Recycling and/or reusing: When product innovation meets the recast of WEEE Direct

Jiaxin He[a], Wei Yan[a*], Youwei Li[b], and Danli Lu[a]

[a] *School of Management and Economics, University of Electronic Science and Technology of China, Chengdu, China;*

[b] *Hull University Business School, University of Hull, Hull, UK*

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To deal with the growing amount of E-Wastes propelled by new product introduction, increasing governments are considering amending take-back regulations to impose the more stringent collection targets. Motivated by this fact, the paper intends to derive the optimal reuse policy for E-Waste with three factors: product innovation degrees, collection targets and remanufacturing levels. Our analysis reveals that the effects of product innovation are almost opposite to those of the collect targets: as new product innovation degrees enlarge, the incentives for the OEM undertaking reuse strategies (including partial and full reusability) decrease. However, the more stringent collect target provides a higher impetus for the OEM to undertake the partial reusability but deters it to engage in full reusability. Moreover, the higher innovation degree often accompany an increase in new product sales, which results in a higher profitability but hurts the environment. In contrast, the more stringent results in an inverted U-shaped curve for profitability and lower environmental impact. Our results may explain why, in the electronics industry, OEMs compete by introducing new products. These findings also suggest that policy makers must be cautious in amending take-back regulations for the E-Waste because the too stringent collection targets may heavily hurt market players.

Keywords: Innovation; remanufacturing; take-back regulation; sustainable operations

1. Introduction

Product innovation is seen as a critical important strategy to succeed in the furious market competition (Klein et al. 2021, Nathan and Rosso 2022). For example, in the electronics industry, many original equipment manufacturers (OEMs) such as Apple, Samsung, and Huawei, spend about 7% to 16% of revenue on product innovation (Bajpai 2021). Recently, although the negative impact of the COVID-19 pandemic is expected, Samsung continues to invest over 20 trillion won throughout 2020—"Despite the highly uncertain market conditions upon the pandemic, Samsung will continue making consistent investments in technologies to widen the gap with competitors" said

Kim Ki-nam, vice chairman of Samsung's semiconductor division (Song 2020).

Although product innovation can create a competitive advantage and bring a substantial profit for the OEMs, it induces the old products be discarded and results in an additional burden on the environment (Zoller and Gerigk 2007, Plambeck and Wang 2009). Consider again the electronics industry, in which the typical products, such as Cell phones, TVs and PCs, would be discarded due to the new and better product arising in the same market (Sachs 2006). It is reported that, the e-waste is expanding about 3-5% a year—almost tripled the amount of municipal waste (Environment Agency 2022). The worldwide amount of e-waste generated in 209 alone reached approximately 48.6 million tons (Statista 2023).

To deal with the growing amount of e-waste, more and more environmental agencies are considering amending take-back regulations to impose the more stringent collection targets. For example, a recent recast of WEEE Direct required firms to collect 45% of the new products that sold in the European Union market by 2016, after which this collection target increased to 65% in 2019 (European Commission 2015). Similarly, in 2021, China set the collection targets for companies in categories of TV, refrigerator, air conditioner, washing machine and compel them to recycle about 30-70% of the new units sold in the Chinese market by 2023 (China NDRC 2021).

Confronting the take-back regulations from governments, most OEMs have taken one of two tracks of the reuse strategies. On the one hand, some firms engage in product reusing and offer remanufactured versions of their products. Xerox (Xerox 2013), Nikon (Nikon 2022) and Canon (Canon 2022) are well-known examples that are heavily involved in taking their used products, remanufacturing them back to “as new” condition, and selling them again. On the other hand, many OEMs recycle the end-of-life products, but reuse few of them. For example, although Hewlett-Packard recycles the used products, it rarely turns those recycled or discarded units into remanufacturing, given the cannibalization of new products by remanufactured ones (Guide and Li 2010).

From a research perspective, the following questions may arise:

(1) Confronting the used disposal propelled by new product innovation, should the governments and environmental agencies need to amend take-back regulations to impose the more stringent collection targets?

(2) What are the implications of the innovation degrees and/or collection targets on OEM's reuse decisions and profitability?

(3) What are the implications of the innovation degrees and/or collection targets on environmental performance?

Based on the current practices in the electronics industry, this paper intends to derive the optimal reuse policy for E-Waste with three factors: new product innovation degrees, collection targets and remanufacturing levels. For this purpose, we develop a model that identifies a trade-off between regulations that benefit OEMs by introducing new products and benefits the environment by reusing the collected cores. That is, the profit-maximizing OEM sells the new products (including existing and/or upgraded versions); meanwhile, it collects the end-of-life products that are implemented by take-back regulations. The collected cores are involved in the options of recycling only (no reuse), partial reuse, and full reuse.

Despite the pioneering work of Esenduran et al. (2017) has focused on the impacts of take-back regulation on the remanufacturing industry, they ignored the fact that, in the electronics industry, the used disposal is propelled by new product introduction. Thus, we go a further step to focus on how the product innovation degrees affect the above interactions. In particular, in contrast that of "increasing the target of reusing may induce a counterintuitive drop in remanufacturing" in Esenduran et al. (2017), our analysis reveals that the more stringent collection targets spur the OEM to adopt the partial reuse strategy, but deters the full reusability.

On the other hand, Galbreth et al. (2013) assumed the products are sold in three versions: new, upgraded (used products remanufactured to the technological innovation) and remanufactured (used products remanufactured to their original functionality) and have considered how the remanufacturing products market is divided by the rate of the product innovation. Noted that, there are two major aspects that differ from them: First, all products in our model are sold in three versions: new (the existing versions with their original functionality and/or upgraded versions with the technological innovation), and remanufactured ones. That is, we intend to highlight how the rate of the potential innovation in the new product market affects the OEM's reuse decisions, by dividing the new products into the existing versions and/or upgraded versions. Second, based on the current practices in the electronics industry, we assume that the OEMs must recycle their own e-waste to meet the requirement of WEEE but allow them to choose whether should reuse those recycled units. That is, we extend the model of Galbreth et al. (2013) to consider the optimal reuse options when product innovation meets the recast of

WEEE Direct.

Our analysis reveals that the effects of product innovation are almost opposite to those of the collection targets: as new product innovation degrees enlarge, the incentives for the OEM undertaking reuse strategies (including partial and full reusability) decrease. However, the more stringent collection target provides a higher impetus for the OEM to undertake the partial reusability, but deters it to engage in full reusability. This is inconsistent with the argument in Esenduran et al. (2017): increasing the target of reusing may induce a counterintuitive drop in remanufacturing. Moreover, our analysis suggests that, to hold a relatively high profitability, the OEM needs to make an effort in product innovation and meanwhile should better shift from full reusability to partial reusability. However, we observe that the OEM's profitability has an inverted-U shape with the collection targets. In addition, we also present some suggestions targeted to the environmental agencies: although the stringent collection targets create benefits for the environment, however, to avoid heavily hurting market players, policy makers should not indulge in introducing the regulations tools that impose too stringent collection targets.

The remainder of the paper are arranged as follows: Reviewing of the mainly relative literature in §2. Then, formulating our two stylized models in §3. In §4, we would make the detailed analysis by summarizing the main results. Finally, we conclude our work and makes a necessary discussion in §5.

2. Relevant literature

This paper is particular related to the following two streams of literature: (i) impacts of take-back regulation and (ii) product innovation decisions. Table 1 make a review to explain the possible contributions of this study.

Table 1. The possible contributions to research.

	Product innovation	Collection targets	Reuse decisions
Esenduran et al. (2017), Plambeck and Wang (2009)	×	√	√
Galbreth et al. (2013), Cheng-Han (2013), Li et al. (2018), and Qian et	×	×	√

al. (2019)			
This paper	√	√	√

2.1 Impacts of take-back regulation

There is a well-established researches, e.g., Zhou et al. (2017), Wang et al. (2021), Xu et al. (2022) and Kushwaha et al. (2022), that highlight on the impacts of take-back regulations but we only review those closely related to our work.

In particular, Esenduran et al. (2017), motivated by examples from the electronic products, develop two theoretical models in which an independent remanufacturer competes with the OEM in the same market. Using these two models, they intend to highlight how the differentiated take-back regulations affect on optimal reusing strategies. Evidently, our aim is quite different from theirs. For example, we contribute to the pioneering work by considering how the rate of the potential innovation in the new product market affects the OEM's reuse decisions. More specifically, although the pioneering work provides the inspiration to consider the optimal reuse policy under the take-back regulations, they ignored the fact that, in the electronics industry, OEMs compete by introducing new products at a blistering pace, which results in the used products being discarded. That is, they ignored the fact that, in the electronics industry, the disposal is propelled by product innovation (Plambeck and Wang 2009).

On the other hand, following Plambeck and Wang (2009), we also highlight the strategies of new product innovation that meet the recast of WEEE Direct. However, there are two major aspects that differ from them: First, besides allowing consumers to purchase the new product and dispose of e-wastes, this paper goes a further step to assume that the OEM remanufactures the e-wastes and resells the remanufactured products in the same market. That is, this paper extends them by considering three key factors: innovation degrees, collection targets and remanufacturing levels. Second, the reuse decisions involved of no reuse, partial reuse, and full reuse are included in Plambeck and Wang (2009), whereas these three options are thoroughly considered in our study.

2.2 Product innovation decisions

Our paper is related to the literature on product innovation that has considered the fundamental decisions related to survive in the new product market[1]. For example, Yin et al. (2010) focused on the role that the sequential emergence of the used goods markets plays in shaping the product upgrade strategy of the manufacturer. Recently, Qi et al. (2020) examined the effects of lean and agile practices as well as mass customization and product innovation capabilities on the implementation of servitization. Meanwhile, Orji and Liu (2020) employed fuzzy logic to prioritize the key drivers of innovation-led lean approaches to achieve sustainability in the manufacturing supply chain. More recently, Shen et al. (2021) studied the value of a supply chain innovation in which one upstream supplier and one downstream manufacturer co-develop on product innovation. Subsequently, Fan et al. (2022) built an evolutionary game model to study the dynamic impact of government policies on the diffusion of green innovation. In addition, numerous researchers, such as Atuahene-Gima (2005), Wang et al. (2021), and Oh et al. (2022) have provided empirical evidence and experimental results on production innovations. However, as a set, they do not consider the reuse decisions and environmental implications.

Several studies, including Galbreth et al. (2013), Cheng-Han (2013), Li et al. (2018), and Qian et al. (2019), have focused on product innovation in the remanufacturing industry. Especially, Galbreth et al. (2013) assumed the products are sold in three versions: new, upgraded (used products remanufactured to the technological innovation) and remanufactured (used products remanufactured to their original functionality) and have considered how the remanufacturing products market is divided by the rate of the product innovation. However, as mentioned earlier, by dividing the new products into the existing versions and/or upgraded versions, we highlight how the rate of the potential innovation in the new product market affects the OEM's reuse decisions. That is, the products in our model are sold in three versions: new (the existing versions with their original functionality and/or upgraded versions with the technological innovation), and remanufactured ones. Moreover, besides the relationship between the product innovation and reuse decisions, we also dedicated significant attention to the impacts of take-back regulations. That is, based on the current practices in the electronics industry, we assume that the OEMs must recycle their own e-waste to meet the requirement of WEEE but allow them to choose whether

[1] We refer interested readers to Sorescu et al. (2018) for a complete discussion on new product innovation.

should reuse those recycled units. That is, we extend the model of Galbreth et al. (2013) to consider the optimal reuse options when product innovation meets the recast of WEEE Direct.

3. Model formulation

We intend to focus on how the rate of the potential innovation in the new product market affects the OEM's reuse decisions, by dividing the new products into the existing versions and/or upgraded versions (Table 2 summarizes the relevant variables). Following Yin et al. (2010), we model a factor, $\delta = 1 + d$, to represent the consumers' valuation about upgraded products, which associates with the innovation degree of $d \geq 0$. That is, $d > 0$ represents the percentage of upgrade beyond baseline, while $d = 0$ represents the existing version. All consumers are strategic and vertical differentiation between new and remanufactured products (Zhang and Zhang 2018, Qian et al. 2019, Zhou et al. 2021). That is, to reflect the cannibalization problem between the new and remanufactured versions, we assume that, for the existing version of the new product, the consumer's willingness-to-pay would be uniformly distributed in the range of [0, 1]. However, the consumer's willingness-to-pay is a discount $\phi \in (0,1)$ of that for the existing version. Then, we could derive the following inverse demand functions:

$$\begin{aligned} p_n &= (1+d)(1-q_n) - \phi q_r \\ p_r &= \phi(1-q_n-q_r) \end{aligned} \tag{1}$$

Where the subscript n, r denotes the new and remanufactured products, respectively. Then p_n is the market-clearing price of the new product, and p_r is the market-clearing price of the remanufactured product (if remanufacturing).

According with the fact that the WEEE Direct requires the OEMs to recycle their used product at a lower bound, assuming that $q_r \leq t q_n$, where $t \in (0,1)$ represents the lower bound of recycling (Esenduran et al. 2017). It should be noted that, the more stringent regulations would result in a higher collection target of t. Like Esenduran et al. (2017), we use c_u, c_n, c_r to denote the per unit recycling, producing, remanufacturing cost, respectively.

In our two models, the OEM would choose the optimal units for both products. Then, the OEM's optimization problem is

$$\pi = \left(p_n - c_n \right) q_n + \left(p_r - c_r \right) q_r - c_u t q_n \\ s.t.\ 0 \le q_r \le t q_n \tag{2}$$

Based on Eqs. (1) and (2), we find that the optimal reuse strategies for e-waste mainly involved with three factors of product innovation, collection targets and remanufacturing levels. In particular, Maximizing the OEM's profits with the feasibility constraint of $0 \le q_r \le t q_n$, we can derive the Nash equilibrium with the Lagrangian and characterize the OEM's reusing scenarios as (1) "Recycling only (No reuse)" strategy where the manufacturer would recycle used products but remanufacture nothing, i.e., $q_r = 0$; (2) "Partial reuse" strategy in which the manufacturer remanufactures a partial of collected components, i.e., $0 < q_r < t q_n$; and (3) "Full reuse" strategy where all collected components are remanufactured, i.e., $q_r = t q_n$. [2] We use superscript $j \in \{N, P, F\}$ to denote the reusing scenarios of "Recycling only (No reuse)", "Partial reuse" and "Full reuse", respectively.

4. Analysis and main results

In this section, like Galbreth et al. (2013), we begin our analysis by characterizing the OEM's equilibrium reuse options, and then highlight the impacts on the amount of products, OEM profits, and environment performance.

4.1 Characterization of equilibrium

It should be noted that, whether the OEM will undertake the reuse strategy or not, depends on the key components of the remanufacturing costs, i.e., c_r , innovation degrees, i.e., d , and collection targets, i.e., t . In this subsection, we first characterize the OEM's optimal reuse decision using the cost of c_r in the following proposition. [3]

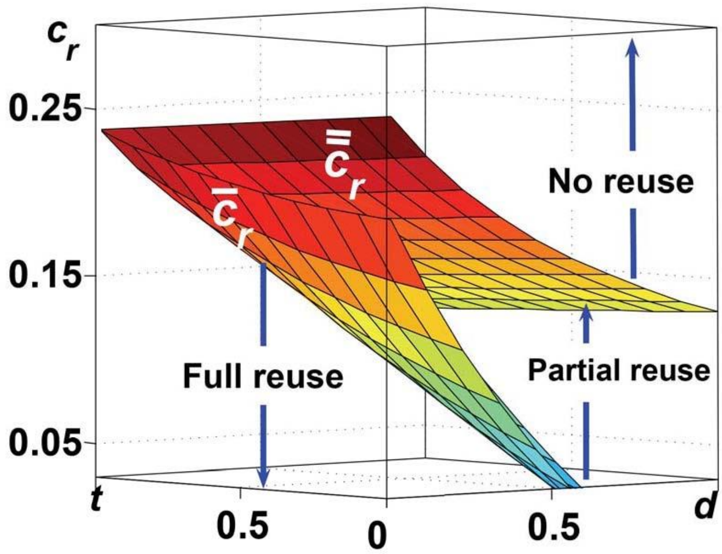
[2] Similar definition can be found in Galbreth et al. (2013). And note that some firms may use different terms for these strategies. For example, Apple pioneered industry-leading levels of traceability to build a gold supply chain of exclusively recycled content with 100 percent recycled tin and 45 percent certified recycled rare earth elements iClarified. (2022). "Apple Announces Expanded Use of Recycled Materials Across Its Products." Retrieved 2023-4-20, from https://www.iclarified.com/85630/apple-announces-expanded-use-of-recycled-materials-across-its-products..

[3] For clarity, the detailed proofs can be found in the appendix

Proposition 1. (Optimal reuse decisions) *There exists two thresholds of* $\bar{\bar{c}}_r = \frac{(c_n + c_u t)\phi}{1+d}$ *and* $\bar{c}_r = \frac{(\phi t + c_n + c_u t + tc_n - t - td + c_u t^2)\phi}{1+d+\phi t}$ *such that in equilibrium, the OEM would choose one of the following reuse decisions:*

Region	q_n	q_r
$c_r < \bar{c}_r$ *(Full reuse in Fig. 1)*	$q_n^F = \frac{1+d+\phi t - c_n - tc_r - c_u t}{2(1+\phi t^2 + 2\phi t + d)}$	$q_r^F = tq_n^F$
$\bar{c}_r < c_r < \bar{\bar{c}}_r$ *(Partial reuse region in Fig. 1)*	$q_n^P = \frac{1+d-c_n-c_u t - \phi + c_r}{2(1+d-\phi)}$	$q_r^P = \frac{\phi c_n + \phi c_u t - c_r - dc_r}{2\phi(1+d-\phi)} < tq_n^P$
$\bar{\bar{c}}_r < c_r$ *(No reuse region in Fig. 1)*	$q_n^N = \frac{1+d-c_n-c_u t}{2(1+d)}$	$q_r^N = 0$

Figure 1. **OEM's optimal reuse decisions**



Proposition 1 shows that the remanufacturing cost c_r plays a strategic role in shaping the reuse decisions: There is a threshold cost of $\bar{c}_r$, below which the OEM has the incentive to undertake full reusability with $q_r = tq_n$. When the remanufacturing cost varies in $\bar{c}_r < c_r < \bar{\bar{c}}_r$, the profits of product reusability decreases, hence the OEM would adopt the partial reusability with $q_r < tq_n$. Finally, when the remanufacturing costs become pronounced, i.e., $c_r > \bar{\bar{c}}_r$, such a disadvantage in remanufacturing leads the OEM to have no incentives to undertake reusability anymore, i.e., $q_r = 0$. Note that, the threshold values satisfy $\overline{c}_r < \overline{\overline{c}}_r$ means that, given a cost parameter c_r, the OEM always has a lower incentive to undertake the full reusability strategy. Fig. 1, illustrates the above optimal reuse decisions[4].

Clearly, the above characterization of the thresholds depends critically on the parameters of the collection target (i.e., t) and product innovation levels (i.e., d). Further elaboration on the thresholds $\overline{c}_r$ and $\overline{\overline{c}}_r$ can reveal an alternative way of influencing reuse decisions, via relative parameters of t and d, as shown in the following corollary.

Corollary 1. *The two thresholds of* $\overline{\overline{c}}_r = \dfrac{(c_n + c_u t)\phi}{1+d}$ *and* $\overline{c}_r = \dfrac{(\phi t + c_n + c_u t + tc_n - t - td + c_u t^2)\phi}{1+d+\phi t}$ *depend on the parameters of* d *and* t*; furthermore,*

(i) ***(Impacts of innovation degrees on reuse decisions)*** *for a given collection target of* t*, the incentives for the OEM undertaking reuse strategies (including partial and full reusability) decrease with the innovation rates,* i.e., $\partial \overline{c}_r / \partial d < 0$ and $\partial \overline{\overline{c}}_r / \partial d < 0$*; moreover, if product innovation degree* $d > \overline{d} = \dfrac{tc_n + t^2 c_u + t\phi - t + c_n + c_u t}{t}$ *, the full reusability is not a feasible option for the OEM.*

(ii) ***(Impacts of collection targets on reuse decisions)****, for an given innovation rate of* d*, the OEM's incentive of* $\overline{c}_r$ *(*$\overline{\overline{c}}_r$*) is decreasing (increasing) in the collection target, i.e.,* $\partial \overline{c} / \partial t < 0$ *(* $\partial \overline{\overline{c}} / \partial t > 0$ *); moreover, if the collection target of* $t > \overline{t} = \dfrac{1+d-c_n-\phi-c_u-\sqrt{(1+d-c_n-\phi-c_u)^2-4c_u c_n)}}{2c_u}$ *, the full reusability is not a feasible option for the OEM.*

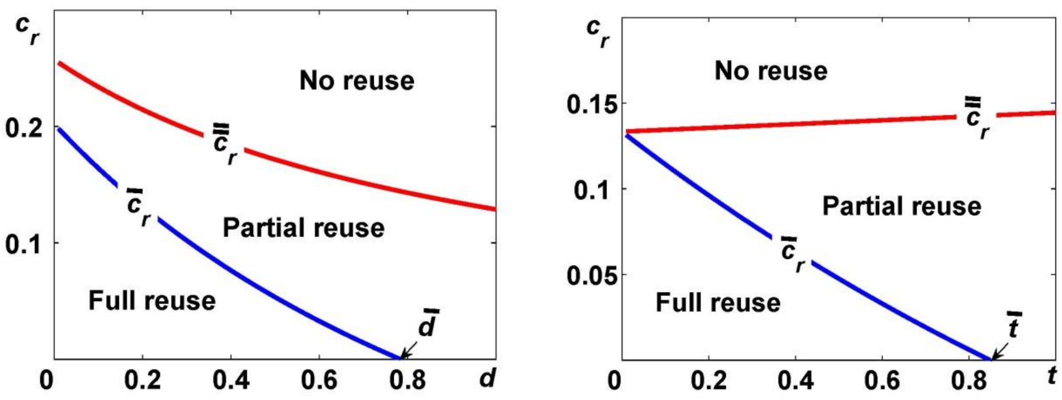
Corollary 1 follows from the characterization of the two thresholds that have several noteworthy features. First, as new product innovation degree of d increases, the incentives for the OEM undertaking reuse strategies (including partial and full reusability) decreases, i.e., $\partial \overline{c}_r / \partial d < 0$, $\partial \overline{\overline{c}}_r / \partial d < 0$ (see, Fig. 2(a)). However, the more stringent collection target provides a higher impetus for the OEM to undertake the

[4] All figures generated with the base values of $c_n = 0.35, c_u = 0.05, \phi = 0.6$.

partial reusability, but deters it to engage in full reusability, i.e., $\partial\bar{\bar{c}}/\partial t > 0$, $\partial\bar{c}/\partial t < 0$ (see, Fig. 2(b)). Second, for a certain new product innovation degree of d or a certain collection target of t, the incentive for the OEM to undertake the full reusability is always lower than that for the partial reusability, i.e., $\bar{c}_r < \bar{\bar{c}}_r$. Third, when $d > \bar{d}$ or $t > \bar{t}$, the OEM would not adopt the full reuse strategy at all. That is, the full reusability is not always a feasible option for the OEM.[5]

To summarize, Corollary 1 shows that the more stringent collection targets lead to the OEM with the higher incentive to adopt the partial reuse strategy. An argument is inconsistent with that in Esenduran et al. (2017) : "increasing the target of reusing may induce a counterintuitive drop in remanufacturing". However, as mentioned earlier, they ignored the fact that, in the electronics industry, the used disposal is propelled by innovation (Plambeck and Wang 2009). In particular, based on Fig. 2(b), we can conclude that, at the extreme case of $t > \bar{t}$, the OEM would only undertake partial reuse, but not adopt the full reuse strategy at all (i.e., $\bar{c}_r < 0$).

Figure 2. Impacts of d and t on optimal reuse decisions.



(a) d on optimal reuse decisions (b) t on optimal reuse decisions.

4.2 Impacts on the amount of products

In the analysis thus far, we have characterized the incentives for the OEM following a threshold policy and found that both the innovation degrees and collection targets depend on the thresholds. We now highlight how the innovation degrees and collection targets impact the OEM's best-response on the amount of new and

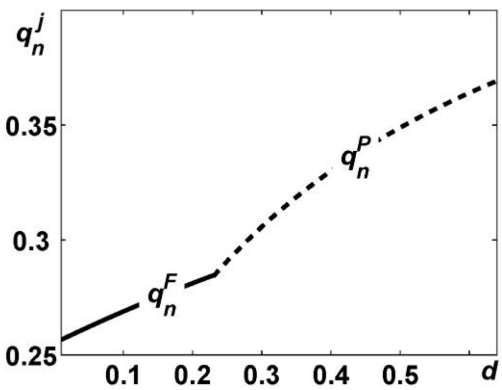
[5] When $d > \bar{d}$, the bound for full reuse strategy $\bar{c}_r < 0$, meaning that the OEM should not adopt full reuse if the innovation rates is relative large.

remanufactured products [6]. Based on the outcomes in Proposition 1, we provide the following result.

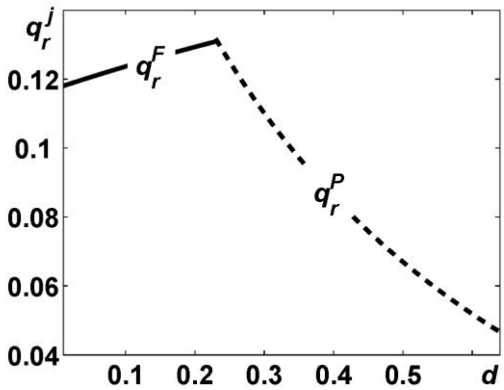
Proposition 2. ***(Impacts of innovation rates on quantities)***, *(i) for a given collect target of* t *, the new products quantities increase with innovation rates, i.e.,* $\partial q_n^F / \partial d > 0; \partial q_n^P / \partial d > 0$ *; however, under the full (partial) reuse region, the remanufactured products quantities increase (decrease) with innovation rates, i.e.,* $\partial q_r^F / \partial d > 0$ *(*$\partial q_r^P / \partial d < 0$*)*.

(Impacts of collection targets on quantities), *(ii) for a given innovation rate of* d *, the amounts of new (remanufactured) products decrease (increase) with collect targets, i.e.,* $\partial q_n^F / \partial t < 0; \partial q_n^P / \partial t < 0$ *(*$\partial q_r^F / \partial t > 0; \partial q_r^P / \partial t > 0$*).*

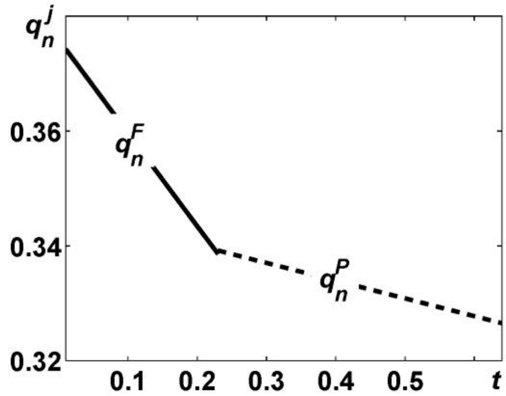
Figure 3. Impacts of d and t on optimal quantities



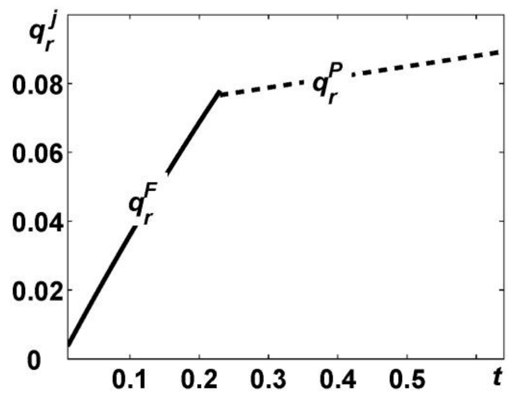
(a) d on q_n^j



(b) d on q_r^j



(c) t on q_n^j



(d) t on q_r^j

Intuitively, as illustrated in Fig. 3(a)[7], we can conclude that, whether under the full reuse or partial reuse regions, the amount of new products increase with innovation

[6] That is, we would only pay attention on the variations in the optimal outcomes under reuse decisions.

degrees, i.e., $\frac{\partial q_n^F}{\partial d} > 0; \frac{\partial q_n^P}{\partial d} > 0$. In particular, for a given collection target t, as the innovation degrees enlarge, the amount of new products increases due to the minimal cannibalization effect from remanufacturing, as such, $q_n^F < q_n^P$. Surprisingly, Fig. 3(b) illustrates that, under the full reuse region, the remanufactured products increase with innovation degrees. As mentioned in Proposition 1, if $c_r < \overline{c}_r$, under the full reusing scenario, the product reusing is a quite profitable business and results in $q_r = tq_n$. As such, if $c_r < \overline{c}_r$, consistent with the units of new products, the amounts of remanufactured product increase with innovation degrees (see, the variations of q_n^F in Fig 3(b)).

On the other hand, Proposition 2 (ii) confirms the traditional wisdom: the more stringent collection targets spur OEMs to provide more units of remanufactured products (i.e., $\frac{\partial q_r^F}{\partial t} > 0; \frac{\partial q_r^P}{\partial t} > 0$), but less quantities of the new products (i.e., $\frac{\partial q_n^F}{\partial t} < 0; \frac{\partial q_n^P}{\partial t} < 0$). As explained in Proposition 1, the OEM always has a lower incentive to undertake the full reusability strategy, that is, $\overline{c}_r < \overline{\overline{c}}_r$ is always true. Proposition 2 (ii) establishes that another way to achieve the same outcome is from remanufactured units. Based on Fig. 3(d), the amounts of remanufactured products under the full reusable and partial reusable regions satisfy $q_r^F < q_r^P$. Thus, for a given innovation degree d, the OEM would undertake the full reusable strategy with the lower units (compared to the partial reusability scenario) as a result of the more stringent collection targets.

4.3 Impacts on economic profitability

Qian et al. (2019) showed that the new product innovation strategy can effectively enhance the manufacturer's competitiveness and increase profits. This may consistent with the fact that innovative companies deliver more profits than the industry average (Zoller and Gerigk 2007). However, we add a word to the relationship between the product innovation and profitability and find that the differentiated reusable strategies would impact on the above profitability. Specifically, if the OEM cares more about the

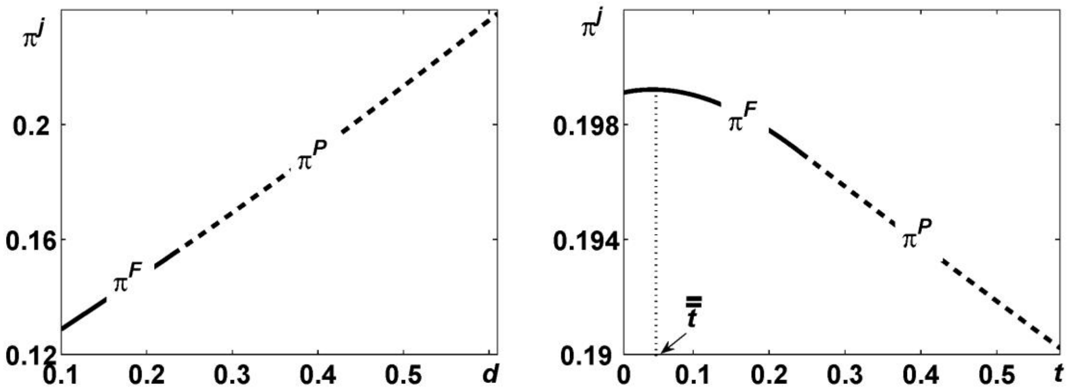
[7] To highlight the impacts of innovation degrees (collection targets), we hereafter further pick $c_r = 0.1, t = 0.45, (d = 0.4)$.

profitability, it needs to make an effort in product innovation and meanwhile should shift from full reusability to partial reusability to hold a relatively higher profitability, i.e., (see, Fig. 4(a)).

Proposition 3. ***(Impacts of innovation rates on profitability)***, *(i) for a given collect target* t *, the profits increase with innovation degrees, i.e.,* $\partial\pi^F/\partial d > 0$ *,* $\partial\pi^P/\partial d > 0$ *; furthermore* $\pi^F < \pi^P$ *.*

(Impacts of collect targets on profitability), *(ii) for a given innovation degree* d *, there is an inverted U relationship between the profits and the collect targets with a maximum at* $t = \bar{\bar{t}} = \dfrac{\phi c_n - c_r - c_r d - c_u - dc_u}{\phi(1+d+c_r+c_u-\phi-c_n)}$.

Figure 6. Impacts on d and t economic profitability



(a) d on π^j (b) t on π^j

One might expect the more stringent collection target to spur OEMs to remanufacture more to offset collection costs than they would have otherwise (USIT Commission 2012, Esenduran et al. 2017). However, we find that, this is not always true when the collection target of t exceeds the value of $\bar{\bar{t}}$ (see, Fig. 4(b)). In spite of the fact that the reusability strategy can contribute to profitability and sustainable performance, the remanufacturing also creates the potential cannibalization problems for the new products sales. The cannibalization effect dominates when the collection target of t exceeds the value of $\bar{\bar{t}}$. As such, we suggest that, to avoid hurting the profitability of the OEMs, the government should confine herself to impose the more stringent collection targets that over the equilibrium collection targets.

To highlight the impacts of WEEE on reusability strategies, we go a deeper step to focus on the value of $\bar{\bar{t}}$ and provide the following corollary.

Corollary 2. *The value of* $\bar{\bar{t}} = \frac{\phi c_n - c_r - c_r d - c_u - dc_u}{\phi(1+d+c_r+c_u-\phi-c_n)}$ *depends on the parameter of* d *; furthermore,* $\partial\bar{\bar{t}}/\partial d < 0$.

Proposition 3 (ii) reveals that, from the OEM's profit maximizing perspective, policy makers should not indulge in introducing other regulations tools that impose the more stringent collection targets, but need to take steps to help the OEM to benefit more from higher collection targets. Corollary 2 further indicates that, it is important to relate the suggestions in Proposition 3 (ii) to the industry rate of innovation d is high, because the profit maximizing OEM always chooses the lower value of $\bar{\bar{t}}$, when the innovation degree of d enlarges.

In practice, most take-back regulations have recently been revised to impose new higher collection levels. For example, a recent recast of WEEE Direct required firms to collect 45% of the new products that sold in the European Union market by 2016, after which this collection target increased to 65% in 2019 (European Commission 2015). In fact, although the WEEE Directive with the more stringent collection targets can spur OEMs to provide more units of remanufactured products, however, from the economic perspective, the stringent collection targets that over equilibrium collect levels may hurt market players, furthermore the equilibrium levels of $\bar{\bar{t}}$ would be particularly low in the electronics industry with high innovation degrees.Impacts on environmental performance.

4.4 Impacts on environmental performance

In this subsection, we intend to analyze the environmental performance associated with differentiated reuse regions. In practice, the total environmental impact is comprised of the impact in the production, use and disposal; however, the pioneering work usually calculates it with stylized models (Agrawal et al. 2011). For example, to be consistent with the energy usage in industrial ecology, (Galbreth et al. (2013)) quantify the environmental impact as total virgin material usage. Like them, in this subsection, we also define the virgin material usage is given as $E^j = q_n^j + \beta q_r^j$, then we can characterize the environmental performance associated with the OEM's reuse decisions as follows.

Proposition 4. *(i)* ***(Impacts of innovation rates on environmental performance)****, for a given collect target* t*, the environmental impacts increase with innovation degrees, i.e.,* $\partial E^F / \partial d > 0; \partial E^P / \partial d > 0$.

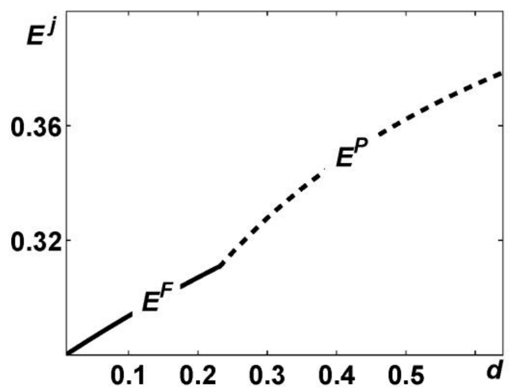
(ii) (Impacts of collection targets on environmental performance), *for a given innovation degree* d*, the environmental impacts decrease with collection targets, i.e.,* $\partial E^F / \partial t > 0; \partial E^P / \partial t > 0$.

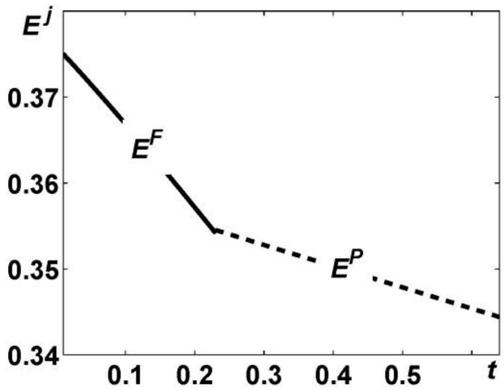
As Fig. 5 (a)[8] shown that, we can conclude that, whether under the full reuse or partial reuse regions, as innovation degrees enlarge, the environmental impacts increase and environmental performance decrease, i.e., $\frac{\partial E^F}{\partial d} > 0; \frac{\partial E^P}{\partial d} > 0$. The intuition is that increasing the innovation degrees enlarges the potential market for new products and promotes new products sales. The higher products sales increase total virgin material usage and is detrimental to the environment (Galbreth et al. 2013, Zhou et al. 2021).

However, Proposition 4(ii) reveals that, whether under the full reuse or partial reuse regions, the more stringent collection targets result in the environmental impacts decrease, i.e., $\frac{\partial E^F}{\partial t} < 0; \frac{\partial E^P}{\partial t} < 0$. In particular, we find that the environmental impacts under the full reuse region are higher than that under the partial reuse region, i.e., $E^F > E^P$ (see, Fig. 5 (b)). The intuition can be explained as follows: On the one hand, we define the virgin material usage is given as $E^j = q_n^j + \beta q_r^j$, as such, the environmental impacts are mainly dependent on new products producing rather than the higher reuse units. On the other hand, as indicated in Proposition 2(ii): the more stringent collection targets spur OEMs to provide more units of remanufactured products (i.e., $q_r^P > q_r^F$), but fewer quantities of the new products (i.e., $q_n^P < q_n^F$).

Figure 5. Impacts of d and t on environmental performance

[8] *To highlight the impacts of environmental performance, we further pick* $\beta = 0.2$.





(a) d on environmental performance (b) t on environmental performance

5. Conclusion

To deal with the growing amount of e-waste propelled by innovation, more and more governments and environmental agencies are considering amending take-back regulations to impose the more stringent collection targets. For example, the European Union intend to recast the WEEE Direct required firms to collect 45% of the new products that sold in the European Union market by 2016, after which this collection target increased to 65% in 2019 (European Commission 2015). Similarly, in 2021, China set the collection targets for companies in categories of TV, refrigerator, air conditioner and washing machine and compel them to comply to recycle about 30-70% of the new units sold in the Chinese market by 2023 (China NDRC 2021).

Although the pioneering work of Esenduran et al. (2017) has focused on impacts of take-back regulation on the remanufacturing industry, they ignored the fact that, in the electronics industry, the used disposal is propelled by product innovation (Plambeck and Wang 2009). As such, based on the current practices in the electronics industry, we extend them by deriving the optimal reuse policy for e-waste with three factors: new product innovation degrees, collection targets and remanufacturing levels. That is, we develop a model, in which the profit-maximizing OEM sells the new products (including existing and/or upgraded versions); meanwhile, it collects the end-of-life products that are implemented by take-back regulations. The collected cores are involved the optimal reuse decisions of recycling only, partial reuse, and full reuse.

Our work derives several important implications for industry. Our analysis reveals that the effects of product innovation are almost opposite to those of the collection targets: as new product innovation degrees enlarge, the incentives for the OEM undertaking reuse strategies (including partial and full reusability) decrease. However, the more stringent collection target provides a higher impetus for the OEM to undertake the partial reusability, but deters it to engage in full reusability. The latter result is inconsistent with that in (Esenduran et al. 2017) : “increasing the target of reusing may induce a counterintuitive drop in remanufacturing”. In addition, our analysis suggests that, if the OEM intends to increase its profitability, it need make an effort in product innovation and meanwhile should better shift from full reusability to partial reusability.

We also present some suggestions targeted to the environmental agencies. In particular, we observe that the OEM's profitability has an inverted-U shape with the collection targets. That is, the stringent collection targets that over equilibrium collect levels may hurting market players. Furthermore, this tendency is particularly notable in the industry with high innovation degrees. As such, we suggest that, although the stringent collection targets create benefits for the environment, however, to avoid heavily hurt market players, policy makers should not indulge in introducing the regulations tools that impose too stringent collection targets.

We now provide several possible directions for the future researches. First, to focus on the implications of take-back regulations, we do not address other mechanisms for carbon emissions. However, Kok et al. (2018) have indicated that the optimal emissions regulations can be potentially useful to encourage companies to carry out remanufacturing activities with a benefit for environmental performance and social welfare. Second, we assume that the consumers are all strategic and would prefer the new product to the remanufactured one. However, in practice, there are some green consumers who usually prefer the environmental friendly products. Hence, it is desirable for the future research to address potential implications of green decisions based on environmental concerns. Third, we have ignored the possible penalizes that will cost the OEM if it does not responsible for the possible reusability of the WEEE Directive, relaxing this assumption could expand the applicability of the results.

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