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Research article

How strategic consumers shape manufacturer refurbishment strategies under collection target

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Abstract: This paper examines a critical challenge in the circular economy: How manufacturers can formulate profitable refurbishment strategies under mandatory collection targets when facing strategic consumers. We develop a two-period game-theoretic model in which the manufacturer's collection effort is constrained by an exogenously mandated collection target. Our analysis examines the viability of refurbishment as a function of this target, the quality of the refurbished products, and the consumers' willingness to wait. We reveal the following key insights: (1) Stringent collection targets can paradoxically suppress refurbishment activities by forcing manufacturers to collect beyond economically viable limits; (2) refurbishment becomes profitable only when the quality of refurbished products is sufficiently high to offset cannibalization effects on new product sales; (3) the impact of strategic consumers' behavior on social welfare varies significantly across different compliance scenarios, with increased consumer patience sometimes reducing overall welfare; and (4) in competitive settings, a manufacturer's all-collection strategy can serve as an effective barrier to entry against independent refurbishers. Our findings offer valuable insights for policymakers designing product take-back regulations and for manufacturers developing circular economy strategies in markets with strategic consumers.

Keywords: strategic consumers; collection target; refurbishment; social welfare; game theory
Mathematics Subject Classification: 91-10, 91B42

1. Introduction

According to the Global E-waste Monitor 2024, 62 million tonnes of electronic waste (e-waste) were generated globally in 2022. Regrettably, approximately 77.7% of this e-waste was neither formally collected nor recycled, despite its potential to cause significant environmental contamination. Moreover, e-waste often contains toxic additives and hazardous substances, such as mercury, which can impair human brain development and neurological function. In response to this increase in e-waste generation, numerous countries have enacted take-back regulations to encourage the proper disposal and reuse of these products. For instance, the European Union's Waste Electrical and Electronic Equipment (WEEE) Directive establishes collection targets to hold producers accountable for the end-of-life management of their products [1]. Similarly, Japan's Home Appliance Recycling Law mandates that manufacturers take physical and financial responsibility for recycling specific categories of appliances, such as air conditioners and refrigerators [2].

However, a significant implementation gap has emerged, revealing a critical dilemma for manufacturers. There is a growing disconnect between the policy aim of promoting a high-value circular economy and the operational reality on the ground. To comply with stringent collection targets, manufacturers may face perverse incentives to prioritize the volume of collected items over their quality or suitability for refurbishment. In practice, this can lead to the paradoxical outcome where high collection rates are achieved, but largely through recycling low-value materials, while economically and environmentally superior refurbishment activities are scaled back or abandoned. This tension between regulatory compliance and profitable value retention forms the core practical problem that this study seeks to address.

To meet the collection target imposed by take-back regulations, manufacturers typically collect a proportionate amount of their end-of-life products [3]. For example, a manufacturer producing 100 units with a 50% collection target must collect at least 50 units. However, whether to collect only the mandated minimum or to exceed it is a strategic decision that underpins subsequent operational choices. A pivotal aspect of reverse supply chain management is the refurbishment strategy—a strategic framework that dictates whether to restore collected products to a functional state and, if so, to what extent (e.g., basic repairs, component replacement, or full-scale reconditioning). This dual focus on collection thresholds and refurbishment intensity highlights the interdependent nature of these strategic choices in optimizing resource utilization and cost-efficiency. Notwithstanding the considerable progress in collection and refurbishment—evidenced by KMK Metal Recycling's 65% collection rate under the WEEE Directive and Röhm/Nextchem's chemical recycling of PMMA (Poly(methyl methacrylate)) waste—a pivotal factor is frequently disregarded. This factor, strategic consumer behavior, can fundamentally disrupt or enhance these meticulously designed operational processes.

Strategic consumers expect future market developments and do not base their purchases solely on their immediate needs [4]. Within regulated take-back systems, their behavior critically impacts manufacturers' collection and refurbishment operations. For example, value-conscious consumers often defer purchases, awaiting price drops or refurbished versions. A case in point is Apple's release of a certified refurbished MacBook Air shortly after the new model's launch in 2023. This early availability heightens the consumer's buy-now-or-wait dilemma, potentially cannibalizing new product sales and disrupting reverse supply chains. Furthermore, strategic consumers' expectations regarding the quality and pricing of refurbished goods can significantly influence the demand for both new and refurbished products. If strategic consumers perceive that future refurbished products will offer comparable quality at a lower cost, they are more likely to defer their purchases. This behavior presents both an opportunity and a challenge for the refurbishment industry. The industry's growth depends on meeting these high consumer expectations; failure to do so could undermine the economic viability of the entire refurbishment ecosystem.

In short, the manufacturer must balance its dual roles as a seller and a collector–refurbisher in the face of strategic consumers. This challenge gives rise to two core research questions: What is the impact of strategic consumers on a manufacturer's optimal collection and refurbishment strategies? How should a manufacturer choose these strategies under the constraints of collection targets?

To address these questions, we develop a two-period supply chain model subject to a collection target. In this model, the manufacturer is responsible for production, sales, and collection. Consumers strategically choose which product (new or refurbished) to purchase and when to purchase it (in the first or second period). The manufacturer must therefore decide its collection quantity and the portion to refurbish in the second period.

The findings indicate that, in addition to the collection target and the quality of refurbished products, the consumers' willingness to wait is a key determinant of the manufacturer's optimal collection and refurbishment strategies. When the manufacturer meets the collection target, a higher consumer willingness to wait increases the volume of refurbishment. Conversely, when the manufacturer exceeds the collection target, a lower willingness to wait can undermine the policy's effectiveness, prompting the manufacturer to collect less.

Our discussion then focused on the manufacturer's profits and the consumer surplus. We found that an increase in consumers' willingness to wait reduces the manufacturer's total profit. However, it also creates an opportunity for profit from refurbishment activities, which, in turn, helps the manufacturer meet the collection target more easily. Furthermore, a higher willingness to wait can increase the consumer surplus, as consumers benefit when the manufacturer exceeds the collection target.

The last section extends the analysis to social welfare and the potential market entry of an independent refurbisher. From the government's perspective, an increase in consumers' willingness to wait can improve social welfare when the manufacturer meets the collection target. However, if the manufacturer voluntarily exceeds the target, a higher willingness to wait may reduce social welfare. The potential entry of a refurbisher significantly influences the manufacturer's collection and refurbishment decisions while providing consumers with more options. In some cases, the manufacturer may forgo refurbishment when consumers show little willingness to wait. Conversely, when consumers are sufficiently patient, the manufacturer can use an all-collection strategy to block the refurbisher's market entry.

The remainder of the paper proceeds as follows. Section 2 introduces the related literature and identifies the research gaps. Section 3 presents the model and notation employed in this paper. Section 4 outlines the impact of consumers' willingness to wait on collection and refurbishment strategies, and analyzes the profits and consumer surplus. Section 5 provides an extended discussion of social welfare, reuse efficiency, and the situation where a refurbisher enters the market. The final section concludes the paper and proposes managerial insights.

2. Literature review

This paper is chiefly related to collection and refurbishment under take-back regulations and strategic consumers, each of which is reviewed as follows.

2.1. Take-back regulations

The research conducted in this paper is pertinent to studies that consider situations in which governments implement take-back regulations. For a firm, a take-back regulation can be considered as a behavioral constraint [5] or an expression of environmental responsibility [6]. The prevailing regulation models for product collection primarily encompass tax-based and collection rate-based approaches. The fundamental principle of the tax model is the imposition of environmental taxes on products, utilizing economic incentives to guide market entities in reducing environmental harm and ultimately achieving environmental protection objectives [7]. The collection rate model is a key element in this framework, with governments typically establishing explicit collection targets for waste products [3]. These targets serve to constrain corporate recycling practices, thereby facilitating the implementation of extended producer responsibility (EPR). An examination of product collection regulatory mechanisms from the perspective of "behavioral constraints" illuminates that within the collection rate model, collection targets directly become significant constraints in manufacturers' pursuit of profit maximization. This has compelled them to optimize collection processes and enhance their recycling efficiency. For instance, Xu et al. [8] analyzed the optimal output problem under the manufacturer's collection target constraint. In the context of environmental responsibility, two perspectives emerge for consideration when addressing the environmental benefit problem. First, the collected products can contribute to the utility of reductions in environmental pollution [9]. Second, the environmental impact of the entire process can be measured from the perspective of product life cycle assessment (LCA) [10]. In our model's setting, we follow the approach of considering the take-back regulation to be a constraint on the manufacturer's behavior by embedding the collection target into a minimum requirement for the manufacturer's collection volume. Moreover, the LCA method is utilized for calculating the environmental benefits. Although similar trade-offs have been considered in previous literature, this paper focuses more on dynamic settings, such as the consumer waiting and the delayed appearance of refurbished products as vulnerable products.

2.2. Collection and refurbishment strategies

Research on collection and refurbishment strategies has evolved to address various operational decisions, yet a critical gap remains in integrating regulatory constraints with strategic consumers' behavior. Early foundational work established the environmental and economic rationale for these practices, demonstrating that collection under take-back regulation promotes sustainability [11,12] and that refurbishment can be a profitable endeavor [13−16]. A pivotal framework for this discourse is the categorization of collection into voluntary and mandatory approaches [17], which our study builds upon. However, the literature has largely developed along two parallel, yet seldom intersecting, paths—each offering deep insights but also possessing inherent blind spots. One significant stream has extensively analyzed competitive dynamics and market outcomes, such as the competition between new and refurbished goods [18,19] and the impact of patent licensing [20]. For instance, Zheng et al. [19] crucially found that refurbished products can reduce consumers' willingness to purchase, highlighting the role of consumers' preferences. However, these models of competition and consumer response predominantly operate in a context that is free from binding policy mandates. Conversely, research focusing on critical operational factors under these regulations, such as refurbishment quality decisions [21], often treats consumer demand as static or myopic. This stream provides valuable insights into compliance and operational efficiency but frequently fails to incorporate the forward-looking, strategic waiting behavior of consumers—a factor that can dramatically alter the profitability and feasibility of refurbishment. This bifurcation has created a divided analytical landscape. Studies incorporating strategic consumers typically lack a regulatory dimension, whereas studies analyzing regulatory compliance often assume simplistic consumer behavior. Consequently, the core interactive tension—how a manufacturer's compliance with a mandatory collection target dynamically interacts with its refurbishment strategy when the consumers are strategic—remains inadequately understood. The simultaneous pressure from both policy and strategic market behavior constitutes a distinct and underexplored decision-making scenario. Our study aims to bridge this divide by directly confronting this tension. We integrate these two disjointed streams by investigating how a manufacturer's optimal strategy is shaped under the dual pressure of binding regulatory targets and strategic consumer patience. This approach allows us to address a question that previous research, by focusing on either aspect in isolation, has not been able to fully answer.

2.3. Strategic consumers

A substantial corpus of literature examines strategic consumer behavior in operational contexts, where forward-looking customers expect future price reductions or product availability [22,23]. This research has demonstrated that strategic waiting necessitates sophisticated intertemporal pricing strategies by firms. However, the application of this theory to closed-loop supply chains (CLSCs) remains nascent and critically limited. Existing studies have primarily explored these dynamics in simplified settings, such as monopoly markets [24] or single-product scenarios [25,26]. Though recent work has begun to introduce competition, such as Yang and Wu [27], who studied inter-firm rivalry, a pivotal context is consistently missing: The presence of binding take-back regulations. This omission creates a significant gap in our understanding. In the regulated CLSC context that we study, the manufacturer's problem is not merely one of pricing to manage strategic waiting or competing with a refurbisher. It is a complex, three-way trade-off: The firm must simultaneously (1) comply with a mandatory collection target (a regulatory constraint) (2) manage the cannibalization between new and self-produced refurbished products (an operational challenge, and (3) counteract the strategic delay of consumers who expect the launch of lower-priced refurbished goods (a behavioral challenge). To the best of our knowledge, no extant study has hitherto attempted to integrate these three forces. The extant literature on strategic consumers has neglected to address the regulatory compulsion to collect, whereas the literature on take-back regulations has frequently assumed simplistic and myopic consumer behavior. The present study addresses this lacuna in the existing literature. The integration of the strategic consumer paradigm into the regulated CLSC model enables us to transition from a focus on pricing and competition to a more fundamental inquiry. The study will explore how the strategic consumers' willingness to wait affects the manufacturer's core collection and refurbishment strategy when the manufacturer is under pressure from a policy target. This provides meaningful insights into the complex interplay among environmental policy, competitive operational decisions, and micro-level consumer behavior.

Our study makes the following key contributions to the literature on CLSCs under regulation. (1) Integrating strategic consumers into regulated CLSC models: A novel analytical model was developed that incorporates strategic consumer behavior (i.e., intertemporal choice) into the study of take-back regulations. This enables the simultaneous endogenization of the decision-making process of consumers in regard to the choice of product (new or refurbished) and the source of purchase (manufacturer or independent refurbisher), under the binding constraint of a collection target. (2) Characterizing optimal strategies under a triple trade-off: We characterize the manufacturer's optimal collection and refurbishment strategies as a function of the key parameters (e.g., refurbished quality, willingness to wait), revealing that the optimal decision is determined by a critical triple trade-off between complying with the regulations, managing cannibalization, and mitigating strategic consumers' delay. (3) Unveiling the preemptive role of the collection strategy: When the model is extended to a competitive setting, a novel finding is revealed, namely that the manufacturer's optimal collection strategy can serve as a preemptive barrier to entry against an independent refurbisher. This identifies a strategic motive for collection that has hitherto been the subject of only limited exploration, namely the pursuit of regulatory compliance.

3. Model

3.1. The manufacturer's decision

We consider a market of consumers that can be served by a manufacturer(M) over two periods and a policy imposing a take-back regulation requiring the manufacturer to meet the collection target. Thus, the manufacturer not only provides new products throughout the period (t=1,2) but also collects end-of-life items from the early period (t=1) and sells refurbished goods in the late period (t=2). To match the real situation, we assume the new products have the same quality, which does not vary across the periods. However, since the materials used in refurbished products are derived from collected products, refurbished products usually differ from new products in terms of quality and performance. Without loss of generality, we normalize the quality of new products to be 1 and set α as the quality of refurbished products, where $0<\alpha<1$ should be held. To distinguish between the production costs of new and refurbished products, we denote the cost of new products as c_n and the cost of refurbished products as c_r. Here, following previous research [16], we define $c_r < c_n\alpha$, which ensures that refurbishment is cost-effective.

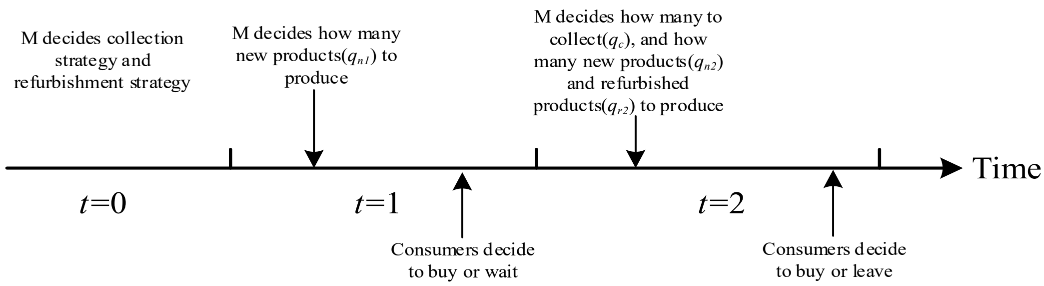

Figure 1. Strategy decision sequence.

The strategy decision sequence is illustrated in Figure 1. A three-stage sequence is adopted to capture the hierarchical nature of strategic and operational decisions in a regulated environment. The first stage (*t=0*) reflects the long-term, sunk investments a manufacturer must make in its circular economy capabilities prior to market entry, a realistic feature of many industries. Then the manufacturer enters the market at $t=1$ and decides how many new products q_{n1} to provide. Subsequently, consumers arrive and decide whether to make a purchase immediately or defer until the next period. At the start of the $t=2$ period, the manufacturer decides the quantity of end-of-life items to be collected (q_c), as well as the number of new (q_{n2}) and refurbished products (q_{r2}) to be produced. Finally, the consumers arrive and decide on the purchase of either of the two products, or else they choose to leave the market without making a purchase. This structure allows us to cleanly separate the firm's strategic commitment from its subsequent operational decisions, thereby providing a sharp analytical lens through which to examine how these commitments shape and are shaped by strategic consumer behavior under a binding collection target. This commitment assumption is also a standard analytical tool in game-theoretic models [27] that allows us to derive a clear benchmark equilibrium and cleanly isolate the strategic interactions among the firm, the consumers, and regulations.

In our model, the manufacturer's dual role encompasses both the provision of goods to the market and the pursuit of the collection target (β_c), which is derived from the take-back regulation. Therefore, we have $\beta_c q_{n1} \le q_c \le q_{n1}$. According to previous research [28], we assume that the collection costs incurred by the manufacturer are $k_c q_c^2 / 2$, where k_c represents the collection factor. In addition, the materials utilized in the production of refurbished products are derived from collected items and, as such, are subject to the requirement $0 < q_{r2} < q_c$. Ultimately, the manufacturer's expected profit in the t=2 period can be written as

$$M_2 = (p_{n2} - c_n) q_{n2} + (p_{r2} - c_r) q_{r2} - k_c q_c^2 / 2$$
$$s.t. \begin{cases} \beta_c q_{n1} \le q_c \le q_{n1} \\ q_{r2} \le q_c \\ q_c \ge 0, q_{r2} \ge 0 \end{cases} \quad (1)$$

The manufacturer's problem in the first period is to choose p_{n1} to maximize its total profit across both periods, which is given by $M_1 = (p_{n1} - c_n) q_{n1} + M_2$, where M_2 is the value function derived from solving the second-period problem. Therefore, the total expected profit in the t=1 period is as follows:

$$M_1 = (p_{n1} - c_n) q_{n1} + M_2 \quad (2)$$

3.2. The strategic consumer

A consumer's price perception of an individual product depends on its quality (q) and is given as vq, where v represents the heterogeneity of consumers in making price judgments about a product and follows a uniform distribution between 0 and 1. However, the manufacturer does not know in advance the exact value of a consumer's price perception, except the distribution of v. Thus, a consumer with v values the new products at v (the quality of new products is normalized to 1) and values the refurbished products at αv (the quality of refurbished products is $q=\alpha$).

We consider a fixed market of consumers who are present at the beginning of the planning horizon. This two-period model captures the intertemporal choice of consumers regarding their purchasing timing, rather than the usage duration of a product. Specifically, consumers who purchase a new product in the first period exit the market and derive utility from its use for that period. The strategic decision for consumers is therefore whether to buy a new product immediately in Period t=1 or to deliberately wait until Period t=2 to purchase a refurbished product (or a leftover new product), weighing the trade-off between earlier ownership and a potential price discount. This modeling approach is standard in the literature on strategic consumers and durable goods [27] and allows us to cleanly analyze the impact of waiting behavior on the manufacturer's optimal strategy. Moreover, if there are two types of products (new and refurbished) in Period t=2, consumers also decide which one to buy or just leave the market without buying. In the event of a purchase being made in Period 2, the consumer's utility is discounted by δ ($0 \le \delta \le 1$), which is indicative of the consumer's propensity to wait. Therefore, the utility of the consumer buying the new product is $U_{nt} = \delta^{t-1}\left(v - p_{nt}\right)$, and the utility is $U_{r2} = \delta\left(\alpha v - p_{r2}\right)$ if the consumers choose refurbished products. In the case where consumers do not buy any product, we set their utility to 0. Therefore, the purchase decision of the consumer in Period t is as follows:

$$U_t^* = max\left\{\delta^{t-1}\left(v - p_{nt}\right), \delta\left(\alpha v - p_{r2}\right), 0\right\} \tag{3}$$

It is evident that consumers will purchase in the $t=1$ period if $U_1^* > U_2^*$ and will defer their purchases until the t=2 period if $U_1^* < U_2^*$. If $U_1^* = U_2^* = 0$, consumers will exit the market without making a purchase.

To simplify the model, it is necessary to normalize the market size to 1. The demand for the products in different periods is contingent upon their qualities and the firm's pricing strategy. When consumers arrive at the market in the first period (t = 1), they are only able to observe the price of the new product (p_{n1}), but they can form a belief about the price p_{n2} in the next period (t=2). The consumers can make purchasing decisions in Period t=1 based on their observations and beliefs. In this study, the assumption [27] is made that strategic consumers possess rational expectations, thereby ensuring that their beliefs are accurate in a state of equilibrium.

Subsequently, utilizing the principle of consumer utility, we derive the demand function for each period. A consumer with the valuation v chooses to purchase in Period t=1 if $v - p_{n1} > \delta\left(v - \overline{p}_{n2}\right)$, which is equivalent to $v \ge \overline{v} = \frac{p_{n1} - \delta \overline{p}_{n2}}{1-\delta}$ if $v - \overline{p}_{n2} > \alpha v - \overline{p}_{r2}$. Notably, $\overline{p}_{n2}$ indicates the consumer's price beliefs in Period t=1 for the next period, which, under rational expectation, is equal to the endogenous equilibrium price (p_{n2}^*) in the subgame. Thereby, the demand in Period t=1 is $q_{n1} = 1 - \overline{v}$. During the second period, a consumer with the valuation v chooses to purchase new products if $\delta\left(v - p_{n2}\right) > \delta\left(\alpha v - p_{r2}\right)$, which is equivalent to $v \ge v^* = \frac{p_{n2} - p_{r2}}{1-\alpha}$, or the consumer will buy refurbished products if $v < v^* = \frac{p_{n2} - p_{r2}}{1-\alpha}$, where $v > \frac{p_{r2}}{\alpha}$ should be held. However, when $v < \frac{p_{r2}}{\alpha}$, consumers will leave the market without buying anything. Finally, the demand for new products in Period t=2 is $q_{n2} = \overline{v} - v^*$, and the demand for refurbished products is $q_{r2} = v^* - \frac{p_{r2}}{\alpha}$. Table 1 contains all the parameters, decision variables, and objectives used in our model.

Table 1. Notation used.

Parameter	
c_n	Unit cost of the new product
c_r	Unit cost of the refurbished product
α	The quality of the refurbished product
β_c	Collection target
k_c	Collection factor
δ	Consumer's willingness to wait
Decision variable	
q_{n1}	Number of new products in the first period
q_{n2}	Number of new products in the second period
q_c	Number of collected products
q_{r2}	Number of refurbished products in the second period
p_{n1}	Unit price of new products in the first period
p_{n2}	Unit price of new products in the second period
p_{r2}	Unit price of refurbished products in the second period
Objective	
M_1	The manufacturer's profit in the two periods
M_2	The manufacturer's profit in the second period
CS	Consumer surplus
E	Environmental benefit
SW	Social welfare

4. Analysis

We solve the model via backward induction using the Lagrangian first-order conditions. For each scenario, we first derive the demand in both periods from the consumers' utility maximization, then solve for the manufacturer's optimal production decisions. This section first characterizes the manufacturer's optimal collection and refurbishment strategies under the influence of strategic consumers. We then analyze the resulting implications for the manufacturer's profits and consumer surplus.

4.1. Collection and refurbishment strategies of the manufacturer

The take-back regulation constrains the collection behavior of the manufacturer, which has a direct impact on the production of new products as well as the reuse stage, so we first analyze the possible collection strategies of the manufacturer.

Lemma 1. There will be three collection strategies for the manufacturer under the take-back regulation, as follows:

(1) Mandatory compliance mode (C_0): The manufacturer will collect enough products to achieve the collection target;

(2) Voluntary compliance mode (C_+): The manufacturer will overachieve the collection target;

(3) Perfect compliance mode ($C_=$): As a special case of the voluntary mode, the manufacturer will collect all products.

Lemma 1 indicates that the manufacturer's willingness to collect may differ under the take-back regulation. For example, if the collection target is too high, the manufacturer may choose the mandatory compliance mode to achieve the collection target. However, if refurbishment is profitable, the manufacturer may overachieve the collection target and sell refurbished products. When the manufacturer tries to collect all end-of-life items, this will be the optimal solution for extended producer responsibility. However, the situation where the manufacturer cannot achieve the collection target is not discussed in this paper, because manufacturers who fail to meet the collection target will be fined or banned by the government (such as Northern Compliance Ltd, UK).

Next, we characterize the manufacturer's possible refurbishment strategies under different collection strategies. For simplicity, we use R_j to denote the manufacturer's refurbishment strategies, where $j \in \{0,+,=\}$ represents no refurbishment, some refurbishment, and refurbishment of all.

Proposition 1. The necessary conditions of refurbishment for the manufacturer in C_0 mode are as follows:

(1) Scenario C_0R_0: $\beta_c \le 1/\sqrt{2k_c}$;

(2) Scenario C_0R_+: (*i*) $\frac{c_r}{c_n} < \alpha \le \frac{2+3c_r-2c_n}{2+c_n}$; (*ii*) $\frac{2+3c_r-2c_n}{2+c_n} < \alpha < 1+c_r-c_n$, and $\sqrt{\frac{2+3c_r-2\alpha-c_n(2+\alpha)}{2k_c(\alpha+c_n-1-c_r)}} \le \beta_c \le 1$; (*iii*) $\frac{2+3c_r-2c_n}{2+c_n} < \alpha < 1+c_r-c_n$, $0<\beta_c<\sqrt{\frac{2+3c_r-2\alpha-c_n(2+\alpha)}{2k_c(\alpha+c_n-1-c_r)}}$, and $\delta > \delta_1$;

(3) Scenario $C_0R_=$: $\beta_c > \frac{2(c_n\alpha-c_r)}{(1-c_n)(k_c+2\alpha(1-\alpha))}$, $0<c_r<\alpha$, and (*i*) $0<\alpha\le 1/2$, and $\beta_c < \frac{\alpha-c_r-\alpha(1-c_n)}{\alpha(1-c_n)(1-\alpha)}$; or (*ii*) $1/2<\alpha<1$ and $\beta_c \le 1/(2\alpha)$,

where $\delta_1 = \frac{c_n\alpha-3c_r+2\alpha+2c_n-2+2k_c\beta_c^2(\alpha+c_n-1-c_r)}{\alpha+c_n+c_n\alpha-1-2c_r}$.

Proposition 1(1) gives the threshold of the collection target that may affect the manufacturer's willingness to collect, which also indicates that the policymaker should set an appropriate collection target. Otherwise, too high a collection target will make the manufacturer quit the market. Proposition 1(2) shows that there are three cases leading the manufacturer to choose C_0R_+ strategy. If the refurbished product is of low quality, the manufacturer can give the new product and the refurbished product with significantly different prices to strategic consumers. Specifically, in the second period, consumers will be attracted by the refurbished product, because the refurbished product has higher utility at this time. However, if the refurbished product is of high quality, the manufacturer's C_0R_+ strategy may be affected by the collection target and the consumers' willingness to wait. If the collection target is very high, the manufacturer faces more collection tasks and needs refurbishment to bring benefits. On the other side, if the collection target is low, the manufacturer should consider the consumer's willingness to wait and then decide whether to refurbish or not, because a small amount of collection has little impact on the manufacturer, and the consumers' low willingness to wait will lead to less profit margin for the manufacturer in the second period. Proposition 1(3) shows that for refurbished products with different qualities, the collection target should always be higher than $\frac{2(c_n\alpha - c_r)}{(1-c_n)(k_c + 2\alpha(1-\alpha))}$, which guarantees that the policy will be effective and the manufacturer can achieve the collection target. Moreover, we can see that when α is higher than 1/2, the collection target's value range becomes large ($1/(2\alpha) > \frac{\alpha - c_r - \alpha(1-c_n)}{\alpha(1-c_n)(1-\alpha)}$), which also means that the higher the quality of a manufacturer's refurbished product, the more resilient it is to the constraints of the take-back regulation. Thus, improving the refurbished product's quality is an important way for enterprises to cope with a regulation policy. All of the manufacturer's refurbishment strategies in the C_0 mode are shown in Figure 2.

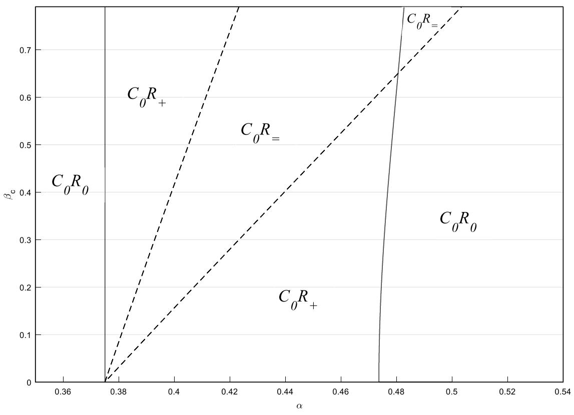

Figure 2. Refurbishment strategies in the C_0 mode.

Proposition 2. In the C_+ and $C_=$ modes, the manufacturer's unique refurbishment strategy is to refurbish all collected products.

Proposition 2 reveals that the manufacturer will make full use of the collected products in the C_+ and $C_=$ modes. In terms of cost, collected products have already incurred collection costs, which become sunk costs if they are not refurbished. When all collected products are refurbished, the fixed costs (e.g., equipment depreciation, upfront research and development, etc.) shared per unit of product will be lower, and the scale effect will be visible. At the same time, the cost of raw materials for refurbished products is usually lower than the production of new products, which can save money. In terms of benefits, refurbished products can be sold in the market and increase revenue. When the collection quantity is higher than the collection target, it means that more available resources can be converted into profitable products and profits can be maximized.

In the market, refurbished products can enrich the product line to meet different consumer needs. Some consumers focus on environmental protection and have a preference for refurbished products; others pursue cost-effectiveness, and the relatively low price of refurbished products can attract this group. By refurbishing all collected products, the manufacturer can expand her/his market share, improve her/his brand image, and enhance market competitiveness. Moreover, by controlling the supply of refurbished products, she/he can avoid the market being captured by other competitors (e.g. refurbishers) due to insufficient refurbished products, which will be discussed further in Section 5.2. In the case of the car manufacturer Toyota, for example, Toyota has actively pursued voluntary recycling programs worldwide, with the number of recycled vehicles far exceeding the local government regulation target. Toyota refurbishes collected cars, with some parts being refurbished and reused in production, and some refurbished cars being reintroduced into the market. In terms of cost-effectiveness, refurbishment reduces the cost of purchasing parts and improves profits. In market competition, Toyota's refurbished vehicles have met the demand for low-priced vehicles in emerging markets and expanded its market share. Moreover, Toyota's behavior also has been recognized and supported by governments, enhancing its brand image.

Proposition 3. In the C_0R_+ strategy, the number of collected products q_c may decrease in β_c, if $\delta < \frac{3-2k_c}{2}$ and $\sqrt{\frac{3\text{-}2\delta}{2k_c}} < \beta_c < 1$.

Generally, a high collection target always leads to the number of collected products increasing. However, Proposition 3 gives a counter-intuitive conclusion. If the consumer's willingness to wait is lower than $\frac{3-2k_c}{2}$ and the collection target is high enough, the manufacturer will cut down the number of new products in the first period to reduce her/his collection tasks ($\frac{\partial q_{n1}}{\partial \beta_c} < 0$, as shown in the Appendix, Proof of Proposition 3). The managerial insight here is that the collection target should not be set too high, especially when the consumers have low expectations for the products with a low time value in the second period.

Moreover, we also find that the number of new products in the second period will rise as the collection target and the consumers' willingness to wait climb. This is because the demand in the first period(q_{n1}) becomes small and most consumers choose to purchase products in the second period. Moreover, as the price of new products decreases as the consumers' willingness to wait increases, a high δ could make q_{n2} and q_{r2} become higher. The reason is that since the manufacturer knows that the demand in the first period is quite low and consumers will enter the market in the second period to buy their products, they set high prices to reap more benefits.

4.2. The manufacturer's profit

In this section, with the aim of determining the global optimum and characterizing the optimal strategy regions, we first analyze the manufacturer's profit in the second stage and then explore how the total profits are affected by strategic consumers in the first stage. After that, we discuss whether there is a dominant collection and refurbishment strategy by comparing the profits.

Proposition 4. In the second period, in the C_0R_+ and $C_=R_=$ scenarios only, the manufacturer's profit will increase in δ; however, in the first period, the manufacturer's profit always decreases in δ.

Proposition 4 presents the impact of the consumer's willingness to wait on the manufacturer's profit. In the C_0R_+ scenario, the manufacturer only refurbishes some of the collected products because, at this time, the collection target is not high according to Proposition 1. Thus the manufacturer's profit is related to the quality of the refurbished products and the consumer's willingness to wait. Though the manufacturer will not refurbish products as long as the collection target is too low, if, however, the quality of the refurbished product is high at this time, and the consumer's willingness to wait is also high, the manufacturer will choose to refurbish some of the products because refurbishment is profitable in the second period. If the manufacturer changes her/his strategy to $C_0R_=$, the manufacturer needs to refurbish all collected products under a high collection target (according to Proposition 1). At this time, the collection target and the quality of refurbished products become the main factors that affect the manufacturer's profit.

In the $C_=R_=$ scenario, the manufacturer will collect all products and refurbish them in the second period. Since the collected products all come from the new products in the first period, the demand for new products q_{n1} is related to the consumer's willingness to wait. Specifically, the consumer's willingness to wait may affect whether the consumers buy now or wait. This may affect the nondifference point of the consumer's utility in two periods. As the consumer's willingness to wait increases, the consumer's utility in the second period will become high. Then the consumers will enter the second period to purchase, which makes the manufacturer's profit in the second period greater.

When the consumer's willingness to wait is large, this means that most consumers prefer to purchase products in the second period, which means that the demand in the first period is small and the manufacturer earns little.

Proposition 5. For the manufacturer, $M_2^{<C_+R_=>}$ is always higher than $M_2^{<C_0R_=>}$ and $M_2^{<C_0R_=>}$ may be higher than $M_2^{<C_0R_0>}$ if and only if they are in equilibrium: $\beta_c < \frac{2(c_n\alpha - c_r)}{(1-c_n)(1-\alpha)}$ and $\alpha \in \left(\frac{3-\sqrt{1+8k_c}}{4}, 1\right)$.

Proposition 5 suggests that as long as the manufacturer chooses to refurbish all the collected products, voluntary mode is the dominant collection strategy, which also means that the manufacturer should overachieve the collection target in the second period when the refurbishment market is worth entering. In compliance mode, the manufacturer should adopt the refurbishment strategy $R_=$ if the quality of the refurbished product is high enough and the collection target is not high. This result also tells us that high-quality refurbished products may lead to product competition in the second period. Whether the manufacturer could prevent her/his competitor (refurbisher) entering the market through the collection strategy is an interesting point, which will be discussed in Section 5.2.

Proposition 6. In the first period, the manufacturer's profit under different refurbishment strategies may differ and have the relationships shown below:

(1) $M_1^{<C_0R_=>} > M_1^{<C_0R_0>} > M_1^{<C_0R_+>}$, if (*i*) $\frac{c_r}{c_n} < \alpha < \alpha_0$ and $0 < \beta_c < \frac{2(c_n\alpha - c_r)}{\alpha(1-\alpha)(1-c_n)}$, or (*ii*) $\alpha_0 < \alpha < 1$;

(2) $M_1^{<C_0R_0>} > M_1^{<C_0R_+>} > M_1^{<C_0R_=>}$, if (*i*) $Max\{0, \delta_1\} < \delta < Min\{1, \delta_2\}$ with Condition (*A*) or (*ii*) $0 < \delta < Max\{0, \delta_1\}$ or $Min\{1, \delta_2\} < \delta < 1$ with Condition (*B*), where $B = C_U A$;

(3) $M_1^{<C_0R_0>} > M_1^{<C_0R_=>} > M_1^{<C_0R_+>}$, in other cases.

From Proposition 6, there are some interesting insights. First, from the revenue perspective, it is not wise for the manufacturer to refurbish some of the collected products and waste others, as $M_1^{<C_0R_0>}$ is always higher than $M_1^{<C_0R_+>}$. This result proves the correctness of Proposition 2, which also shows that refurbishment strategy R_+ is not advisable and will never be the optimal choice. The reasons for this finding are similar to those of Proposition 2.

Second, there will be two cases when the manufacturer can make refurbishment decision $R_{=}$. In Case 1, the quality of the refurbished products is low and the collection target is not high. In this case, the competitiveness of refurbished products is lower than that of new products and the regulation's restraint is weak. The manufacturer could use differentiated product pricing and put the refurbished products into the low-end market, which may attract some consumers with low expectations in the second period. However, in Case 2, the quality of refurbished products is high (similar to the quality of new products), so the collection target will not affect the manufacturer's refurbishment decision. The manufacturer should better make full use of the collected items, because at this time, the refurbished products have the same competitiveness as new products and have a substitution effect. Meanwhile, the cost of refurbished products is low (according to Proposition 1), which indicates that the refurbished products have a high profit margin. The manufacturer ought to put the refurbished products into the market, so that her/his products are diversified and consumers can have an alternative option in the second period. This is also a price reduction strategy to attract consumers, just like the iPhone SE did.

Finally, we find that the consumer's willingness to wait will affect the manufacturer's refurbishment strategy, especially when the manufacturer prefers to waste the collected items (R_0). For example, if the consumer's willingness to wait is not high ($Max\{0, \ \delta_1\} < \delta < Min\{1, \ \delta_2\}$), the manufacturer had better give up refurbishing when the collection target is very high (e.g., $\frac{\sqrt{2}}{2} < \beta_c < 1$). The reason is that the new products with high costs will depreciate in the second period and the manufacturer may spend more on collection and refurbishment. The benefit brought by the refurbished products is not enough to make up for the collection cost and the loss of new products in the second period. Other situations can be found in Appendix B, Proof of Proposition 6.

Corollary 1. $M_1^{<C_+R_=>}$ is always higher than $M_1^{<C_0R_=>}$.

Corollary 1 serves as a supplementary conclusion to Proposition 6, indicating that collection strategy C_+ is superior to strategy C_0, when the manufacturer decides to enter the refurbishment market. This result is similar to that of Proposition 5. Because the refurbished products can help the manufacturer achieve economies of scale, the collection strategy will directly affect the profits and whether the manufacturer chooses to differentiate the products' pricing or diversify product sales. Therefore, C_+ is the dominant strategy when the manufacturer decides to enter into the refurbishment market.

4.3. Consumer surplus

The consumers' willingness to wait shapes intertemporal market demand, whereas their differentiated valuation of new versus refurbished products determines the purchase utility. This makes the analysis of consumer surplus (*CS*) across different collection and refurbishment strategies essential.

In our two-period model, consumers decide in the first period whether to purchase a new product or to wait. In the second period, they may buy a new product, a refurbished product, or exit the market. Accordingly, total consumer surplus aggregates three components, namely first-period new product purchases, second-period new product purchases, and second-period refurbished product purchases, as follows:

$$CS = \int_{\bar{v}}^{1}\left(v - p_{n1}\right)dv + \int_{\frac{p_{n2}-p_{r2}}{1-\alpha}}^{\bar{v}} \delta\left(v - p_{n2}\right)dv + \int_{\frac{p_{r2}}{\alpha}}^{\frac{p_{n2}-p_{r2}}{1-\alpha}} \delta\left(\alpha v - p_{r2}\right)dv \ . \tag{4}$$

Proposition 7. As the consumer's willingness to wait δ increases, the consumer surplus always increases when the manufacturer adopts the C_0R_0 or $C_0R_=$ strategy.

According to Proposition 7, we know that the consumer surplus generally increases with the consumers' willingness to wait, without considering the C_0R_+ strategy (which may not be an optimal choice) in Proposition 6. We now take a closer look at the two strategies in which the consumers' higher willingness to wait would benefit consumers. In the C_0R_0 strategy, the manufacturer will not make use of the collected items and only new products will be sold in the second period. If the consumer's willingness to wait is high, the price in the first period will be low ($\frac{\partial p_{n1}^{<C_0R_0>}}{\partial \delta} = -\frac{1-c_n}{4} < 0$), which also means that consumers will not enjoy significant discounts on products through waiting. Though the new product's price could be lower in the second period than in the first period (i.e., $p_{n1}^{<C_0R_0>} - p_{n2}^{<C_0R_0>} = \frac{(1-c_n)(1-\delta)}{4} > 0$), as δ increases, the price difference between the two periods will become smaller and smaller. However, in the $C_0R_=$ strategy, there are two products competing in the second period. As refurbished products enter the market, consumers who are willing to wait could purchase their desired products at a lower price. On the one hand, the consumer's high willingness to wait will make the new product's price low, as mentioned before. On the other hand, the demand in the second period will be larger than that in the C_0R_0 strategy ($q_{n2}^{<C_0R_=>} + q_{r2}^{<C_0R_=>} > q_{n2}^{<C_0R_0>}$), which indicates that more consumers may benefit from low-price products.

To facilitate our discussion, we compare consumer surplus under two strategies as follows:

$$CS^{<C_0R_0>} - CS^{<C_0R_=>} = -\frac{1}{8}(1-c_n)^2(1-\alpha)\alpha\beta_c^2\delta < 0. \tag{5}$$

It is obvious that the consumer surplus is always higher with the $C_0R_=$ strategy. This finding shows that refurbished products could bring more profits to the manufacturer and will also benefit consumers. We also find that as the consumer's willingness to wait δ increases, the difference between $CS^{<C_0R_0>}$ and $CS^{<C_0R_=>}$ becomes greater, which reveals that a coming alternative product will lead consumers to wait, as it is worth waiting for.

Corollary 2. There is a threshold collection target $\beta_c^* = \frac{2(c_n\alpha - c_r)}{(1-c_n)\alpha'}$ that makes the consumer surplus higher with the $C_+R_=$ strategy compared with when the manufacturer adopts the $C_0R_=$ strategy, if (1) $0 < c_n \le \frac{\alpha'}{\alpha' + 2\alpha}$ and $0 < \beta_c < \beta_c^*$ or (2) $\frac{\alpha'}{\alpha' + 2\alpha} < c_n < 1$, $\frac{c_n(\alpha' + 2\alpha) - \alpha'}{2} < c_r < c_n\alpha$, and $0 < \beta_c < \beta_c^*$, where $\alpha' = k_c + 2\alpha - 2\alpha^2$.

Corollary 2 is illustrated in Figure 3 and presents two cases where the consumers could benefit more from the manufacturer's $C_+R_=$ strategy. Condition (1) reveals when the cost of new products is lower than $\frac{\alpha'}{\alpha' + 2\alpha}$ and the collection target is lower than β_c^*, as shown in Figure 3 (left: Case 1). At this time, the low costs of new and refurbished products make the manufacturer's voluntary collection behavior conducive to further amplifying consumer utility in the second period. However, in Condition (2), both of the products are costly, as shown in Figure 3 (right: Case 3). Collection not only helps the manufacturer save on production costs but also enhances the availability of the second-period market and promotes competition between new and refurbished products, which always benefits consumers. We also find that Case 2 in Figure 3 (right) promises the consumer high utility. This is because the higher utilization of collected products by the manufacturer makes the cost of refurbished products almost 0. Therefore, the selling price of refurbished products will also be low, and consumers will have higher utility when purchasing refurbished products. More importantly, Corollary 2 has proven that the collection strategy C_+ could achieve a "win–win" situation for consumers and the manufacturer according to Proposition 5 and Corollary 1. This suggests that a high collection target may force the manufacturer to fulfil her/his environmental responsibilities, but it does not bring substantial benefits to the consumer. A properly set collection target, on the other hand, will not only motivate the manufacturer to collect, but will also benefit consumers, resulting in a Pareto improvement.

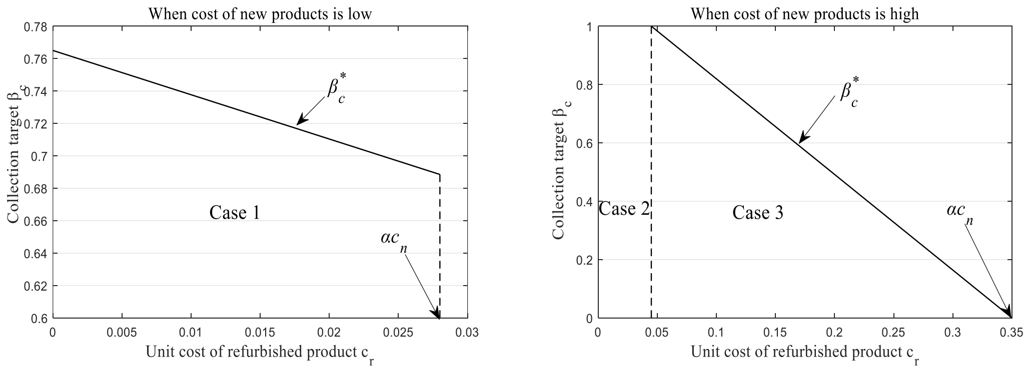

Figure 3. Consumer surplus with the $C_+R_=$ strategy.

The formulation for consumer surplus under the strategy $C_=R_=$ is complicated, and we iterate through the different values of the parameters and find that consumer surplus typically rises as the consumer's willingness to wait rises (similar to the conclusion in Proposition 7). However, in the extreme case, as shown in Figure 4, where the quality of the refurbished product is the same as the quality of the new product and the cost of the refurbished product is very low, there is a situation where consumer surplus decreases as the consumer's willingness to wait increases. This counterintuitive outcome can be explained by a strategic hold-up mechanism enabled by high consumer patience. When the refurbished products' quality is sufficiently high (approaching that of new products), it becomes a highly attractive substitute. An increase in the consumers' willingness to wait signals to the manufacturer that a larger segment of the market is willing to delay their purchase for this attractive refurbished option. In response, the manufacturer strategically raises the price of the refurbished product in the second period. This price increase allows the manufacturer to capture a greater share of the total surplus generated by the high-quality refurbished product. Crucially, the extent of this price increase can, under certain conditions (e.g., when α is high and the refurbishing cost is low), outstrip the incremental utility that consumers gain from waiting, leading to a net reduction in consumer surplus. Thus, enhanced consumer patience strengthens the manufacturer's bargaining power in the second period, enabling a surplus extraction that ultimately harms consumers in equilibrium.

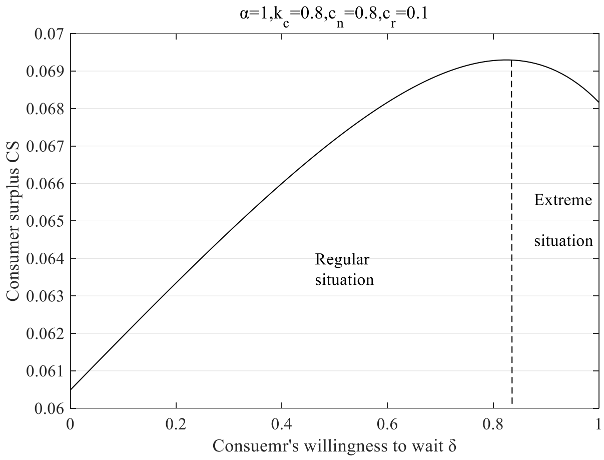

Figure 4. Consumer surplus with the $C_=R_=$ strategy.

5. Extended discussion

5.1. Social welfare

This section analyzes social welfare, which, from a policy perspective, comprises three components: The manufacturer's profit, consumer surplus, and environmental impact. We examine how take-back regulations and strategic consumer behavior jointly determine these welfare outcomes.

To analyze the impact of consumer's willingness to wait on environmental outcomes, we try to use the LCA approach. LCA focuses on a product's environmental outcomes over its life cycle from manufacturing to disposal, which shows the entire process that the product may have. In this paper, according to previous research, our work assumes that the environmental impact of one product at each stage of its life is clearly known. We divide the life cycle of a product into five stages: the manufacturing stage (*m*), the collection stage (*c*), the refurbishment stage (*r*), the consumption stage (*s*), and the final disposal stage (*d*) by the consumer. For each stage, we define the environmental impact as (unit environmental impact of this stage) *(amount of product at this stage). We let e_i (where *i*=*m,c,r,s,d*) represent the product's environmental impact at each stage. The environmental impact of new products in the manufacturing stage usually comes from material extraction, processing, product assembly, energy use, and transportation. As new products will be produced in two periods in our model, the total environmental impact at this stage(*m*) can be expressed as $E_m = e_m\left(q_{n1} + q_{n2}\right)$. Similarly, the environmental impact of refurbished products at the refurbishment stage includes dismantling, sorting, cleaning, welding, and waste management. Thus, the total environmental impact at this stage (*r*) can be written as $E_r = e_r q_{r2}$. When the collected product can reduce environmental pollution, we use $-e_c$ to denote the environmental improvement of each collected item at this stage, and the total environmental impact at this stage (*c*) is denoted as $E_c = -e_c q_c$. A high proportion of the total environmental impact comes from the consumers, who have an impact on the environment mainly at the point of consumption and at final disposal of the product. For the consumption stage, there will be $q_{n1}+q_{n2}+q_{r2}$ products in the two-period market, and we define the environmental impact at this stage (s) as $E_s=e_s\left(q_{n1}+q_{n2}+q_{r2}\right)$. However, since some of the products (q_c) are collected by the manufacturer, there will be $q_{n1}+q_{n2}+q_{r2}-q_c$ products needed for consumers to dispose. Thus, the environmental impact of final disposal is $E_d=e_d\left(q_{n1}+q_{n2}+q_{r2}-q_c\right)$. Here, we make the reasonable assumption that the per-unit environmental impact is the same for new and refurbished products at the final disposal stage. The environmental impact at each stage is summarized in Table 2. Finally, the total environmental impact can be written as

$$E=e_m\left(q_{n1}+q_{n2}\right)-e_cq_c+e_rq_{r2}+e_s\left(q_{n1}+q_{n2}+q_{r2}\right)+e_d\left(q_{n1}+q_{n2}+q_{r2}-q_c\right) \tag{6}$$

Table 2. Environmental impacts.

Stage in life cycle	Environmental impact
Manufacturing stage (m)	$e_m\left(q_{n1}+q_{n2}\right)$
Collection stage (c)	$-e_cq_c$
Refurbishment stage (r)	e_rq_{r2}
Consumption stage (s)	$e_s\left(q_{n1}+q_{n2}+q_{r2}\right)$
Disposal stage (d)	$e_d\left(q_{n1}+q_{n2}+q_{r2}-q_c\right)$

The social welfare is then given as:

$$SW=M_1+CS-E\,. \tag{7}$$

We now discuss how the total social welfare changes with the consumer's willingness to wait under different collection and refurbishment strategies.

Proposition 8. In compliance mode (C_0), the total social welfare always rises as the consumer's willingness to wait increases; however, in voluntary mode (C_+), the total social welfare may decline as the consumer's willingness to wait increases.

Proposition 8 indicates that social welfare increases with consumers' willingness to wait when the manufacturer meets the collection target. This positive relationship is driven by three reinforcing mechanisms that align consumers' behavior with the circular economy's objectives. First, it enhances environmental and resource efficiency. A higher willingness to wait reflects greater consumer acceptance of refurbished products, which directly promotes resource recycling. By substituting new production with refurbishment, significant savings in raw materials and energy are achieved, waste generation is reduced, and the overall environmental footprint diminishes. Second, it improves economic efficiency within the supply chain. Consumers' patience creates a predictable demand for refurbished goods, enabling manufacturers to optimize production planning. Shifting output from new to refurbished products utilizes existing components at a lower cost, thereby reducing system-wide costs and increasing operational efficiency. Third, it strengthens the synergy between policy and market forces. Strategic consumer demand complements regulatory collection targets, providing economic impetus for manufacturers to invest in and scale their refurbishment operations. This policy–market alignment fosters the development of the refurbishment industry, which, in turn, amplifies welfare gains through market expansion and product accessibility. A representative example is Caterpillar's remanufacturing program, which boosts welfare by providing cost-effective, reliable equipment while concurrently reducing resource consumption and environmental impact.

However, when the manufacturer exceeds the collection target, social welfare may decrease as δ increases. This counterproductive outcome can be explained by four key mechanisms. First, over-collection leads to resource misallocation and elevated costs. Collecting beyond the optimal point consumes additional energy and resources, reducing overall resource efficiency and potentially increasing the environmental burden rather than alleviating it. Second, it distorts the product mix in the market. An excessive focus on refurbishment can create an imbalance between new and refurbished products, failing to meet consumer demand for new goods and thereby hindering the market's health and welfare. Third, it misaligns with strategic consumer behavior. A high consumer willingness to wait often signals a stronger preference for new products in the future. Overproducing refurbished goods in this context contradicts revealed consumer preferences, reducing the effectiveness of the strategy. Fourth, the net benefits of refurbishment can become negative. The production process for refurbished goods itself carries environmental and economic costs. When these costs exceed the combined economic and environmental benefits of reuse—a risk under forced over-collection—the activity becomes welfare-reducing. This tension is illustrated in practice by cases such as Fuji Xerox, where advanced design for recycling and high recovery rates are sometimes achieved at a cost that may undermine the net social benefit.

5.2. Reuse efficiency

The issue of reuse efficiency for collected products is integral to research on collection targets. Policymakers face the practical challenge of implementing effective targets, exemplified by the WEEE Directive's recovery goals [5] and Portugal's reuse mandates [16]. Although our model centers on the manufacturers' refurbishment strategies, evaluating reuse efficiency remains an important area for enquiry. Here, we analyze reuse efficiency to derive significant policy insights.

We define reuse efficiency as the ratio of refurbished products to collected products, drawing on the concept of reuse targets in the WEEE Directive. On the basis of existing results (Lemma 1), we compare this efficiency across three compliance scenarios. Our model reveals a critical insight: Reuse efficiency manifests in three distinct regimes, each tied to a fundamental manufacturer strategy. The first is the inefficient regime (0% efficiency), which occurs under the C_0R_0 scenario, where the manufacturer does not refurbish. Here, the manufacturer collects only to meet the high target, gathering cores that are economically unsuitable for refurbishment. Consequently, all collected products are channeled to low-value material recycling, resulting in zero reuse efficiency. This outcome underscores how blunt, high-volume collection mandates can fail to promote a high-value circular economy. Another scenario is the efficient regime, where the reuse efficiency is 100%. This usually occurs under the $C_0R_=$, $C_+R_=$, and $C_=R_=$ scenarios, where the manufacturer chooses to refurbish every available core because it is profitable to do so. This represents an ideal but likely rare scenario where market incentives are perfectly aligned with circular goals. The last scenario is the pragmatic regime, when reuse efficiency is a function of the collection target and the consumer's willingness to wait, as shown in Figure 5. This is the most insightful scenario, emerging under the C_0R_+ scenario. Here, the manufacturer complies with the regulation by meeting the collection target but makes a profit-driven decision to only refurbish the subset of collected cores that are economically viable (i.e., those with sufficiently high quality and a low refurbishment cost). The remaining cores are disposed of or recycled. The reuse efficiency in this case is endogenously determined by the manufacturer's profit maximization calculation.

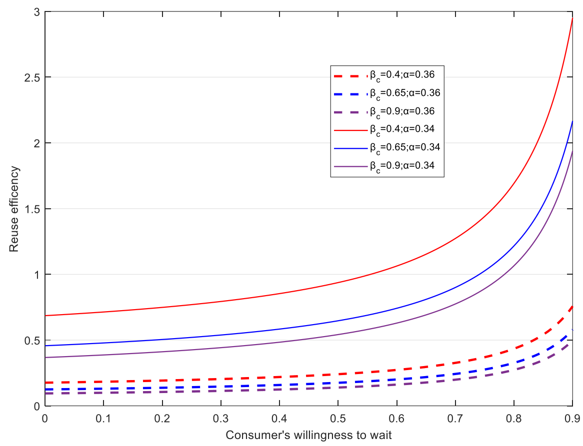

Figure 5. Reuse efficiency under the C_0R_+ scenario.

Observation 1. High collection targets and high refurbished product quality do not necessarily lead to high reuse efficiency. However, consumers' increased willingness to wait can contribute to higher reuse efficiency.

This trichotomy challenges a common presumption in circular economy policies: That aggressive collection targets automatically yield high-value product reuse. Paradoxically, our findings show that stringent targets can suppress reuse efficiency by forcing manufacturers into a compliance mode where quantity eclipses value, diverting end-of-life products to low-value recycling. Critically, high reuse efficiency is not a direct output of a policy's stringency but an emergent property of aligned incentives.

Conversely, the pragmatic regime, enabled by a moderately binding target, offers a viable pathway for a sustainable refurbishment ecosystem. Here, the regulatory target sets a collection baseline, but profit incentives, not mere compliance, drive the manufacturers' decisions. This creates a crucial intersection of policy and market forces: The manufacturer selectively refurbishes the most economically viable cores, endogenously generating a positive reuse efficiency rate. This self-regulating mechanism ensures that refurbishing is economically sustainable, not solely reliant on regulatory coercion.

Consequently, our findings advocate for a pivotal shift in policy design from prioritizing mere collection volume to specifically incentivizing quality and value-retention processes. This could involve targeted reuse subsidies, fees differentiated by circularity performance, or certification standards for high-value outcomes. Such a refined policy framework is essential to catalyze the transition from a waste-management system to a truly value-driven circular economy.

5.3. Competition with a refurbisher

In this section, we will investigate how the consumer's willingness to wait affects the manufacturer's collection and refurbishment strategy when she/he faces a refurbishment competitor trying to enter the market. Following previous research [16], we model the market where the manufacturer and the refurbisher have separate collection channels and assume that a fraction τ of the end-of-life products is available for the manufacturer to collect, and the other fraction $\left(1-\tau\right)$ is available for the refurbisher. This also means that the maximum amount of product that can be collected by the manufacturer is τq_{n1} and that of the refurbisher is $\left(1-\tau\right)q_{n1}$. We also assume that the cost and the selling price of the refurbisher are the same as those of the manufacturer, which ensures that there will be no cost advantage or price competitiveness of the refurbisher in the market to influence our previous conclusions. We use q_r to represent the refurbisher's product decision parameter. However, unlike the manufacturer, the refurbisher will not be subject to take-back regulations. Hence, we use the following new goal function for the manufacturer in the second period:

$$M_2 = (p_{n2}-c_n)q_{n2} + (p_{r2}-c_r)q_{r2} - k_c q_c^2 / 2$$
$$s.t.\begin{cases} \beta_c q_{n1} \le q_c \le \tau q_{n1} \\ q_{r2} \le q_c \\ q_c \ge 0, q_{r2} \ge 0 \end{cases} . \tag{8}$$

The goal function for the refurbisher is

$$R_2 = (p_{r2}-c_r)q_r - k_c q_r^2 / 2$$
$$s.t. 0 \le q_r \le \left(1-\tau\right)q_{n1} . \tag{9}$$

When there is a competitor in the market, the manufacturer's refurbishment decision differs from the conclusion in Proposition 1.

Proposition 9. In compliance mode (C_0), the manufacturer can choose the R_0 strategy if and only if (1) $0 < c_n < c_n^*$, or $c_n^* < c_n$ and $c_r^* < c_r$; and (2) $\delta \le \tau$, or $\delta > \tau$ and $\alpha < \frac{1-\delta}{1-\tau}$. However, in other cases, the manufacturer would be better to adopt a refurbishment strategy (R_+ or $R_=$) to compete with the refurbisher.

Proposition 9 suggests that since there is a refurbisher in the market, it is possible for the manufacturer to choose to abandon the refurbishment strategy when the manufacturer recycles products only according to the collection target β_c. This is because from the cost perspective c_n and c_r, refurbishment involves a series of complex processes, including disassembly, testing, repair, and reassembly, all of which require a large amount of human, material, and financial resources. If the cost of refurbishment (e.g., the purchase of special equipment, technology development, labor costs, etc.) is too high, and the benefits (e.g., profits from product sales, savings in raw material procurement costs, etc.) brought by refurbished products entering the market after refurbishment do not cover the cost, the manufacturer will tend to only recycle the products. For example, the refurbishment of some high-end electronic products may require expensive testing equipment and professional and technical personnel. When these costs exceed the expected profits of the refurbished products, collection only without refurbishing will be a reasonable choice. From the perspective of the consumer's willingness to wait δ, if the consumers' willingness to wait is low, it means that they are more inclined to buy new products than to wait for the launch of refurbished products. In this case, even if the manufacturer carries out refurbishment, the product may face the risk of stagnation. For example, if new products are updated very quickly in the market, consumers pursue the latest technology and styles, and their willingness to wait for refurbished products is extremely low, the manufacturer can avoid losses caused by product backlog by choosing to only collect without refurbishment. From the perspective of the recyclable market size τ, when the recyclable market size is small (such as $\delta > \tau$), it means that the number of products collected by the manufacturer is limited. In this case, economies of scale may not be realized by conducting refurbishment. The fixed costs of refurbishment (e.g., equipment investment, site rental, etc.) spread over a small number of collected products will result in a significant increase in the refurbishment cost per unit of product. From the point of view of the consumers, the coefficient of the consumers' price perception of refurbished products α reflects the consumer's perception of the value of refurbished products. If α is low (e.g, $\alpha < \frac{1-\delta}{1-\tau}$), i.e., they believe that the value of refurbished products is much lower than that of new products, even if the manufacturer reduces the price of refurbished products, it will be difficult to attract enough consumers to buy them. Market conditions, such as strong brand preference and low consumer acceptance of refurbished products, can deter manufacturers from refurbishing to avoid intense price competition. Dell's strategic evolution provides a clear example. Initially, in some emerging markets, consumers' low willingness to wait for refurbished goods, coupled with a small-scale recoverable product base and the low perceived value of refurbished items, led Dell to adopt a collection-only strategy. Collected products were centrally processed or transferred to other regions. As market conditions evolved—with growing consumer environmental awareness, increased willingness to wait, and an expanded recoverable market—Dell transitioned its strategy. Through technological innovation, it improved the quality and perceived value of refurbished products. Subsequently, Dell entered the refurbishment business in these markets, offering affordable and reliable refurbished products to compete with other refurbishers, thereby achieving both economic and environmental benefits. This strategic shift aligns with the refurbishment strategies for both firms under the C_0 mode, as illustrated in Figure 6.

The management insights of Proposition 9 are the following. (1) The manufacturer should accurately assess the cost of each link of refurbishment and dynamically adjust the collection and refurbishment strategy according to the cost and benefit; at the same time, the manufacturer should improve the quality of refurbished products, strengthen brand building, and change the consumer's perception of refurbished products, so as to improve the price perception coefficient and strengthen the competitiveness of the market. In addition, the manufacturer should actively expand her/his collection channels, expand the scale of the recyclable market, realize the economies of scale of refurbishment, and reduce the unit costs. Finally, firms should also pay close attention to market dynamics (such as the consumers' willingness to wait, the recyclable market size, and the price perception factor) and lay out strategies in advance to adapt to market changes.

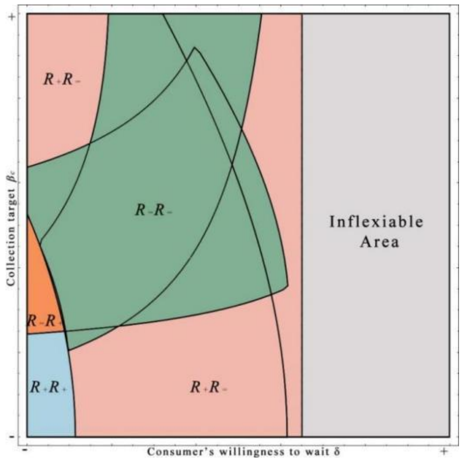

Figure 6. Refurbishment strategies under the C_0 mode.

However, the refurbisher's refurbishment decision is relatively simple under the C_+ mode, as shown in Figure 7. One reason is that the manufacturer has only the $R_=$ strategy under the C_+ mode; the other reason comes from the relatively stable impact of the recyclable market size and the consumer's willingness to wait.

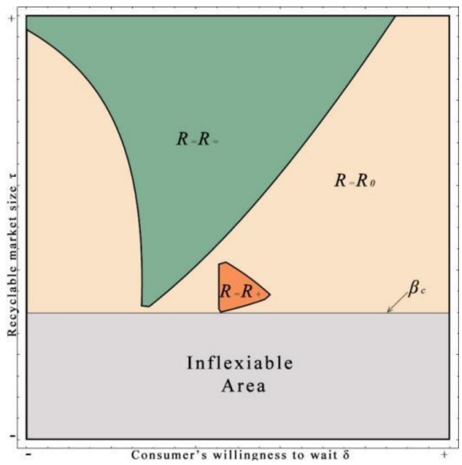

Figure 7. Refurbishment strategies under the C_+ mode.

Observation 2. For the refurbisher, her/his main refurbishment strategies are R_0 and $R_=$ when the manufacturer prefers the voluntary mode (C_+).

When the consumer's willingness to wait is low, consumers are more likely to choose to buy new products. This pattern of consumer behavior results in a higher immediate demand for new products. At this point, even if the refurbisher has a large recyclable market size, it is still difficult for her/him to satisfy the consumers' demand for immediate purchases in the short term. If the market demand cannot absorb the refurbished products of the refurbisher in a timely manner, the refurbisher will be exposed to the risk of inventory backlogs, leading to higher operating costs. Therefore, it is a rational decision for the refurbisher to choose not to enter the market. For example, the recycling market for used cars is large, but it is difficult for refurbished cars to meet consumer demand for new cars in a short period of time, and consumers believe that new cars are more secure in terms of performance and safety. It is difficult for a refurbisher to enter the market at this time to gain sufficient market share, so few refurbishers enter the market to compete with manufacturers such as Tesla under these circumstances.

As the consumer's willingness to wait increases and the recyclable market size for the refurbisher is small, the refurbisher faces relatively low recycling costs and management difficulties, and she/he can focus on specific segments of the market to satisfy consumer demand for unique or environmentally friendly products, and achieve precision marketing. Taking high-end headphones as an example, targeting audiophile users, recycling high-end headphones and carrying out fine restoration and upgrades to launch refurbished products with special features can help refurbishers compete in the market and form a competitive position with manufacturers. For example, some niche brands focus on the refurbishment of high-end Sennheiser headphones.

Observation 3. If the consumer's willingness to wait is not high, the manufacturer could prevent the refurbisher's market encroachment by collecting all end-of-life products.

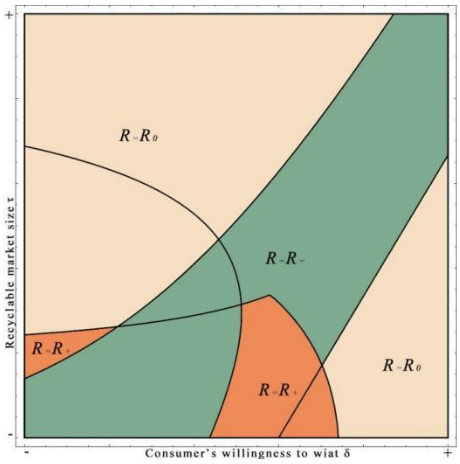

Figure 8. Refurbishment strategies under the $C_=$ mode.

By collecting all end-of-life products (as shown in Figure 8, upper left area), the manufacturer can cut off the supply source of the refurbisher at the beginning. Since the refurbisher lacks sufficient end-of-life products for refurbishment, she/he naturally cannot enter the market to compete with the manufacturer. This not only protects the manufacturer's market share but also avoids the price competition and market disruption that may result from refurbished products. For example, Apple has a strong brand influence. In order to prevent market encroachment by refurbishers, Apple actively promotes trade-in activities to encourage their consumers to return old iPhones (such as iPhone 6, 7, and 8) on the one hand; on the other hand, it constantly upgrades its product technology and shooting, so that there is a big gap between old iPhones and new ones in terms of performance and functionality, which reduces consumers' interest in refurbished mobile phones. This has enabled Apple to successfully stop the market encroachment of refurbishers and maintain its leading position in the smartphone market.

6. Conclusion and remarks

This paper investigates how strategic consumers influence manufacturers' collection and refurbishment strategies under take-back regulations. These decisions become critical when a government-mandated collection target coincides with product competition. We develop a two-period dynamic game model wherein the manufacturer decides his/her collection quantity and refurbishment share. The core analysis classifies the manufacturer's collection strategies and derives the critical conditions for different refurbishment strategies. The model is then extended in two directions: Evaluating social welfare from a government perspective and examining market entry by an independent refurbisher.

Our findings yield concrete, actionable implications for both policymakers and manufacturers navigating the complexities of take-back regulations. First, we demonstrate that regulatory pressure and consumer behavior create a complex interplay that governs the viability of refurbishment. A pivotal finding is that stringent collection targets can paradoxically suppress high-value refurbishment by forcing manufacturers to collect beyond economically viable limits. This highlights a critical policy trade-off between quantity collected and value retained. Second, our analysis of strategic consumers reveals nuanced impacts. Notably, we find that an increase in consumers' willingness to wait can, under certain conditions, lead to a decrease in consumer surplus. This counterintuitive result arises because strategic waiting does not merely expand consumers' options; it fundamentally alters the strategic interaction in the second period. Increased consumer patience strengthens the manufacturer's position by guaranteeing a larger future market for refurbished goods. The manufacturer rationally responds by raising prices to appropriate more of the generated surplus, a form of value capture that can, under specific conditions of high refurbished quality and low cost, overwhelm the value created by waiting, thereby reducing net consumer welfare. This finding highlights a critical tension between consumers' patience and the manufacturer's market power in dynamic markets with durable goods. Third, in a competitive context, we show that the manufacturer's collection strategy serves a dual purpose. Beyond mere compliance, an collect-all strategy can act as a preemptive barrier to entry, securing a supply of cores and impeding the market entry of independent refurbishers.

On the basis of these findings, we derive the following structured recommendations for key stakeholders. For policymakers, it is better to calibrate collection targets to avoid counterproductive Outcomes. Stringent mandates can paradoxically undermine high-value refurbishment. Policies should therefore set targets that incentivize collection volume without pushing manufacturers beyond the point where refurbishment becomes unprofitable, thus preserving the economic viability of a circular model. Moreover, regulators should try to design policies that incentivize value retention, not mere volume. Regulatory tools should be refined to specifically promote processes that retain product value, such as refurbishment. Introducing quality standards or certification for refurbished products can enhance consumer trust and market demand, thereby aligning policy mechanisms with the broader goals of a circular economy. Last, we should aim for a regulatory framework that aligns profit with compliance. Effective regulation should recognize and harness the synergy between corporate profitability and social welfare. The goal is to create a policy environment where compliance is not a net cost but can be integrated into a sustainable and economically rational business strategy. Manufacturers should adopt a strategic view of collection. Beyond treating collection as a compliance cost, forward-looking manufacturers should consider it a potential source of competitive advantage. A preemptive or collect-all strategy can secure critical raw material (cores) and act as a barrier to entry against independent refurbishers. Moreover, manufacturers should pay attention to dual-focus investment: Product quality and consumer insight. Profitability hinges on both the product's perception and market timing. Significant investment should be directed towards ensuring the quality and reliability of refurbished products to minimize the cannibalization of new sales. Concurrently, continuous monitoring of consumers' waiting behavior is essential, as this parameter directly influences optimal pricing and production planning. Finally, manufacturers should engage proactively in the policy dialogue. Manufacturers possess critical operational insights that can inform better policy. They should actively contribute to regulatory discussions, advocating for evidence-based, pragmatic designs that support both environmental goals and long-term business viability.

This paper also puts forward several promising directions for future research. First, the interaction between regulatory compliance and strategic investment decisions warrants further exploration. Our model treats refurbished product quality as an exogenous parameter. A natural and valuable extension would be to endogenize quality, allowing manufacturers to invest in technological upgrades. This would shift the focus to the optimal allocation of resources between quality enhancement and operational scale, revealing new insights into competitive positioning under regulation. Second, the value recovery strategy from collected products can be expanded. Our analysis focus on the value regained through refurbishment. In practice, manufacturers can also derive salvage value from material recycling or component harvesting. Integrating this alternative recovery option into the model would more fully capture the economic trade-offs in reverse supply chains, especially in industries with a high material value. Third, the roles of different actors and consumer types in the ecosystem merit deeper investigation. Future work could examine collaborative models, such as manufacturers authorizing third-party refurbishers. Furthermore, segmenting consumers into groups with heterogeneous preferences (e.g., "green" vs. conventional consumers) could provide a richer understanding of how demand for refurbished goods is shaped and how it influences supply chain strategies. Fourth, at a more foundational level, the model's core behavioral and structural assumptions offer fruitful grounds for extension. Our analysis relies on the standard assumptions of rational consumer expectations and a uniform distribution of valuations to ensure tractability and derive clear insights. Relaxing these assumptions could enhance the model's descriptive realism and reveal new dynamics. For instance, introducing systematic biases in how consumers perceive refurbished products' quality or modeling distinct consumer segments with different willingness-to-wait profiles could significantly alter the equilibrium outcomes and policy implications. Exploring these directions would further bridge our theoretical findings with the complexities of real-world markets.

Use of Generative-AI tools declaration

The authors declare that they have not used AI tools in the creation of this article.

Author contributions

Xintong Chen：conceptualization, methodology, validation, formal analysis, resources, writing—original draft preparation, writing—review and editing; Qiangfei Chai: conceptualization, validation, investigation, supervision; Zelin Wang: software, validation, data curation, visualization, project administration; All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare there is no conflict of interest.

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