Managing Collecting or Remarketing Channels: The Impact of Different Strategies on Remanufacturing Outsourcing

Abstract:

Cannibalisation is a major concern for original equipment manufacturers (OEMs) when they outsource remanufacturing operations to third-party remanufacturers (3PRs). In dealing with the cannibalisation from the 3PRs, many OEMs (such as Sun, Apple, Hewlett Packard, Bosch Tools, and Gateway) use core collecting or remanufactured product remarketing. Motivated by examples from industry, we have developed two models in which an OEM produces new products but outsources remanufacturing operations to a 3PR. The two potential strategies for dealing with the cannibalisation from remanufactured products are: (1) collecting used cores from consumers, or (2) remarketing all remanufactured products to consumers. Among other results, we have found the minimising cannibalisation problems do not equate with maximising profits. In particular, if the collection cost coefficient is not pronounced, the aggressive response by the OEM minimises the cannibalisation problems from the 3PR's remanufacturing. On the other hand, it induces lower profitability for the OEM in Model C. Further, as the collection cost coefficient is moderate, remarketing remanufactured products can secure Pareto improvements. As such, we suggest that practising managers combine the cannibalisation problems of remanufacturing with the costs of collecting used cores.

Keywords: Remanufacturing outsourcing; recycling; remarketing; *environmental impact*

1. Introduction

Cannibalisation is a major concern when the original equipment manufacturers (OEMs) consider remanufacturing as an integral part of the business (Debo et al. 2005, Atasu et al. 2010). This is particularly noticeable when they outsource the remanufacturing operations to third-party remanufacturers (3PRs). Indeed, it opens a second, profitable, remanufactured goods market that is not directly controlled by themselves (Oraiopoulos et al. 2012). According to a comprehensive survey of the USA remanufacturing industry, only 6% of over 2000 remanufacturing enterprises were OEMs (Hauser and Lund 2008).

31 “3PRs have built over \$100 million per year [in] businesses...buying used computer
32 equipment, refurbishing it, and selling or leasing it out to someone else” (Review 2005),
33 allowing the 3PRs to take this as an opportunity creates cannibalisation problems and
34 damages to OEM’s profitability. As such, many managers at OEMs frequently equate,
35 minimising the cannibalisation problems from the 3PRs’ remanufacturing with
36 maximising profits (Atasu et al. 2010).

37 In practice, OEMs have two main options to deal with the cannibalisation problems,
38 stemming from remanufacturing outsourcing undertaking used core collecting or
39 remanufactured product remarketing. More specifically, although remanufacturing
40 operations are outsourced to the 3PRs, some OEMs participate in the remanufacturing
41 operations by collecting used cores. For example, to reduce the used cores of the 3PRs’
42 remanufacturing, Sun Microsystems (Sun), one of the leading PC manufacturers to
43 deliberately set a high relicensing fee so that the resale value of its used equipment
44 decreases. On the contrary, many other OEMs minimise the cannibalisation problems
45 stemmed from remanufacturing outsourcing through remarketing the remanufactured
46 products. For instance, although Apple has outsourced remanufacturing to 3PRs, such as
47 Foxconn and Alps Electric, their computers and notebooks are sold in their stores (Yan
48 et al. 2015). A similar case also appears for OEMs, such as Hewlett Packard, Bosch
49 Tools, and Gateway (Atasu et al. 2008).

50 The above motivations provide two differentiated strategies for minimising
51 cannibalisation problems. In the former scenario, given that used products act as cores
52 for remanufacturing, the 3PRs’ remanufactured products face a *collecting* constraint.
53 While in the latter case, the 3PRs’ remanufactured products face *marketing* constraints,
54 given that the remanufactured products are remarketed by OEMs. For the related firms,
55 it is critical to gain an accurate understanding as to how different strategies impact on
56 the equilibrium behaviour of related parties. In confronting the cannibalisation problems
57 from the 3PRs, under what conditions does one strategy is better than the other? This
58 important operational decision has received little attention in the literature related to
59 remanufacturing outsourcing.

60 The primary goal of this paper is to provide a detailed analysis of how the different

strategies conducted by OEMs impact the cannibalisation problem and, further, influence the economic and environmental benefits when remanufacturing operations are outsourced to 3PRs. More specifically, motivated by observations from current practice, we developed two models in which an OEM produces new products but outsources its remanufacturing operations to a 3PR with two possible options for dealing with cannibalisation problems caused by remanufacturing: (1) participating in remanufacturing operations by collecting cores from consumers (Model C), or (2) participating in remanufacturing operations by remarketing all remanufactured products to consumers (Model R). Using these two models, we intend to address the following questions:

(1) How do different options conducted by OEMs for minimising cannibalisation affect equilibrium decisions?

(2) From the economic performance perspective, does one strategy is better than the other?

(3) From the environmental impact, does one strategy is better than the other?

Our paper, from our understanding, is the first paper to highlight how the different strategies (such as the use of core collecting and remanufactured product remarketing) conducted by OEMs impact cannibalisation problems and influence the industries economics and environments. The main contribution of this paper is therefore twofold.

From the modelling perspective, by building onto existing work that focuses on managing used core collecting (Raz and Souza 2018) or on remanufactured product remarketing (Wu and Zhou 2019), we provide a complementary framework that evolves from examining individual activities to considering a business with three subprocesses (used core collecting, remanufactured product remarketing, and market cannibalisation). That is, we intend to highlight the implications of managing cannibalisation problems with these two different strategies in remanufacturing outsourcing. Following this, we will go a step further to compare these strategies in regard to their economic and/or environmental implications.

From an insight perspective, this work provides a more accurate understanding of how OEMs should operate on a tactical level when they outsource the remanufacturing

operations to 3PRs. In particular, our analysis suggests that minimising cannibalisation problems does not always equate with maximising profits. In particular, if the collection cost coefficient is not pronounced, the aggressive response by the OEM minimises the cannibalisation problems from the 3PR's remanufacturing. However, it also induces lower profitability for the OEM in Model C. Further, as the collection cost coefficient is moderate, remarketing remanufactured products can secure Pareto improvements. As such, we suggest that practising managers should combine the cannibalisation problems of remanufacturing with the cost of collecting used cores.

The rest of the paper is organised as follows: Section 2 reviews the related literature and explains our contributions in more detail, Section 3 describes both models and analyses their optimal decisions, Section 4 and Section 5 examine both models and present the main results and Section 6 concludes our work by discussing on our main results and providing future research directions.

2. Literature Review

Our work draws on three streams of literature: (1) used cores collecting, (2) remanufactured products remarketing, (3) managing cannibalisation problem from 3PRs's remanufacturing (a quick overview is presented in Table 1)

Insert Table 1 here

Used core collecting has been well-studied from the reverse supply chain. For example, (Savaskan et al. 2004) discussed OEMs' used product collection options and explored appropriate reverse channel structures. (Örsdemir et al. 2014) further explored a case where an OEM competed with a 3PR and indicated that the OEM is more likely to limit core availability as the 3PR's competitive position gets stronger. Subsequently, (Hahler and Fleischmann 2017) proposed a sequential bargaining model with complete information that captures used core collection and determined the optimal strategies of the product holder and the recommerce provider. Recently, (Raz and Souza 2018) investigated how recycling can be a strategic source of supply in the presence of a changing market. More recently, (Goltsos et al. 2019) explored the time-varying interactions of material and information flows in the different elements of

121 remanufacturing supply chains. Meanwhile, (Yang et al. 2019) analysed a robust
122 optimisation model for studying the remanufacturing decision problem when the quality
123 information of the cores is partly unknown in a remanufacturing system. In the above
124 work, used cores collecting is framed as the reverse logistics design that oversimplifies
125 the remanufactured products remarketing and cannibalisation of new products sales. In
126 contrast, we consider the collection operation as a decision for the OEM to deal with the
127 cannibalisation problems from 3PRs' remanufactured products. Furthermore, as a set,
128 the above papers do not allow the OEM the flexibility to act as a marketer for
129 remanufactured products. However, in practice, remanufacturing outsourcing provides
130 OEMs (such as Land Rover) with the potential flexibility to purchase remanufactured
131 products from a 3PR (such as Caterpillar Remanufacturing Services) Following this,
132 they can remarket them to consumers. Therefore, we complement this stream of research
133 by addressing how the decisions about used core collecting differ from that of
134 remanufacturing product remarketing in the cannibalisation problems management, as
135 well as their economic and environmental benefits.

136 Remanufactured product remarketing is another important focus of the literature on
137 remanufacturing that studies market segmentation and cannibalisation problems. For
138 example, (Yan et al. 2015) considered that the OEM has two options to market
139 remanufactured products and explored the channel selection strategy. Related to this
140 stream of work, (Zou et al. 2016) further stated that the OEM obtains higher profits
141 through outsourcing. For example, a 3PR performs remanufacturing operations, while
142 the marketing of the remanufactured products is performed by the OEM rather than
143 through authorisation. (Wang et al. 2017) explored an OEM that sold both new and
144 remanufactured goods through their retailer, as well as the impacts on both parties'
145 profits and the environment. (Wu and Zhou 2019) revisit the effects of buyer-specific
146 versus uniform pricing in a closed-loop supply chain in which one supplier sells a
147 component that cannot be remanufactured to one OEM and TPR. This stream of
148 research mainly focuses on studying whether the presence of remanufactured products
149 impacts the perceived value of new products, as well as how this process occurs. These
150 works do not consider used core collecting decisions. They also ignore that the OEMs

151 have the flexibility of minimising the cannibalisation problems by limiting the quantities
152 of used cores. We therefore draw and extend from prior research in remanufactured
153 product remarketing to model a situation in which the OEM chooses whether to collect
154 used cores or sell remanufactured products. This provides a detailed understanding of
155 how the decisions about how remanufactured product remarketing differs from that of
156 used core collection in the cannibalisation problems and managing further in the
157 economic and environmental benefits.

158 Our paper is also related to the literature that addresses cannibalisation issues in
159 remanufacturing. (Majumder and Groenevelt 2001) examined how third-party
160 remanufacturing can induce competitive behaviour when remanufactured products
161 cannibalise the demand for original products. (Debo et al. 2005) found that as the
162 number of remanufacturers increases, the OEMs' profits decreases. Similarly, (Ferguson
163 and Toktay 2006) found that as an entrant becomes more competitive, an OEM should
164 increase their efforts to deter the entry of independent remanufacturers. (Oraiopoulos et
165 al. 2012) showed that the competition from a third-party not only generates relicensing
166 revenues for the OEMs but also increases the marginal revenue of the new products
167 regarding the cannibalisation effect. Recently, (Huang et al. 2019) considered the
168 competition between one TPR and one OEM. They investigated the incentives of cost
169 information sharing. To our knowledge, previous studies of managing cannibalisation
170 problems in remanufacturing have not examined what conditions the strategy of used
171 core collecting differs from that of remanufactured product remarketing. In this paper,
172 we report the results of cannibalisation problems managing concerning the different
173 strategies. We further comment on how the decisions about remanufactured product
174 remarketing differ from that of the used core collection in their economic and
175 environmental benefits.

176 **3. Model Description and Assumptions**

177 The primary goal of this paper is to explore how decisions on used core collection
178 and remanufactured product remarketing are made by OEMs and their effects on
179 economic and environmental factors. As shown in Figure 1, we consider that an OEM
180 has two possible options when dealing with cannibalisation problems that arise from

3PR remanufacturing: (1) participating in remanufacturing operations by collecting cores from consumers and selling them to the 3PR (Model C) or (2) participating in remanufacturing operations by purchasing all remanufactured products from the 3PR and remarketing them to consumers (Model R). We discuss and layout our key assumptions below.

insert Figure 1 here

We make the following assumptions:

Assumption 1. *The unit cost of remanufacturing a used core (c_r) is lower than that of producing a new product (c_n); i.e., $c_r < c_n$.*

Prior literature affirms that companies can save 40–65% in manufacturing costs through remanufacturing (Giutini and Gaudette 2003). This occurs because remanufacturing can effectively reduce procurement costs by reusing components and parts (Zou et al. 2016). This assumption is widespread in the supply chain literature (Ferguson and Souza 2010, Xiong et al. 2013, Yan et al. 2015).

Assumption 2. *Consumer willingness-to-pay for a new product is heterogeneous and uniformly distributed in the interval $[0, 1]$. For each consumer, the ratio of the willingness-to-pay for a remanufactured product to that for a new product is γ ($0 \leq \gamma \leq 1$).*

Assumption 2 represents a vertical differentiation model that allows for heterogeneity in the willingness-to-pay for quality among consumers (i.e., all willingness-to-pay for remanufactured products is lower than that for new products; (Debo et al. 2010, Xiong et al. 2013, Zou et al. 2016). Note that such heterogeneity in willingness-to-pay for new and remanufactured products is supported by empirical evidence (Guide Jr and Li 2010, Agrawal et al. 2012, Subramanian and Subramanyam 2013).

Assumption 3. *The market size of the consumer population is assumed to not change over time and is normalised to 1.*

Assumption 3 is widely accepted in remanufacturing research ((Savaskan et al.

2004, Ferguson and Souza 2010, Xiong et al. 2013, Yan et al. 2015, Wang et al. 2017).

Based on Assumptions 2-3, we can derive inverse demand functions for new and remanufactured products as follows:

$$\begin{aligned} p_n &= 1 - q_n - \gamma q_r \\ p_r &= \gamma(1 - q_n - q_r) \end{aligned} \quad (1)$$

We should note that consumers usually discount the value of remanufactured products. Consequently, this creates the problem of cannibalisation between new and remanufactured products (Yan et al. 2015). For example, consumers will not purchase remanufactured products if, $\gamma = 0$, because they regard them to be of lower quality than new ones. However, if, $\gamma = 1$, consumers are willing to pay the same amount for remanufactured and new products.

Assumption 4. *Without the loss of generality, we assume a collection cost function of $\frac{1}{2}kq_r^2$, where k is a scaling parameter.*

We borrow this assumption from previous literature (Ferguson and Toktay 2010, Jacobs and Subramanian 2012, Atasu and Souza 2013, Zou et al. 2016). Therefore, additional effort is required to recover larger volumes due to the cost of collecting used products increases non-linearly with the quantity collected (Zou et al. 2016).

Assumption 5. *All decisions are considered in a single-period setting in both models.*

We focus on the average supply chain profit per period, given that (Savaskan et al. 2004) assumed products that exist in the market previously could be returned to the OEM for reuse. This approach enables us to focus on steady-state profits, facilitates analytical tractability in our model, and contributes to the solution of our problems. All relevant variables are defined in Table 2.

Insert Table 2 here

4 Model Formulation and Solution

In this section, we analyse two remanufacturing models: Model C and Model R.

Variable Π_x^i refers to the profits for player x under Model j . Subscript

$x \in \{m, 3p, t\}$ denotes the players of the OEM, 3PR and total supply chain, respectively.

Meanwhile, superscript $j \in \{C, R\}$ denotes Model C and Model R, respectively.

4.1 Model C

The sequence of events for Model C is as follows. First, the OEM announces a patent license fee per remanufactured product (i.e., f). Sequentially, both the OEM and the 3PR determine the optimal quantities of new and remanufactured products, respectively. Therefore, the OEM and 3PR problems are, respectively, as follows:

$$\begin{aligned} \max_{q_n, f} \Pi_m^C &= (p_n - c_n)q_n + fq_r - \frac{1}{2}kq_r^2 \\ \max_{q_r} \Pi_{3p}^C &= (p_r - c_r)q_r - fq_r \end{aligned} \quad (2)$$

We solve the problem with backward induction to determine the subgame perfect equilibrium and present the equilibrium decisions and profits in Table 2. For clarity, all proofs are provided in the appendix.

4.2 Model R

The sequence of events in Model R is as follows. First, the OEM announces the wholesale price (i.e., w^l). Sequentially, both the OEM and the 3PR determine the optimal quantities of new and remanufactured products, respectively. Therefore, both parties' problems are as follows:

$$\begin{aligned} \max_{q_n, q_r} \Pi_m^R &= (p_n - c_n)q_n + (p_r - w)q_r \\ \max_{w_r} \Pi_{3p}^R &= (w - c_r)q_r - \frac{1}{2}kq_r^2 \end{aligned}$$

We can summarise all the equilibrium decisions in Table 3 using backward induction.

Insert Table 3 here

To enable the comparison of the interior point solutions to both models (i.e.,

¹ This assumption is consistent with the fact that although Apple have outsourced remanufacturing to 3PRs, in such outsourcing Apple is still the leader. Such assumption of the upstream agent is unable to influence the wholesale price for the dominant downstream agent is previously well established in the marketing literature (see, e.g., Geylani, T., A. J. Dukes and K. Srinivasan (2007). "Strategic Manufacturer Response to a Dominant Retailer." *Marketing Science* 26(2): 164-178. and Raju, J. and Z. J. Zhang (2005). "Channel Coordination in the Presence of a Dominant Retailer." *Ibid.* 24: 254-262.

$0 < q_r < q_n$) according to (Xiong et al. 2013) and (Yan et al. 2015), we make the following assumption:

Assumption 6. In both our models, the cost of remanufacturing a core is not sufficiently small or large. That is: $\frac{-k + c_n k - 4\gamma + 6c_n \gamma + 4\gamma^2 - 2c_n \gamma^2}{2 + 2\gamma} < c_r < c_n \gamma$.

5. Analysis

In this section, we start by comparing the equilibrium decisions of the two models. Subsequently, we enrich our analysis by exploring the relative profitability and the environmental outcomes of both models.

5.1 Comparison of optimal outcomes

After comparing the equilibrium outcomes in Table 3, we first consider the differences in the optimal quantities of new and remanufactured products, estimated by Models C and R in the following proposition.

Proposition 1: (i) *The OEM is more likely to provide greater quantities of new products in Model C than in Model R; essentially: $q_n^{C*} > q_n^{R*}$;*

(ii) *When the collection cost coefficient is not relatively high, (i.e., $k < k_1$) the optimal quantities of remanufactured products in Model C are lower than that in Model R (i.e., $q_r^{T*} < q_r^{R*}$). Otherwise, the opposite is true.*

Proposition 1 reveals that the OEM sells more new products in Model C than that in Model R ($q_n^{C*} > q_n^{R*}$). This means all remanufactured products that are remarketed by the 3PRs trigger an aggressive response by the OEM. This is because more new products become available in the market. Therefore, the potential market for remanufactured products decreases. The following is intuitive: in Model C, new products are distributed by the manufacturer, while all remanufactured products are provided by the 3PR. However, in Model R, both products are sold by the OEM. More specifically, remanufactured product remarketing is the only source for 3PR's profits. Thus, the 3PR would care less about the potential cannibalisation of new products sales. This puts pressure on the OEM to choose a higher quantity for new products when remanufactured

product remarketing by the 3PRs compared with that in Model R.

Proposition 1 further shows that when the collection cost coefficient is relatively low (i.e., $k < k_1$). This means that when marginal revenue of selling remanufactured products is high, the optimal quantities of remanufactured in Model C is lower than that of Model R (i.e. $q_r^{C*} < q_r^{R*}$). This may be attributed to several reasons. When the collection cost coefficient is relatively low, the OEM likely provides fewer quantities of remanufacturing in Model C. This is because it usually distributes relatively more units of new products ($q_n^{C*} > q_n^{R*}$). Therefore, since the OEM sells so many new products, the size of the potential market for the remanufactured products decreases. If the 3PR sells more units of remanufactured products, its price will decrease dramatically. Thus, when the collection cost coefficient is relatively low compared to Model R, the 3PR provides fewer quantities of remanufacturing in Model C.

Nonetheless, as long as the collection cost coefficient is relatively high (i.e. $k > k_1$), the optimal quantities of remanufacturing in Model R will be lower than that in Model C (i.e. $q_r^{C*} > q_r^{R*}$). This can be interpreted. Recall that, as the collection cost coefficient increases (in particular, $k > k_1$), the marginal revenue from remanufactured products decreases. In Model R, since both products are distributed by the OEM, the OEM decreases the quantities of remanufactured as its marginal revenue decreases. This is to mitigate the cannibalisation problem from remanufactured products. While in Model C, since remanufactured product remarketing is the only source for the 3PR's profits and the marginal revenue from remanufactured products is small, the 3PR has no choice but to sell more units of remanufactured products.

5.2 Comparison of profitability

So far, we have focused on how different strategies influence the equilibrium behaviour of related parties. In this subsection, we intend to analyse from an economic performance perspective. Is one strategy is better than another? To understand, we first turn our attention to the difference in the OEM profitability estimates of the models, which is summarised as follows (see Figure 2):

Proposition 2. *When the collection cost coefficient is not relative high (i.e. $k < k_1$), the equilibrium profit of the OEM is lower in Model C than in Model R (i.e., $\Pi_M^{C*} < \Pi_M^{R*}$). Otherwise, the opposite is true.*

Insert figure 2 here

Interestingly, Proposition 2 shows that minimising the cannibalisation problems does not always equate with maximising profits. In particular, if the collection cost coefficient is not pronounced (i.e., $k < k_1$), the aggressive response by the OEM (i.e., $q_n^{R*} < q_n^{C*}$ in Proposition 1) minimises the cannibalisation problems from the 3PR's remanufacturing (i.e., $q_r^{C*} < q_r^{R*}$ in Proposition 1). However, it also induces lower profitability for the OEM in Model C (i.e., $\Pi_M^{C*} < \Pi_M^{R*}$).

The presence of remanufactured products, indeed, reduces the sales of new products. This is especially true if all remanufactured products are sold at lower prices. However, we need a better understanding of the competition between new and remanufactured products. It should be noted that remanufacturing is a way to generate additional profits. Lower-priced remanufactured products can reach consumers who have a lower willingness-to-pay and would not buy new products. This means that, under certain conditions, the remanufactured product may be profitable despite its price is lower than the new one. Proposition 2 provides support for this detailed understanding: Compared to Model C, the OEM offers lower quantities of new products than in Model R, which results in the price of new products increasing and the size of the potential market for the remanufactured products being relatively high. If the collection cost coefficient is not pronounced (i.e., $k < k_1$), the OEM can transform the cannibalisation into a cash cow. The market segmentation can be “milked” to obtain higher profits from the low-priced remanufactured products and induce ($\Pi_M^{C*} < \Pi_M^{R*}$). That is, when the collection cost coefficient is not pronounced, the 3PR's remanufacturing can provide the additional profits that outweigh the cannibalisation costs if the OEM adopts a less aggressive response to the lower units of new products.

To study the influence of introducing remanufactured products in the OEM market of new products, (Atasu et al. 2010) found that, cannibalisation is not a major concern when remanufactured versions are perfect substitutes for new products. However, it becomes a concern when remanufactured, and new products differ. Proposition 2 reveals that practising managers should focus both on the cost of collecting used cores and the cannibalisation problems of remanufacturing. Although we conducted a similar analysis on the effects of introducing remanufactured products in the OEM market of new products, our work differs in two important aspects: First, in contrast to Atasu et al.'s (2010) assumption of a manufacturer undertaking both new and remanufactured product production, we assume that the remanufacturing operations are outsourced to the 3PR. This is consistent with the fact that, in the USA remanufacturing industry, only 6% of more than 2000 remanufacturing enterprises were OEMs (Hauser and Lund 2008). Second, the researchers mainly discussed the effects of cannibalisation problems and supply constraints. However, in combining the cannibalisation problems, we separate the decisions about the quantities of used cores to collect and the units of remanufactured products to remarket. We further address how the different strategies conducted by OEMs influence the cannibalisation problem and the economic and environmental benefits.

The difference in 3PR profitability estimated by the two models (based on the equilibrium outcomes in Table 3) can be summarised as follows (see Figure 3):

Proposition 3. *When the collection cost coefficient is relatively low (i.e., $k < k_2$), the 3PR's profit in Model C is greater than that in Model R (i.e., $\Pi_{3P}^{C*} > \Pi_{3P}^{R*}$). Otherwise, the opposite is true.*

Insert Figure 3 here

Recall that $q_n^{R*} < q_n^{C*}$ means that the OEM's profit from new products sales in Model R is always lower than that in Model C. Additionally, make note that, when the collection cost coefficient is relatively low (i.e., $k < k_2$), the marginal revenue of selling remanufactured products is high. As such, to compensate for the profit "loss" in new products sales and maximise its profits from remanufactured product sales, the OEM

should set a relatively lower input price (i.e., wholesale price) through countervailing the buyer power in Model R. The lower wholesale price naturally results in the 3PR's profitability in Model R becoming lower than that in Model C.

Based on Propositions 2 and 3, we now can summarise our findings on profitability in the following corollary:

Corollary 1. (i) *If the collection cost coefficient is low (i.e., $k < k_2$), the OEM (3PR) would obtain higher (lower) profits from Model R than in Model C.*

(ii) *If the collection cost coefficient is moderate (i.e., $k_2 < k < k_1$), compared to Model C, Model R can create a win-win result for both parties.*

(iii) *If the collection cost coefficient is high, (i.e., $k > k_1$), the OEM (3PR) would obtain lower (higher) profits from Model R than in Model C.*

This corollary follows directly from Proposition 2 and Proposition 3 and its parts (i) and (iii) are interpreted in Proposition 2 and Proposition 3, respectively. However, Part (ii) is interesting because it indicates that, compared to used core collecting, remarketing remanufactured products can secure Pareto improvements, as long as the collection cost coefficient is moderate. Take note that when the collection cost coefficient is relatively low (i.e., $k < k_2$), the 3PR's profitability in Model C becomes higher than that in Model R. Corollary 1 further reveals that, when the collection cost coefficient is moderate, the 3PR's profitability in Model C becomes lower than that in Model R.

The rationale is that, as mentioned earlier, the competition in Model C is always fiercer than that in Model R. This is to due to the fact that under the former scenario, all new products are distributed by the OEM, while all remanufactured products are provided by the 3PR. Accordingly, when compared to Model R, as the collection cost coefficient increases to k_2 , the decline of the 3PR's profit in Model C is higher than that in Model R. This results in 3PR's profitability in Model C becoming lower than that in Model R.

5.3. Comparison of Environmental Impacts

In this subsection, we address the final question posed at the beginning of this paper: In examining environmental impact, is one strategy better than the other? In this analysis, we use i_n and i_r to represent the per-unit impacts of new and remanufactured products,

respectively. Since remanufacturing requires less material and energy than manufacturing new products, we make the following assumption:

Assumption 7. The per-unit environmental impact of a new product is greater than that of a remanufactured one ($i_n > i_r$).

We use E^C and E^R to represent the environmental impacts of Models C and R, respectively. Further, based on Proposition 1, Proposition 2, and Assumption 7, we offer the following proposition.

Proposition 5. *Model R is greener than Model C for $k < \hat{k}(i_n; i_u)$. Otherwise, the opposite is true.*

Obviously, the environmental impact depends not only on the quantities of remanufactured products but also on the units of new products. In particular, in the instance of $k < \hat{k}(i_n; i_u)$, the higher environmental impact in Model C is due to the increase in environmental impact from the production, usage and disposal of new products (i.e., $i_n q_n^{C*} > i_n q_n^{R*}$). These new products become dominant over decreases in environmental impact, created by fewer used products remanufacturing (i.e., $(i_n - i_u) q_r^{C*} < (i_n - i_u) q_r^{R*}$).

6. Numerical Study

In this section, we provide a quantitative study to reanalyse our main results related to the economic and environmental outcomes. As (Esenduran et al. 2016) mentioned, we pick three representative products: refrigerator, liquid crystal display (LCD) monitors, and mobile phones as representative products for our quantitative study.

6.1 Data Sources

We first explain in detail how we collected the data for all parameters as follows, including the cost of manufacturing (c_n) and potential market size (Q) of refrigerators. Our findings were consistent with the US Department of Energy (2013) and (Esenduran et al. 2016), who established the price from e-retailers to range between \$500 and \$1500. We have chosen $c_n \in \{375, 750, 1125\}$, assuming a 25% markup. Like (Debo et al. 2005),

we selected 17-inch LCD monitors as a representative product, which ranged between \$50 and \$150. According to (Esenduran et al. 2016) and (TGD 2006), we also assume that the marginal revenue of monitors is quite lean, and its production costs almost equal to the sale prices ($c_n \in \{50, 100, 150\}$). For mobile phones, consistent with (Ovchinnikov 2011) who established $c_n \in \{150, 300\}$, we chose $c_n \in \{50, 100, 150\}$. Given that, in our study, the potential market size is normalized to 1, consistent with (Atasu and Souza 2013), we chose such for LCD monitors. This results in the ratio of $\frac{c_n}{Q} = 0.25$.

Cost of the collection (k): Consistent with (Esmaeili et al. 2016), who assumed the collection cost for the three products, we chose $k \in \{1.5, 1.75, 2\}$ for refrigerator, $\{0.6, 0.7, 0.8\}$ for 17-inch LCD monitors, and $\{0.1, 0.15, 0.2\}$ for mobile phones to represent the coefficient of the collecting cost being high, moderate, and low, respectively.

Consumer value discount (γ) and Energy usage parameters (i): It has been argued that the consumer value discount for remanufactured products can vary from 45% to 85% (Marion, 2004). Therefore, we selected $\gamma \in \{0.5, 0.65, 0.8\}$. For refrigerators, from the references of (Gutowski et al. 2011), we chose $i_n = 6909MJ$. For LCDs, from EPA (2013), we chose $i_n = 2073MJ$. Following (Esmaeili et al. 2016), we chose $i_n = 200MJ$ for mobile phone. According to the report of Ezroj (2010), which argued that remanufacturing could require up to 80% less energy than manufacturing, we set the energy level required for remanufacturing as $i_u = i_n \times 0.8$.

All numerical study parameters are provided in Table 4.

Insert Table 4 here

6.2 Simulation on main results

In this section, we will describe how the difference in equilibrium decisions (such as optimal quantities) of new (remanufactured) the products in Figure 5, influence the economic performance of the OEM (3PR) in Figure 7 and environmental outcomes in

Figure 9, respectively.

Insert Figure 5 here

Figure 5 illustrates that, for any collection cost coefficient, the optimal quantities of the new products in Model C are always greater than that in Model R. However, as Proposition 1 (ii) shows, the optimal quantities of remanufactured products in Model C are higher than that in Model R for refrigerators (see Figure 6a). In contrast, when the collection cost coefficient is moderate (see the LCD monitor in Figure 6b) or low (see mobile phone in Figure 6c), the optimal quantities of the remanufactured products in Model C are always lower than that in Model R. Additionally, Figures 5 and 6 reveal that, as the remanufacturing cost c_r increases, the quantity of new (remanufactured) products increases (decreases).

Insert Figure 6 here

Figure 7a demonstrates that, when the collection cost is pronounced (i.e., under the scenario of a refrigerator), the OEM's profitability in Model C becomes greater than that in Model R. However, when the collection cost is not pronounced (i.e., under the scenarios of LCD monitor and mobile phone), as Figure 7b and Figure 7c demonstrate, the OEM's profitability in Model C becomes lower than that in Model R. This is quite consistent with the theoretical argument discussed in Proposition 2.

Insert Figure 7 here

Consistent with the theoretical argument discussed in Proposition 3, Figure 8a and Figure 8b show that, for the refrigerator and LCD monitor, the 3PR's profitability in Model C becomes lower than that in Model R. However, under the scenario of mobile phone (as seen in Figure 5c), the 3PR's profitability in Model C is always greater than that in Model R.

Insert Figure 8 here

Figure 9 shows that when the collection cost increases, the difference in the environmental impact between Model C and Model R decreases. Although we can not derive the results in Proposition 4 directly from Figure 9, based on the outcomes in Figure 9, we can indirectly conclude that there is a threshold of $(\gamma k(i_n; i_u)=4.56)$. This threshold is below the environmental impact in Model C, and greater than that in Model

R.

Insert Figure 9 here

From our numerical studies on the refrigerator, LCD monitor and mobile phone, we can directly observe that the influence of the remanufacturing cost on the total remanufacturing (Proposition 1), OEM, and 3PR (propositions 2-3) continue to hold. Although the numerical studies on these three products can not perfectly support Proposition 4, we can conclude that the collection cost increases. Furthermore, the difference in the environmental impact between Model C and Model R decreases. Therefore, based on the variations in the optimal outcomes in Figure 9, we can indirectly conclude that there is a threshold of $(k(i_n; i_u)=4.56)$, below the environmental impact in Model C, and greater than that in Model R. Our numerical studies also indirectly support Proposition 4.

7. Discussion and Conclusions

This paper was motivated by examples from industry. We developed two models in which an OEM produces new products and outsources remanufacturing operations to a 3PR, with two possible strategies for dealing with cannibalisation problems arising from remanufacturing. First, participating in remanufacturing operations by collecting cores from consumers (Model C). Second, participating in remanufacturing operations by remarketing remanufactured products to consumers (Model R).

The existing literature focuses mainly on whether OEMs should participate in used core collecting and remanufactured product remarketing, separately. These two dimensions are both essential strategies to deal with the cannibalisation problems from remanufacturing. To our knowledge, this is the first paper to highlight how these different strategic choices of OEMs can affect the economic and/or environmental outcomes related to remanufacturing outsourcing. Our analysis reveals different strategies undertaken by OEMs influence the related outcomes of both practising managers and environmental groups.

How do the different options for minimising the cannibalisation effect equilibrium decisions? Based on Proposition 1, we can conclude that, when $k < k_1$ is compared to remarketing remanufactured products, collecting used core remanufactured products

triggers an aggressive response by the OEM to deal with the cannibalisation problems ($q_n^{C*} > q_n^{R*}$). This argument is partly consistent with the results of (Guide Jr and Li 2010), who argue that, although annual returns of used products in excess of \$800 million, a leading networking equipment manufacturer scraps almost all of their product returns. They do this instead of remanufacturing because they fear the cannibalisation of new product sales. Proposition 1, however, further reveals that in the instance of $k > k_1$, more new products are available in the market. However, 3PR provides more units of remanufactured products to compete with them ($q_r^{C*} > q_r^{R*}$).

From a profit-maximisation perspective, does one strategy have an advantage over the other? Propositions 2 and 3 indicate that the scaling parameter of collection cost plays an important role in determining both parties' profit estimates of the two models. If the collection cost coefficient is not pronounced, the aggressive response by the OEM minimises the cannibalisation problems from the 3PR's remanufacturing. However, it also induces lower profitability for the OEM in Model C. Based on Corollary 1, we can further conclude that, when the collection cost coefficient is moderate, remarketing remanufactured products can create a win-win result for both parties. As such, we suggest that practising managers should combine the cannibalisation problems of remanufacturing with the cost of collecting used cores.

Finally, Proposition 4 indicates that in the instance of $k > \hat{k}(\text{in}; \text{iu})$, undertaking used core collection is greener than remarketing remanufactured products. However, based on the numerical simulation that generated estimates for refrigerators, LCDs and mobiles, we find that, for any of these three products, comparing remarketing remanufactured products, undertaking used core collection has a higher environmental impact and is harmful to our environment. This implies that a "rational" OEM (particularly when its profitability in Model R is greater than that in Model C) has no particular incentive to improve the environmental profile if they know that their profitability may be hurt by the cannibalisation of remanufacturing. As such, environmental groups and agencies should focus their attention on encouraging the 3PRs to undertake used core collection or design a clearer framework to simulate the OEMs'

used core collection. For example, California has issued an Advance Recovery Fee (ARF) for a wide variety of consumer electronics and appliances. The amount of the ARFs is set, based on the size, weight, and the degree of recycling undertaken by an OEM (Sachs, 2006). Similarly, in 2007, Minnesota issued the Minnesota Electronics Recycling Act that requires brand owners to collect and recycle the equivalent to 80% by weight of obligated products during the program year (Hickle 2013). However, if the OEM does not fulfil the above obligation, the law stipulates per pound products with either 0.3\$, 0.4\$, or 0.5\$. The amount is determined by how close they are to meeting their obligation (Ezroj 2010).

This research could be extended in several directions. Firstly, we assumed that the OEM was limited to a linear wholesale price. While this is common in reality and standard in the literature, it would be advantageous to understand the implications of an OEM, using a more complex pricing mechanism. Second, we assumed that all remanufactured products were identical. In reality, consumers exhibit differing preferences for remanufactured products sold by different sellers. We hope this research will open further thought-provoking avenues of research. Finally, given our focus on sustainability issues, we did not consider certain other factors, including the strategies of leasing and selling. This may be an important role in the remanufacturing of durables.

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