Price competition with OEM-remanufactured products

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Abstract

Despite environmental and economic advantages of remanufacturing, the potential for cannibalizing the sales of new product by OEM-remanufactured products is a key obstacle for OEMs to remanufacture their end-of-life products. In this paper, we investigate the OEM-remanufacturing strategy and its impacts on price decisions by adopting a game-theoretic framework, where there is competition between a remanufacturer who sells third-party remanufactured products and an OEM who offers new products and chooses whether to introduce OEM-remanufactured products. We formulate consumer valuation for the products in the consideration of consumers' perceived similarity between the new and OEM-remanufactured products and, moreover, characterize the chain members' equilibrium pricing behavior concerning the availability of used products for remanufacturing. We elaborate the impacts of the entry of the OEM-remanufactured products on equilibrium results and show that the provision of OEM-remanufactured products is not necessarily harmful to the remanufacturer especially when consumers perceive the less similarity between the OEM's products. Results of this study intend to provide managerial insights for managers response to the changes in competitive dynamics, consumer characteristics, and cost factors.

Key words: Pricing; Game theory; Closed-loop supply chain; Remanufacturing

1. Introduction

Remanufacturing is a process of restoring a used product to like-new condition by rebuilding or replacing certain components, and providing a warranty for the remanufactured product that is at least as good as the warranty for a new product, as defined by Ijomah et al. (2004). Because of the decrements in the raw materials and production processes, remanufactured products commonly are sold with lower prices than new products and meet the demand of consumers who desire environment-friendly products with like-new quality. Hence, these drivers encourage remanufacturers to enter a market and sell third-party remanufactured products, which are made of end-of-life products that were originally produced by original equipment manufacturers (OEMs). The entrant of third-party remanufactured products erode the sales of new products produced by OEMs. According to a Gartner report (Tripathi et al., 2009), in the printer-cartridge industry, competition from third-party remanufactured cartridges caused printer OEMs to suffer a significant decline in sales revenues of new printer cartridges, which are forecasted to exceed $13 billion in 2010. In the face of such a great threat from remanufactured products, a growing number of OEMs also offer OEM-remanufactured products to satisfy the demand of green and budget-constrained consumers. For example, Caterpillar provides remanufactured versions of most of their products, and remanufacturing division contributes about 8% of Caterpillar's revenue (Martin et al., 2010). Moreover, another consideration for OEMs to introduce remanufacturing is aim to deter remanufacturers by strategically collecting used products, which decreases the availability of used products for remanufacturing (Debo et al., 2005).

However, despite these attractive features, some of OEMs still do not remanufacture their used products. For example, Hewlett-Packard only remanufactures enterprise products (such as servers, storage infrastructures, networking products, etc) but officially declared to produce only single-use print cartridges and not to offer remanufactured cartridges (HP Inc., 2009). In addition, Cisco insists on the sales of new products and ignores the secondary market, even though the demand for used networking equipment

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grow substantially over the next few years (Wall Street Journal, 2009). Main concerns causing to this phenomenon are that the provision of OEM-remanufactured products may cannibalize the demand of new products and that OEMs spend the majority of time and resources focusing on their sales of new products that lead to higher margins (Agrawal et al., 2012; Atasu et al., 2008; Ferguson, 2010). As a result, the intent of this paper is to provide managerial insights for the entry of OEM-remanufactured products. Specifically, we develop a game-theoretical model to consider product cannibalization and price competition and, subsequently, characterize the influences of potential market and cost drivers on the chain members' equilibrium decisions and profitabilities in the absence and presence of OEM-remanufactured products.

There are two streams of literature that are related to this study: One examines the market segmentation under price competition between new and third-party remanufactured products, and the other examines the entry of OEM-remanufactured products. The studies in the first stream claimed that the presence of third-party remanufactured products provide consumers low-end substitutes for new products, and thus OEMs and remanufacturers compete with each other on their prices to acquire greater market shares (Atasu et al., 2008; Debo et al., 2005; Ferrer and Swaminathan, 2006, 2010; Ferguson and Toktay, 2006; Guide and Li, 2010; Majumder and Groenevelt, 2001; Wu, 2012a,b,c). For example, Majumder and Groenevelt (2001) developed the competition between an OEM and a local remanufacturer while considering the availability of end-of-life products for remanufacturing. They outlined the impacts of costs and collection of used products on the chain members' equilibrium decisions and profits. Such a formulation of the interaction between new and remanufactured products are commonly adopted in the later studies. Ferrer and Swaminathan (2006, 2010) further investigated the competitive relationship between new and third-party remanufactured products in monopoly and duopoly environments regarding finite- and infinite-planning horizons; moreover, they characterized the parametric effects on market segment and on chain members' strategies. Wu (2012c) further developed two-period and multiple-period models to explore the impacts of OEM product-design strategy for deterring the entry of remanufacturers in the presence of price competition between an OEM and a remanufacturer. Furthermore, Wu (2012a) based on the works of Wu (2012c) to discover the interaction between OEM product-design strategy and remanufacturer collection policy.

The studies in the second stream considered the OEM strategy of introducing remanufactured products into the market to deter remanufacturers or to gain economic benefits from remanufacturing (Ferguson and Toktay, 2006; Agrawal et al., 2012; Martin et al., 2010). Ferguson and Toktay (2006) modeled a competitive supply chain in which an OEM preemptively collect used products to limit remanufacturer's capacity for remanufacturing, and they further identified the cost conditions under which to remanufacture the collected products would be profitable for the OEM. Nonetheless, the market demand in Ferguson and Toktay (2006) is formulated as a linear additive form which is commonly adopted in the literature but ignore the impact of the presence of remanufactured products on consumer valuation for products. Agrawal et al. (2012) provided an empirical investigation on consumer willingness to pay (WTP) for products in the absence and presence of third-party remanufactured product and of OEM-remanufactured product. With the aid of the empirical results in Agrawal et al. (2012) and Martin et al. (2010), we formulate the market demand from consumers' utility functions that will be affected by the entry of OEM-remanufactured product. Our model allows to capture the concept of Agrawal et al. (2012), that is, the consumer valuation for new products will be affected by the provision of OEM-remanufactured product. Moreover, our numerical results correspond to the findings in Agrawal et al. (2012) in terms of OEM strategy for remanufacturing, and we further elaborate the effect of the change in the consumer valuation for remanufactured products. As a result, our paper complements the literature in remanufacturing by formulating the impacts of the entry of OEM-remanufactured products on chain members' price decisions with the consideration of consumer valuation for products.

2. The model

We consider a supply chain model consisting of two chain members: an OEM and a remanufacturer. (We refer to the OEM as female and the remanufacturer as male.) The OEM sells new products with a unit sales price p_n, and the remanufacturer recovers used products and sells third-party remanufactured products with a unit sales price p_r. Thus, price competition emerges in the sales market. Because of an inability to produce entire products from raw materials, the remanufacturer's capacity is determined by the collected quantity of used products. For deterring the remanufacturer, the OEM can choose to collect used products and, subsequently, sells OEM-remanufactured products with a unit sales price p_o, which decreases the availability of used products for the remanufacturer and cannibalizes the sales of third-party remanufactured product. However, OEM-remanufactured products also cannibalize the sales of the new product, which indicates that offering OEM-remanufactured products is not necessarily beneficial for the OEM. Therefore, we examine two cases denoted by case I and case II, which respectively represent the scenarios in which the OEM does not and does offer OEM-remanufactured products. We assume that other products in the dedicated market and other markets do not affect the demand for the products under consideration. This assumption allows us to specifically focus on the competition between the products sold by the OEM and the remanufacturer. We also consider the supply chain members to be risk-neutral and profit maximizing and to have complete information for the games (Cachon and Lariviere, 1999; Goyal and Netessine, 2007). Furthermore, according to Atasu et al. (2008); Ferrer and Swaminathan (2006); Ferguson and Toktay (2006); Majumder and Groenevelt (2001); Ray et al. (2005), we apply the assumption that a new product purchased in the previous periods cannot provide positive utility for the customers in the subsequent periods; thus, the product has a useful lifetime of only one sale period. This assumption claims that the consumers' purchasing behaviors across the periods are independent. Throughout the paper, we let the subscript i take the values of r, n and o, denoting the third-party remanufactured product, the new product, and OEM-remanufactured product, respectively. In addition, let k take the values of r and o, denoting the remanufacturer and the OEM, respectively.

2.1. *Market demand*

We consider that the market consists of Q consumers, who are price sensitive and make purchasing choices depending on their utility functions. A consumer's valuation for a new product is denoted by α, and her/his valuation for a remanufactured product is assumed to be lower, denoted by $\rho\,\alpha$ ($0 < \rho < 1$). For the sake of simplicity, $\bar{\rho} \equiv 1 - \rho$. Following Ghosh and Morita (2012); Salop (1979) and Shulman et al. (2011), we let x ($f(x) \sim \text{Uniform}[0, 1]$) denote each consumer's location in a Salop's circular city, which represents the product characteristic space and enables us to formulate the changes on demand when the OEM opts to offer OEM-remanufactured products. Moreover, we cap-

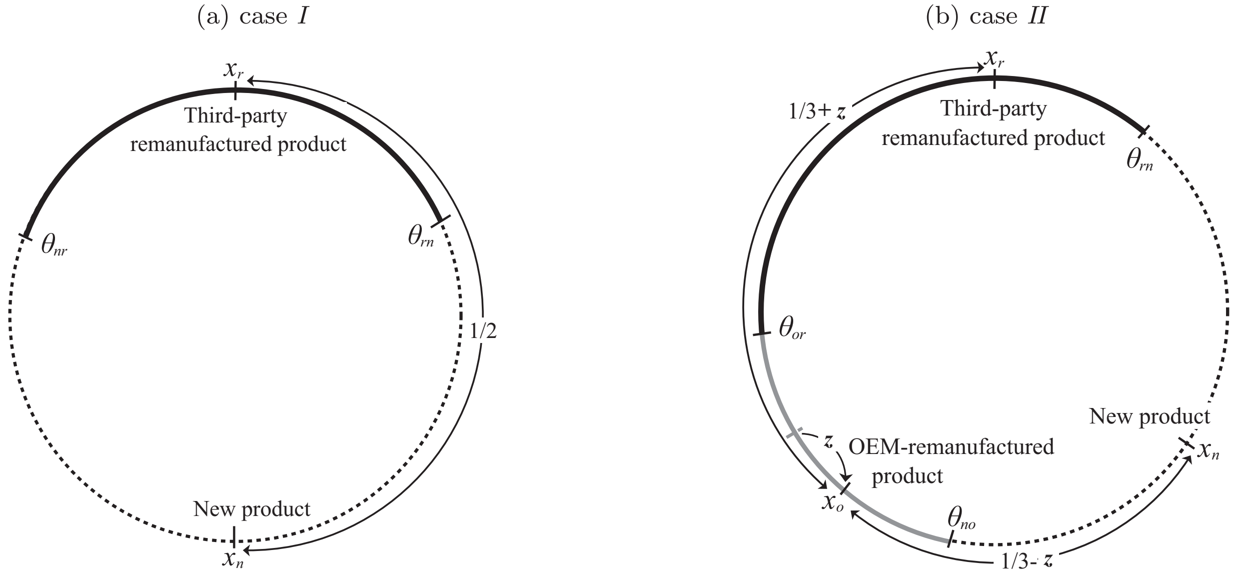

Figure 1. Formulation of production differentiation (thick arc: χ_r, dotted arc: χ_n, gray arc: χ_o)

ture the heterogeneity of consumer preference by assuming that consumers are uniformly distributed along the circle of circumference, in which product i locates at the point x_i. We use $|x_a - x_b|$ to denote the minimum distance between the points x_a and x_b, i.e., the closer arc length around the circle. Therefore, the utility that a type-x consumer receives from a third-party remanufactured product is $U_r = \rho\,\alpha - p_r - |x - x_n|$, the utility from a new product is $U_n = \alpha - p_n - |x - x_n|$, and the utility from OEM-remanufactured product is $U_o = \rho\,\alpha - p_o - |x - x_o|$. Note that we focus on the case where α is large enough so that each consumers can receive positive utility from at least one product.

Each consumer locates between two kinds of products and buys the product that provides him or her with the higher utility. In case I, the new and third-party remanufactured products are located equidistantly around the circle, as depicted in Figure 1(a). Thus, the distance between x_r and x_n equals 1/2. By solving $U_r = U_n$, we derive two indifference points $\theta_{rn} = (1/2 - \alpha(1-\rho) + p_n - p_r)/2$ and $\theta_{nr} = (1/2 + \alpha(1-\rho) + p_n - p_r)/2$ on which consumers are indifferent between the new and third-party remanufactured products. The consumers who locate in $\chi_r \equiv [\theta_{nr}, x_r] \cap [x_r, \theta_{rn}]$ purchase the third-party remanufactured products, and the remainder proportion of consumers purchase the new products. As a result, the demand quantity of the third-party remanufactured and new products can be calculated as

$$d_r = Q \times \int_{x\in\chi_r} f(x)\,\mathrm{d}\,x = \frac{Q}{2}\left(1 - 2\alpha\bar{\rho} + 2p_n - 2p_r\right),$$
$$d_n = Q \times \int_{x\in\chi_n} f(x)\,\mathrm{d}\,x = \frac{Q}{2}\left(1 + 2\alpha\bar{\rho} - 2p_n + 2p_r\right).$$

In case *II*, because both the new and OEM-remanufactured are produced and sold by the OEM, consumers may perceive a certain degree of similarity between these two products, whcih may intensifies proudct cannibalization. In reality, many OEMs concern that their owned remanufactured products would severely cannibalize their sales of new products, and consequently they do not offer remanufactured products (Agrawal et al., 2012; Ferguson, 2010; HP Inc., 2009). We formulate the level of consumers' perceived similarity between the new and OEM-remanufactured products in terms of z, $0 \le z < 1/3$. Thus, we have $|x_n - x_o| = 1/3 - z$, $|x_r - x_n| = 1/3 + z$, and $|x_o - x_r| = 1/3$, as shown in Figure 1(b). This formulation is reasonalbe to show that consumers experience the greatest product differentiation between the new and third-party remanufactured products, because these two products are different in product types and are provided by different manufacturers. Next, solving the equality of the utilities between two products gives the indifference points θ_{rn}, θ_{no}, and θ_{or}. The consumers who locate on $\chi_i \equiv [\theta_{ji}, x_i] \cap [x_i, \theta_{ij'}]$ $(j, j' \in \{r, n, o\}/i$ and $j' \ne j)$ purchase product i. Hence, the demand quantity of the products in case *II* can be derived as follows

$$d_r = \frac{Q}{2}\left(\frac{2}{3} + z - \alpha\bar{\rho} + p_n + p_o - 2p_r\right),$$
$$d_n = \frac{Q}{2}\left(\frac{2}{3} + 2\alpha\bar{\rho} - 2p_n + p_o + p_r\right),$$
$$d_o = \frac{Q}{2}\left(\frac{2}{3} - z - \alpha\bar{\rho} + p_n - 2p_o + p_r\right).$$

2.2. *Case I: OEM only provides new products*

Before the processes of recovery, the remanufacturer has to collect the used products for remanufacturing. We use γQ to denote the available quantity of used products in the return market, where γ is a scale parameter compared with the sales market. According to Ferguson and Toktay (2006), we formulate that the remanufacturer incurs a variable collection cost that is convex increasing in the collection quantity of used products, specifically, in the quadratic form $\kappa\, d_r^2$, where κ is an elasticity parameter and d_r is the quantity of used products for remanufacturing. This formulation is intended to capture the fact that the marginal cost required for additional quantity of collection is increasing. In production processes, the OEM bears a production cost c per unit, and the remanufacturer carries a recovery cost $c - \delta_r$ per unit, where δ_r denotes a unit of cost savings from remanufacturing (Atasu et al., 2008; Ferrer and Swaminathan, 2006, 2010). Because the capacity for remanufacturing depends on the availability of used products, the remanufacturer's profit-maximizing problem is constrained by the available quantity of used products, as follows:

$$\max_{p_r \geq 0} \; \Pi_r = (p_r - c + \delta_r - \kappa\, d_r)d_r, \quad \text{s.t.} \;\; d_r \leq \gamma\, Q. \tag{1}$$

The OEM's objective can be written as the following:

$$\max_{p_n \geq 0} \; \Pi_n = (p_n - c)d_n.$$

The OEM and the remanufacturer determine their price decisions simultaneously, knowing that they will face price competition in the sales market. We derive the equilibrium prices of case I, as shown in Proposition 1 (please note that the proofs of the propositions presented in this paper are all included in the online supplementary):

Proposition 1 *(i) There exists a unique equilibrium price for each chain member. (ii) Let* $\bar{\gamma} \equiv (3 - 2(\alpha\bar{\rho} - \delta_r))/(6 + 4Q\kappa)$*. When* $\gamma \geq \bar{\gamma}$*, the capacity constraint in (1) is held such that the equilibrium prices of case* I *can be derived as*

$$p_r^* = \frac{3 + 6c + 6Q\kappa + 4cQ\kappa - 2(\alpha + 2Q\alpha\kappa)\bar{\rho} - 4\delta_r}{6 + 4Q\kappa}, \quad \textit{and}$$
$$p_n^* = \frac{3 + 6c + 4Q\kappa + 4cQ\kappa + 2\alpha\bar{\rho} - 2\delta_r}{6 + 4Q\kappa}.$$

When $\gamma < \bar{\gamma}$*, the remanufacturing capacity is constrained by the availability of used products such that the equilibrium prices of case* I *are given by* $\tilde{p}_r^* = 3/2 + c - 2\gamma - \alpha\bar{\rho}$*, and* $\tilde{p}_n^* = 1 + c - \gamma$*.*

Proposition 1 shows that there exists a threshold of the return market scale above which remanufacturing is no longer constrained by the available quantity of used products. Moreover, we assert that the equilibrium prices in both statuses of remanufacturing are unique. By substituting the equilibrium prices into the demands and profits of the OEM and the remanufacturer, we can obtain their demands and profits at equilibrium. To gain intuition, we illustrate the members' choices of prices at equilibrium through an example with $\alpha = 1.2$, $\rho = 0.75$, $c = 0.2$, $\delta_r = 0.1$, $\kappa = 0.01$ and $Q = 25$. If $\gamma \geq \bar{\gamma} = 0.3714$, the remanufacturer obtains a sufficient capacity for remanufacturing, and the chain members determine their prices as $p_r^* = 0.6571$ and $p_n^* = 0.8286$. The corresponding members' profits are $\Pi_r^* = 4.3112$ and $\Pi_o^* = 9.8776$. However, if $\gamma = 0.35 < \bar{\gamma} = 0.3714$, the remanufacturer's capacity is constrained, and the members adjust their equilibrium prices as $\tilde{p}_r^* = 0.8$ and $\tilde{p}_n^* = 0.9$. Notably, the members' profits are improved: $\tilde{\Pi}_r^* = 4.6875$ and $\tilde{\Pi}_o^* = 12.2500$. This result is due to the absence of severe price competition when the remanufacturer chooses his price at the level to which all the available quantity of used products are remanufactured.

The following proposition characterizes the trends of the threshold $\bar{\gamma}$ with regard to parametric changes.

Proposition 2 *$\partial\,\bar{\gamma}/\partial\,\alpha < 0$, $\partial\,\bar{\gamma}/\partial\,\rho > 0$, $\partial\,\bar{\gamma}/\partial\,\delta_r > 0$, $\partial\,\bar{\gamma}/\partial\,\kappa < 0$, and $\partial\,\bar{\gamma}/\partial\,Q < 0$.*

From of Proposition 2, we acknowledge that the capacity for remanufacturing is less likely to be constrained when the quantity of used products increases. Moreover, when the remanufacturer faces the increasing collection cost or the higher consumer valuation for the new product, the remanufacturer will decrease his production quantity, and thus, his capacity is also less possible to be constrained. On the contrary, when the consumer valuation for the third-party remanufactured product increases or when remanufacturing provides greater cost savings, the remanufacturer increases the production quantity, leading the remanufacturer's capacity to be more probably limited.

2.3. *Case II: OEM provides new and OEM-remanufactured products*

In case *II*, both of the chain members collect used products for remanufacturing, and hence, they share the available quantity $\gamma\,Q$. Let γ_o and γ_r ($\gamma_o + \gamma_r = \gamma$) denote the shares of γ held by the OEM and the remanufacturer, respectively. We model the OEM's cost structures associated with collection and remanufacturing similar to those of the remanufacturer, that is, the OEM obtains a unit of cost savings δ_o and incurs the collection cost $\kappa\,d_o^2$. The remanufacturing problems of the remanufacturer and the OEM are constrained by their collected units; specifically, their objectives are given by

$$\max_{p_r \geq 0}\ \Pi_r = (p_r - c + \delta_r - \kappa\,d_r)d_r, \quad \text{s.t.}\ \ d_r \leq \gamma_r\,Q, \tag{2}$$

and

$$\max_{p_n, p_o \geq 0}\ \Pi_o = (p_n - c)d_n + (p_o - c + \delta_o - \kappa\,d_o)d_o, \quad \text{s.t.}\ \ d_o \leq \gamma_o\,Q. \tag{3}$$

The equilibrium prices of case *II* can be obtained as shown in Proposition 3.

Proposition 3 *(i) There exist unique equilibrium prices for the chain members. (ii) Let*

$$\bar{\gamma}_r \equiv \frac{16 + 6z + 3Q(6+z)\kappa - 3\alpha(2+3Q\kappa)\bar{\rho} - 6\delta_o + 3(4+3Q\kappa)\delta_r}{36 + 3Q\kappa(19+6Q\kappa)} \quad \textit{and}$$

$$\bar{\gamma}_o \equiv \frac{20 - 15z + 24Q\kappa - 6Qz\kappa - 3\alpha(7+6Q\kappa)\bar{\rho} + 3(11+6Q\kappa)\delta_o - 12\delta_r}{6(12 + Q\kappa(19+6Q\kappa))}.$$

Member k's capacity for remanufacturing is unconstrained by the available quantity of used products whenever $\gamma_k \geq \bar{\gamma}_k$. The equilibrium prices can be derived as follows (all of the equilibrium prices are detailed in Appendix A):

(1) when $\gamma_r < \bar{\gamma}_r$ and $\gamma_o < \bar{\gamma}_o$, $p_r = \tilde{p'}^{\dagger}_r$ $p_n = \tilde{p'}^{\dagger}_n$, and $p_o = \tilde{p'}^{\dagger}_o$;

(2) when $\gamma_r < \bar{\gamma}_r$ and $\gamma_o \geq \bar{\gamma}_o$, $p_r = \tilde{p}^{\dagger}_r$, $p_n = \tilde{p}^{\dagger}_n$, and $p_o = \tilde{p}^{\dagger}_o$;

(3) when $\gamma_r \geq \bar{\gamma}_r$ and $\gamma_o < \bar{\gamma}_o$, $p_r = {p'}^{\dagger}_r$, $p_n = {p'}^{\dagger}_n$, and $p_o = {p'}^{\dagger}_o$;

(4) When $\gamma_r \geq \bar{\gamma}_r$ and $\gamma_o \geq \bar{\gamma}_o$, $p_r = p^{\dagger}_r$, $p_n = p^{\dagger}_n$, and $p_o = p^{\dagger}_o$.

Proposition 3 states that in case *II*, member k's capacity for remanufacturing is constrained by the availability of used products when the scale of return market obtained by member k is under a threshold $\bar{\gamma}_k$. Hence, four possible scenarios emerge based on the statuses of the chain members' remanufacturing capacities, and there exist unique equilibrium prices in each scenario.

3. Analysis

In this section, we characterize the chain members' equilibrium prices and demands with regard to the changes in cost- and market-associated parameters. The characteristics of the equilibrium prices in case *I* are identified in Proposition 4.

Proposition 4 *(i) The parameter effects on the equilibrium prices in case I are characterized in Table 1. (ii) The ordinal relationships of the equilibrium prices in case I are as follows: $\tilde{p}^*_k > p^*_k$ and $P^*_n > P^*_r$, where $P \in \{p, \tilde{p}\}$.*

Part (i) of Proposition 4 reveals that when $\gamma \geq \bar{\gamma}$, the equilibrium prices of the new and remanufactured products behave differently with regard to the changes of consumer valuation: The product with the greater consumer valuation will be sold with a higher unit sales price, leading the rival product to be sold with a lower unit sales price. Nonetheless, when $\gamma < \bar{\gamma}$, the absence of price competition results in that $\tilde{p}^*_r$ depends on the available quantity of used products and $\tilde{p}^*_n$ is independent of the consumer valuation. With respect to the effects of cost parameters, we observe that when $\gamma < \bar{\gamma}$, the absence of price

Table 1

Trends of the equilibrium prices in case I with respect to parametric changes

Parameter (ψ)	Equilibrium prices (P)			
	p_r^*	p_n^*	$\tilde{p}_r^*$	$\tilde{p}_n^*$
α	$\searrow$	$\nearrow$	$\searrow$	–
ρ	$\nearrow$	$\searrow$	$\nearrow$	–
Q	$\nearrow$	$\nearrow$	–	–
κ	$\nearrow$	$\nearrow$	–	–
δ_r	$\searrow$	$\searrow$	–	–

"$\nearrow$": $\partial P/\partial\psi > 0$; "$\searrow$": $\partial P/\partial\psi < 0$; "–": $\partial P/\partial\psi = 0$.

competence leads both of the equilibrium prices to be independent of Q, κ, and δ_r. When $\gamma \geq \bar{\gamma}$, the equilibrium prices behave consistently with regard to the market size Q and cost-associated parameters κ and δ_r: The greater size of the sales market mitigates the intensity of price competition and thus leads both of the equilibrium prices to increase. Moreover, the greater collection cost (cost savings) increases (decreases) the remanufacturer price, and then the intensity of price competition becomes weak (strong), which makes the OEM rise (decrease) her price.

Part (ii) of Proposition 4 indicates that as long as the collected quantity of the used products is not sufficient for remanufacturing, the remanufacturer determines the price at the level to which $d_r^I = \gamma Q$, and thus price competition between the OEM and the remanufacturer vanishes. As a result, the chain members choose the greater prices at equilibrium in the status when remanufacturing is constrained. Moreover, because the remanufactured products possess lower costs in production and consumers experience the higher valuation for the new product than the third-party remanufactured product, the remanufacturer will stimulate demand by choosing a lower sales price for his remanufactured product than that of the new product at equilibrium. Such scenarios have occurred in reality; for example, Gray and Charter (2007) pointed out that due to the energy and material cost savings, the remanufactured products could be (and sometimes were) sold at 30-70% of the prices of the new products.

We now turn the attention to the effects of parametric changes on the equilibrium demands in Proposition 5.

Proposition 5 *The trends of the demands at equilibrium with respect to the changes in α, ρ, z, δ_r, and δ_o are summarized in Table 2.*

Table 2

Trends of the equilibrium demands with respect to parametric changes

	Demands at equilibrium (D)															
	Case I				Case II											
(ψ)	d_r^*	d_n^*	$\tilde{d}_r^*$	$\tilde{d}_n^*$	$d_r^\dagger$	$d_n^\dagger$	$d_o^\dagger$	$\tilde{d}_r^\dagger$	$\tilde{d}_n^\dagger$	$\tilde{d}_o^\dagger$	${d'}_r^\dagger$	${d'}_n^\dagger$	${d'}_o^\dagger$	$\tilde{d'}_r^\dagger$	$\tilde{d'}_n^\dagger$	$\tilde{d'}_o^\dagger$
α	$\searrow$	$\nearrow$	–	–	$\searrow$	$\nearrow$	$\searrow$	–	$\nearrow$	$\searrow$	$\searrow$	$\nearrow$	–	–	–	–
ρ	$\nearrow$	$\searrow$	–	–	$\nearrow$	$\searrow$	$\nearrow$	–	$\searrow$	$\nearrow$	$\nearrow$	$\searrow$	–	–	–	–
z	–	–	–	–	$\nearrow$	$\nearrow$	$\searrow$	–	$\nearrow$	$\searrow$	$\nearrow$	$\searrow$	–	–	–	–
δ_r	$\nearrow$	$\searrow$	–	–	$\nearrow$	$\searrow$	$\searrow$	–	–	–	$\nearrow$	$\searrow$	–	–	–	–
δ_o	–	–	–	–	$\searrow$	$\searrow$	$\nearrow$	–	$\searrow$	$\nearrow$	–	–	–	–	–	–

"$\nearrow$": $\partial D/\partial \psi > 0$; "$\searrow$": $\partial D/\partial \psi < 0$; "–": $\partial D/\partial \psi = 0$.

From Proposition 5, we note that the demands in case I and case II behave similarly and the demand of a remanufactured product will be independent of the parametric changes once its capacity is constrained. When consumers evaluate the new product with greater valuation, the demands of the new product increase but the demands of the remanufactured products decrease; however, the demands will be changed in the opposite direction with respect to ρ. Moreover, because member k will choose a lower sales price for her/his remanufactured product when obtaining the greater cost savings δ_k, the price advantage increases the demand of her/his remanufactured products but decreases the demands of the new products and the competitor's remanufactured products. When consumers experience the higher level of consumers' perceived similarity, the fiercer product cannibalization between the OEM's products benefits the demands of the third-party remanufactured products but hurts the demands of the OEM-remanufactured product. It is notable that the higher level of the perceived similarity is not harmful to the demands of the new product, except when the OEM's remanufacturing is constrained. That is because the OEM will adjust the pricing strategy to divert the demands into the new product which gives the higher sales margin, which, however, is not held whenever the OEM's pricing strategy is limited by the bindingness of remanufacturing.

In the following proposition, we explore the effects of parametric effects on the chain members' equilibrium profits. However, in case II, because the OEM's profits possess the characteristics of both new and remanufactured products, the analyses of the OEM's profits is analytical intractable, and hence we focus on the statuses when the price competition from the remanufacturer is absent (i.e., the remanufacturer's capacity is constrained).

Proposition 6 *The equilibrium profits of the remanufacturer and the OEM behave as* *follows: In case I,*

(i) $\partial\,\Pi_r^*/\partial\,\alpha < 0$*,* $\partial\,\Pi_r^*/\partial\,\rho > 0$*,* $\partial\,\Pi_r^*/\partial\,\delta_r > 0$*,* $\partial\,\tilde{\Pi}_r^*/\partial\,\alpha < 0$*,* $\partial\,\tilde{\Pi}_r^*/\partial\,\rho > 0$*,* $\partial\,\tilde{\Pi}_r^*/\partial\,\delta_r > 0$*;*

(ii) $\partial\,\Pi_o^*/\partial\,\alpha > 0$*,* $\partial\,\Pi_o^*/\partial\,\rho < 0$*,* $\partial\,\Pi_o^*/\partial\,\delta_r < 0$*,* $\partial\,\tilde{\Pi}_o^*/\partial\,\alpha = \partial\,\tilde{\Pi}_o^*/\partial\,\rho = \partial\,\tilde{\Pi}_o^*/\partial\,\delta_r = 0$*.*

In case II,

(iii) $\partial\,\Phi_r^\dagger/\partial\,\alpha < 0$*,* $\partial\,\Phi_r^\dagger/\partial\,\rho > 0$*,* $\partial\,\Phi_r^\dagger/\partial\,z > 0$*,* $\partial\,\Phi_r^\dagger/\partial\,\delta_r > 0$*,* $\partial\,\Pi_r^\dagger/\partial\,\delta_o > 0$*,* $\partial\,\tilde{\Pi}_r^\dagger/\partial\,\delta_o = 0$*,* $\partial\,{\Pi'}_r^\dagger/\partial\,\delta_o > 0$ $\partial\,\tilde{\Pi'}_r^\dagger/\partial\,\delta_o = 0$*, where* $\Phi \in \{\Pi, \tilde{\Pi}, \Pi', \tilde{\Pi'}\}$*;*

(iv) $\partial\,\tilde{\Pi}_o^\dagger/\partial\,\alpha > 0$*,* $\partial\,\tilde{\Pi}_o^\dagger/\partial\,\rho < 0$*,* $\partial\,\tilde{\Pi}_o^\dagger/\partial\,z > 0$*,* $\partial\,\tilde{\Pi}_o^\dagger/\partial\,\delta_r = 0$*,* $\partial\,\tilde{\Pi}_o^\dagger/\partial\,\delta_o < 0$*;*

(v) $\partial\,\tilde{\Pi'}_o^\dagger/\partial\,\alpha < 0$*,* $\partial\,\tilde{\Pi'}_o^\dagger/\partial\,\rho > 0$*,* $\partial\,\tilde{\Pi'}_o^\dagger/\partial\,z < 0$*,* $\partial\,\tilde{\Pi'}_o^\dagger/\partial\,\delta_r = 0$*,* $\partial\,\tilde{\Pi'}_o^\dagger/\partial\,\delta_o > 0$*.*

From Proposition 6, when OEM's remanufacturing is unconstrained, the greater consumer valuation for the new (remanufactured) product is harmful (beneficial) for the sales of the remanufactured product sold by the remanufacturer in both cases. The result is attributed to the decreases (increases) of the sales price and demand of the third-party remanufactured product. On the contrary, the increase (decrease) of α (ρ) is beneficial for the sales of the new product sold by the OEM. Each of the chain members can benefit from obtaining the greater cost savings due to the increasing price competitiveness, but she/he hurts by the greater rival cost savings. Moreover, the increase of consumers' perceived similarity between the new and OEM-remanufactured products is avail to the remanufacturer and the OEM in case *II*. This result manifests that while facing the increase of the consumer perceived similarity, the OEM's price strategy that shifts the demands to the new product is beneficial for the OEM. In other words, the OEM's profit mainly depend on the sales of new product. Thus, the OEM's profit decreases in her cost savings, i.e., $\partial\,\tilde{\Pi}_o^\dagger/\partial\,\delta_o < 0$, because the increases of d_o hurts the OEM's sales of new product.

When OEM's remanufacturing is constrained, we find that the parameters have no impacts on the OEM's profit in the absence of OEM-remanufactured product. However, in the presence of OEM-remanufactured product, the parameters behave differently on $\tilde{\Pi'}_o^\dagger$ from $\tilde{\Pi}_o^\dagger$. Specifically, $\tilde{\Pi}_o^\dagger$ behaves similar to the remanufacturers' profit with regard to the changes of parameters, except z. As a result, we infer that the OEM's profit is mainly contributed by the sales of the OEM-remanufactured product. When the availability of used products limits both chain members' remanufacturing capacities, OEMs can mitigate the negative impact by introducing OEM-remanufactured products into the market when faced the increase of ρ and δ_o. However, the OEM's adjustment of price strategy becomes ineffective, and hence the increase of the consumers' perceived similarity is harmful to the OEM.

We now numerically demonstrate the sensitivity of the chain members' equilibrium results. In Figure 2, we discuss of the impacts of the change in the remanufacturing status on the rival equilibrium profit in case II regarding the effects of ρ, α, Q and z. It can be observed that each of the chain members can gain benefit whenever the competitor's remanufacturing is constrained because of the absence of price competition from the rival remanufactured product. Moreover, as consumer valuation for remanufactured products is greater, the bindingness of each member's remanufacturing will lead to the greater benefit for the competitor. On the contrary, when consumer valuation for new products is greater, the influence of the remanufactured products is mitigated, and thus each member obtains the smaller benefit from the bindingness of the rival remanufacturing. Moreover, because the greater market scale amplifies the impacts of price competition, the bindingness of the rival remanufacturing leads to a higher benefit when the market scale is greater. In addition, the influence of the market scale on the OEM's profit is more significant than that on the remanufacturer's profit. This result indicates that for obtaining a higher profit, the OEM is suggested to offer remanufactured products to seize the availability of used products for the remanufacturer when the market scale is great. Besides, we find that when consumers perceive the higher similarity between the OEM's products, the impact of the OEM-remanufactured product on price competition is dampened, and thus the bindingness of the OEM's remanufacturing is less beneficial to the remanufacturer. Contrarily, the third-party remanufactured product is more competitive when z increases, and thus the bindingness of the remanufacturer's capacity leads to a greater benefit for the OEM. Therefore, the OEM should strategically collect the used products to deter the remanufacturer's capacity when consumers perceive the higher similarity between the OEM's products.

4. Conclusions

This study provides insights for OEM managers who may choose to remanufacture their end-of-life products to decrease the intensity of competition from remanufacturers. We formulate a two-period model in which only the OEM exists in the market and sells new

(a) $(\Pi'^{\dagger}_r|_{\gamma_r=0.58,\gamma_o=0.12}) - (\Pi^{\dagger}_r|_{\gamma_r=0.45,\gamma_o=0.25})$ (b) $(\tilde{\Pi}^{\dagger}_o|_{\gamma_r=0.2,\gamma_o=0.5}) - (\Pi^{\dagger}_o|_{\gamma_r=0.45,\gamma_o=0.25})$

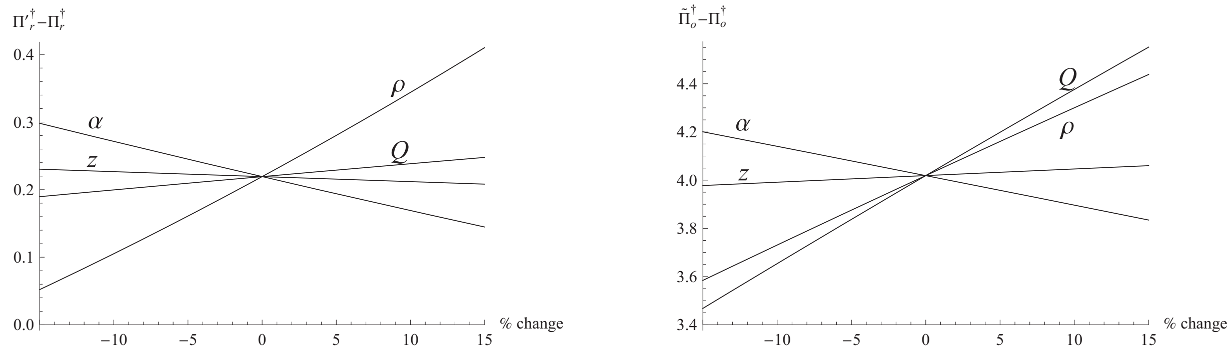

Figure 2. Impacts of the status of remanufacturing capacities with regard to percent changes in parameters ($\alpha = 1.3$, $\rho = 0.7$, $c = 0.3$, $\delta_r = \delta_o = 0.1$, $\kappa = 0.01$, $Q = 15$, and $z = 0.1$).

products in the first period; subsequently, the remanufacturer enters the market to compete with the OEM on their prices and the OEM opts to introduce OEM-remanufactured product to deter the remanufacturer in the second period. Our model captures some of the key factors describing purchasing choices of heterogeneous consumers and deriving OEMs to launch remanufacturing processes. We further characterized the effects of these factors on the equilibrium prices, demand quantities, and profitabilities and provided a comparative analysis for elaborating the impacts of the entry of OEM-remanufactured products.

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Table 3

Summary of equilibrium prices of case *II*

When $\gamma_r < \bar{\gamma}_r$ **and** $\gamma_o < \bar{\gamma}_o$

$$\tilde{p'}^{\dagger}_{r} = \frac{1}{3}\left(6 + 3c + z - 3\alpha\bar{\rho} - 4\gamma_o - 8\gamma_r\right),$$
$$\tilde{p'}^{\dagger}_{n} = \frac{1}{3}\left(4 + 3c - 2\gamma_o - 4\gamma_r\right)$$
$$\tilde{p'}^{\dagger}_{o} = 2 + c - \frac{z}{3} - \alpha\bar{\rho} - 2\gamma_o - 2\gamma_r$$

When $\gamma_r < \bar{\gamma}_r$ **and** $\gamma_o \geq \bar{\gamma}_o$

$$\tilde{p}^{\dagger}_{r} = \frac{2(1+Q\kappa)(6+3c+5z-3\alpha\bar{\rho}-12\gamma_r)+\eta_2}{12+9Q\kappa}$$
$$\tilde{p}^{\dagger}_{n} = \frac{20+18c+6z+Q(18+15c+7z)\kappa+3\alpha(2+Q\kappa)\bar{\rho}-24(1+Q\kappa)\gamma_r+\eta_2}{6(4+3Q\kappa)}$$
$$\tilde{p}^{\dagger}_{o} = \frac{(2+3Q\kappa)(6+3c+5z-3\alpha\bar{\rho}-12\gamma_r)+3\eta_2}{6(4+3Q\kappa)}$$

When $\gamma_r \geq \bar{\gamma}_r$ **and** $\gamma_o < \bar{\gamma}_o$

$$p'^{\dagger}_{r} = \frac{(1+2Q\kappa)(10+9c-9z+3\alpha\bar{\rho}-12\gamma_o)+4\eta_1}{33+18Q\kappa}$$
$$p'^{\dagger}_{n} = \frac{16+21c-10z+2Q(8+9c-6z)\kappa+6\alpha(3+2Q\kappa)\bar{\rho}-6(1+2Q\kappa)\gamma_o+2\eta_1}{33+18Q\kappa}$$
$$p'^{\dagger}_{o} = \frac{24+15c-26z+6Q(4+3c-4z)\kappa-6\alpha\bar{\rho}-6(7+6Q\kappa)\gamma_o+3\eta_1}{33+18Q\kappa}$$

When $\gamma_r \geq \bar{\gamma}_r$ **and** $\gamma_o \geq \bar{\gamma}_o$

$$p^{\dagger}_{r} = \frac{4(1+Q\kappa)\eta_1+(1+2Q\kappa)(2(1+Q\kappa)(2+3c-z+3\alpha-3\alpha\rho)+\eta_2)}{36+3Q\kappa(19+6Q\kappa)}$$
$$p^{\dagger}_{n} = \frac{(14+5Q\kappa(5+2Q\kappa))(2+3c-z+3\alpha-3\alpha\rho)+4(1+Q\kappa)\eta_1+(1+2Q\kappa)\eta_2}{6(12+Q\kappa(19+6Q\kappa))}$$
$$p^{\dagger}_{o} = \frac{(2+3Q\kappa)((1+2Q\kappa)(2+3c-z+3\alpha-3\alpha\rho)+2\eta_1)+(7+6Q\kappa)\eta_2}{6(12+Q\kappa(19+6Q\kappa))}$$

$$\eta_1 \equiv 6c + (2 + 3z)(1 + 2Q\kappa) - 3(\alpha + 2Q\alpha\kappa)\bar{\rho} - 6\delta_r$$

$$\eta_2 \equiv 4 + 6c - 4z + 6Q\kappa + 3cQ\kappa - 7Qz\kappa - 3Q\alpha\kappa\bar{\rho} - 6\delta_o$$