsen *et al.* [41] develop eight models to compare and evaluate the performance of three subsidy policies in terms of optimal pricing, welfare maximization, and optimal investment. They indicate that if subsidies are provided to consumers, social welfare and supply chain members' profits always increase. For environmental considerations, some researchers recognize tax policy as effective regulation in guiding recycling and remanufacturing activities characterized by low energy consumption and high output from the point of view of environmental economics (e.g., Bazan *et al.* [42]; Yang *et al.* [43]; Liu *et al.* [44]; Ding *et al.* [45]; Hu *et al.* [46]). In these studies, the government is considered as the leader aiming to coordinate a socially responsible closed-loop supply chain with product recycling through taxation policies, while the manufacturer is the follower aiming to maximize economic benefits through the provision of new and remanufactured products. There are also scholars who combine subsidies and tax policies, i.e., reward-penalty mechanism. For instance, Wang *et al.* [4] design an RPM to investigate WEEE collection responsibility sharing under different power structure. Wang *et al.* [47] investigate the RPM under the price competition between

TABLE 1. Our paper vs. literature.

	RPM	Remanufacturing	Market segmentation	Pricing decision	Collection rate	Buy back
Wang et al. (2015)	√	√		√	√	√
Seifbarghy et al. (2015)			√	√		
Yoo and Kim (2016)		√		√		√
Gan et al. (2017)		√		√		
Miao et al. (2017)				√		
Wang et al. (2017)	√	√		√	√	√
Miao et al. (2018)			√	√		√
Zhang et al. (2018)	√	√		√	√	√
Zhu et al. (2019)		√		√		
Chen et al. (2019)	√	√	√	√	√	
He and Yuan (2020)		√		√		√
Ding et al. (2020)		√		√		√
Hu et al. (2020)		√	√	√		√
Xue et al. (2021)		√	√	√	√	√
Yang et al. (2021)		√	√	√		
This paper	√	√	√	√	√	√

two manufacturers in the CLSC. Chen and Akmalul'Ulya [6] propose three green CLSC models based on RPM to analyze the optimal decision-making behavior of the manufacturer. The results suggest that the manufacturer should set a lower transfer price when considering decentralized channels. Zhang *et al.* [48] find that compared with a single policy, RPM can lower the price of the product and increase the collection rate of WEEE in the context of game theory. Our work is similar to the above literature in examining the impact of RPM on decision-making of CLSC. The difference is that, compared to Wang [4] *et al.* and Chen and Akmalul'Ulya [6], we only consider the manufacturer-led game model and mainly compare the pricing and collection decisions of CLSC with and without RPM, which is not considered in their work. Compared to Zhang *et al.* [48], we mainly focus on the impact of RPM on decisions and profits of the manufacturer and the recycler when the recycler deviates from benchmark targets. More importantly, we present the manufacturer's optimal pricing decision and the recycler's optimal collecting decision when the government imposes an RPM.

In summary, the main contributions of our work are as follows: (i) We focus on the differentiated pricing decision in the framework of market segmentation by distinguishing consumers' valuations of new and remanufactured products. (ii) In this paper, the actual collection rate is taken as an endogenous variable, and the optimal collecting decision of the recycler under the supervision of the lowest target rate is derived. (iii) we compare the pricing and collecting decision of a CLSC with and without RPM, and then analyzed the impact of RPM on social welfare and environmental improvement within a market segmentation framework.

III. MODEL DESCRIPTION AND ASSUMPTIONS

This section describes decentralized dynamic game models, and put forward some assumptions.

A. MODEL DESCRIPTION

Consider a CLSC with market segmentation for new and remanufactured products. As shown in Fig. 1, the manufacturer acts as the game leader, and determines the prices of new products and remanufactured products in the end-consumer market, respectively; the recycler then acts as the follower, and determines the collection rate of WEEE and then sells the collected WEEE to the manufacturer at a certain price. We also consider the situation where the government sets up an RPM to encourage the manufacturer's responsibility of recycling. The RPM, as an external government incentive mechanism, includes an appropriate reward-penalty intensity and a target collection rate, which imposes reward and penalty according to the performance evaluation for monitoring. Specifically, the manufacturer will be subject to a certain intensity of economic penalty from the government in the case that the collection rate is lower than the target collection rate. On the contrary, the government will reward the manufacturer when the collection rate exceeds the target rate. All the notations are summarized in Table 2.

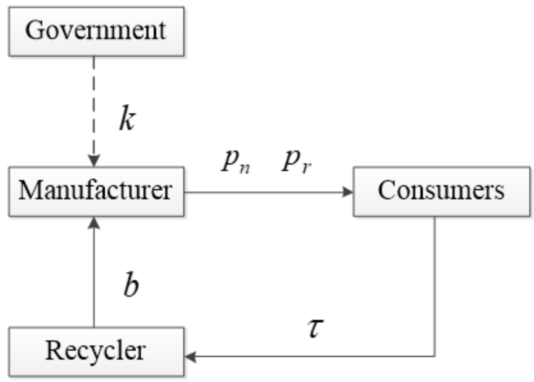

FIGURE 1. The CLSC with government's RPM.

B. MODEL ASSUMPTIONS

Assumption 1: Similar with Jena [49], we assume that remanufacturing has the advantages of production cost, i.e., $\Delta = c_r - c_n < 0$. It means that, the cost of using collected WEEE as components and materials to produce a product is less than that of using new components and materials to produce a product.

TABLE 2. Notations and corresponding description.

Symbols	Descriptions
Decision variables	
p_n	The price of new products
p_r	The price of remanufactured products
τ	The collection rate of WEEE
Parameters	
c_n	The unit production cost by using a new component
c_r	The unit production cost by using a WEEE component
c	The unit collection cost of WEEE
b	The buyback price of a WEEE
k	The reward-penalty intensity for each unit collection rate deviating from the target
τ_0	The target collection rate stipulated by the government
ε	The unit hazard cost of unrecycled WEEE to the environment
v	The valuation of a new product for consumers
ϕ	The upper bound of the valuation v
δ	Consumers' preference for a remanufactured product
q_n	The demand of new products
q_r	The demand of remanufactured products
Derived functions	
π_m	Profit of the manufacturer
π_c	Profit of the recycler
E	Environmental damage caused by unrecycled WEEE
SW	Social welfare
Indexes	
Superscript	
*	Equilibrium solutions without RPM
**	Equilibrium solutions with RPM
Subscript	
r	Remanufactured products
n	New products
c	The recycler
m	The manufacturer

Assumption 2: Because of a lower production cost, the manufacturer gives priority to the use of WEEE when WEEE and new materials exist simultaneously [4]. The collected WEEE can be used as components and materials, thus there is no need to assume a trivial remanufacturing rate and this assumption does not affect the development of managerial insights.

Assumption 3: The investment cost of recycling is expressed as $I = m\tau^2/2$, where m is a scale parameter of WEEE return. This implies a nonlinear cost upward trend with WEEE actual collection rate to a certain level.

Assumption 4: New products and remanufactured products show no difference in function, but they do vary in consumers' perceived value [23]. Considering the consumers' willingness to pay for both kinds of products, we assume

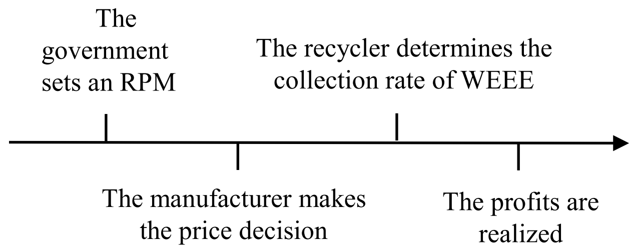

FIGURE 2. The timeline and sequence of events.

that each consumer has a valuation of v for a new product. Let $\delta v (0 < \delta < 1)$ denote the consumer's valuation for a remanufactured product, where δ is the consumer's preference parameter. Assume that v is uniformly distributed in the region $[0, \phi]$.

According to the above assumptions, we can find that the utilities each consumer obtains from new and remanufactured products are given by

$$u_n = v - p_n$$
$$u_r = \delta v - p_r$$

Furthermore, the demands of new and remanufactured products are inversely related to the corresponding prices. We obtain that the inverse demand functions of the two kinds of products can be expressed as follows.

$$p_n = \phi - q_n - \delta q_r$$
$$p_r = \delta (\phi - q_n - q_r)$$

Hereinto, $\frac{p_r}{p_n} \leq \delta \leq 1 - \frac{p_n - p_r}{\phi}$, which ensures that the demands of new products and remanufactured products are all non-negative. Thus, we can further obtain the demand functions of new and remanufactured products as follows.

$$q_n = \phi - \frac{p_n}{1-\delta} + \frac{p_r}{1-\delta}$$
$$q_r = \frac{1}{1-\delta}\left(p_n - \frac{p_r}{\delta}\right)$$

Thus, the total demand can be expressed as $Q = q_r + q_n = \phi - \frac{p_r}{\delta}$. Note that since our focus is on the decision-making of the CLSC under market segmentation, the situations where consumers only buy new products or remanufactured products are not considered in this paper. To further understand the market segmentation process, we present supplementary explanation of this assumption and the proof process in Appendix A1.

IV. MODELS

In the section, we analyze the members' equilibrium solutions in the decentralized CLSCs with and without RPM, respectively. The game scenarios and decision sequences are depicted in Fig. 2.

A. DECISION-MAKING OF A CLSC WITHOUT RPM

We examine the optimal decisions of the members when considering that the government does not propose RPM to

TABLE 3. Equilibrium solutions in two cases.

Equilibrium solutions in the case without RPM	Equilibrium solutions in the case with RPM
$\tau^{*}=\frac{(b-c)(\delta\phi-c_r)}{2[b(b-c)+\delta m]}$	$\tau^{**}=\frac{(b-c)(\delta\phi-c_r)}{2[b(b-c)+\delta m]}+\frac{(b-c)k}{2m\delta[b(b-c)+\delta m](1-\delta)}$
$p_n^{*}=\frac{\phi+c_n}{2}+\frac{b(b-c)(\delta\phi-c_r)}{2[b(b-c)+\delta m]}$	$p_n^{**}=\frac{\phi+c_n}{2}+\frac{b(b-c)(\delta\phi-c_r)}{2[b(b-c)+\delta m]}-\frac{k}{2[b(b-c)+\delta m](1-\delta)}$
$p_r^{*}=\frac{\delta\phi+c_r}{2}+\frac{b(b-c)(\delta\phi-c_r)}{2[b(b-c)+\delta m]}$	$p_r^{**}=\frac{\delta\phi+c_r}{2}+\frac{b(b-c)(\delta\phi-c_r)}{2[b(b-c)+\delta m]}-\frac{k}{2[b(b-c)+\delta m](1-\delta)}$
$\pi_c^{*}=\frac{m(b-c)^2(\delta\phi-c_r)^2}{8[b(b-c)+\delta m]^2}$	$\pi_c^{**}=\frac{m(b-c)^2(\delta\phi-c_r)^2}{8[b(b-c)+\delta m]^2}+k(b-c)^2\left[(\delta\phi-c_r)+\frac{k}{2m\delta(1-\delta)}\right]$
$\pi_m^{*}=\frac{(\phi-c_n)^2}{4(1-\delta)}+\frac{(\delta\phi-c_r)(2\delta c_n-\delta\phi-c_r)}{4\delta(1-\delta)}-\frac{b^3(b-c)(\delta\phi-c_r)^2}{4\delta[b(b-c)+\delta m]}+\frac{(b^2-1)[b(b-c)(\delta\phi-c_r)]^2}{4\delta[b(b-c)+\delta m]^2}$	$\pi_m^{**}=\frac{(\phi-c_n)^2}{4(1-\delta)}-\frac{b(b-c)(\delta\phi-c_r)^2[b(b-c)+\delta^2 m]}{4\delta^2[b(b-c)+\delta m]^2}-k\tau_o+\frac{(\delta\phi-c_r)(2\delta c_n-\delta\phi-c_r)}{4\delta(1-\delta)}+k(b-c)\{\frac{(\delta\phi-c_r)[\delta^2 b(b-c)+\delta^3 m+b]}{2\delta^2[b(b-c)+\delta m]^2}+\frac{2\delta[b(b-c)+\delta m](1-\delta)k-(b+m)k}{4m\delta^2[b(b-c)+\delta m]^2(1-\delta)^2}\}$

encourage the manufacturer to take part in recycling and remanufacturing. Then, the manufacturer's profit function is given by

$$\max_{p_n,p_r}\pi_m=(p_n-c_n)\left(\phi-\frac{p_n}{1-\delta}+\frac{p_r}{1-\delta}\right)+\frac{p_r-c_r}{1-\delta}\left(p_n-\frac{p_r}{\delta}\right)-\tau b\left(\phi-\frac{p_r}{\delta}\right) \quad (1)$$

The recycler's profit function is given by

$$\max_{\tau}\pi_c=\tau(b-c)\left(\phi-\frac{p_r}{\delta}\right)-\frac{m\tau^2}{2} \quad (2)$$

Because $\partial^2\pi_c/\partial\tau^2=-m<0$, from the first-order condition of Eq. (2), we can obtain the recycler's best response function, which can be expressed as

$$\tau=\frac{(b-c)\left(\phi-\frac{p_r}{\delta}\right)}{m} \quad (3)$$

Then, Substituting Eq. (3) into Eq. (1), we calculate that

$$\frac{\partial^2\pi_m}{\partial p_n^2}\frac{\partial^2\pi_m}{\partial p_r^2}-\left(\frac{\partial^2\pi_m}{\partial p_n p_r}\right)^2=\frac{4m\delta+4b(b-c)}{\delta^2(1-\delta)m}>0,$$

which indicates that π_m is strictly joint concave in p_n and p_r. Thus, solving $\frac{\partial\pi_m}{\partial p_n}=0$ and $\frac{\partial\pi_m}{\partial p_r}=0$ yields the equilibrium solutions summarized in Table 3.

B. DECISION-MAKING OF A CLSC WITH RPM

In this case, the impact of the government is considered by introducing RPM. Under RPM, the manufacturer is rewarded when the collection rate exceeds the target collection rate; otherwise, penalties are levied for the unmet part. Now, we can obtain the manufacturer's profit function in the following.

$$\max_{p_n,p_r}\pi_m=(p_n-c_n)\left(\phi-\frac{p_n}{1-\delta}+\frac{p_r}{1-\delta}\right)+\frac{p_r-c_r}{1-\delta}\left(p_n-\frac{p_r}{\delta}\right)-\tau b\left(\phi-\frac{p_r}{\delta}\right)+k(\tau-\tau_0) \quad (4)$$

The recycler's profit function is given by

$$\max_{\tau}\pi_c=\tau(b-c)\left(\phi-\frac{p_r}{\delta}\right)-\frac{m\tau^2}{2} \quad (5)$$

The concavity conditions are consistent with the foregoing case, we are not repeat them here. The equilibrium solutions under RPM are shown in Table 3.

V. COMPARISON ANALYSIS

In this section, we investigate the effect of RPM set by the government on both members' optimal decisions, and conduct the sensitivity analyses to illustrate the influences of critical parameters on the optimal decisions and profits of the manufacturer and the recycler. It is worth noting that all of the following analyses are from the manufacturer's point of view, in the hope of inspiring the recycler's enthusiasm for collecting WEEE. All proofs are given in Appendix A2.

A. COMPARISION BETWEEN THE TWO CASE

We compare the members' optimal decisions and profits under the two cases, and examine the effect of RPM. We first compare the recycler's optimal collection rate and the manufacturer's optimal price decisions, then the following proposition is obtained.

Proposition 1: (1) For the collection rate, there is $\tau^{**} > \tau^{*}$. (2) For the optimal prices, there exists a threshold k^P of the reward-penalty intensity, when $k > k^P$, $p_n^* > p_r^* > p_n^{**} > p_r^{**}$; when $k < k^P$, $p_n^* > p_n^{**} > p_r^* > p_r^{**}$. Here, k^P is given in the proof.

Proposition 1 can be illustrated as follows. Part (1) shows that the collection rate of WEEE in the CLSC with RPM is larger than that in the CLSC without RPM. It means that RPM is effective in inducing recycler to enhance the collection rate of WEEE. From the perspective of the manufacturer, because the production cost can be reduced by using collected WEEE, it is possible for the manufacturer to lower the production cost by inducing the recycler to increase the collection rate. Hence, we infer that the manufacturer can increase the buyback price to reach such a goal. At the same time, when the recycler's collection rate is increased and higher than the target collection rate, the manufacturer can avoid the government economic penalties and obtain rewards.

Part (2) demonstrates that, under the same case, the price of new products is higher than that of remanufactured products regardless of whether the government sets up the RPM. It is because that the consumers' valuation of remanufactured products is lower than those of new products. The consumers are still willing to buy the new products even if the remanufactured products' price is much lower. Hence, the manufacturer needs to set a lower price for the remanufactured products to attract a fraction of consumers who have preferences for remanufactured products with a lower price. Moreover, if the reward-penalty intensity k exceeds a certain threshold, then the price of new products under the case with RPM is even lower than the price of remanufactured products under the case without RPM. Recall that the collection rate is higher under the case with RPM, the manufacturer would choose to use a higher volume of WEEE to make products to achieve the purpose of reducing total manufacturing costs, so as to gain an advantage in market competition at lower prices.

Next, we compare the members' optimal profits under the two cases, and obtain the following proposition.

Proposition 2: (1) For the recycler's profit, there is $\pi_c^{**} > \pi_c^*$. (2) For the manufacturer's profit, there exist two thresholds k_1 and k_2 of the reward-penalty intensity, when $2[b(b-c)+\delta m]\delta(1-\delta) > (b+m)$, for $0 < k < k_1$ or $k > k_2$, $\pi_m^{**} > \pi_m^*$; for $k_1 < k < k_2$, $\pi_m^{**} < \pi_m^*$; otherwise, for $0 < k < k_1$ or $k > k_2 \pi_m^{**} < \pi_m^*$; for $k_1 < k < k_2$, $\pi_m^{**} > \pi_m^*$. Here, the expressions of k_1 and k_2 are given in the proof.

Proposition 2 respectively shows comparative results of profits of the manufacturer and the recycler in the two cases. Part (1) of Proposition 2 suggests that the recycler's profit in the CLSC with RPM is larger than that in the CLSC without RPM. This because the collection rate of WEEE is higher in the CLSC with RPM, it means that the recycler obtains a fraction of remanufacturing profit by selling the collected WEEE to the manufacturer at a certain price.

Part (2) of Proposition 2 indicates that comparative results of the manufacturer's profit are affected not only by the intensity of reward-penalty, but also by the buyback price. Results reveal that under RPM, the manufacturer obtains higher profit when the government imposes low or high intensity of reward-penalty and the manufacturer sets a high buyback price Otherwise, if the buyback price is low (i.e., $2[b(b-c)+\delta m]\delta(1-\delta) < (b+m)$ holds), the manufacturer obtains lower profit when the government imposes low or high intensity of reward-penalty. In contrast, when the manufacturer faces moderate intensity of reward-penalty, a low buyback price can also enable the manufacturer to obtain higher profit. Because if the manufacturer sets a higher buyback price, it means that more remanufacturing profit is transferred to the recycler, resulting in a decrease in its own profit.

Given the results above, we next discuss effects of critical parameters on decision variables and profits of the manufacturer and the recycler under RPM in the following corollaries. Note that the values of the parameters in the following numerical studies are set based on Propositions 1-2 and meet the requirements of positivity and validity.

B. THE IMPACT OF REWARD-PENALTY INTENSITY ON EQUILIBRIUM SOLUTIONS

This subsection shows the impact of reward-penalty intensity on the equilibrium solutions, which is summarized in the following corollaries.

Corollary 1: The recycler's collection rate τ^{**} increases with k, while the prices of the new products and the remanufactured products p_n^{**} and p_r^{**} decrease with k.

We present the influence of RPM on decision variables in Figs. 3-4 when $c_n = 6$, $c_r = 3$, $c = 1$, $b = 3.5$, $\delta = 0.5$, $\phi = 10$, $\tau_0 = 0.5$. As shown in Fig. 3, the collection rate of WEEE increases with the increase of k. We also note that if the reward-penalty intensity k is relatively small, the recycler's collection rate may not reach the target value set by the government. With respect to the prices, Fig. 4 shows that the price of both new and remanufactured products decreases with the increase of k. This because with the increase of k, more WEEE is used for remanufacturing due to the enhancement of collection rate, thus reducing total remanufacturing cost. According to Proposition 2, the manufacturer will reduce the prices of products. Therefore, the greater the k becomes, the greater the space for cost savings is, thereby the prices fall accordingly.

Corollary 2: (1) The recycler's profit π_c^{**} increases with k. (2) There exists a threshold k^m of the reward-penalty intensity, when $2[b(b-c)+\delta m]\delta(1-\delta) > (b+m)$, for $0 < k < k^m$, the manufacturer's profit π_m^{**} decreases with k; for $k^m < k$, π_m^{**} increases with k; otherwise, for $0 < k < k^m$, π_m^{**} increases with k; for $k^m < k$, π_m^{**} decreases with k. Here, the expression of k^m is given in the proof.

We present the influence of RPM on profits in Figs. 5-6 when $c_n = 6$, $c_r = 3$, $c = 1$, $\delta = 0.5$, $\phi = 10$, $\tau_0 = 0.5$, $k \in (1, 8)$.

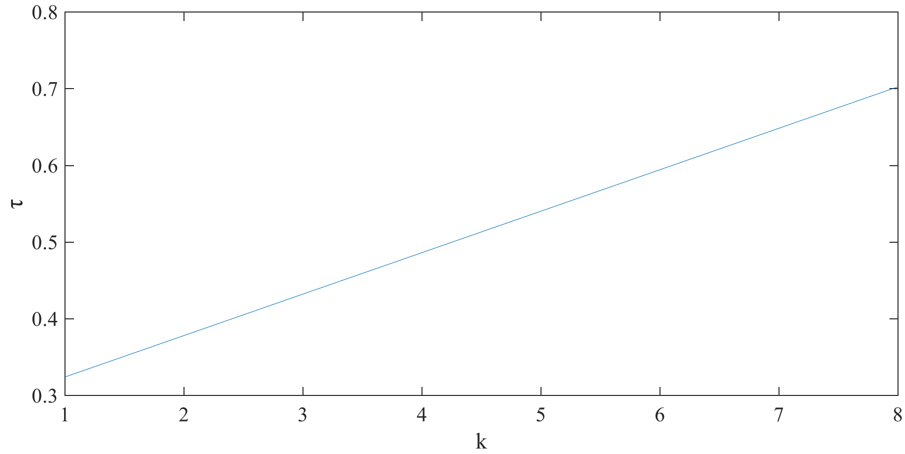

FIGURE 3. The collection rate τ vs. k.

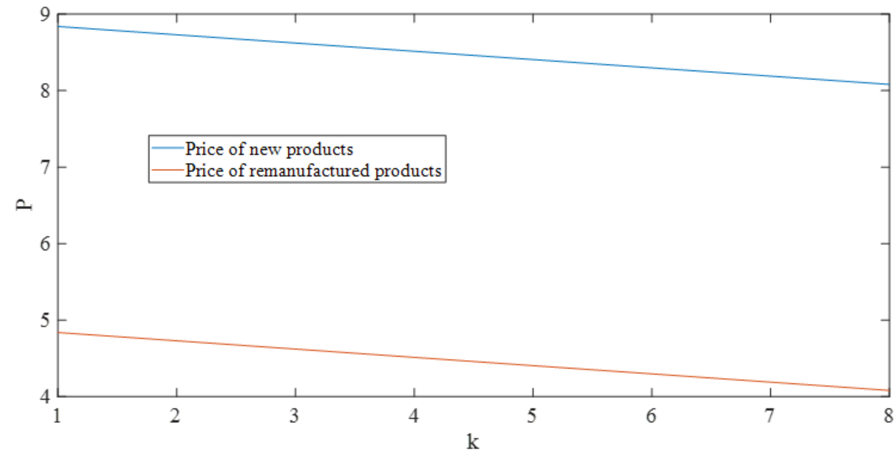

FIGURE 4. The price p vs. k.

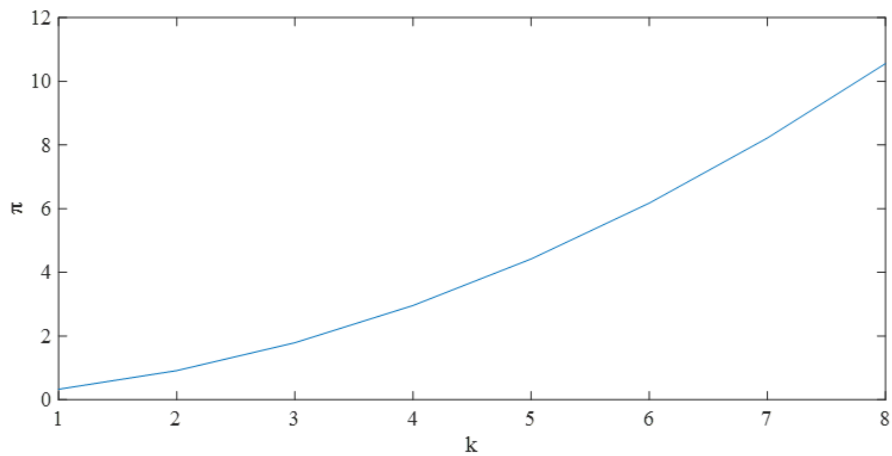

FIGURE 5. π_c^{**} vs. k.

As shown in Fig. 5, we note that the profit of the recycler increases with the increase of reward-penalty intensity k. The reason is that, although the recycler needs a certain cost for collecting WEEE, it will be compensated by manufacturer's buyback. If the collection rate of the recycler does not reach the target value set by the government, with the increase of k, the manufacturer faces greater economic penalties. In order to avoid being punished, the manufacturer will increase its buyback price to promote the collection rate of the recycler, so the profit of the recycler will increase.

With respect to the manufacturer, we also note that the impact of k on manufacturer's profit is related to the buyback

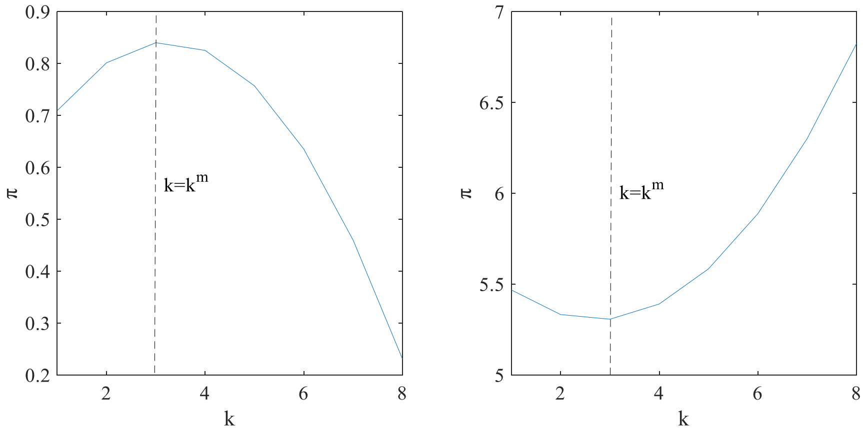

FIGURE 6. π_m^{**} **vs.** k **when** $b = 1.2$ **(left) and when** $b = 4.2$ **(right).**

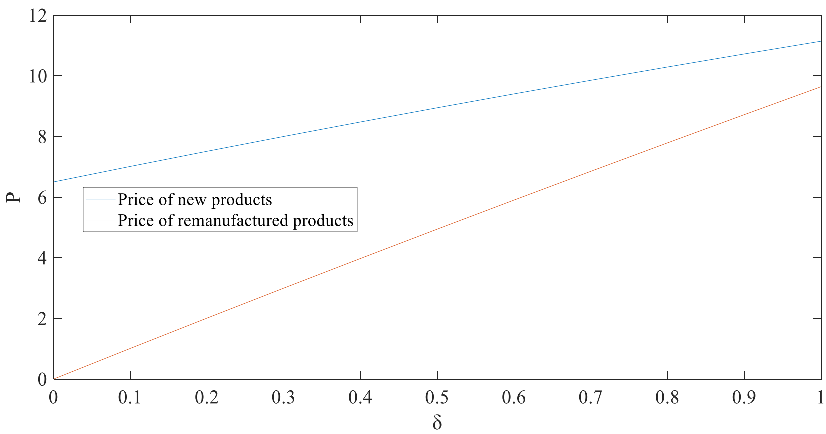

FIGURE 7. **The price** p **vs.** δ **without RPM.**

price b. As shown in the left diagram of Fig. 6, the condition $2[b(b-c)+\delta m]\delta(1-\delta) < (b+m)$ is satisfied when the manufacturer sets a low buyback price. In this case, the manufacturer's profit increases in k when $0 < k < k^m$ but decreases in k when $k^m < k$. This because the manufacturer is able to obtain more remanufacturing profits at a low buyback price. In this case, even if the collection rate is lower than the target value, because k is small, the manufacturer receives less economic penalties. However, as k increases, economic penalties become greater, resulting in the total profit of the manufacturer is declining. Conversely, when the manufacturer sets a high buyback price, even if the manufacturer obtains certain economic rewards, the total profit decreases because a small k is not enough to make up for the loss of remanufacturing profit. With the increase of k, economic rewards are increasing, as a result, the total profit of the manufacturer is increasing, as shown in the right diagram of Fig. 6.

C. THE PRICING DECISION VS. CONSUMENS PREFERENCES

This subsection examines the impact of consumer preferences on the pricing decision within the market segmentation framework.

Corollary 3: The prices p_n^* and p_r^* increase in δ under market segmentation without RPM, while the prices p_n^{**} and p_r^{**} decrease in δ under market segmentation with RPM when δ is sufficiently high.

We present the influence of consumer preferences δ on price decision in Figs. 7-8 when $c_n = 6, c_r = 3, c = 1, k = 4$, $\phi = 10$, $\tau_0 = 0.5$, $\sigma \in (0, 1)$. Corollary 3 indicates that the price of both new and remanufactured products is increasing in consumer preferences. This means that the manufacturer would raise prices in a market where consumers' valuations of remanufactured products are increasing (denoted by $\delta\phi$). This he does to increase his profitability. Moreover, it is less intuitive that RPM leads to lower product prices when δ is sufficiently high, as shown in Fig. 8. Regardless of other factors, when δ is sufficiently high, a rise in prices caused by consumers' valuations only leads to a slight decline in total demand (due to $\partial Q/\partial p_r = -1/\delta < 0$). However, RPM designed by the government not only reduces the prices of both new and remanufactured products, but also enhances the collection rate. This means that RPM generates a greater volume of WEEE to be use for remanufacturing, thereby reducing the prices, especially under high consumer preferences, the decline is even greater. Therefore, RPM lower the prices in response to higher consumer preferences.

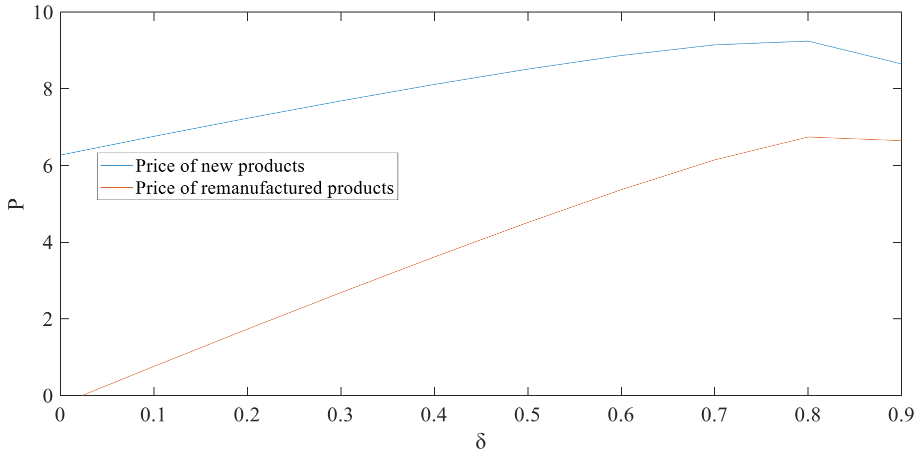

FIGURE 8. The price p vs. δ with RPM.

D. SOCIAL WELFARE AND ENVIRONMENT VS. REWARD-PENALTY INTENSITY

This subsection examines the impact of reward-penalty intensity on the social welfare and the environmental sustainability of CLSC. According to Wang *et al.* [4] and Chen and Akmalul'Ulya [6], the environmental damage function is defined as the total amount of uncollected WEEE multiplied by the unit hazard cost, i.e., $E = \varepsilon(1-\tau)Q$. Social welfare is composed of the profits of supply chain members, consumer surplus and environmental damage function, which can be expressed as $SW = \pi_m + \pi_c + CS - E$. Because the demand is linear, consumer surplus can be defined as $CS = Q^2/2$. Therefore, the environmental damage function and the social welfare under market segmentation without RPM are:

$$E^* = \varepsilon(1-\tau^*)(\phi - p_r^*/\delta)$$
$$SW^* = \pi_m^* + \pi_c^* + (\phi - p_r^*/\delta)^2/2 - E^*$$

The environmental damage function and the social welfare under market segmentation with RPM are:

$$E^{**} = \varepsilon(1-\tau^{**})(\phi - p_r^{**}/\delta)$$
$$SW^{**} = \pi_m^{**} + \pi_c^{**} + (\phi - p_r^{**}/\delta)^2/2 - E^{**}$$

We present the influence of RPM on the environmental damage function and the social welfare in Fig. 9 when $c_n = 6, c_r = 3, c = 1, b = 3.5, \delta = 0.5, \phi = 10, \tau_0 = 0.5, k \in (1, 8)$. For convenience, let $\varepsilon = 1$, which is consistent with that of Wang *et al.* [4] and Chen and Akmalul'Ulya [6]. As shown in Fig. 9, the environmental damage E with RPM is lower than it is without RPM. As k increases, the decreasing trend of E becomes obvious. This mainly because RPM effectively improves the collection rate of WEEE, thereby reducing the environmental damage caused by those uncollected WEEE. Fig. 9 also reveals that the social welfare increases in k, but only k is high, will the social welfare with RPM is higher than it is without RPM. The reason is that when k is low, the collection rate is low, resulting in greater environmental damage, and the manufacturer's profit would also be economically punished because of the low collection rate. The results numerically indicate that RPM is more desirable from the perspective of environmental improvement and social welfare.

VI. EXTENSION

A word of caution is needed that the above research assumes that the reward intensity is equal to the penalty intensity. In this section, we make a further consideration about more aspects of RPM by distinguishing the intensity of reward and penalty. How the government measures the difference between reward and penalty? Such a consideration has certain practical significance for studying the pricing and collecting decision of remanufacturing on a larger scale.

A. THE CASE WHERE REWARD AND PENALTY ARE OF DIFFERENCE

In this case, assume that k_r indicates the reward intensity when τ_r is higher than the target collection rate τ_0, and k_p denotes the penalty intensity when τ_p is lower than τ_0. Then, for calculation convenience, let $a = k_p/k_r$ represent the ratio of penalty to reward. Through the derivation of the formula yields the following proposition.

Proposition 3: The ratio $a \in [0, 1]$, i.e., the reward is always greater than the penalty.

In the case of RPM, because $\tau_r \geq \tau_0 \geq \tau_p$, we obtain that $k_r \geq k_p$, which suggests that the reward mechanism is dominant. In general, the reward is greater than the penalty is intuitive since the government needs to strike a balance between environmental benefits and economic benefits. Effective incentives can not only increase social and economic benefits, but also increase the collection rate, reduce resource consumption and minimize damage to the environment.

Base on the analysis above, we next seek influence of the change of a on decision variables and profits.

B. THE DECISION VARIABLES AND PROFITS VS. a

We use the values of parameters: $c_n = 6$, $c_r = 3$, $c = 1$, $b = 3.5$, $m = 1$, $\phi = 10$, $\delta = 0.5$ and $\tau_0 = 0.5$. In particular, from Fig. 3, we assume that $k_r = 1$, in which

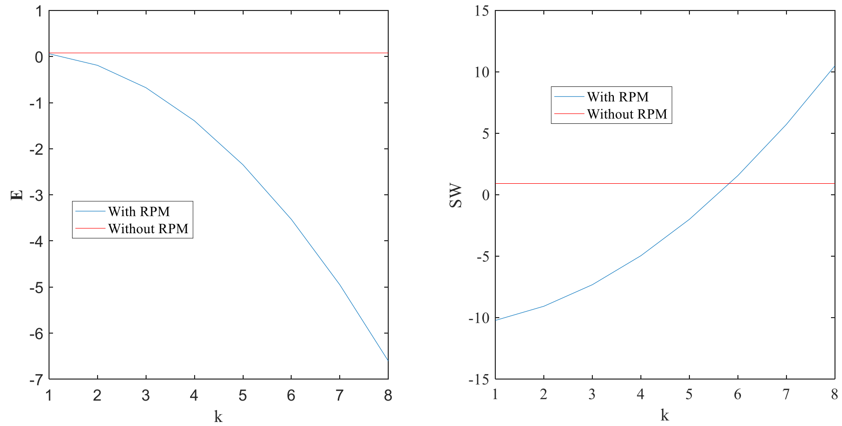

FIGURE 9. The E and SW vs. k.

TABLE 4. The results of decision variables and profits vs. a.

	$a=0.1$	$a=0.2$	$a=0.3$	$a=0.4$	$a=0.5$	$a=0.6$	$a=0.7$	$a=0.8$	$a=0.9$	$a=1$
p_n	8.94	8.92	8.91	8.90	8.88	8.87	8.86	8.86	8.85	8.85
p_r	4.94	4.92	4.91	4.90	4.89	4.88	4.87	4.86	4.85	4.84
τ	0.32	0.38	0.43	0.49	0.54	0.59	0.65	0.70	0.76	0.81
π_m	0.35	0.37	0.40	0.43	0.46	0.49	0.52	0.55	0.58	0.61
π_c	0.05	0.07	0.09	0.12	0.15	0.18	0.21	0.25	0.29	0.33

case the collection rate is lower than the target collection rate, thus the manufacturer is punished by the government (if the manufacturer is rewarded, we cannot discuss the value of a). We study the changes in the prices of new and remanufactured products, the profits of the manufacturer and the recycler as well as the collection rate when a goes from 0 to 1. The main results are summarized in Table 4.

Given a fixed k_r, we note from Table 4 that with the increase of a, the prices of new and remanufactured products both decrease slightly, while the profits of the manufacturer and the recycler as well as the collection rate of WEEE are increasing. Moreover, if the reward intensity is the same as the penalty intensity, i.e., $a = 1$, the manufacturer and the recycler can get the maximum profits. Because when the reward is more powerful than the penalty, the weak penalty may not be able to alert the manufacturer effectively. If the collection rate is lower than the target set by the government, the manufacturer will receive insufficient penalties. However, as penalty intensity increases, the penalty cost of the manufacturer deviating from the target collection rate increases, which significantly stimulates the remanufacturing activity of the manufacturer. At the same time, the recycler will have more incentive to collect the waste products due to extra profit caused by reward intensity, thereby increasing the collection rate. Therefore, the government should impose equal reward and penalty.

VII. CONSLUSION AND MANAGERIAL INSIGHTS

Due to different valuations for new products and remanufactured products, consumers have a different willingness to pay. Considering consumers' preferences, we separately set up CLSC models with and without RPM. Our models capture a market where remanufactured products are valued less than new products thereby identifying a potential low-end market. Through comparative analysis and numerical examples, the optimal solutions with and without RPM under the same parameters are compared, and the effects of reward-penalty intensity and consumer preferences on decision variables and profits of the manufacturer and the recycler are discussed. The following conclusions and insights can be summarized.

(i) We study an RPM composed of reward-penalty intensity and target collection rate to make recycling and remanufacturing activities beneficial to the economy and the environment. Our key findings are as follows. For the government, the introduction of RPM can always improve the environmental sustainability of CLSC and the social welfare. For the recycler, we find that as long as the government sets up an RPM, the recycler always gets part of the extra profit, which is the result of the increase in the collection rate of WEEE. This suggests that before bringing remanufacturing strategy into operation, it would be very significant in practice to invest in improving actual collection rate as the core of collecting decision. For the manufacturer, we find that the buyback price is a crucial element in determining an increase in the profit: when the government imposes a lower or a higher reward-penalty intensity, a higher buyback price makes the manufacturer more profit; on the contrary, when the government imposes moderate intensity of reward-penalty, a lower buyback price makes the manufacturer more profit. Our results provide a basis for how the manufacturer can make corresponding adjustments according to changes in reward-penalty intensity to maximize its own profit.

(ii) We characterize a special set of products in the sense that generating a demand for remanufactured products by selling new products, on which an increase in prices of two products is made due to consumer preferences. It is illustrated by the finding that selling new and remanufactured products at lower price is optimal under market segmentation on account of greater demand for remanufactured products. Moreover, the increase in reward-penalty intensity leads to a decrease in prices of new and remanufactured products and an increase in collection rate of WEEE, so as to supply more products in response to the increase of demand. These phenomena have implications for pricing decision that both manufacturer and recycler profit in the form of creating more future value rather than satisfying immediate value. Specific to the manufacturer, in a market where consumers have preferences for remanufactured products, and even the preferences may become higher and higher, the implementation of a low-price decision can increase total profit by selling new products and remanufactured products at lower prices in exchange for increased demand.

(iii) We extend basic model to the difference in reward-penalty intensity. With the increase of penalty intensity, i.e., the value of a gradually approaches 1, the members of the CLSC can continuously increase their profits, corresponding to the prices of new and remanufactured products fall less and less. When the penalty is equal in intensity to the reward, the prices will fall at a constant rate. This phenomenon reflects important policy implications that when designing a reward-penalty mechanism, the optimal combination is that reward equals penalty.

The research limitations and directions for future research are proposed below. First, this paper assumes the manufacturer and the recycler are monopolists in the market. One may deeply study the situation where competitions between multiple manufacturers or recyclers exist in the market. Second, in this study, the supply chain information is perfect symmetric. We can consider a decision model in the case of information asymmetry exists between the manufacturer and the recycler, which may yield interesting findings. We leave these questions for future research.

APPENDIX A1

Supplementary Derivation of Assumption 3:

We assume each consumer has a valuation of v for a new product, which is subject to uniform distribution of $[0, \phi]$, and the density function is

$$f(x) = \begin{cases} \dfrac{1}{\phi}, & x \in [0, \phi] \\ 0, & x \notin [0, \phi] \end{cases}$$

Then δv $(0 < \delta < 1)$ denotes the consumer valuation of a remanufactured product. The utilities that consumers obtain from new and remanufactured products are respectively given by

$$u_n = v - p_n$$
$$u_r = \delta v - p_r$$

To make sense of our research, we assume that $u_r > 0$ and $u_n > 0$, otherwise consumers will not buy any products. Then we discuss two cases: $u_n > u_r$ and $u_n < u_r$.

(1) $u_n > u_r$. The consumers only purchase new products. Substitute Eqs.(1) and (2) into the conditions $u_n > 0$ and $u_n > u_r$, we have $v > p_n$ and $v > (p_n - p_r)/(1-\delta)$. Then we consider two scenarios as follows:

(i) When $p_n > (p_n - p_r)/(1-\delta)$, i.e., $\delta < p_r/p_n$, we derive that $u_n > u_r$. In this case, consumers only purchase new products, and the demand of new products is

$$q_n = \phi \int_{p_n}^{\phi} f(x)dx = \phi - p_n$$

(ii) When $p_n < (p_n - p_r)/(1-\delta)$, i.e., $\delta > p_r/p_n$, we discuss the following two situations:

(a) When $(p_n - p_r)/(1-\delta) < \phi$, i.e., $\delta < 1 - (p_n - p_r)/\phi$, the demand of new products is

$$q_n = \phi \int_{(p_n - p_r)/(1-\delta)}^{\phi} f(x)dx = \phi - (p_n - p_r)/(1-\delta)$$

(b) When $(p_n - p_r)/(1-\delta) > \phi$, or $\delta > 1-(p_n - p_r)/\phi$, the consumers don't buy the new products.

(2) $u_n < u_r$. The consumers only purchase remanufactured products. Substitute Eqs. (1) and (2) into the conditions $u_r > 0$ and $u_n < u_r$, we have $p_r/\delta < v < (p_n - p_r)/(1-\delta)$. Then we consider two scenarios as follows:

(i) When $p_r/\delta < (p_n - p_r)/(1-\delta)$, i.e., $\delta > p_r/p_n$, we discuss the following two situations:

(a) When $(p_n - p_r)/(1-\delta) < \phi$, i.e., $\delta < 1 - (p_n - p_r)/\phi$, the demand of remanufactured products is

$$q_r = \phi \int_{p_r/\delta}^{(p_n - p_r)/(1-\delta)} f(x)dx = (p_n - p_r/\delta)/(1-\delta)$$

(b) When $(p_n - p_r)/(1-\delta) > \phi$, i.e. $\delta < 1-(p_n - p_r)/\phi$, the demand is

$$q_r = \phi \int_{p_r/\delta}^{\phi} f(x)dx = \phi - p_r/\delta$$

(ii) When $p_r/\delta > (p_n - p_r)/(1-\delta)$, i.e. $\delta < p_r/p_n$, $q_r = 0$.

In conclusion, the consumer's demand function for two products is

$$(q_n, q_r) = \begin{cases} (\phi - p_n, 0), & \delta < p_r/p_n \\ \left(\phi - \frac{p_n - p_r}{1-\delta}, \frac{p_n - p_r/\delta}{1-\delta}\right)\frac{p_r}{p_n} & < \delta < 1 - \frac{p_n - p_r}{\phi} \\ (0, \phi - p_r/\delta), & \delta > 1 - \frac{p_n - p_r}{\phi} \end{cases}$$

We don't consider the case where consumers only buy new products or remanufactured products. Thus, we assume that $\frac{p_r}{p_n} < \delta < 1 - \frac{p_n - p_r}{\phi}$ and derive the demand functions

$$p_n = \phi - q_n - \delta q_r$$
$$p_r = \delta(\phi - q_n - q_r)$$

APPENDIX A2

Proof of Proposition 1:

Part (1):

$$\tau^{**} - \tau^* = \frac{(b-c)(\delta\phi - c_r)}{2[b(b-c)+\delta m]} + \frac{(b-c)k}{2m\delta[b(b-c)+\delta m](1-\delta)} - \frac{(b-c)(\delta\phi - c_r)}{2[b(b-c)+\delta m]} = \frac{(b-c)k}{2m\delta[b(b-c)+\delta m](1-\delta)}$$

Since $\frac{(b-c)k}{2m\delta[b(b-c)+\delta m](1-\delta)} > 0$, we derive $\tau^{**} - \tau^* > 0$.

Part (2):

$$p_n^* - p_r^* = p_n^{**} - p_r^{**} = \frac{(1-\delta)\phi + (c_n - c_r)}{2} > 0,$$

$$p_n^{**} - p_n^* = p_r^{**} - p_r^* = -\frac{k}{2[b(b-c)+\delta m](1-\delta)} < 0.$$

Therefore $p_n^* > p_n^{**} > p_r^{**}$ and $p_n^* > p_r^* > p_r^{**}$ holds. Furthermore,

$$p_n^{**} - p_r^* = \frac{[(1-\delta)\phi + (c_n - c_r)][b(b-c)+\delta m](1-\delta) - k}{2[b(b-c)+\delta m](1-\delta)}.$$

Thus, when $k < k^P$, $p_n^{**} > p_r^*$; when $k > k^P$, $p_n^{**} < p_r^*$, where $k^P = [(1-\delta)\phi + (c_n - c_r)][b(b-c)+\delta m](1-\delta)$. By sorting out the above comparison results, we obtain results of Proposition 1.

Proof of Proposition 2:

To simplify the calculation, we first determine two formulas $S = b(b-c) + \delta m$ and $Y = \delta\phi - c_r$. According to previous assumptions, we have $b > c$ and $\delta\phi - c_r \geq 0$. Thus $S > 0$ and $Y > 0$.

Because

$$\pi_c^{**} - \pi_c^* = \frac{(b-c)^2[(Y + k/2m\delta(1-\delta))]}{4\delta(1-\delta)S^2} > 0,$$
$$\pi_c^{**} > \pi_c^*.$$

Then,

$$\pi_m^{**} - \pi_m^* = \frac{(b-c)[2S\delta(1-\delta) - (b+m)]}{4m\delta^2(1-\delta)^2S^2}k^2 + \left[\frac{Y(b-c)\left(s + b/\delta^2\right)}{2S^2} - \tau_0\right]k + \frac{Y^2b^3(b-c)}{4S\delta} - \frac{b(b-c)\left[b(b-c)+\delta^2 m\right]}{4S^2\delta^2} - \frac{Y^2b^2\left(b^2-1\right)(b-c)^2}{4S^2\delta}.$$

Note that our analysis focuses on real-valued solutions and attempts to determine the effective range of reward-penalty intensity, so the primary condition should be satisfied that $B^2 - 4AD > 0$, where

$$B = \left[\frac{Y(b-c)\left(s + b/\delta^2\right)}{2S^2} - \tau_0\right]$$
$$A = \frac{(b-c)[2S\delta(1-\delta) - (b+m)]}{4m\delta^2(1-\delta)^2S^2}$$
$$D = \frac{Y^2b^3(b-c)}{4S\delta} - \frac{b(b-c)\left[b(b-c)+\delta^2 m\right]}{4S^2\delta^2} - \frac{Y^2b^2\left(b^2-1\right)(b-c)^2}{4S^2\delta}$$

When $B^2 - 4AD > 0$ holds, we consider two positive real-valued solutions:

$$k1 = -\frac{B}{2A} - \frac{\sqrt{B^2 - 4AD}}{2A} \quad \text{and}$$
$$k2 = -\frac{B}{2A} + \frac{\sqrt{B^2 - 4AD}}{2A}.$$

Then we discuss two cases: $A > 0$ and $A < 0$. It is obvious that

1) When $A > 0$, i.e., $2S\delta(1-\delta) > (b+m)$, if $0 < k < k1$ or $k > k2$, then $\pi_m^{**} > \pi_m^*$; if $k1 < k < k2$, then $\pi_m^{**} < \pi_m^*$.
2) When $A < 0$, i.e., $2S\delta(1-\delta) < (b+m)$, if $0 < k < k1$ or $k > k2$, then $\pi_m^{**} < \pi_m^*$; if $k1 < k < k2$, then $\pi_m^{**} > \pi_m^*$.

Therefore, proposition 2 is proved

Proof of Corollary 1:

$$\frac{\partial p_n^{**}}{\partial k} = \frac{\partial p_r^{**}}{\partial k} = \frac{-1}{2[b(b-c)+\delta m](1-\delta)} < 0 \quad \text{and}$$
$$\frac{\partial \tau^{**}}{\partial k} = \frac{b-c}{2[b(b-c)+\delta m](1-\delta)} > 0.$$

Therefore, we obtain results of Corollary 1.

Proof of Corollary 2:

Part (1):

$$\frac{\partial \pi_c^{**}}{\partial k} = \frac{(b-c)^2\left[(\delta\phi - c_r) + \frac{k}{m\delta(1-\delta)}\right]}{4\delta[b(b-c)+\delta m]^2(1-\delta)} > 0.$$

Part (2):

Combined with Proposition 3, the profit of the manufacturer can be rewrite as

$$\pi_m^{**} = \frac{(b-c)[2S(1-\delta)-(b+m)]}{4m\delta^2(1-\delta)^2S^2}k^2 + \left[\frac{Y(b-c)(S+b/\delta^2)}{2S^2} - \tau_0\right]k + \frac{(\phi-c_n)^2}{4(1-\delta)} + \frac{Y(2\delta c_n - \phi\delta - c_r)}{4\delta(1-\delta)} - \frac{b(b-c)Y^2[b(b-c)+\delta^2 m]}{4\delta^2 S^2}.$$

Note that π_m^{**} is a quadratic equation of one variable with respect to k, so there is a symmetry axis $k^m = -B/2A$, such that when $2S\delta(1-\delta) > (b+m)$, for $0 < k < k^m$, $\partial\pi_m^{**}/\partial k < 0$; for $k > k^m$, $\partial\pi_m^{**}/\partial k > 0$; when $2S\delta(1-\delta) < (b+m)$, for $0 < k < k^m$, $\partial\pi_m^{**}/\partial k > 0$; for $k > k^m$, $\partial\pi_m^{**}/\partial k < 0$.

Therefore, Corollary 2 is proved.

Proof of Corollary 3:

$$\frac{\partial p_n^*}{\partial\delta} = \frac{\phi b^2(b-c)^2 + bmc_r(b-c)}{2[b(b-c)+\delta m]^2} > 0,$$
$$\frac{\partial p_r^*}{\partial\delta} = \frac{\phi b^2(b-c)^2 + bmc_r(b-c)}{2[b(b-c)+\delta m]^2} + \frac{\phi}{2} > 0,$$
$$\frac{\partial p_n^{**}}{\partial\delta} = \frac{\partial p_n^*}{\partial\delta} + \frac{km(1-\delta) - k[b(b-c)+\delta m]}{2[b(b-c)+\delta m]^2(1-\delta)^2},$$
$$\frac{\partial p_r^{**}}{\partial\delta} = \frac{\partial p_n^*}{\partial\delta} + \frac{\phi}{2} + \frac{km(1-\delta) - k[b(b-c)+\delta m]}{2[b(b-c)+\delta m]^2(1-\delta)^2}.$$

Note that the sign of formulas $\partial p_n^{**}/\partial\delta$ and $\partial p_r^{**}/\partial\delta$ depends on the sign of formula $\frac{km(1-\delta)-k[b(b-c)+\delta m]}{2[b(b-c)+\delta m]^2(1-\delta)^2}$. Through simple judgment, there are monotone increasing intervals and monotone decreasing intervals with δ as the boundary, which is supplemented by numerical simulation.

Proof of Proposition 3:

When collection rate exceeds the target collection rate τ_0, government implements incentives, the corresponding reward intensity and collection rate are expressed as k_r and τ_r. Similarly, when collection rate is lower than the target collection rate, the corresponding penalty intensity and collection rate are denoted by k_p and τ_p, i.e., ak_r and τ_p. According to the expression of τ^{**}, we have

$$\tau_r = \frac{(b-c)(\delta\phi - c_r)}{2[b(b-c)+\delta m]} + \frac{(b-c)k_r}{2m\delta[b(b-c)+\delta m](1-\delta)}$$
$$\tau_p = \frac{(b-c)(\delta\phi - c_r)}{2[b(b-c)+\delta m]} + \frac{(b-c)ak_r}{2m\delta[b(b-c)+\delta m](1-\delta)}$$

Based on RPM, the collection rate under different conditions satisfies $\tau_r \geq \tau_0 \geq \tau_p$, thereby we can derive that $k_r \geq ak_r$, i.e. $0 \leq a \leq 1$. Proposition 3 is then proved.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this article, and it is the original research that has not been published previously, and not under consideration for publication elsewhere.

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