Strategic Remanufacturing under Competition

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Abstract: We investigate firms' remanufacturing strategies for the case of a duopoly. On the one hand, remanufactured products cannibalize sales of new products of the same firm thereby hurting its profits. On the other hand, they can be part of a profitable marketing strategy that targets different customer preferences by providing a larger number of alternatives to customers. This paper studies the tradeoff between these effects and how it is influenced by competition. We develop a model where demand functions for new and remanufactured products of each firm are derived from utility maximization by a representative consumer. This allows us to capture preference and substitution effects between all offered products in the market. We discuss how equilibrium strategies are affected by factors such as competition, substitutability, production cost as well as remanufacturing cost. For example, when competitive intensity between new and new products, and remanufactured and remanufactured products, is (high), both (neither) firms offer remanufactured products in a symmetric equilibrium. If substitution between new and remanufactured products of the same firm is low, but the remanufactured product has a lower margin than the new product, firms can be worse off from remanufacturing.

Keywords: pricing, remanufacturing, competition, operations-marketing interface

1 Overview

Remanufacturing is the process of taking used products and restoring and reselling them. Remanufacturing has been employed in industry as a strategy for numerous reasons (Atasu, Guide, and Van Wassenhove 2010; Kleindorfer, Singhal, and Van Wassenhove 2005). For example, firms can use remanufacturing

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to gain market share, to reduce production costs, to follow government rules, or to cater to green consumers. However, remanufactured products can potentially cannibalize the sales of the new products sold by the same firm. Thus optimizing on the marketing decisions for remanufactured products is desirable, including whether they should be offered in the first place.

Remanufacturing can be observed in the US automobile market, for example with certified pre-owned cars. The used-car market in the US is comparable to that of the new car market and estimated at over $370 billion annually, but it has traditionally been outside the manufacturer's control. Traditionally, used-car owners sold their cars in the secondary market as dealer trade-ins or private sales to individual consumers. The current practice of certified pre-owned (CPO, i.e. remanufactured) cars was introduced by luxury-car manufacturers for maintaining their brand reputation. Unsurprisingly, CPO cars have gained popularity. Manufacturers offer fully inspected, refurbished, high-quality used cars, benefiting from the reputation of their brands, and extended warranties provided to reassure about quality (Sultan 2010). Similarly, Xerox, a printing equipment maker, manages its remanufacturing business successfully (Atasu, Guide, and Van Wassenhove 2010). According to Atasu, Guide, and Van Wassenhove (2010), Xerox recovers models and parts from used or leased high-end imaging equipment, and then blends them with new models and parts. It recoups a savings on the manufacturing costs and offers the remanufactured products at a lower price compared to the new products.

We examine whether, and at what price, remanufactured products should be provided by a firm in the market. Furthermore, we consider this in the context of competing firms and examine the equilibrium outcome when each firm may decide to sell or not sell a remanufactured version of its product. Obtaining the demand function of each product, new and remanufactured, which will depend on four prices, is difficult. We develop the demand functions based on a representative consumer approach and set the assumptions needed for it to have reasonable properties such as being downwards sloping. Once the demand function is obtained, we can write the profit equations and solve the game where each firm maximizes its profits.

2 Literature review

The Operations Management literature on remanufacturing has examined its various facets and uses. Kleindorfer, Singhal, and Van Wassenhove (2005) provide an extensive review of remanufacturing research of the past two decades. Atasu, Guide, and Van Wassenhove (2010) discuss remanufacturing practices and the issues raised from these practices. Consumer return, a component of remanufacturing, was studied by Su (2009). Debo, Toktay, and Van Wassenhove (2005) consider the joint pricing and production technology selection problem faced by a firm, which plans to introduce a remanufacturable product into a market of heterogeneous consumers. They assume that production of remanufacturable product is more costly than a single-use product, and investigate the tradeoff between the benefit of capturing lower willingness-to-pay consumers and the additional cost of allowing products to be remanufactured. They further evaluate how the tradeoff changes, based on the profile of consumers and the corresponding pricing policy. Chen and Chang (2013) examine price competition between new and remanufactured products of the same firm in a dynamic setting. The dynamic constraint is that past period sales of the product will affect current period availability to remanufacture. In the context of used goods collection, Savaskan, Bhattacharya, and Van Wassenhove (2004) analytically compare different strategies. We consider a static model where the availability constraint for remanufacturing does not play a role.

The above papers assume that the manufacturer is a monopoly and Govindan, Soleimani, and Kannan (2015) in a review of closed-loop supply chains also did not note competition as an issue. A more complete picture necessitates inclusion of competition. Ferguson and Toktay (2006) model remanufacturing under competition, but consider the competition to be between a third-party remanufacturer and the original equipment manufacturer (OEM) of the remanufactured products. This is different from the present paper which models competition between two OEMs both providing new products and remanufactured products.

Atasu, Sarvary, and Van Wassenhove (2008) investigate the profitability of the remanufacturing strategy from a demand-related perspective, i.e. in the presence of a green consumer segment, and under the scenario of OEM competition and product life cycle effects. They assume that all consumers prefer one brand over the other. They find threshold points as functions of the green segment size, market growth rate, and consumer valuations, above which a monopoly will profit from remanufacturing. They investigate remanufacturing under competition, and conclude that remanufactured products can be applied for price discrimination.

Örsdemir, Kemahlıoğlu-Ziya, and Parlaktürk (2014) is another paper focusing on a remanufacturing problem related to ours. They investigate the competition between an OEM and an independent remanufacturer (IR). They characterize how the OEM competes with the IR in equilibrium and find that the OEM relies more on quality (quantity, respectively) as a strategic lever when it has a stronger competitive position (weaker position, respectively). They also compare against a benchmark in which the OEM remanufactures, and find that encouraging IRs to remanufacture may not benefit the environment. Our problem is different in the sense that we have two OEMs competing with each other; moreover, both of them have the capability to remanufacture.

Van Den Heuvel and Wagelmans (2008) examine a handful of models, one of them is a lot-sizing model with a remanufacturing option. They show the equivalence of this model with a classical model: the lot-sizing model with inventory bounds. Different from their models, our paper examines remanufacturing option in the framework of game theory.

Zhang et al. (2014) investigate the problem of designing contracts in a closed-loop supply chain. Remanufacturing cost is the potential private information. Two different contracts are examined, each under complete information and private information. They derived the manufacture's optimal contracts in each case, and analyze the impact of information on the equilibrium results of supply chain members. In our paper, all the information is public, and the focus is the strategic option of whether remanufacturing or not under competition.

Our paper contributes to the literature by investigating remanufacturing strategy under the competition between new and remanufactured products offered by each firm in a duopoly. To our knowledge, it is the first to investigate firm's remanufacturing policy with quality differentiation and brand competition.

3 Model

Consider two firms, 1 and 2, competing for sales. For both firms, the production costs of a new product and a remanufactured produce are c_n and c_r respectively, where $c_n > c_r$. Firm $i \in \{1, 2\}$ sets the quantity q_{ni} (or alternatively and equivalently, the price p_{ni}) of its new product, and q_{ri} of its remanufactured product, if the latter is offered. Note that while both firms of course offer their new product, it is possible for either firm to also offer or not offer a remanufactured product. We denote firm i's optimal profit under a specific remanufacturing strategy as $\pi_i(x, y)$, where $x \in \{n, r\}$ and $y \in \{n, r\}$ denote the strategies of the firm and its rival, where n denotes that a firm is providing only the new product and r denotes that it is providing both new and remanufactured products.

The sequence of events is as follows: Firms invest in their remanufacturing capability. Next, firms move concurrently on pricing decisions for their new products and, if offered, their remanufactured products. Thereafter, the demands of the new and remanufactured products for each firm are realized and profits obtained.

Following Singh and Vives (1984), we assume a continuum of identical consumers and focus on a representative consumer's utility maximization to derive the product demand curves. We approximate demands as continuous variables. Their paper considers two competing firms, each producing one product, whereas we allow for two products, one new and the other remanufactured, produced by each firm. Singh and Vives assume a sector of two firms producing substitutable products, and there is a numeraire good. The representative consumer's direct utility function is separable in the utility of consumption of the goods and the numeraire good. The quasi-linear utility function removes income effects, so that partial equilibrium analysis can be done.

In the Singh and Vives (1984) model, the representative consumer maximizes

$$u(q_1, q_2) - \sum_{i=1}^{2} p_i q_i, \tag{1}$$

where q_i and p_i are the quantity and price of the product from firm i. The utility function $u(q_1, q_2)$ is quadratic and strictly concave, given by

$$u(q_1, q_2) = \alpha_1 q_1 + \alpha_2 q_2 - \frac{\beta_1 q_1^2 + 2\gamma q_1 q_2 + \beta_2 q_2^2}{2} \tag{2}$$

In our model, the representative consumer maximizes

$$(q_{n1}, q_{n2}, q_{r1}, q_{r2}) - \sum_{i=1}^{2} p_{ni} q_{ni} - \sum_{i=1}^{2} p_{ri} q_{ri}. \tag{3}$$

The utility function $U(q_{n1}, q_{n2}, q_{r1}, q_{r2})$ which we propose is an extension of the Singh–Vives utility function to include four products. That is,

$$\begin{aligned} U(q_{n1}, q_{n2}, q_{r1}, q_{r2}) = \alpha_{n1} q_{n1} + \alpha_{n2} q_{n2} + \alpha_{r1} q_{r1} + \alpha_{r2} q_{r2} - \frac{1}{2}(\beta_{n1} {q_{n1}}^2 + \beta_{n2} q_{n2}^2 + \beta_{r1} q_{r1}^2 \\ + \beta_{r2} q_{r2}^2 + 2\gamma_{n12} q_{n1} q_{n2} + 2\gamma_{r12} q_{r1} q_{r2} + 2\gamma_{n1r1} q_{n1} q_{r1} + 2\gamma_{n1r2} q_{n1} q_{r2} \\ + 2\gamma_{n2r1} q_{n2} q_{r1} + 2\gamma_{n2r2} q_{n2} q_{r2} \end{aligned}$$

However, this function has a large number of parameters to deal with, resulting in lengthy expressions which obscure the main insights. Thus, we will make some simplifying assumptions to focus on the key aspects of the study. We will begin by assuming that the two players are symmetric. An example of this kind of symmetric duopoly is the competition between HP and Canon in printers and photocopiers, where their products, market share, as well as service are very similar. Therefore we have:

$$\alpha_{n1} = \alpha_{n2} \overset{\Delta}{=} \alpha_{n0},$$

$$\alpha_{r1} = \alpha_{r2} \overset{\Delta}{=} \alpha_{r0},$$

$$\beta_{n1} = \beta_{n2} \overset{\Delta}{=} \beta_{n},$$

$$\beta_{r1} = \beta_{r2} \overset{\Delta}{=} \beta_{r},$$

$$\gamma_{n1r1} = \gamma_{n2r2} \overset{\Delta}{=} \gamma_0.$$

Because the two players are symmetric, the substitutability between new and remanufactured products are symmetric, to the extent that the impact of the remanufactured product has identical impact to the consumer's utility regardless of which remanufacturer it comes from. An illustrative example would be remanufactured printer that is sold by HP or Canon.

$$\gamma_{n1r1} = \gamma_{n1r2} \overset{\Delta}{=} \gamma_0,$$

$$\gamma_{n2r1} = \gamma_{n2r2} \overset{\Delta}{=} \gamma_0.$$

With these simplifications, we get the utility function:

$$\begin{aligned} U(q_{n1}, q_{n2}, q_{r1}, q_{r2}) = \alpha_{n0}(q_{n1} + q_{n2}) + \alpha_{r0}(q_{r1} + q_{r2}) - \frac{1}{2}(\beta_n {q_{n1}}^2 + \beta_n {q_{n2}}^2 + \beta_r {q_{r1}}^2 \\ + \beta_r {q_{r2}}^2 + 2\gamma_{n12} q_{n1} q_{n2} + 2\tilde{a}_{r12} q_{r1} q_{r2} + 2\gamma_0 q_{n1} q_{r1} + 2\gamma_0 q_{n1} q_{r2} \\ + 2\gamma_0 q_{n2} q_{r1} + 2\gamma_0 q_{n2} q_{r2}) \end{aligned}$$

Upon maximization by the representative consumer, the first-order conditions will produce the following four price functions (or inverse demand functions):

$$p_{n1} = \alpha_{n0} - \beta_n q_{n1} - \gamma_{n12} q_{n2} - \gamma_0 (q_{r1} + q_{r2}),$$

$$p_{r1} = \alpha_{r0} - \beta_r q_{r1} - \gamma_{r12} q_{r2} - \gamma_0 (q_{n1} + q_{n2}),$$

$$p_{n2} = \alpha_{n0} - \beta_n q_{n2} - \gamma_{n12} q_{n1} - \gamma_0 (q_{r1} + q_{r2}),$$

$$p_{r2} = \alpha_{r0} - \beta_r q_{r2} - \gamma_{r12} q_{r1} - \gamma_0 (q_{n1} + q_{n2}).$$

In subsequent analysis, we will focus on a particular case where the following two additional conditions are met:

– The price functions have the same slope with respect to the underlying product, i.e.

$$\beta_r = \beta_n \triangleq \beta_0,$$

– The price functions have the same slope with respect to the competing product from same category. By product category, it is either new or remanufactured, i.e.

$$\gamma_{n12} = \gamma_{r12} \triangleq \gamma_{12};$$

The motivation is that when the linear demand functions are describing products close to each other, their demand will also be alike.

Now the utility function is:

$$U(q_{n1}, q_{n2}, q_{r1}, q_{r2}) = \alpha_{n0}(q_{n1} + q_{n2}) + \alpha_{r0}(q_{r1} + q_{r2}) - \frac{\beta_0}{2}\left(q_{n1}^2 + q_{n2}^2 + q_{r1}^2 + q_{r2}^2\right)$$
$$+ \gamma_{12}(q_{n1}q_{n2} + q_{r1}q_{r2}) + \gamma_0(q_{n1}q_{r1} + q_{n1}q_{r2} + q_{n2}q_{r1} + q_{n2}q_{r2}).$$

There are two sets of interaction terms in this utility function. The coefficient γ_{12} measures the competitive intensity or substitutability within the same category of products (product category is either new or both remanufacture). In contrast, γ_0 measures competitive intensity or substitutability across different product category. Finally, it should be the case that $\alpha_{n0} > \alpha_{r0}$, i.e. a brand new product will give more utility *ceteris paribus* than a remanufactured product. This is clear from the lower market prices charged for used, refurbished, certified pre-owned and other forms of remanufactured products compared to new products.

To focus on the effects of substitutability from competing products, we normalize the utility function with respect to β_0, and have:

$$U(q_{n1}, q_{n2}, q_{r1}, q_{r2}) = \alpha_n(q_{n1} + q_{n2}) + \alpha_r(q_{r1} + q_{r2}) - \frac{1}{2}\left(q_{n1}^2 + q_{n2}^2 + q_{r1}^2 + q_{r2}^2\right) \\ - \beta(q_{n1}q_{n2} + q_{r1}q_{r2}) - \gamma(q_{n1}q_{r1} + q_{n1}q_{r2} + q_{n2}q_{r1} + q_{n2}q_{r2}). \tag{4}$$

where we define:

$$\beta \triangleq \gamma_{12}/\beta_0$$

$$\gamma \triangleq \gamma_0/\beta_0$$

$$\alpha_n \triangleq \alpha_{n0}/\beta_0$$

$$\alpha_r \triangleq \alpha_{r0}/\beta_0$$

Let us consider what these coefficients represent. The coefficient β measures competitive intensity or substitutability within the same category of products (product category is either new or both remanufacture). Therefore β is same-category-products-substitutability-parameter. In contrast, γ measures competitive intensity or substitutability across different product category. Therefore γ is different-category-products-substitutability-parameter. Finally, $\alpha_n > \alpha_r$, since as mentioned a new product gives more utility *ceteris paribus* than a remanufactured product.

Next, to determine the conditions for the utility function to be concave with respect to q_{n1}, q_{r1}, q_{n2}, q_{r2}, we check whether its Hessian matrix is negative definite. It is straightforward to confirm that all of principal minors of the Hessian meet the requirements for the Hessian matrix to be negative definite if the following conditions hold:

$$1 - \beta > 0,\ 1 + \beta > 2\gamma^2,\ 1 + \beta > 2\gamma.$$

Furthermore, these conditions for the utility function to be concave are all satisfied if,

$$1 > \beta > \gamma > 0,$$

which we will assume henceforth. The requirement that $\beta > \gamma$ is reasonable because substitution effects from the same category of the products should always be larger than the competition from different product category. Because $\beta \triangleq \gamma_{12}/\beta_0$ and $\gamma \triangleq \gamma_0/\beta_0$, therefore $1 > \beta$ and $1 > \gamma$ indicate that the slope of a product price is higher to the underlying product quantity, compared with the competing product. Moreover, $\beta > 0$ and $\gamma > 0$ indicate that the slope of price is negative: the more the quantity, the less the price.

Upon taking the first-order condition of the representative consumer's utility maximization problem with respect to quantity choices, we obtain a linear demand structure which can be arranged into the following price (or inverse demand) functions:

$$\begin{pmatrix} p_{n1} \\ p_{r1} \\ p_{n2} \\ p_{r2} \end{pmatrix} = \begin{pmatrix} \alpha_n \\ \alpha_r \\ \alpha_n \\ \alpha_r \end{pmatrix} - \begin{pmatrix} q_{n1} \\ q_{r1} \\ q_{n2} \\ q_{r2} \end{pmatrix} - \beta \begin{pmatrix} q_{n2} \\ q_{r2} \\ q_{n1} \\ q_{r1} \end{pmatrix} - \gamma \begin{pmatrix} q_{r1} + q_{r2} \\ q_{n1} + q_{n2} \\ q_{r1} + q_{r2} \\ q_{n1} + q_{n2} \end{pmatrix} \tag{5}$$

Since the margins for the products $p_n - c_n$ and $p_r - c_r$ should be positive, we require that $\alpha_n > c_n$ and $\alpha_r > c_r$. We next invert the inverse demand equations to obtain the demand functions:

$$\begin{aligned} \left((1+\beta)^2 - 4\gamma^2\right) \begin{pmatrix} q_{n1} \\ q_{r1} \\ q_{n2} \\ q_{r2} \end{pmatrix} &= (1+\beta) \begin{pmatrix} \alpha_n \\ \alpha_r \\ \alpha_n \\ \alpha_r \end{pmatrix} - 2\gamma \begin{pmatrix} \alpha_r \\ \alpha_n \\ \alpha_r \\ \alpha_n \end{pmatrix} \\ &+ \begin{pmatrix} \frac{-\left(1+\beta-2\gamma^2\right)}{1-\beta} & \gamma & \frac{\beta+\beta^2-2\gamma^2}{1-\beta} & \gamma \\ \gamma & \frac{-\left(1+\beta-2\gamma^2\right)}{1-\beta} & \gamma & \frac{\beta+\beta^2-2\gamma^2}{1-\beta} \\ \frac{\beta+\beta^2-2\gamma^2}{1-\beta} & \gamma & \frac{-\left(1+\beta-2\gamma^2\right)}{1-\beta} & \gamma \\ \gamma & \frac{\beta+\beta^2-2\gamma^2}{1-\beta} & \gamma & \frac{-\left(1+\beta-2\gamma^2\right)}{1-\beta} \end{pmatrix} \begin{pmatrix} p_{n1} \\ p_{r1} \\ p_{n2} \\ p_{r2} \end{pmatrix} \end{aligned} \tag{6}$$

Finally, we impose conditions to ensure that the demand functions behave in a typical manner to price changes, i.e. that they are downwards sloping with respect to own price and increasing in the prices of competing products. This condition is given in Lemma 1 and thus we assume that the required condition $(1+\beta)\alpha_r > 2\gamma\alpha_n$ holds henceforth.

Lemma 1: *If and only if* $(1+\beta)\alpha_r > 2\gamma\alpha_n$, *then positive demand is possible for each product and the demand functions will behave typically to price changes*. (Proofs: See Appendix.)

4 Analysis

In the previous section, we developed the demand functions which are functions of the prices of new and refurbished products on the market. We stated assumptions needed to ensure that the utility, demand and profit functions have reasonable properties. We may now proceed with the analysis of firms' behavior. We first analyze a centralized market where a monopoly controls both firms and thus all four products. Thereafter we will analyze the duopoly equilibrium behavior when the two firms are independent.

4.1 Monopoly

As a benchmark, we consider a monopoly and begin by deriving the results when remanufactured products are not provided. This is the Singh–Vives model of two products, but with a single firm selling both products. The firm's profit function is,

$$\pi(n,n) = \max_{q_{n1},\, q_{n2}} (p_{n1} - c_n)q_{n1} + (p_{n2} - c_n)q_{n2},$$

i.e. the sum of the profits from the two new products. The firm maximizes its objective with respect to quantities because prices are inverse demand functions that depend on quantities as discussed in the previous section. The prices can be obtained by modifying eq. (5) so that the quantities of the remanufactured products sold are zero. In other words, the inverse demand functions are:

$$p_{n1} = \alpha_n - q_{n1} - \beta q_{n2} \text{ and } p_{n2} = \alpha_n - q_{n2} - \beta q_{n1}$$

Substituting these into the objective function and performing the optimization, we find that the optimal quantities are $q_{n1} = q_{n2} = (\alpha_n - c_n)/2(1+\beta)$. Inserting back into the profit expression yields,

$$\pi(n,n) = \frac{(\alpha_n - c_n)^2}{2(1+\beta)} = \frac{m_n^2}{2(1+\beta)} \tag{7}$$

as the optimal profit where we defined,

$$m_n \equiv \alpha_n - c_n.$$

This m notation is useful and occurs often. It is related to the profit margin of a product, as it is the highest feasible price minus the marginal cost of the product.

Next, we proceed to solve the monopolist's profit maximization problem when remanufactured products are also provided. In this case, the objective of the firm is given by,

$$\pi(r,r) = \max_{q_{n1},q_{n2},\ q_{r1},q_{r2}} (p_{n1}-c_n)q_{n1} + (p_{n2}-c_n)q_{n2} + (p_{r1}-c_r)q_{r1} + (p_{r2}-c_r)q_{r2} - F,$$

where F is the investment in remanufacturing capability. The inverse demand functions derived earlier in eq. (5) are substituted into this objective function and it is maximized with respect to the quantity decisions. The optimal quantities are obtained and inserted back into the objective function to yield the firm's optimal profit, which is obtained to be

$$\pi(r,r) = \frac{(1+\beta)({m_n}^2+{m_r}^2)-4\gamma m_n m_r}{2(1+\beta)^2-8\gamma^2} \tag{8}$$

where $m_n = \alpha_n - c_n$, and $m_r = \alpha_r - c_r$.

It is now possible to compare the optimal monopoly profits from providing remanufactured product or not from eqs. (7) and (8). The difference is given by,

$$\pi(r,r)-\pi(n,n) = \frac{(2\gamma m_n-(1+\beta)m_r)^2}{2(1+\beta)^3-8(1+\beta)\gamma^2} - F \tag{9}$$

Theorem 1: *Under a monopoly, when F = 0, the manufacturer prefers remanufacturing to no remanufacturing. This preference is strict if* $2\gamma m_n-(1+\beta)m_r \neq 0$.

The insights of Theorem 1 are reasonable given that in a single decision-maker scenario, offering an additional option (of remanufactured products) will at least dominate not having that option, because the quantity of remanufactured products can be set to zero. In that case, the firm will achieve the same profit as the case without remanufactured goods, and possibly it can achieve more. Indeed, when $2\gamma m_n-(1+\beta)m_r \neq 0$, the firm is strictly better off from providing remanufactured products due to capturing more market share which outweighs the disadvantage of cannibalization of new product sales.

4.2 Competition without remanufacturing

We now consider the case of competing independent manufacturers. For comparison purposes, we begin again with the scenario where the firms do not provide remanufactured products. Each firm $i \in \{1,2\}$ maximizes its objective function, which is $(p_{ni} - c_n)q_{ni}$. The inverse demand functions when only the two new products compete have already been mentioned in eq. (5). We substitute these into the objective functions and then differentiate with respect to the quantity decision to get the reaction function for each firm. Due to symmetry, the equilibrium values are

$$q_{n1} = q_{n2} = \frac{m_n}{2+\beta} \tag{10}$$

The equilibrium profit for each firm is denoted as $\pi(n, n)$ (because of symmetry, the subscript i is dropped) given by

$$\pi(n, n) = \frac{m_n^2}{(2+\beta)^2} \tag{11}$$

Remark 1: *The equilibrium profit function is decreasing and convex in the products-substitutability-parameter β.*

The basic intuition for Remark 1 is that more substitutable products have a greater downward effect on profit of competing products. Each individual firm's profits and the sum of their profits are less than that of the monopolist in the corresponding scenario.

4.3 Competition with remanufacturing

When both firms provide remanufactured products, the inverse demand functions are given by eq. (5). Each firm maximizes its profit function, which for firm i is given by the expression

$$\pi(r, r) = \max_{q_{ni},\, q_{ri}} (p_{ni} - c_n)q_{ni} + (p_{ri} - c_r)q_{ri} - F\cdot$$

After making the appropriate substitutions, the necessary conditions for maxima yield the optimal demand decisions

$$q_{n1} = q_{n2} = \frac{m_n(2+\beta) - 3m_r\gamma}{(2+\beta)^2 - 9\gamma^2},\ q_{r1} = q_{r2} = \frac{m_r(2+\beta) - 3m_n\gamma}{(2+\beta)^2 - 9\gamma^2} \tag{12}$$

The following conditions are required. Assumptions (A)–(C) we have discussed earlier.

Assumption A: $(1+\beta)\alpha_r > 2\gamma\alpha_n$, together with,

Assumption B: $\alpha_n > \alpha_r$, implies:

$$\frac{\alpha_n + \alpha_n\beta - 2\alpha_r\gamma}{(1+\beta)^2 - 4\gamma^2} > 0 \text{ and } \frac{\alpha_r + \alpha_r\beta - 2\alpha_n\gamma}{(1+\beta)^2 - 4\gamma^2} > 0.$$

Assumption C: $1 > \beta > \gamma > 1$.

Assumption D: $m_n(2+\beta) - 3m_r\gamma > 0$; $m_r(2+\beta) - 3m_n\gamma > 0$. This ensures that demand for the corresponding product is nonnegative. Given that the profit function is concave, the optimal demand will be zero rather than negative, which is equivalent to not offering that product at all.

The optimal profits when both firms choose remanufacturing are denoted as $\pi(r,r)$ for each firm due to symmetry. This is given by

$$\pi(r,r) = \frac{(2+\beta)^2 - 3(1+2\beta)\gamma^2}{\left((2+\beta)^2 - 9\gamma^2\right)^2}\left(m_n{}^2 + m_r{}^2\right) + \frac{2(\beta-4)(2+\beta)\gamma + 18\gamma^3}{\left((2+\beta)^2 - 9\gamma^2\right)^2}(m_n m_r) - F\cdot$$

Rearranging terms, we have:

$$\pi(r,r) = -F + \frac{\left(m_n^2 + 2\gamma m_n m_r + m_r^2\right)\left[(2+\beta) \ -3\gamma\ \right]^2 + 6(2+\beta)\gamma\ (1-\gamma)(m_n - m_r)^2}{\left((2+\beta)^2 - 9\gamma^2\right)^2}.$$

which is positive when $F = 0$ since $0 \le \gamma \le 1$.

4.4 Equilibrium in the super-game

So far we have considered scenarios where the available remanufacturing strategies of the firms, specifically whether remanufacturing is allowed or not, is exogenous. In this section, we consider the equilibrium in the super-game when the firms make the decision of whether or not to offer a remanufactured product.

Assume that firm 1 decides to invest in the capability to remanufacture while firm 2 does not. (The case that firm 1 decides not to have the capability to remanufacture while firm 2 does will have the same conclusion with an appropriate change of notation.) We have the linear inverse demand functions from a modification of eq. (5):

$$p_{n1} = a_n - q_{n1} - \beta q_{n2} - \gamma q_{r1},$$

$$p_{n2} = a_n - \beta q_{n1} - q_{n2} - \gamma q_{r1},$$

$$p_{r1} = a_r - q_{r1} - \gamma(q_{n1} + q_{n2}).$$

Denote the profit of the firm which does not provide a remanufactured product, given that its rival does provide it, as $\pi(n, r)$, and the profit of the firm which provides a remanufactured product, given the rival does not provide it, as $\pi(r, n)$. Therefore, the profit functions of firm 1 and firm 2 subject to the above inverse demand functions are, respectively,

$$\pi(r, n) = \max_{q_{n1},\, q_{r1}} (p_{n1} - c_n)q_{n1} + (p_{r1} - c_r)q_{r1} \text{ , and}$$

$$\pi(n, r) = \max_{q_{n2}} (p_{n2} - c_n)q_{n2}.$$

Thus, $\pi_i(x, y)$ where $i \in \{1, 2\}$ and $x, y \in \{n, r\}$ is player i's maximum profit given its remanufacturing strategy x and the rival's strategy y. After inserting the inverse demand functions, the first-order conditions for a maximum of the firms' problems yield the following equilibrium demand functions:

$$\begin{pmatrix} q_{n1} \\ q_{r1} \\ q_{n2} \end{pmatrix} = \frac{1}{8 - 2\beta^2 - 10\gamma^2 + 4\beta\gamma^2} \begin{pmatrix} \gamma^2 + 4 - 2\beta & \gamma(\beta - 4) \\ -3\gamma(2-\beta) & 4 - \beta^2 \\ 4 - 2\beta - 2\gamma^2 & -2\gamma(1-\beta) \end{pmatrix} \begin{pmatrix} m_n \\ m_r \end{pmatrix}.$$

Substituting these into the profit functions of each firm, we get the optimal profit for each firm. Then Table 1 provides the profit for each subgame.

Remark 2: *From Table 1, if $\forall i, \pi_i(n, n) > \pi_i(r, n)$, then both firms not remanufacturing is a pure strategy Nash Equilibrium. If $\forall i, \pi_i(r, r) > \pi_i(n, r)$, then both firms remanufacturing is a pure strategy Nash Equilibrium.*

To assess whether (n, n) is an equilibrium, we examine the incentive of each firm to deviate from this strategy. If $\pi_1(r, n) - \pi_1(n, n)$ (and by symmetry $\pi_2(r, n) - \pi_2(n, n)$) is negative, then (n, n) is a pure strategy Nash Equilibrium. To assess whether (r, r) is an equilibrium, we examine the incentive of each firm to deviate from this strategy. If $\pi_1(n, r) - \pi_1(r, r)$ (and by symmetry $\pi_2(n, r) - \pi_2(r, r)$) is negative, then (r, r) is a pure strategy Nash Equilibrium.

4.5 Numerical analysis

Because of the complexity of the profit expressions, it is difficult to give an explicit solution of the super-game. Therefore, we resort to numerical analysis to shed some light on the characteristics of the equilibrium. Consider $c_n = 0.1$, $c_r = 0.05$, $\alpha_n = 1$, $\alpha_r = 0.7$, and $F = 0$.

Figure 1 is a phase diagram that shows the parameter values for which different equilibria occur. (The white areas in Figure 1 are ruled out due to Assumption A–D. The remaining areas meet those assumptions.)

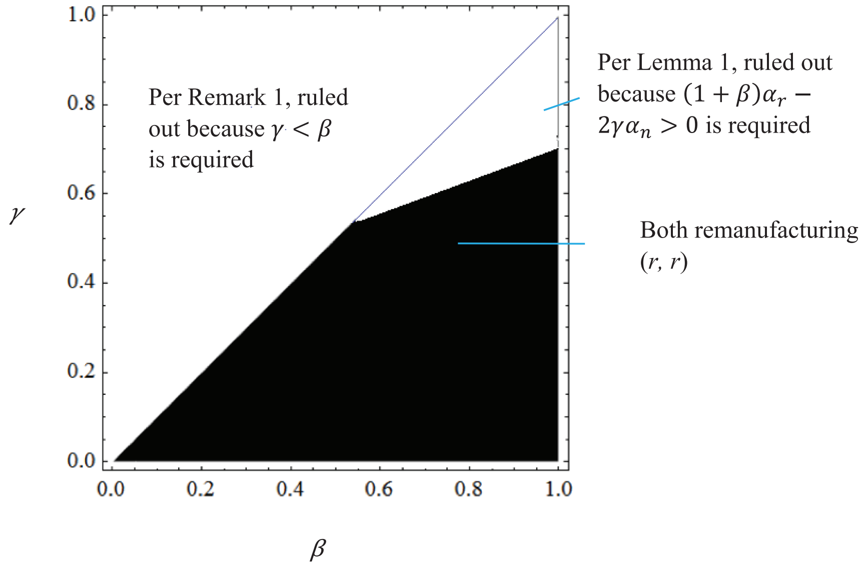

Figure 1: Phase diagram for equilibrium strategies.

From Figure 1, we observe that when β is small, firms reduce their profits by unilaterally deviating from (n, n) where neither is remanufacturing.[1] This indicates that both firms remanufacturing will be an equilibrium for small β. From Figure 1, we also observe that both firms doing remanufacturing can be an equilibrium.

Figure 2 compares the firms' profits when both firms remanufacture versus when neither remanufacture.

From Figures 1 and 2, we observe that when γ is large, although in equilibrium both firms remanufacture, they can be worse off compared with the

1 We also verified Figure 1 using a grid of β and γ values and the game theory software "Gambit" to ensure that all possible equilibria, including mixed strategy equilibria were numerically obtained.

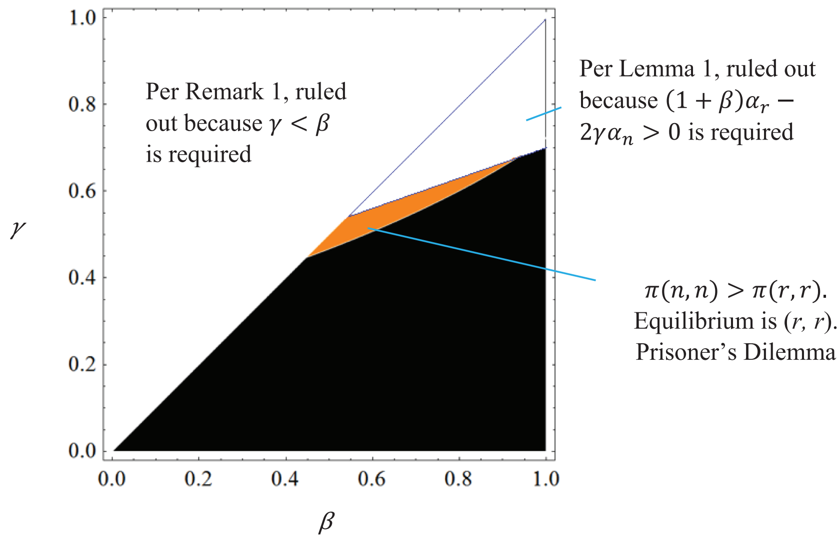

Figure 2: Comparison between $\pi(r,r)$ and $\pi(n,n)$.

scenario that neither of them remanufacture. This *prisoner's dilemma* arises because of competition. It is shown in the region of Figure 2 where $\pi(n,n) > \pi(r,r)$.

In the next section, we add further theoretical analysis of the problem to shed light on the observations from the numerical analysis.

4.6 Analysis when competition is present

We showed numerically that both firms remanufacturing is an equilibrium for small β while neither firm remanufacturing is an equilibrium for large β. Furthermore, it is possible for some values of β that remanufacturing occurs because of the Prisoner's dilemma argument. It is worthwhile to compare the profits under each scenario to get better bounds on the β's that delineate these outcomes. We look at the profit difference $\pi(r,r) - \pi(n,n)$ and attempt to sign it.

***Theorem* 2:** *Compared with not remanufacturing, remanufacturing may benefit or hurt firms according to the following rule. If $m_n < m_r$ or $\gamma m_n > m_r$ for $\beta < \beta_1 \triangleq \frac{3\gamma m_n}{m_r} - 2$ but β not too small, firms will be better off, while for $\beta > \beta_1$ but β not too large, firms will be worse off. By contrast, if $\gamma m_n < m_r < m_n$ for $\beta < \beta_1$, but β not too small, firms will be worse off, while for $\beta > \beta_1$ but β not too large, firms will be better off.*

The parameters $m_n = a_n - c_n$ or $m_r = a_r - c_r$ measures the profitability margin of a product. Compared with new products, remanufactured products that have intermediate profitability (but less than that of new products) will hurt firms in fierce competition, but may benefit firms in moderate competition. The reason is that with comparable but less profitability compared with new products, remanufactured products will intensify competition. Therefore, when there is more competition, the disadvantage of competition increases, which more than offsets the benefit of product differentiation.

By contrast, if the profitability of remanufactured product is small or large, the conclusion is reversed. The reason is that significant difference of profitability will hurt the new products with less competition, because fierce competition in remanufactured product will enhance cannibalization effects. However, when competition between new products is strong, cannibalization effects will be alleviated.

4.7 Comparison between monopoly and duopoly

Under duopoly, when prisoner's dilemma is present, decision makers will have one of following two cases in equilibrium:

- both firms choose not to offering remanufactured products, but could have been better off by offering remanufactured products.
- both firms choose to offer remanufactured products, but could have been better off by not offering remanufactured products.

Either of the above two cases, the total optimal profits are no better than the scenario of no remanufacturing in equilibrium.

Note that under duopoly, the total optimal profits of the two players without remanufacturing are $\frac{2m_n^2}{(2+\beta)^2}$, while the optimal profit for the monopoly is $\frac{m_n^2}{2(1+\beta)}$. The former is smaller than the later given the fact that $0 < \beta < 1$. We thus have the following theorem.

Theorem 3: *Under prisoner's dilemma, monopoly's profit is greater than the sum of the duopoly profits.*

Thus, in terms of total profits, monopoly offering remanufacturing will be better than monopoly without remanufacturing, which is in turn better than duopoly without remanufacturing, which is in turn no worse than any case when prisoner's dilemma occurs.

5 Conclusions

In this paper, we have studied the impact of remanufacturing on the sales of new product under competition. On one hand, the cannibalization effect from remanufactured products hurt the firm. On the other, remanufacturing can provide advantages and be an effective marketing strategy to offer products that satisfy different preferences and gain competitive advantage. In this paper, we analyzed the tradeoff with a utility based model. We derived the demand functions from maximization of a direct utility function of a representative consumer to capture preferences on new products and remanufactured products. We provided an extensive evaluation from the perspective of competing firms as to how the strategy of remanufacturing will be affected by different exogenous factors, such as market parameters, competition, substitutability, production cost as well as remanufacturing cost.

In summary, we have following managerial insights:

- Remanufacturing option does not hurt but helps a monopoly manufacturer as long as the costs of providing the remanufactured version are sufficiently low.
- Two competing manufacturers may be worse off by adopting remanufacturing options.
- Due to competition, the equilibrium can be for both firms to offer remanufactured versions even though the situation where neither are remanufacturing is more profitable.

5.1 Future research

There are several avenues for future research. One is to consider asymmetric firms. Asymmetry in brand preferences would result in different patterns of substitution that are at the moment are reduced to two parameters β and γ. This reduction could be relaxed in future analysis. Another direction for future study is to include explicit segments of consumers with heterogeneous preferences over new vs remanufactured product.

The role of supply chain partners and other industry members may also be considered. For example, some refurbished products are recertified by the manufacturer and others by third parties. For example Dell owns dellrefurbished.com, Apple.com sells certified refurbished Apple products etc., and these are also available from Best Buy, Newegg and other retailers. When a manufacturer sells remanufactured products, such as a Lexus dealer selling CPO

Lexus cars, it has the advantage of managing cannibalization of new Lexus cars by older ones. A third party such as Carmax that offers preowned cars is less concerned. Thus an extension could be to look at remanufactured product competition between a manufacturer and a third party.

Research may also consider the cost of not remanufacturing in the following context: When a manufacturer offers an exchange policy to encourage consumers to upgrade to its latest version, such as Apple accepting trade-in of old phones by consumers. The manufacturer can then choose to remanufacture the returned product or dispose of it.

Finally, other possible directions that are worth exploring include models considering uncertain demand and capacity constraints.

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Appendix A

Table 1: Matrix of subgame equilibrium payoffs.

	Firm 2 does not remanufacture (*n*)	Firm 2 remanufactures (*r*)
Firm 1 does not remanufacture (*n*)	$\pi_i(n,n) = \frac{m_n{}^2}{(2+\beta)^2}, \forall i \in \{1,2\}.$	$\pi_1(n,r) = \frac{(m_n(2-\beta-\gamma^2)-(1-\beta)m_r\gamma)^2}{(4-\beta^2-5\gamma^2+2\beta\gamma^2)^2},$ $\pi_2(r,n) = -F + \frac{1}{4(4-\beta^2-5\gamma^2+2\beta\gamma^2)^2} \times \Big\{\Big(((6\beta-11)\gamma^4+4(\beta-2)^2-\gamma^2(\beta-2)(3\beta-2)\Big)m_n{}^2 + ((\beta^2-4)^2+\gamma^2(16+\beta^2(2\beta-9)))m_r{}^2 + (48+\beta(4\beta-34))\gamma^3 - 2(24-16\beta+\beta^3)\gamma)m_n m_r\Big\}.$
Firm 1 remanufactures (*r*)	$\pi_1(r,n) = -F + \frac{1}{4(4-\beta^2-5\gamma^2+2\beta\gamma^2)^2} \times \Big\{\Big(((6\beta-11)\gamma^4+4(\beta-2)^2-\gamma^2(\beta-2)(3\beta-2)\Big)m_n{}^2 + ((\beta^2-4)^2+\gamma^2(16+\beta^2(2\beta-9)))m_r{}^2 + (48+\beta(4\beta-34))\gamma^3-2(24-16\beta+\beta^3)\gamma)m_n m_r\Big\}.$ $\pi_2(n,r) = \frac{(m_n(2-\beta-\gamma^2)-(1-\beta)m_r\gamma)^2}{(4-\beta^2-5\gamma^2+2\beta\gamma^2)^2}.$	$\pi_i(r,r) = \frac{(m_n^2+2\gamma m_n m_r+m_r^2)[(2+\beta)\ -3\gamma\ ]^2}{((2+\beta)^2-9\gamma^2)^2} + \frac{6(2+\beta)\gamma\ (1-\gamma)(m_n-m_r)^2}{((2+\beta)^2-9\gamma^2)^2},$ $\forall i \in \{1,2\}.$

Appendix B

Proof of Lemma 1

Examining each of the demand functions, the first term in each demand function when the prices are all zero (i.e. market potentials) are positive if and only if,

$$\frac{\alpha_n + \alpha_n\beta - 2\alpha_r\gamma}{(1+\beta)^2 - 4\gamma^2} > 0 \text{ and } \frac{\alpha_r + \alpha_r\beta - 2\alpha_n\gamma}{(1+\beta)^2 - 4\gamma^2} > 0.$$

This occurs if and only if $\alpha_r(1+\beta) > 2\alpha_n\gamma$. This gives the condition in Lemma 1 because the other conditions are implied.

The demands are decreasing in own price, and increasing in the rival product price if and only if,

$$\frac{\left(1+\beta-2\gamma^2\right)}{(1-\beta)\left((1+\beta)^2-4\gamma^2\right)} > 0,\ \frac{\left(\beta+\beta^2-2\gamma^2\right)}{(1-\beta)\left((1+\beta)^2-4\gamma^2\right)} > 0, \text{ and } \frac{\gamma}{(1+\beta)^2-4\gamma^2} > 0.$$

Simplifying these, we have the requirements

$$\beta+\beta^2-2\gamma^2 > 0,\ \alpha_n(1+\beta) - 2\alpha_r\gamma > 0, \text{ and } 1+\beta-2\gamma > 0.$$

The last inequality is always satisfied since $1 > \beta > \gamma$. The first inequality is implied from the third. Finally, the middle inequality holds because $\alpha_n > \alpha_r$.
■

Proof of Theorem 1

Because $1 > \beta > \gamma$, we can show that $2(1+\beta)^3 - 8(1+\beta)\gamma^2 \geq 0$. Furthermore, in $\pi(r,r) - \pi(n,n) = \frac{(2\gamma(\alpha_n - c_n) - (1+\beta)(\alpha_r - c_r))^2}{2(1+\beta)^3 - 8(1+\beta)\gamma^2}$, the numerator is a square and hence nonnegative. Thus, the entire expression is nonnegative. Moreover, $\pi(r,r) = \pi(n,n)$ if the numerator is zero, i.e. if $2\gamma(\alpha_n - c_n) = (1+\beta)(\alpha_r - c_r)$.
■

Proof of Theorem 2

Firms are indifferent between adopting remanufacturing strategy and not adopting it iff $\pi(r,r)(\beta) - \pi(n,n)(\beta) = 0$. Therefore, we have,

$$0 = \left(\beta - \frac{-2c_r + 2\alpha_r + 3c_n\gamma - 3\alpha_n\gamma}{c_r - \alpha_r}\right)\frac{\alpha_r - c_r}{\left((2+\beta)^3 - 9(2+\beta)\gamma^2\right)^2}$$
$$\times\left[(2+\beta)^2(2\beta-5)\gamma(\alpha_n - c_n) + (2+\beta)^3(\alpha_r - c_r) - 3(2+\beta)(1+2\beta)\gamma^2(\alpha_r - c_r)\right.$$
$$\left. + 27\gamma^3(\alpha_n - c_n)\right].$$

The first term yields the root $\beta_1 = \frac{-2c_r + 2\alpha_r + 3c_n\gamma - 3\alpha_n\gamma}{c_r - \alpha_r}$. The second term $\frac{\alpha_r - c_r}{\left((2+\beta)^3 - 9(2+\beta)\gamma^2\right)^2}$ is always positive. The third term yields all the other possible roots of β. Substituting root β_1 into the third term, we have,

$$\frac{54\gamma^3(\alpha_n - c_n)(\alpha_n - c_n + \alpha_r - c_r)}{(\alpha_r - c_r)^3}\left((\alpha_n - c_n) - (\alpha_r - c_r)\right)\left(\gamma(\alpha_n - c_n) - (\alpha_r - c_r)\right).$$

The above term is positive if $\alpha_n - c_n < \alpha_r - c_r$ or $\gamma(\alpha_n - c_n) > \alpha_r - c_r$. Therefore, for $\beta < \beta_1$, firms will be better off, while for $\beta > \beta_1$ and β not too large, firms will be worse off. By contrast, if we have $\gamma(\alpha_n - c_n) < \alpha_r - c_r < \alpha_n - c_n$ then for $\beta < \beta_1$, firms will be worse off, while for $\beta > \beta_1$ with β not too large, firms will be better off.
■

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