Remanufacturing as a Marketing Strategy

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The profitability of remanufacturing systems for different cost, technology, and logistics structures has been extensively investigated in the literature. We provide an alternative and somewhat complementary approach that considers demand-related issues, such as the existence of green segments, original equipment manufacturer competition, and product life-cycle effects. The profitability of a remanufacturing system strongly depends on these issues as well as on their interactions. For a monopolist, we show that there exist thresholds on the remanufacturing cost savings, the green segment size, market growth rate, and consumer valuations for the remanufactured products, above which remanufacturing is profitable. More important, we show that under competition remanufacturing can become an effective marketing strategy, which allows the manufacturer to defend its market share via price discrimination.

1. Introduction

Remanufacturing recovers value from used products by replacing components or reprocessing used parts to bring the product to like-new condition. Because it reduces both the natural resources needed and the waste produced, remanufacturing helps reduce the environmental burden. Because remanufactured products are kept out of the waste stream longer, landfill space is preserved and air pollution is reduced from products that would have had to be re-smelted or otherwise reprocessed.

Examples from industry show that there is a big market for remanufactured products. According to Remanufacturing Central (2005), in 1997, the estimated total annual sales of 73,000 remanufacturing firms in the United States was $53 billion. As the remanufacturing literature (Guide and Van Wassenhove 2003, Geyer et al. 2007, Guide et al. 2006) points out, successful examples from industry, such as those of Kodak (Geyer et al. 2007), BMW, IBM, DEC, and Xerox (Ayres et al. 1997) show that remanufacturing can be profitable.

The decision to remanufacture is difficult because managers have little guidance and industry practice is very diverse. Some manufacturers fear cannibalization from remanufactured products. They either do not remanufacture at all, or they sell remanufactured products to invisible/secondary channels to avoid cannibalization. Other manufacturers sell remanufactured products through direct channels (see, e.g., Bosch Tools, Gateway, and Sun). The central question manufacturers seem to face is, "When do benefits from remanufacturing outweigh losses from cannibalization?" For example, Bosch Tools of USA does not know exactly how remanufactured products affect primary product sales, so they use simple heuristics to decide on remanufacturing. Bosch generally remanufactures products only if their market share is small and remanufacturing leads to sufficiently high cost savings.[1] Management acknowledges that it needs more sophisticated tools for making effective and differentiated remanufacturing decisions.

The primary goal of this paper is to provide manufacturers with guidelines for remanufacturing decisions. We identify profitability conditions for remanufacturing by considering the following important characteristics of a remanufactured product: (i) The remanufactured product is typically a natural *low-cost* alternative to the new product. (ii) Remanufactured products usually have *lower valuation* from regular consumer segments. (iii) Remanufacturing has

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[1] Based on the authors' personal interview with Randy Valenta, product service director at Robert Bosch Tool Corporation.

a *green image* because it reduces waste generated and reuses old material. As such, it provides high value to a relatively small (albeit growing) green consumer segment. (iv) A remanufactured product usually has the same functionality as a new product. Because it is a low-price alternative, manufacturers often believe it *cannibalizes* new product sales. (v) Remanufacturing supply is bounded from above by the number of returns from previous sales. Thus, remanufacturable products face *supply constraints*.

In particular, we focus on the demand side aspects of the problem and identify three important drivers of remanufacturing profitability: (i) direct competition between original equipment manufacturers (OEMs), (ii) the existence of a green segment, and (iii) changes in the total market size (product life-cycle effects).

1.1. OEM Competition
The market share concern of Bosch suggests that *OEM competition* may have a significant impact on the profitability of remanufacturing. In other words, remanufacturing may be a better strategy under competition, as the remanufactured product potentially cannibalizes the competitor's new product sales. This issue has been largely neglected in the literature. Our analysis shows that the degree of competition is a significant driver of remanufacturing profitability.

1.2. Green Segments
For certain products, the environmental burden can be very high. Government legislation (such as the Waste Electrical and Electronic Equipment (WEEE) and End-of-Life Vehicle (ELV) Directives of the European Union) or "green" consumer initiatives (NPOs) create important incentives for companies to seriously consider remanufacturing. For instance, ToxicDude (2006) targets companies such as Dell and Apple for sustainable production and forces them to take responsibility for the reuse or recycling of their products. The U.S. Environmental Protection Agency (2001) advises consumers to buy "green" products, i.e., products designed with environmental attributes and recycled inputs. Thus, besides the direct benefits of cost reduction and value added recovery, remanufacturing may provide firms with side benefits such as a "green image." The existence of a *green consumer segment* represents an important marketing opportunity for remanufacturers.

1.3. Market Growth
It is well documented in the marketing literature that products undergo a product life cycle, the stages of which can be characterized by the speed of market growth. As market growth rate determines the likely market size next period, it clearly impacts the remanufacturing decisions of the firm, although a priori it

is not clear how. This suggests that the *market growth rate* can be a driver of profitable remanufacturing. For example, the firm may wonder whether to delay the introduction of the remanufactured product to benefit from additional new product sales or, instead, speed it up to benefit from higher subsequent return rates.

In this paper, we explore the potential of remanufacturing as a strategic marketing tool with a major impact on the firm's competitive advantage, rather than thinking of it as a cost saving device or as compliance with legal requirements. Our results confirm that the three factors mentioned above—competition, market growth, and the proportion of the green segment—have a significant direct impact on the remanufacturing decision. Furthermore, no single factor among the three dominates the others. Instead, these effects are intimately linked and exhibit strong interactions that can nevertheless be summarized in a framework that readily speaks to practice.

Section 2 positions our research in the remanufacturing literature. Section 3 presents a static monopolist model setup that is used as a benchmark. This analysis compares the remanufacturing scenario to one where no remanufacturing is considered. Section 4 extends monopolistic results to a setting that considers the impact of the product life cycle and identifies the existence of an optimal market growth rate for the introduction of remanufactured products. Section 5 extends the benchmark monopoly case to a competitive setting to show that remanufacturing may be a better strategy under OEM competition. Here, we also consider the case where the manufacturer does not remanufacture and a local remanufacturer competes with the OEM's product. Section 6 combines the previous two extensions and considers the impact of OEM competition as well as product life-cycle effects. Section 7 concludes, highlights limitations, and investigates possible avenues for future research. To improve readability, all proofs and mathematical details are relegated to the online appendix, which is provided in the e-companion.[2]

2. Relevant Literature
This paper is related to two main streams of research in the operations literature: market segmentation and remanufacturing. Several papers address the issue of market segmentation for remanufactured products. Majumder and Groenevelt (2001) consider the pricing/remanufacturing decisions of an OEM facing competition from a local remanufacturer and derive conditions on cost/price relations for different reverse logistics settings. Ferrer and Swaminathan (2006)

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[2] An electronic companion to this paper is available as part of the online version that can be found at http://mansci.journal.informs.org/.

study the joint pricing of new and remanufactured products for a monopolist in a multiperiod setting. They characterize the Nash equilibrium outcome and discuss the impact of various system parameters when the manufacturer competes with a local remanufacturer. Debo et al. (2005) investigate joint technology selection and pricing decisions for new and remanufactured products. They derive the manufacturer's optimal remanufacturing decisions as well as conditions on the viability of remanufacturing. They also extend their results to the case of competing remanufacturers. Similar to Majumder and Groenevelt (2001), Ferguson and Toktay (2006) consider the pricing and remanufacturing/collection decisions when facing a competing local remanufacturer. They derive conditions on costs, under which remanufacturing or collection is profitable for a monopoly or under competition, in addition to strategies that deter remanufacturer entry.

Interestingly, all these articles mainly consider competition against local remanufacturers that use an OEM's product returns for remanufacturing. Heese et al. (2005) appears to be the only reference analyzing the profitability of remanufacturing under direct OEM competition. The authors use a Stackelberg duopoly model to show that remanufacturing can be a profitable strategy for the first-moving firm, if the underlying cost structure and market share are appropriate.

Although most articles consider a dynamic multiperiod setting, they ignore market growth over time. Debo et al. (2006) investigate the impact of product life cycle on remanufacturing decisions in the context of a monopoly. They find that optimal remanufacturability levels are higher under fast diffusion.

We contribute to this literature by bringing a marketing perspective to the remanufacturing problem through a focus on factors related to the demand faced by the firm. We combine three aspects of the demand that are typically examined separately by the literature. First, we consider direct OEM competition. Second, we observe the existence of a secondary (green) market segment, which consists of consumers who do not discount the value of the remanufactured product. Finally, we consider the impact of market growth, which turns out to have very significant effects on the profitability of remanufacturing. We also show that remanufacturing decisions may depend on the existence of local remanufacturers. To the best of our knowledge, this is the first paper that simultaneously combines these three demand-side factors in a remanufacturing context.

3. Benchmark: Static Monopoly
We start our analysis with a benchmark scenario that focuses on the impact of the *green segment*. Our goal

Table 1   **Monopoly Model Parameters**

Parameter	Definition
β	Ratio of green consumers in the market
δ	Primary consumer value discount for the remanufactured product
Δ	Total number of consumers in the market
p_n	Sales price for the new product
q_n	New product sales
c_n	Manufacturing cost of the new product
p_r	Sales price for the remanufactured product
q_r	Remanufactured product sales
c_r	Collection and processing cost of the remanufactured product

is to identify the demand conditions under which remanufacturing is profitable.

Consider a *monopolist* with *unconstrained remanufacturable product supply* throughout the product life cycle. Assume that, at a certain stage of the product life cycle, there are Δ consumers in the market. Consumers are heterogeneous with respect to their willingness to pay θ, assumed to be uniformly distributed between 0 and 1. There are two types of consumers: primary consumers and green consumers. The green consumers' proportion in the market is $\beta < 1$. When a primary consumer values the new product at θ, she values the remanufactured product lower, i.e., $\delta\theta$, where $\delta < 1$. The green consumers, on the other hand, value the remanufactured and new products the same. With this representation, the green segment not only represents consumers who are environmentally conscious but also consumers who care only for the functionality of the product rather than its newness.[3] The consumers in the green segment are the types where cannibalization is a real issue because they will buy remanufactured products when these are offered at a lower price.

Given the assumptions and the definitions in Table 1, a primary consumer gets utility ($U_n^P = \theta - p_n$) from the new product and utility ($U_r^P = \delta\theta - p_r$) from remanufactured product. A green consumer gets utility ($U_n^G = \theta - p_n$) from the new product and utility ($U_r^G = \theta - p_r$) from the remanufactured product. The primary consumers purchase the new product if $U_n^P > 0$ and $U_n^P > U_r^P$. Otherwise, the primary consumer purchases the remanufactured product if $U_r^P > 0$. Similarly, the green consumers purchase the new product if $U_n^G > 0$ and $U_n^G > U_r^G$. Otherwise, the green consumers purchase the remanufactured product if $U_r^G > 0$. Throughout our analysis we will consider cases where the manufacturer prices the

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[3] In fact, there could even be consumers who value the remanufactured product more because of its environmental friendliness. Although we will not consider this in our models, we should note that the existence of such consumers would reinforce our results as it would make remanufacturing a more profitable option.

remanufactured product lower than the new product, i.e., $p_n > p_r$, which is the relevant case for practice.

3.1. Demand
When the remanufactured product is not offered, the market can be represented via a single consumer type, since green consumers cannot be differentiated. In this case the market consists of Δ consumers, whose valuations (θ) are uniformly distributed over [0, 1]. It is easy to see that the demand can be written as $q_n = \Delta(1 - p_n)$.

When both new and remanufactured products are sold, the manufacturer has two pricing options:

1. Keep the price low ($p_r \leq \delta p_n$) to sell remanufactured products to both segments. (Recall that primary consumers purchase the remanufactured product if $U_r^P > U_n^P \Rightarrow \delta\theta - p_r > \theta - p_n \Rightarrow p_n\delta > p_r$.) When $p_r \leq \delta p_n$, the new product's demand only comes from primary consumers with high willingness-to-pay:

$$q_n^P = \Delta(1 - \beta)\left(\frac{(-1 + \delta + p_n - p_r)}{-1 + \delta}\right). \quad (1)$$

The price-sensitive primary consumers will buy the remanufactured product:

$$q_r^P = \Delta(1 - \beta)\frac{(\delta p_n - p_r)}{(1 - \delta)\delta}. \quad (2)$$

Green consumers will not buy the new product: $q_n^G = 0$ because $p_n > p_r$. But they will buy the remanufactured product:

$$q_r^G = \Delta\beta(1 - p_r). \quad (3)$$

Then, $q_n = q_n^P$ and $q_r = q_r^P + q_r^G$.

2. Keep the price high ($p_r > \delta p_n$) to maximize profits from the green segment only. (Recall that $p_r > \delta p_n \Rightarrow U_n^P > U_r^P$.) When $p_r > \delta p_n$, primary consumers do not buy the remanufactured product and the demand is formed as follows:

$$q_n = \Delta(1 - \beta)(1 - p_n), \quad (4)$$

$$q_r = \Delta\beta(1 - p_r). \quad (5)$$

As such, the overall demand is kinked with two possible demand regimes. The manufacturer maximizes profits by solving $\max_{p_n, p_r} \Pi_R = (p_n - c_n)q_n + (p_r - c_r)q_r$.

3.2. No Remanufacturing Scenario
Assume first that remanufacturing is not an option; i.e., the manufacturer maximizes profits by offering only the new product. The profit function is $\Pi_{NR} = (p_n - c_n)q_n$, which is maximized by $p_n = (1 + c_n)/2$. Sales are $q_n = \Delta(1 - c_n)/2$, and the profit is given by $\Pi_{NR} = \Delta(1 - c_n)^2/4$.

3.3. Static Remanufacturing Scenario
When the monopolist remanufactures, the remanufactured and new products are priced simultaneously to maximize profits. Assume that the costs are such that

both new and remanufactured products are offered (see Corollaries EC.1 and EC.2 in the online appendix). In this case, the manufacturer uses the pricing strategy described in the following proposition.

PROPOSITION 1. *There exists a β^* (detailed in the online appendix) such that when $\beta \leq \beta^*$, the solution to the monopolist's problem is given by $p_n^* = -(-1 + \beta - c_n + \beta c_n - 2\beta\delta - \beta c_n\delta + \beta\delta^2)/(2(1 - \beta + \beta\delta))$ and $p_r^* = -(-c_r + \beta c_r - \delta - \beta c_r\delta)/(2(1 - \beta + \beta\delta))$. When $\beta \geq \beta^*$, the solution to the monopolist's problem is given by $p_n^* = (1 + c_n)/2$ and $p_r^* = (1 + c_r)/2$.*

Proposition 1 shows that the manufacturer should use two different pricing regimes depending on the green segment size. When the green segment is small ($\beta \leq \beta^*$), the manufacturer prices the remanufactured product low to price discriminate and also capture the price-sensitive customers in the primary market. However, when the green segment is large, the manufacturer uses the high pricing regime to get the maximum profit out of the green segment. This way, the losses from cannibalization are compensated by the high price charged to the green segment. In practice, however, the green segment is expected to be small and we would typically observe a low pricing strategy by manufacturers.

Having identified the optimal pricing strategy under remanufacturing, we would like to know whether remanufacturing is profitable. We can compare the no remanufacturing (*NR*) and remanufacturing (*R*) scenarios to answer this question. Corollary 1 states that the only condition under which a monopolist would remanufacture is when the remanufacturing costs are sufficiently low.[4]

COROLLARY 1. *When $\beta > 0$, remanufacturing is profitable for a monopolist if and only if $c_r < c_n$. When $\beta = 0$, remanufacturing is profitable for a monopolist if $c_r < \delta c_n$.*

We would also like to understand what really drives cannibalization and to what extent cannibalization impacts profitability. Obviously, there are two types of cannibalization in this system: (i) cannibalization from the primary segment (price-sensitive primary consumers purchase the remanufactured product instead of a new one) and (ii) cannibalization from the green segment (green consumers purchase the cheaper remanufactured product instead of the new one). According to Corollary 2, cannibalization does not necessarily lead to lower profit. There are two main drivers of the cannibalization impact: (i) green segment size and (ii) primary consumer discount rate (δ).

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[4] The reader should note that this result is valid under a zero fixed cost assumption. Remanufacturing is profitable only if extra profit obtained from remanufacturing compensates for any fixed costs involved.

COROLLARY 2. *When $\beta \leq \beta^*$, q_r is increasing in δ and q_n is decreasing in δ and β. The profit is convex in β. When $\beta > \beta^*$, q_r and Π_R are increasing in β.*

The impact of the green segment changes depending on the size of this segment. When the green segment is large ($\beta \geq \beta^*$), there is a strong niche in the market that can be captured via the remanufactured product. If remanufacturing is cheaper than new production, the profit increases in β. When the green segment is small ($\beta \leq \beta^*$), the profit is convex in β, which means that the profit can be decreasing in the green segment size. To facilitate the interpretation of these results, the additional profit from remanufacturing is explored in Figures 1 and 2.

Figure 1 represents the extra profit from remanufacturing—i.e., the profit difference between selling versus not selling remanufactured products—for different green segment rates and remanufacturing costs. Figure 1(a) assumes low cost savings from remanufacturing and shows that cannibalization is a concern when the green segment is small. Specifically, when $\beta < \beta^*$, the manufacturer uses the low pricing regime and sells both to primary and green segments. In this case, profits from remanufacturing are decreasing in β. This is due to the fact that the green consumers who could have bought the new product if the remanufactured product were not sold are going for the remanufactured product because it is cheaper.

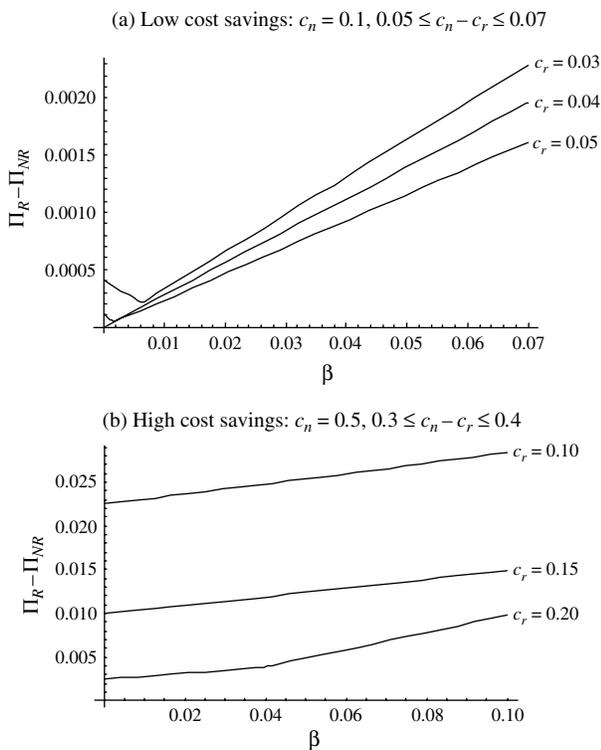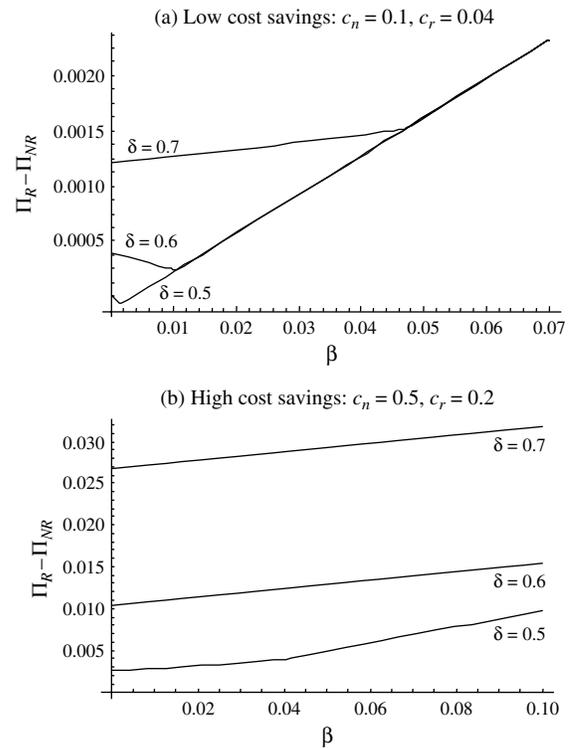**Figure 1   Extra Profits from Remanufacturing When $\delta = 0.5$, $\Delta = 1$, and $c_r \leq \delta c_n$**

(a) Low cost savings: $c_n = 0.1$, $0.05 \leq c_n - c_r \leq 0.07$

(b) High cost savings: $c_n = 0.5$, $0.3 \leq c_n - c_r \leq 0.4$

Figure 2   Extra Profits from Remanufacturing When $\Delta = 1$ and $c_r \leq \delta c_n$

(a) Low cost savings: $c_n = 0.1$, $c_r = 0.04$

(b) High cost savings: $c_n = 0.5$, $c_r = 0.2$

However, when β exceeds β^*, profits are increasing in the green segment size because the manufacturer charges a high price for the green segment. Figure 1(b) illustrates the case when the cost savings from remanufacturing are high. With sufficiently high cost savings ($c_n - c_r$), benefits from remanufacturing always overcome the cannibalization effect.

Primary consumer valuations for the remanufactured product is also a significant driver of the cannibalization impact. Figure 2 explores the profitability of remanufacturing under different levels of primary consumer discount rate (δ) for the remanufactured product. When δ is high, the negative cannibalization impact of the green segment is lost. This is due to the fact that with high δ, the primary consumers can be charged a higher price for the remanufactured product. With this high price, the green consumers are also paying more for the remanufactured product.

4.   Monopolist Facing Product Life Cycle

So far, we have ignored the origins of remanufacturable product supply. Remanufacturable products are reusable returns from earlier sales. To take this into consideration, we assume a two-period monopolistic model. In the first period the market size is normalized to 1. We denote the sales of new products as q_1 and the price as p_1. Total market demand in the first period is given by $q_1 = 1 - p_1$. In the

Figure 3   Market Growth Model

(a) Growth phase ($\Delta > 1$)

(b) Decline phase ($\Delta < 1$)
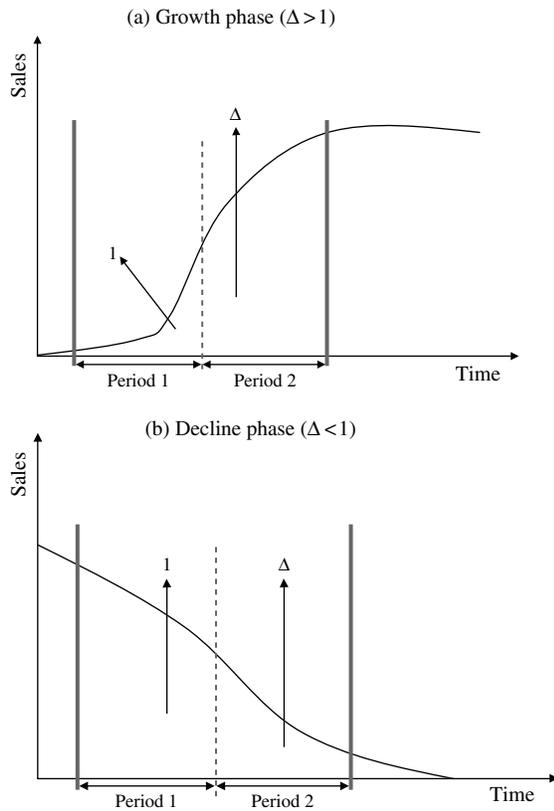
second period the market size expands (shrinks) to $\Delta > 1$ (<1), depending on the product's position in the life cycle. Figure 3 illustrates the two situations captured by our model: when Δ is larger (smaller) than 1 our model applies to early (late) stages of the product life cycle with a growing (shrinking) market. The novelty of this approach lies in representing the *product life-cycle effects* in a two-period model. Using a multiperiod model would not add many insights but would tremendously complicate the analysis.

4.1.   No Remanufacturing Scenario
When the manufacturer maximizes profits by offering only the new product, the return flows have no impact on the manufacturer's decision. The profit function is given by $\Pi_{NR} = (p_n - c_n)q_n + (p_1 - c_n)q_1$, which is maximized by $p_n = p_1 = (1 + c_n)/2$. Sales are $q_n = \Delta(1 - c_n)/2$ and $q_1 = (1 - c_n)/2$. The profit is given by $\Pi_{NR} = (\Delta + 1)((1 - c_n)^2/4)$.

4.2.   Remanufacturing Scenario
In general, only a proportion ρ of used products from the first period can be collected[5] and remanufactured in the second period (see Debo et al. 2005 and

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[5] We assume that collection cost is linear in the quantity collected and is included in c_r. See Ferguson and Toktay (2006) for a discussion on the impact of nonlinear collection costs.

Geyer et al. 2007 for a general discussion). With these elements the manufacturer's two-period objective can be written as

$$\max_{p_n, p_r, p_1} \Pi_R = (p_1 - c_n)q_1 + (p_n - c_n)q_n + (p_r - c_r)q_r, \quad (6)$$

$$\text{s.t.} \quad q_r \leq q_1\rho, \tag{7}$$

Given the assumptions, the first-period demand is defined by the equation $q_1 = 1 - p_1$, and the second-period demand is given by (1)–(5).

LEMMA 1. *Constraint (7) is binding if $\Delta > \bar{\Delta}$ or equivalently if $\rho < \bar{\rho}$, where*

$$\begin{cases} \bar{\Delta} = \dfrac{\rho(1 - c_n)(-1 + \delta)\delta}{\delta(-c_n + \beta(-1 + c_n + \delta)) - c_r(-1 + \beta(1 + (-1 + \delta)\delta))}, \\ \bar{\rho} = \dfrac{(\delta(c_n - \beta(-1 + c_n + \delta)) + c_r(-1 + \beta(1 + (-1 + \delta)\delta)))\Delta}{(-1 + c_n)(-1 + \delta)\delta} \\ \qquad\qquad\qquad\qquad\qquad\qquad \text{when } \beta < \beta^*, \\ \bar{\Delta} = \dfrac{\rho(1 - c_n)}{\beta(1 - c_r)}, \quad \bar{\rho} =\leq \dfrac{-(\beta\Delta) + \beta c_r\Delta}{-1 + c_n} \quad \text{otherwise.} \end{cases}$$

Lemma 1 shows that there exists a market growth level below which remanufacturing is unconstrained. In that case, Proposition 1 applies. However, when the remanufacturable supply is constrained, the pricing rules in Proposition 1 do not apply. Similar to the benchmark scenario, we assume that costs are such that both new and remanufactured products are offered (see Corollaries EC.3 and EC.4 in the online appendix for details). The following proposition identifies the manufacturer's optimal decision.

PROPOSITION 2. *Assume $\Delta > \bar{\Delta}$, where $\bar{\Delta}$ is defined by Lemma 1. Then, there exists a β' (detailed in the online appendix) such that when $\beta < \beta'$, the monopolist's optimal prices are given by*

$$p_r^* = p_{rl}, \quad p_1^* = p_{1l}, \quad and \quad p_n^* = p_{nl}$$

(detailed in the online appendix). When $\beta > \beta'$, the optimal prices of the monopolist are given by

$$p_1^* = \frac{-(-2\rho^2 - \beta\Delta + \beta\rho\Delta - \beta c_n\Delta - \beta\rho c_r\Delta)}{2(\rho^2 + \beta\Delta)},$$

$$p_n^* = \frac{1 + c_n}{2}, \quad and \quad p_r^* = \frac{-(\rho - \rho^2 - \rho c_n - \rho^2 c_r - 2\beta\Delta)}{2(\rho^2 + \beta\Delta)}.$$

Proposition 2 has the same structure as Proposition 1. The monopolist uses a two-level pricing regime (depending on the green segment size) to maximize profits. Similar to the benchmark scenario, to overcome the negative impact of cannibalization, the remanufacturing cost should be sufficiently low. However, there is an important difference when the market growth is considered. Comparing the no

remanufacturing (*NR*) and remanufacturing (*R*) scenarios we obtain:

COROLLARY 3. *When $\beta > 0$, the condition $c_r < c_n$ is not sufficient for profitable remanufacturing when $\Delta > \bar{\Delta}$. There exists a $\tau = (1 - c_n)(1 - c_n + 2\rho(1 - c_r))/(-1 + c_r)^2$ such that remanufacturing is profitable if $\Delta\beta \leq \tau$ when $\beta > \beta^*$. τ is decreasing in c_n and increasing in c_r.*

In the benchmark case, we have found (Corollary 1) that the only condition under which a firm would remanufacture is if the cost of remanufacturing is sufficiently low, i.e., $c_n > c_r$. However, when there is limited supply or fast market growth, an additional condition is required, i.e., $\Delta\beta \leq \tau$. When the remanufacturable supply is constrained, either the market growth rate or the green segment size should be sufficiently low for profitable remanufacturing. Moreover, the profitability depends on the cost margins involved as well as the green segment size and market growth rate. Basically, supply is not sufficient to match demand to compensate the losses from cannibalization if the demand for the remanufacturable products is high and profit margins are low. Therefore, a monopolist facing the product life cycle should consider the market growth rate when making remanufacturing decisions. In particular, under a fast market growth and high demand for remanufactured products, remanufacturing should be avoided.

4.3. Discussion: Remanufacturable Supply and Market Growth

4.3.1. Managing Remanufacturable Supply. There are a number of levers that the manufacturer could use to balance remanufacturing supply and demand. The manufacturer could (i) increase the remanufacturable supply by selling more in the first period, (ii) increase the remanufacturable supply by increasing the reusability rate, or (iii) wait longer before introducing remanufactured products such that the market growth rate is lower and the remanufacturable supply is relatively larger.

Increasing First-Period Sales. The manufacturer is forward-looking when facing a product life cycle. Figure 4 illustrates the optimal new product sales quantities in the first period for different market growth and remanufacturability levels. The optimal sales quantity under product life cycle, say q_1^{plc}, is always larger than in the unconstrained case where the static optimal new product sales in the first period, q_1^s, would be $(1 - 0.5)/2 = 0.25$. This is because the first-period sales determine the remanufacturable product availability in the second period. When the reusability rate is low, the new product prices in the first period will be lower to increase new product sales and assure higher availability of remanufacturable products. The optimal first-period new product sales

Figure 4 Optimal First-Period Sales for Different Market Growth and Remanufacturability Rates When $c_n = 0.5$, $c_r = 0, 2$, $\delta = 0.5$, and $\beta = 0.1$
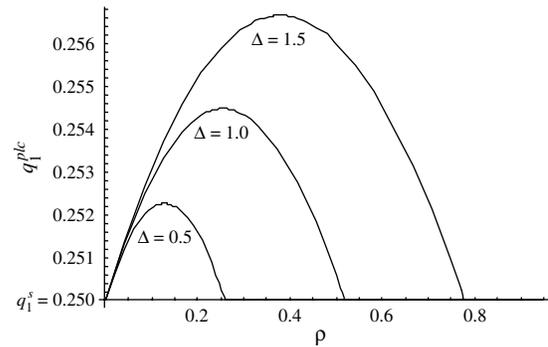
quantities increase up to a certain accessibility threshold and then decrease down to the unconstrained case. This accessibility threshold is increasing in the market growth rate (Δ) because faster growth requires higher remanufacturable product availability. Therefore, before introducing remanufactured products, manufacturers should consider the return accessibility/reusability rates as well as the rate of market growth when making pricing decisions. Examples show that these rates can vary depending on the industry and product specifications. Toktay (2003) and Guide et al. (2006) report that accessibility rates range from 5% to 35% and reusability rates range from 40% to 93%.

Increasing Reusability Rate (ρ). So far, we interpreted the parameter ρ as an upper bound on the reusability rate that is exogenously given. In real life, however, this upper bound can partially be controlled by the OEM. This can be managed, for instance, by building a more efficient collection system, marketing take-back programs to increase end-of-use product return rates, or investing in the design of remanufacturable products. Such investments would naturally increase the right-hand side of constraint (7) by increasing the reusability parameter (ρ). The following corollary identifies how much the OEM would be willing to pay to relax the constraint (7) to increase profits from remanufacturing.

COROLLARY 4. *The manufacturer's willingness to pay for a unit increase in the right-hand side of Equation (7) is given by*

$$\lambda = \begin{cases} \begin{aligned} &(\rho(-1 + c_n)(-1 + \delta)\delta - (-1 + \beta)c_r\Delta \\ &\quad - \delta(c_n - \beta(-1 + c_n + c_r + \delta - c_r\delta))\Delta) \\ &\quad \cdot ((-1 + \beta)\Delta + (-1 + \delta)\delta(\rho^2 + \beta\Delta))^{-1} \\ &\hspace{4cm} \text{when } \beta < \beta^*, \end{aligned} \\ \dfrac{\rho(-1 + c_n) - \beta(-1 + c_r)\Delta}{\rho^2 + \beta\Delta} \quad \text{otherwise.} \end{cases}$$

When $\beta > \beta^*$, λ^* is increasing in β, Δ, and c_n, and decreasing in c_r and ρ. When $\beta \leq \beta^*$, λ^* is increasing in c_n and decreasing in c_r and ρ.

Corollary 4 presents the impact of all remanufacturing related parameters on the reusability investment. Intuitively, the higher the expected demand for remanufactured products (i.e., high green segment and high market growth rate), the more the manufacturer should invest in product design, collection systems, and marketing to increase the reuse rate. The impacts of new production and remanufacturing costs are also interesting. The manufacturer should invest more in increasing the reusability rate when new production cost is high and remanufacturing cost is low. This is because the higher the cost saving from remanufacturing (i.e., new production cost minus remanufacturing cost), the more attractive remanufacturing is. The impact of ρ is even more interesting: the higher the ρ, the less the OEM should invest to increase it. In other words, the marginal contribution from increasing ρ is decreasing. This basically means that manufacturers with high reusability rates should focus on other levers than the reusability itself. Making design changes for remanufacturing and investing in efficient collection systems or take-back marketing are better options, especially when the reusability levels are low and cost savings from remanufacturing are high.

Aligning Market Growth with Remanufacturable Supply. Figure 5 illustrates the impact of market growth and remanufacturability rates on the profitability of remanufacturing. Remanufacturable product availability increases extra profit from remanufacturing, and this effect is stronger for higher market growth levels and higher remanufacturing cost savings, which is quite intuitive. In Figure 5(a) we observe that extra profit from remanufacturing increases in the return availability when the absolute cost savings from remanufacturing are high. Figure 5(b), on the other hand, illustrates that the remanufacturability rate is not that significant when remanufacturing cost savings are low. Figure 5(b) also leads to the interesting observation that there is an interaction between the market growth level and the remanufacturability rate, determining the profitability of remanufacturing. From Corollary 3, we also know that there is an interaction between the green segment size and the market growth rate. For example, when we expect large green segments, low market growth rate is required for profit making from remanufacturing. These observations suggest that there is an optimal market growth rate to introduce remanufactured products. This optimal market growth rate is very easy to determine numerically. Figure 6 illustrates the impact of market growth on the profitability of remanufacturing. The optimal remanufactured product market introduction requires lower market growth rates for lower remanufacturability rates.

Figure 5 **Extra Profit from Remanufacturing When** $\delta = 0.5$

(a) $c_n = 0.5$, $c_r = 0.1$, $\beta = 0.004$

(b) $c_n = 0.1$, $c_r = 0.04$, $\beta = 0.001$
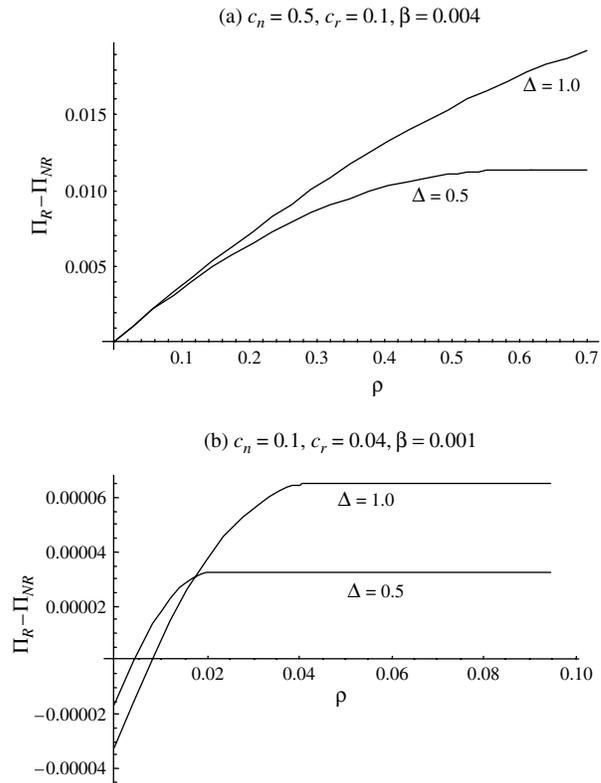
4.3.2. Market Growth and Return Rate Interaction. So far, we did not assume any dependence between the first- and second-period customers. However, it is likely that the two-period demands are somehow related. In a remanufacturing context, especially the consumers' return behavior may attenuate or accentuate market growth. To get a better understanding of such a dependence, we first need to discuss the exact meaning of product returns.

For our purposes, we could classify product returns in two basic categories: (i) End-of-use returns (a proportion of used products could be collected/taken back for reuse purposes). (ii) Commercial/convenience returns (some consumers may return products

Figure 6 **Impact of Market Growth Level on Extra Profits from Remanufacturing at** $\delta = 0.7$, $\beta = 0.1$, $c_n = 0.1$, **and** $c_r = 0.04$
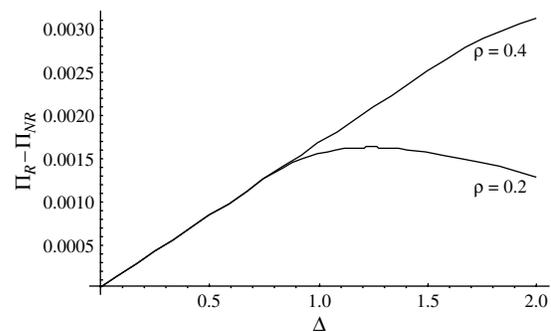
mainly because they do not like the product they purchased at the first-period price). A consumer who returns an end-of-use product is a potential consumer in the second period. Thus, end-of-use return proportion is likely to accentuate the market growth in the second period via repurchases. The impact of commercial/convenience returns can be more complicated. Similar to end-of-use customers, a convenience return consumer could be a potential customer for the cheaper remanufactured product in the second period. But if the reason for returning the product is the consumer's dislike for the product, this may attenuate market growth due to possible negative imitative effects caused by returns. To take these effects into account, we slightly change our market growth definition in two different scenarios:

SCENARIO 1. We redefine the market growth rate as $\Delta' \to \Delta + \gamma\rho$. Δ denotes the exogenous market growth as before, i.e., the density of potential first-time buyers in the second period. γ, on the other hand, reflects the impact of first-period consumers' return behavior on the market growth. With positive (negative) γ, the market growth rate increases (decreases) with the return rate ρ. In other words, γ could be defined as the sensitivity of market growth to product returns. $\gamma > 0$ represents a dominant repurchase case, where returns are mainly of end-of-use type and first-period consumers are potential purchasers in the second period. $\gamma < 0$, on the other hand, applies to a case where negative imitative effects dominate, i.e., high convenience return flows due to product dislike, which decreases the market growth rate. Let us observe how profits from remanufacturing are affected by this dependence.[6]

Figure 7 illustrates how profit savings from remanufacturing are affected by the exogenous growth rate (Δ) and the sensitivity of market growth to return rates (γ). According to Figure 7, there is an optimal market growth rate to introduce the remanufactured products, and this growth rate decreases in γ. In other words, the higher the repurchase from the first-period customers, the lower the Δ at the moment of remanufactured product introduction should be. Conversely, when the negative imitative effects caused by commercial returns dominate, the manufacturer should bring in the remanufactured products at a higher market growth rate to benefit from the higher margin remanufactured products.

SCENARIO 2. The above scenario assumes that the return percentage affects the overall market growth, i.e., for both segments. It is very likely that the repurchasing first-period consumers find the remanufactured product equally attractive as the new

Figure 7 Extra Profit from Remanufacturing When $\delta = 0.7$, $\beta = 0.1$, $c_n = 0.1$, **and** $c_r = 0.04$

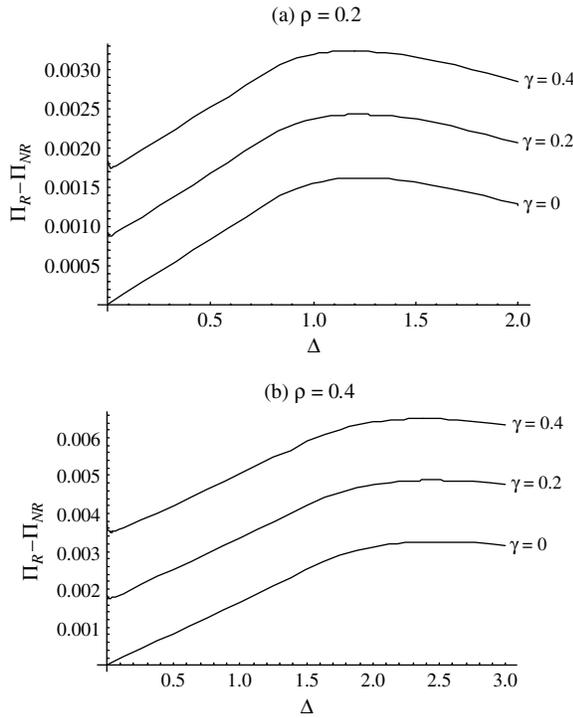(a) $\rho_t = 0.2$

(b) $\rho_t = 0.4$
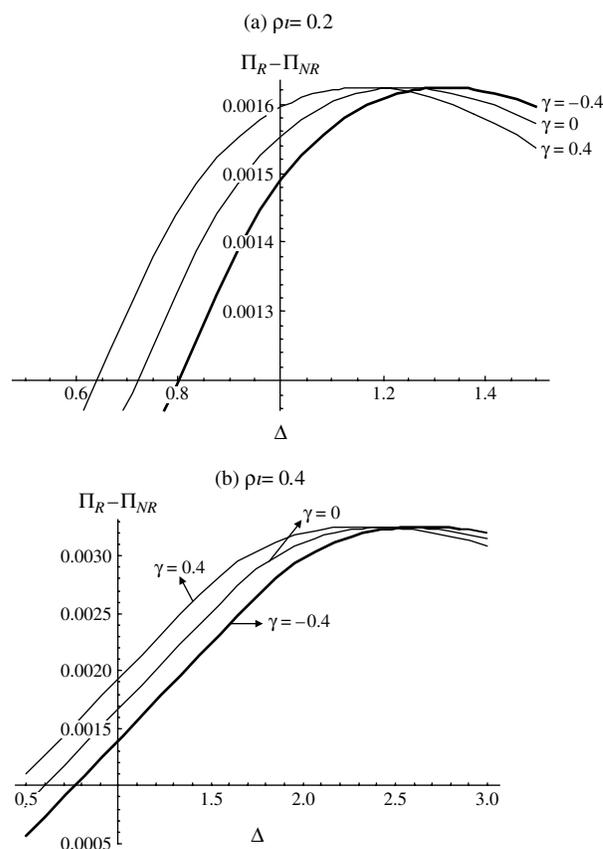
product and behave as green segment customers. In other words, the return rate may influence the market growth for the green segment only. This again requires a formulation change where $\Delta\beta' \to \Delta\beta + \gamma\rho$ in Equations (3) and (5),[7] where the interpretation of Δ and γ is the same as above, but we only consider $\gamma > 0$ because our focus in this scenario is on repurchases.

As shown in Figure 8, the main insight remains the same. The higher the repurchase rate, the lower the market growth rate should be at the moment of introduction. On the other hand, there is an important difference between Figures 7 and 8. The additional profits from remanufacturing in Scenario 1 are insensitive to ρ, but they are increasing with ρ in Scenario 2. Two effects drive this difference: (i) When the repurchasing customers join the green segment only, cannibalization from the primary segment is less of a problem. (ii) Larger green segments have higher additional profits from remanufacturing, as shown before. There is an interesting message to the manufacturer: OEMs are better off if repurchasers join the green segment. Thus, a smart way of creating more profit

[6] The analytical characterization of this scenario can be obtained by replacing Δ with Δ' in Proposition 2.

[7] The structural results from Proposition 2 apply here as well.

Figure 8 Extra Profit from Remanufacturing When $\delta = 0.7$, $\beta = 0.1$, $c_n = 0.1$, and $c_r = 0.04$. Scenario 2: Repeat Purchasers Join the Green Segment Only

Table 2 Additional Model Parameters Under OEM Competition

Parameter	Definition
p_c	Sales price for the competitor's product
q_c	Competitor's sales
c_c	Manufacturing cost of competitor
α	Consumer valuation ratio for competitor's product

rates are usually lower. In general, one would expect higher remanufacturability rates earlier in the life cycle, i.e., when the market growth rate is high, which means more profitable remanufacturing according to our analytical results.

5. Static Competition

In this section, we revert to the static model and introduce a competitor. To improve readability, we call our original monopolist the *manufacturer*. The OEM offering an alternative new product is called the *competitor*. All consumers discount the value of the competitor's product by α, where α can be thought of as the brand image of the competitor when compared to the manufacturer. We limit our analysis to the relevant case where $\alpha \leq 1$.[8] Our goal is to show that remanufacturing can be used as a competitive strategy. To this end, we consider a worst-case scenario for remanufacturing where $\delta \leq \alpha$. This assumption biases our analysis against the remanufactured product because the primary consumers consider the competitor's product as a better alternative than the remanufactured product. (In case $\delta > \alpha$, remanufacturing would always be a better alternative.)

The manufacturer prices the remanufactured product as the cheap alternative in the market, which results in the relevant case where $p_n > p_c > p_r$ (see Table 2). Similar to the benchmark scenario, the primary consumers purchasing the competitor's product can be given by the set $\{\theta \mid U_c^P(\theta) > 0, U_c^P(\theta) > U_r^P(\theta), U_c^P(\theta) > U_n^P(\theta)\}$. Green consumers go for the remanufactured product because it is the cheapest alternative.

5.1. Demand

First, we consider the case without remanufactured products. Consumers with high willingness-to-pay buy the manufacturer's new product:

$$q_n = \frac{\Delta(-1 + \alpha - p_c + p_n)}{-1 + \alpha}. \tag{8}$$

The price-sensitive consumers buy the competitor's product:

$$q_c = \frac{\Delta(p_c - \alpha p_n)}{(-1 + \alpha)\alpha}. \tag{9}$$

from remanufactured products could be to market the remanufactured products to end-of-use product returning customers.

The value of γ would depend on several factors, such as the number of products sold in the first period, the proportion of convenience returns, the proportion of end-of-use returns, repurchase rates, and negative imitative effects caused by convenience returns due to dislike. We assume an exogenous γ, because joint consideration of all those factors in determining γ is beyond our scope. The message is clear: any effect that increases (decreases) the demand for remanufactured products would result in choosing a later (earlier) remanufactured product introduction time at a higher (lower) market growth rate and increasing (decreasing) the remanufacturable supply that is available from the first period.

It is important to note that we have assumed constant remanufacturability rate ρ throughout the life cycle. This assumption is reasonable for simple products with short return lead times such as printer cartridges. It may not necessarily hold for other product categories. For instance, the remanufacturability rates of consumer electronics differ throughout the life cycle. Early on, most product returns are commercial or warranty returns for which return rates are low but reusability rates are high. Later in the life cycle, one would expect end-of-use type of returns, for which return rates can be high but reusability

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[8] In case $\alpha > 1$, the outcome would be similar to the monopoly case because the manufacturer's remanufactured product would mostly compete with his own new product.

Now, assume that the manufacturer offers a reman-ufactured product. Similar to the benchmark scenario, the manufacturer can choose one of two pricing regimes.

1. If the manufacturer keeps the price low to sell the remanufactured product to both primary and green segments, i.e., $p_c/\alpha \geq p_r/\delta$, the manufacturer's new product demand will come from the primary consumers with high willingness-to-pay:

$$q_n = \frac{\Delta(1-\beta)(-1+\alpha-p_c+p_n)}{-1+\alpha}. \tag{10}$$

Some primary consumers with lower willingness-to-pay will go for the competitor's product:

$$q_c = (1-\beta)\Delta\left(\frac{p_c-p_n}{-1+\alpha} + \frac{p_c-p_r}{-\alpha+\delta}\right). \tag{11}$$

The price-sensitive primary consumers will buy the remanufactured product:

$$q_r^P = \frac{(1-\beta)\Delta(\delta p_c - \alpha p_r)}{(\alpha-\delta)\delta}. \tag{12}$$

Green consumers will buy the remanufactured product:

$$q_r^G = \beta\Delta(1-p_r). \tag{13}$$

2. If the manufacturer keeps the price high, i.e., $p_c/\alpha < p_r/\delta$, he aims at selling the remanufactured product to the green segment only. In this case, the primary consumers do not buy the remanufactured product, and the demand is formed as follows. Primary consumers with high willingness-to-pay buy the manufacturer's new product:

$$q_n = \frac{\Delta(1-\beta)(-1+\alpha-p_c+p_n)}{-1+\alpha}. \tag{14}$$

The price-sensitive primary consumers buy the competitor's product:

$$q_c = \frac{\Delta(1-\beta)(p_c-\alpha p_n)}{(-1+\alpha)\alpha}. \tag{15}$$

The green consumers buy the remanufactured product:

$$q_r = \Delta\beta(1-p_r). \tag{16}$$

Again, the overall demand is kinked with the two demand regimes identified. The manufacturer maximizes profits by solving the problem: $\max_{p_n, p_r} \Pi_R = (p_n - c_n)q_n + (p_r - c_r)q_r$, and the competitor uses $\max_{p_c} \Pi_C = (p_c - c_c)q_c$ in the competitive game.

5.2. No Remanufacturing

Without remanufacturing, the manufacturer maximizes profits via the objective $\max_{p_n} \Pi_{NR} = (p_n - c_n)q_n$ and the competitor similarly uses $\max_{p_c} \Pi_C = (p_c - c_c)q_c$ in the game. The resulting optimal prices are $p_n^* = (2 - 2\alpha + 2c_n + c_c)/(4 - \alpha)$ and $p_c^* = (\alpha - \alpha^2 + 2c_c + \alpha c_n)/(4 - \alpha)$, and the optimal sales quantities are $q_n^* = (2 + c_c + \alpha(-2 + c_n) - 2c_n)\Delta/(4 - 5\alpha + \alpha^2)$ and $q_c^* = (-2c_c + \alpha(1 - \alpha + c_c + c_n))\Delta/((-4 + \alpha)(-1 + \alpha)\alpha)$. The optimal profit of the manufacturer equals $\Pi_{NR} = (2 + c_c + \alpha(-2 + c_n) - 2c_n)^2\Delta/((-4 + \alpha)^2(1 - \alpha))$.

5.3. Static Remanufacturing Under Competition from an OEM

Under the remanufacturing option, the Nash equilibrium of the competitive game between the manufacturer and the competitor can be characterized as follows.

PROPOSITION 3. *There is a unique Nash equilibrium under competition in which there exists a β'' such that when $\beta \leq \beta''$ the equilibrium prices are set at $p_n^* = p_{nc}$, $p_r^* = p_{rc}$, and $p_c^* = p_{cc}$ (detailed in the online appendix). When $\beta > \beta''$, $p_n^* = (2 - 2\alpha + c_c + 2c_n)/(4 - \alpha)$, $p_c^* = (\alpha^2 - 2c_c - \alpha(1 + c_n))/(-4 + \alpha)$, and $p_r^* = (1 + c_r)/2$.*

In terms of structure, the competitive case is similar to the benchmark case in that two pricing regimes are used. The important difference is the impact of cannibalization. Cannibalization from remanufactured products affects not only the manufacturer's new product sales but also the competitor's new product sales. Obviously, the remanufactured product brings competitive strength to the manufacturer since it captures the green segment consumers. However, remanufacturing can still be profitable without a green segment because the cost advantage required for profitable remanufacturing can be lower under competition than in the benchmark (monopoly) case (see Corollary EC.5 of the online appendix).

We are interested in finding the conditions where remanufacturing is profitable under competition. Unfortunately, due to the complex structure of the pricing strategy described in Proposition 3, analytical investigation of the general case is tedious and not insightful. However, critical insights can be obtained from some special cases. For instance, one can show that when the competitor has high brand power, the manufacturer's extra profit from remanufacturing is decreasing in the competitor's manufacturing costs (see Corollary EC.6 in the online appendix). In other words, remanufacturing can be a better strategy against a competitor with low manufacturing costs. Considering this observation, assume a worst-case scenario for the manufacturer where the competitor has no cost advantage from new product manufacturing, i.e., his brand power is proportional

to his manufacturing cost. Corollary 5 states the condition for profitable remanufacturing.

COROLLARY 5. *Assume* $\beta > 0$ *and* $c_c = \alpha c_n$. *Then, remanufacturing is profitable* ($\Pi_R \geq \Pi_{NR}$) *if remanufacturing costs are sufficiently low* ($c_r \leq c_r'' = c_n + (4 - 4\sqrt{1-\alpha} - \alpha)(1-c_n)/(4-\alpha)$).

Corollary 5 shows that, for remanufacturing to be profitable, the remanufacturing cost should be below a certain threshold. By simple algebra: $c_r'' - c_n = (4 - 4\sqrt{1-\alpha} - \alpha)(1-c_n)/(4-\alpha) > 0$. This shows two important facts: (i) Cost advantage required for remanufacturing is lower under competition than under the benchmark (monopoly) case. (ii) Under competition, remanufacturing can be profitable even without a cost advantage.

We now turn our attention to the general situation under competition. We are interested in the impact of the competitor's brand power, the green segment size, and their interaction. To isolate the impact of the competitor's manufacturing cost we first assume that the latter has no cost advantage, i.e., $c_c = \alpha c_n$, as shown in Figures 9 and 10. Figure 9 (Figure 10) describes the situation when the manufacturer's cost savings from remanufacturing are high (low). Figure 11 shows the case where the competitor has a cost advantage, i.e., $c_c < \alpha c_n$.

Figure 9(a) illustrates the impact of the green segment size, while Figure 9(b) illustrates the impact of

Figure 9   Extra Profit from Remanufacturing When $c_n = 0.5$, $\delta = 0.5$, and $\Delta = 1$
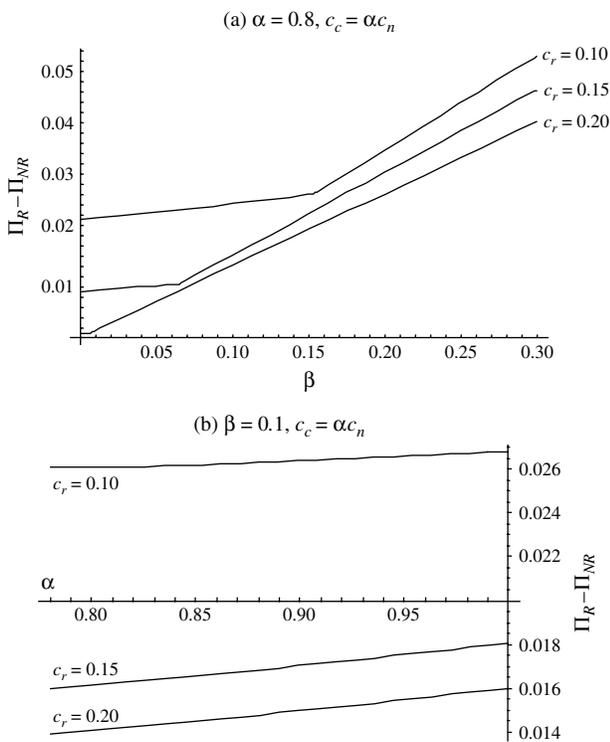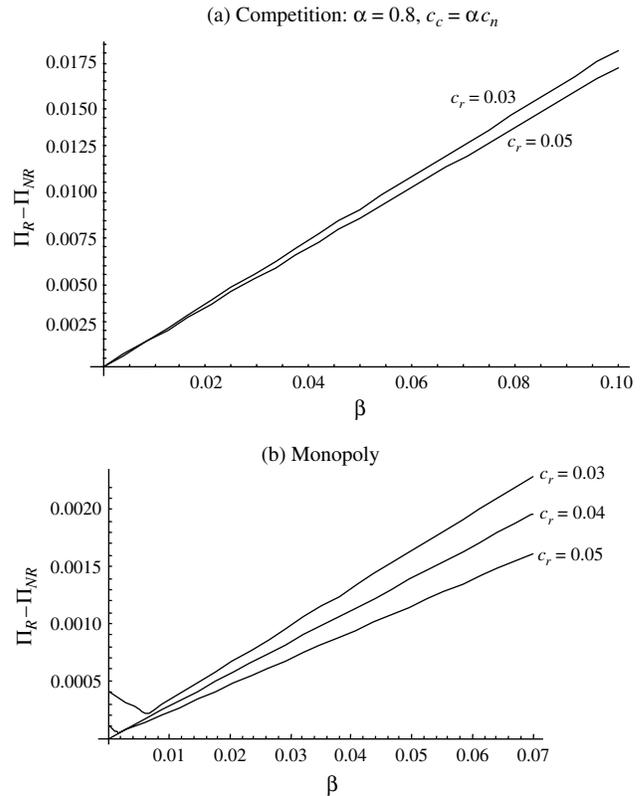

(a) $\alpha = 0.8$, $c_c = \alpha c_n$

(b) $\beta = 0.1$, $c_c = \alpha c_n$

Figure 10   Extra Profit from Remanufacturing When $c_n = 0.1$, $\delta = 0.5$, and $\Delta = 1$

(a) Competition: $\alpha = 0.8$, $c_c = \alpha c_n$

(b) Monopoly

the competitor's brand power on the profitability of remanufacturing. According to Figure 9(a), the extra profit from remanufacturing is increasing in β when the absolute cost savings from remanufacturing are high, similar to the benchmark case scenario. Comparing Figure 9(a) with Figure 1(b) shows that the extra profit from remanufacturing is higher under competition than under monopoly. It is important to note that even when there is no green segment ($\beta = 0$) remanufacturing is more profitable under competition. This is basically because the manufacturer steals from the competitor's share via offering the remanufactured product. Figure 9(b) supports this observation by showing that the extra profit from remanufacturing is increasing in the competitor's brand power. In other words, the stronger the competitor, the higher his market share and thus the higher his brand power, the more his sales are cannibalized by the remanufactured product.

In contrast to Figure 9, Figure 10 considers the case where the manufacturer's absolute cost savings from remanufacturing are low. The important observation is that the manufacturer only uses the high pricing regime, i.e., sells remanufactured products to the green segment only. Note that there is no kink in the profit difference in Figure 10(a), unlike Figure 10(b)

Figure 11   Extra Profit from Remanufacturing When $c_n = 0.1$, $\delta = 0.5$, and $\Delta = 1$

(a) $\alpha = 0.8$, $c_c = \alpha c_n/4$

(b) $\beta = 0.1$, $c_c = \alpha c_n/4$
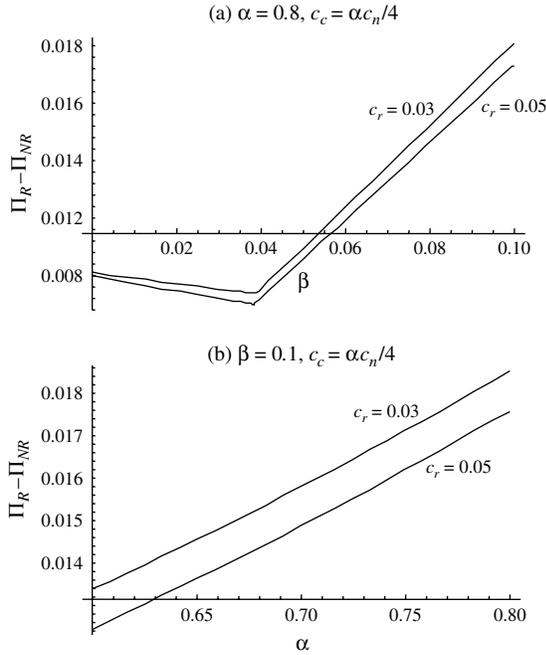
(which is the same as Figure 1(b)). This means that remanufacturing with low cost savings against a competitor without cost advantage has substantial benefits only if the green segment is large. Furthermore, comparing Figure 10(a) with Figure 10(b), we observe that when the green segment is small, extra profit from remanufacturing under competition is close to that under monopoly. In other words, remanufacturing is not a profitable strategy against a high cost competitor unless (i) the green segment is large or (ii) the cost savings from remanufacturing are high.

Similar to Figure 10, Figure 11 represents extra profits from remanufacturing under different remanufacturing cost and green segment levels. The only difference between these two figures is that Figure 11 represents the case when the competitor's manufacturing costs are lower. Comparing these two figures, we observe that the extra profit from remanufacturing is significantly higher under competition than under monopoly. When the competitor has a cost advantage, remanufacturing is a better strategy under competition than under monopoly. The additional market to be captured via the remanufactured product is even higher now. Similar to Figure 9(b), Figure 11(b) illustrates that the profits from remanufacturing are increasing in the competitor's brand power. These observations, combined with earlier results, reinforce the main message of the paper: remanufacturing is a profitable strategy against a strong competitor with low cost and/or with high brand power.

5.4. Extension: Competition with a Local Remanufacturer

In a remanufacturing context, OEM competition is not the only type of competition. As the remanufacturing literature points out, local remanufacturers can come into the market and compete with the new product. The local remanufacturer can use a low pricing strategy and steal market share from the manufacturer from both primary and green segments, which results in high cannibalization.

To explore this case, let us consider the best situation for the manufacturer: assume that the local remanufacturer's cost (c_L) is so high that he uses only the high pricing strategy. Technically, this means $p_r^L \geq \delta p_n \Rightarrow c_L \geq \delta c_n - (1 - \delta)$. In case the local remanufacturer can price lower to capture the primary market's low valuation customers, the manufacturer will be even worse off. Let us denote the manufacturer's profit under remanufacturer competition by Π_{NR}^L.

PROPOSITION 4. *Remanufacturing is profitable ($\Pi_R \geq \Pi_{NR}^L$) under local remanufacturer competition. Furthermore, the profitability of remanufacturing ($\Pi_R - \Pi_{NR}^L$) is increasing in β.*

We have shown that the manufacturer is worse off without remanufacturing even in the best case scenario. Thus, when there is a threat of competition from local remanufacturers, the remanufacturing strategy is necessarily better. However, as a caveat, we have to note that remanufacturing is not the only entry deterrent strategy. A preemptive collection strategy may be better than the remanufacturing strategy when the potential cannibalization impact is stronger, as shown by Ferguson and Toktay (2006).

6. Remanufacturing Under OEM Competition and Product Life Cycle

This section combines the previous two sections to consider the impact of market growth and competition on the profitability of remanufacturing. Following the previous notation, the manufacturer's two-period objective under remanufacturing can be written as

$$\max_{p_n, p_r, p_1} \quad \Pi_R = (p_1 - c_n)q_1 + (p_n - c_n)q_n + (p_r - c_r)q_r, \quad (17)$$

$$\text{s.t.} \quad q_r \leq q_1\rho. \quad (18)$$

Recall that the first-period sales determine the amount of remanufacturable supply for the second period. Competition in the first period would require additional assumptions on the return access in the second period, i.e., whose returns are available and to whom. This increases the complexity of the analysis

significantly.[9] Therefore, without loss of generality, we assume that the second period starts when the competitor enters the market. In other words, the demand in the first period will be the same as in the monopoly case, i.e., $q_1 = 1 - p_1$. The second-period demand will be described by (10)–(12) and (14)–(16). The competitor's objective is $\max_{p_c} \Pi_C = (p_c - c_c)q_c$. Note that under these assumptions the manufacturer's profit under the no remanufacturing scenario is trivial; i.e., the first-period profit is the same as in §4.1, and the second-period profit is the same as in §5.2.

It is important to clarify the meaning of Δ, which depends on the definition of the second period. In this scenario, we define the second period as the time where the remanufactured products are used against a competitor. Therefore, Δ can be defined as the market growth rate at the time when the OEM introduces remanufactured products against a competing OEM. This parameter is a significant driver of the remanufacturing decision as before:

LEMMA 2. *Constraint (18) is binding if* $\Delta > \Delta''$, *where*

$$
\begin{cases}
\Delta'' = \big(\rho(-1+c_n)(\alpha-\delta)\delta(\alpha^2(1+\beta(-1+\delta)) \\
\quad + 2\alpha(1+\beta(-1+\delta))(-2+\delta)+\delta \\
\quad + \beta\delta(-1+(4-3\delta)\delta))\big) \\
\quad \cdot \big((\alpha(1+\beta(-1+\delta))-\beta\delta^2)K\big)^{-1} \\
\qquad\qquad when\ \beta < \beta'', \\
\Delta'' = \dfrac{-\rho+\rho c_n}{\beta(-1+c_r)} \quad otherwise.
\end{cases}
\tag{19}
$$

Lemma 2 shows that there exists a market growth level below which remanufacturing is unconstrained under competition. In that case, Proposition 3 applies. However, when the remanufacturable supply is constrained, the pricing rules in Proposition 3 do not apply. In this case Proposition 5 identifies the manufacturer's optimal decision. Due to the complex structure of the solution, we provide the equations to calculate the equilibrium prices, i.e., the best response functions of the manufacturers, in the online appendix. Because the best responses are linear and the constraint is convex, there is a unique equilibrium.

PROPOSITION 5. *When* $\Delta > \Delta''$, *there is a unique Nash equilibrium. Characterization of the equilibrium outcome is provided in the online appendix.*

As before, we would like to identify the profitability conditions for remanufacturing. In particular, we want to understand the joint impact of competition and market growth rate. Corollary 6 considers the

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[9] If we assumed competition, the demand in the first period would be presented via (8) and (9) with $\Delta = 1$. Then, determining the amount of remanufacturable supply would require additional assumptions, e.g., whether the manufacturer could remanufacture his competitor's product returns or what is the reusability rate of the competitor's product returns.

Figure 12 **Optimal Market Growth Level at** $\delta = 0.7$, $\beta = 0.1$, $c_n = 0.5$, $c_c = 0.3$, $c_r = 0.2$, **and** $\rho = 0.6$
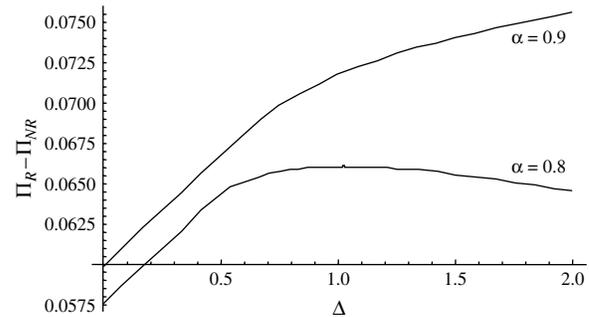
profit impact of remanufacturing under supply constraints and competition.

COROLLARY 6. *Assume* $\beta > 0$. *The condition* $c_r < c_r''$ *is not sufficient for profitable remanufacturing when* $\Delta > \Delta''$. *There exists a* τ'' *(detailed in the online appendix) such that remanufacturing is profitable* $(\Pi_R \geq \Pi_{NR})$ *if* $\Delta\beta \leq \tau''$.

According to Corollary 6, the intuition behind the competition scenario is the same as in the monopoly case: remanufacturing is not profitable under high cannibalization and constrained remanufacturable product supply. But there is more to that: profitability of remanufacturing is affected significantly by the interaction between the market growth rate and the degree of competition. Figure 12 illustrates the impact of the competitor's brand power and the rate of market growth on the profitability of remanufacturing. According to Figure 12, the manufacturer is better off with remanufacturing when the market growth rate is high at the time of entry of the competitor with a strong brand image. When the competitor's brand image is lower, the manufacturer is better off with remanufacturing when the market growth rate is low at the time of entry.

7. Managerial Insights and Concluding Remarks

This work was inspired by problems encountered by Bosch Tools and other firms struggling with the decision whether or not to offer remanufactured products. Firms usually work with heuristic approaches such as that of Bosch Tools, where remanufactured products are sold only if Bosch's market share for that specific product is small and remanufacturing leads to sufficiently high cost savings. Nevertheless, managers acknowledge their need for more sophisticated tools for making effective remanufacturing decisions. This research shows that the remanufacturing decision is driven by factors such as *competition*, *cost savings*, *cannibalization*, and *product life-cycle effects*:

• **Competition:** Our core result states that remanufacturing is more beneficial under competition than

in a monopoly setting. The tougher the competition, the more profitable is remanufacturing. This finding is consistent with Bosch's market share heuristic, where Bosch sells remanufactured products when their market share for that specific product is small. In particular, we have shown that remanufacturing is best against a strong brand image competitor with low manufacturing costs. This is because remanufactured products help the manufacturer compete for the low valuation consumer segments, which would otherwise be lost to low-cost OEM competitors. Obviously, remanufacturing seems to be a better alternative under competition because it captures green segments. However, we have highlighted that remanufacturing is profitable under competition even in the absence of a green segment. For small green segments, the profit savings from remanufacturing are even decreasing in the green segment size.

• **Cost Savings:** Cost savings are a major reason for remanufacturing. There exist cost thresholds that make remanufacturing a profitable alternative. This finding is also in line with Bosch's heuristic approach: firms should carefully consider the degree of cost savings from remanufacturing when making remanufacturing decisions. It is important, however, to understand how these thresholds are shaped under different conditions. For instance, high cost savings are required when the demand for the remanufactured product is low, while low cost savings suffice under high demand for the remanufactured product. The competition is also an important factor that determines these cost thresholds. Remanufacturing cost savings that are not sufficient under monopoly can be sufficient under competition.

• **Cannibalization:** Our results suggest that manufacturers' cannibalization concerns are valid. Nevertheless, the negative impact of cannibalization can be overcome by using a smart pricing strategy. Correct identification of the market segments is crucial to achieve this. When the ratio of customers who are indifferent between the new and remanufactured products (or even value the remanufactured product more because of its environmental attributes) is expected to be high, a high pricing regime should be used. Otherwise, the remanufactured products should be priced low to capture the low valuation customers. Recent experimental work by Li and Guide (2006) shows that cannibalization can be a real concern for business-to-business (B2B) products such as network security appliances, while for business-to-consumer (B2C) products such as a Bosch jigsaw, cannibalization is not a big problem. In this case, our results would suggest using a more aggressive pricing strategy for B2B type remanufactured products compared to B2C type products.

• **Product Life-Cycle Effects:** We have found that the supply constraint—a special feature of remanufacturing systems—combined with life-cycle effects is an important driver of remanufacturing profit. Constrained remanufacturable product availability under fast market growth makes remanufacturing a worse alternative, i.e., requires higher consumer valuations and is more vulnerable to cannibalization. Nevertheless, this effect can be controlled by a smart selection of the remanufactured product introduction time. There is an optimal market growth rate for introducing remanufacturable products: the market size should be sufficiently low to match the supply with the demand, and it should be sufficiently high to maximize sales and thus profit from remanufacturing. Recalling our motivating example, consideration of remanufactured product introduction timing can improve Bosch's remanufacturing decision heuristic.

No single factor above seems to dominate. Instead, their effects are intimately linked and they exhibit strong interactions that can nevertheless be summarized in a framework that readily speaks to practice. Figure 13 summarizes our main results about the impact of cannibalization, cost savings from remanufacturing, and product life-cycle effects. Remanufacturing can be profitable if the cost savings from remanufacturing, the green segment size, and the market growth rates are matched correctly. Fast market growth rates at the moment of remanufactured product introduction should be avoided unless the demand for the remanufactured product is small and there are high cost savings associated with remanufacturing. In addition, even under slow market growth rates, remanufacturing may result in profit loss if the cost savings from remanufacturing are not sufficiently high and the demand for the remanufactured product is low. Otherwise, remanufacturing is a profitable strategy as a low-cost alternative.

The remanufacturing literature is small compared to the importance of the managerial issues that it represents. With new regulations adopted by various developed countries and in the presence of strong consumer pressure, it is likely that remanufacturing will increase in importance on most firms' agendas. Our focus on the demand side of this problem leaves many questions for future research. For example, we have considered scenarios where the green segment buys only the remanufactured product. In our models, this is always the case if the price of the remanufactured product is below the new product price at the equilibrium and there is sufficient supply of remanufactured products. Looking at the green segment's purchasing behavior when these conditions are relaxed would be an interesting future research direction. Relaxing the assumption that the price of

Figure 13   When Is Remanufacturing Profitable?

(a) When the absolute cost difference between remanufacturing
and new production is high

(b) When the absolute cost difference between remanufacturing
and new production is low

the remanufactured product is below the new product price can also lead to different insights. While this assumption reflects most practically relevant scenarios, it may be an interesting future research to identify conditions where a remanufactured product can be sold at a higher price than the new product. It is also possible that some of the exogenous parameters in our models are interdependent. It is likely that market growth rates and green segment size are interlinked with green segment sizes being larger near the end of the product life cycle. How would this affect our results? Similarly, one could consider the issue of how to increase consumer valuations for remanufactured products, keeping green segment sizes constant. Considering multiple markets is also an issue that could be studied in more detail. The competition level or the market structure can be different for different markets, leading to market specific remanufacturing and pricing decisions with possible transfers of collected products across markets. Capacity constraints on new product manufacturing can also be an issue. When

such problems exist, remanufacturing may be an even better alternative. Future research on these issues may provide interesting new insights for firms that consider remanufacturing.

8.   Electronic Companion
An electronic companion to this paper is available as part of the online version that can be found at http://mansci.journal.informs.org/.

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