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Remanufacturing as a Marketing Strategy

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Abstract

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 further issues such as the existence of green segments, OEM competition and product life cycle effects. We show that profitability of a remanufacturing system strongly depends on these issues as well as their interactions. For a monopolist, we show that there exist thresholds on the green segment size, diffusion rate and on consumer valuations for the remanufactured products above which remanufacturing is profitable. Moreover, we show that under competition remanufacturing becomes an effective marketing strategy that allows the manufacturer to defend its market share through 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. Since 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 (EPA1 2005, Remanufacturing Central 2005). Moreover, examples from the industry show that there is a big market for remanufactured products. According to (Remanufacturing Central 2005), in 1997, the estimated total annual sales in the US of 73,000 remanufacturing

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firms was 53 billion dollars. As the remanufacturing literature (Guide and Van Wassenhove 2003, Geyer et.al. 2004, Souza et.al. 2003) points out, successful examples from the industry, such as those of Kodak (Geyer et.al. 2004), BMW, IBM SMEA, DEC and Xerox (Ayres et.al. 1997) show that remanufacturing can be a profitable option. Thus, in today's economic environment, remanufacturing is an important issue to be considered by firms.

Yet, managers have little guidance on the remanufacturing decision. For example, Bosch Tools of USA uses simple heuristics when deciding on whether to remanufacture or not a certain product. Bosch Tools has an informal rule to remanufacture products only if their market share is small and the new product can be priced sufficiently high.[1] This is because Bosch Tools typically does not know how introducing remanufactured products on the market will affect the company's overall profitability. Driven by the fear that the remanufactured product may cannibalize the primary product, most of the time the remanufactured product is not offered. Moreover, the firm operates in different markets in which the firm has different market shares, faces different consumer groups and different competitive and legal environments. Management acknowledges that Bosch needs more sophisticated tools for making effective and differentiated remanufacturing decisions.

Several articles in the operations literature investigate market segmentation for remanufacturing under competition (Debo et.al. 2004, Debo et.al. 2005, Majumder and Groenevelt 2001, Ferguson and Toktay 2005, Ferrer and Swaminathan 2005, Heese et.al. 2005). These articles mainly consider competition with local remanufacturers that use an OEM's product returns for remanufacturing. In this stream of research, the main issues are collection strategies, reverse logistics settings for the OEM, cost dependence of remanufacturing viability and the profitability of remanufacturing. Surprisingly, only (Heese et.al. 2005) consider remanufactured product sales in the case of direct competition with another OEM. Moreover, although the literature is extremely rich in investigating cost effects on remanufacturing, two key issues are generally neglected: (i) green consumer initiatives and (ii) diffusion effects.

For certain products, the environmental burden can be very high. Government legislation (such as the WEEE and ELV directives of the EU) or "green" consumer initiatives (NPOs) create important incentives for companies to seriously consider remanufacturing. For instance, ToxicDude (ToxicDude 2005) targets companies like Dell or Apple for sustainable production and forces them to take responsibility for the reuse or recycling of their products. EPA (EPA2 2005) advises consumers to buy "green" products, i.e. products designed with environmental attributes

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

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, which, in turn extends the consumer base and improves consumer relations. In other words, the existence of these green consumer segments represents an important marketing opportunity for remanufacturers.[2]

Second, it is well-documented in the marketing literature (see e.g. Bass, 1969) that products undergo a life cycle, the stages of which can be characterized by the speed of their diffusion in the market. As diffusion speed determines the likely market size next period, it clearly impacts the remanufacturing decisions of the firm, although *a priori* it is not clear how. For example, the firm may wonder whether to delay the introduction of the remanufactured product under fast product diffusion to benefit from more new product sales or, instead, speed it up to benefit from higher return rates.

The primary goal of this paper is to examine the remanufacturing decision in a model that simultaneously considers (i) direct competition between OEMs, (ii) product diffusion and (iii) the existence and size of a green segment. Rather than thinking of remanufacturing as a cost saving device or compliance with legal requirements, in this paper we would like to explore its potential as a strategic marketing weapon with a major impact on the firm's competitive advantage. Our results confirm this approach by showing that all three factors mentioned above (competition, diffusion speed and the importance 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.

The next section positions our research in the remanufacturing literature. Section 3 presents the model setup followed by model analysis in Section 4, which compares the remanufacturing scenario to one where no remanufacturing is considered by the firm. Our goal is to identify conditions under which remanufacturing is optimal. In section 5, we extend the model and consider the entry threat by third party (local) remanufacturers. Section 6 concludes, highlights limitations and investigates possible avenues for future research. To improve readability most mathematical details are relegated to an Appendix.

[2]For instance, EIA-CEI (EIA 2005) as a manufacturer alliance from the US electronics industry publishes the list of companies that participate in the reuse programs and informs consumers about participating companies. Xerox's "Green Line" products can be considered as a response to this green consumer initiative (Ayres et.al. 1997, Geyer et.al. 2004).

2 Relevant Literature

This paper is related to two main streams of research in the operations literature: market segmentation and remanufacturing. Within this literature, 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 (who remanufactures the OEM's product returns). They obtain conditions on cost/pricing relations for different reverse logistics settings. (Ferrer and Swaminathan 2005) studies the joint pricing of new and remanufactured products for a monopolist under a multi-period setting. They also characterize the Nash equilibrium outcome and discuss the impact of various system parameters when the manufacturer competes with a local remanufacturer. (Debo et.al. 2004) investigates the technology and pricing selection jointly for new and remanufactured products for a constant consumer base. They derive the manufacturer's optimal remanufacturing decisions and obtain conditions for the viability of remanufacturing. They also extend their results for the case where remanufacturers compete. The competition in this paper is with independent remanufacturers, who remanufacture the manufacturer's product. (Ferguson and Toktay 2005) consider the pricing and remanufacturing/collection decisions under the existence of a competing local remanufacturer, similar to (Majumder and Groenevelt 2001). They obtain conditions over costs, under which remanufacturing or collection is profitable for monopoly or competition, in addition to strategies that deter remanufacturer entry. (Heese et.al. 2005) investigates the profitability of remanufacturing under competition for a Stackelberg duopoly model. They show that remanufacturing can be a profitable strategy for the first moving firm, if the underlying cost structure and market share permits.

Although most of these articles consider a dynamic multi-period setting , they ignore the issue of product diffusion in time. However, it is well known in marketing (see (Bass 1969) for a seminal paper) that product sales are different over time and sales in a certain period are affected by sales in the previous periods as well as the remaining market potential. A recent paper by (Debo et.al. 2005) considers this issue and investigates the impact of diffusion on remanufacturing decisions in the context of a monopoly. They find that for faster diffusing products optimal remanufacturability levels are higher.

Our work brings a different (marketing) perspective to the remanufacturing problem by focusing on factors related to the demand faced by the firm (that is, factors outside the firm). The basic question we ask is whether remanufacturing can be considered as a marketing strategy to secure competitive advantage for the remanufacturing firm and under what demand conditions.

In particular we combine three aspects of the demand typically examined separately by the literature. Specifically, we consider an OEM (introducing a new product in the market) that faces competition from a second (follower) low-price manufacturer. While the literature mainly looks at competition between the OEM and independent local remanufacturers, we consider two OEMs directly competing with each other. We show that remanufacturing can be a powerful tool for an OEM to defend its market share when facing a low-priced competitor. We also observe the existence of a secondary (green) market segment, which consists of consumers buying the environmental products if they are offered. Moreover, we consider diffusion in our two period dynamic model, which turns out to have very significant effects on remanufacturing decisions. Finally, in an extension, we show that remanufacturing decisions may depend on the existence of local remanufacturers beyond diffusion, competition and the size of the green segment. To the best of our knowledge, this is the first paper that simultaneously combines these three demand-side factors in the remanufacturing context.

3 Model Setup

Assume a manufacturer (M), who has the option of remanufacturing a certain portion of its products and faces competition by a low-quality independent manufacturer. The decision problem is modelled in two periods in order to capture the dynamics of a remanufacturing system and diffusion effects. For analytical tractability, we assume no discounting between periods which is a common assumption in the two period models in the literature (Majumder and Groenevelt 2001, Ferguson and Toktay 2005). Our model consists of three key elements.

First, we consider the existence of diffusion or market growth/decline. Normalizing the maximum market size to 1 in the first period, we assume that the potential market size in the second period is Δ. The effect of the diffusion parameter, Δ can be interpreted in two different ways: (i) as diffusion speed or (ii) as the phase of the product life cycle. Under the first interpretation, higher Δ corresponds to a faster diffusing product and lower Δ corresponds to a slowly diffusing product. With the second interpretation, when $\Delta \leq 1$ the market is shrinking, i.e., the product is in the maturity phase or at the end of the product life cycle and when $\Delta \geq 1$, the market is growing, i.e., the product is in the growth phase of the product life cycle. Note that, independent of the interpretation, for higher levels of Δ the market potential in the second period is higher.

Second, we consider a heterogenous consumer base with a market composed of two segments: a primary, and a smaller "green" segment. The primary segment consumers have lower valuations for the remanufactured product, although they may buy it if it is offered at a lower price. The green segment consists of consumers who clearly prefer the remanufactured product if it is available. The green consumers never buy the new product in the presence of the remanufactured product because the new product is always more expensive. This is true in our model as long as the size of the green segment is not too large. Specifically, denote the ratio of the green segment to the overall market with parameter β. Then, the potential market for the green segment in the second period is given by $\Delta\beta$. It can be shown (see detailed discussion later) that as long as $0 \leq \beta \leq \bar{\beta} \leq 0.5$ the equilibrium price of the remanufactured product is always smaller than that of the new product. [3] To focus on the practically relevant scenario when β is relatively small, we will start by assuming that such a $\bar{\beta}$ exists, resulting in lower prices for remanufactured products and, by consequence, no substitution from the green segment to the primary segment.[4] Later, we calculate this upper bound and derive conditions under which remanufactured products are priced lower than new products, which is the case in real life.

Third, we consider competition. We assume that the original equipment manufacturer, M is the leader in the market and introduces the new product in the first period. In the second period, a follower OEM, denoted by C enters with a substitute. The level of competition between M and C, denoted α determines the potential market shares of the competing firms. Specifically, M's maximum potential in the second period is $\Delta(\alpha)$, while that of C is $\Delta(1-\alpha)$. We take α as an exogenous parameter, which may reflect M's brand image. Note that if $\alpha = 1$ then the competitor has demand only from substitution (i.e., it does not have brand loyal customers).

As discussed before, primary consumers may shift between the two manufacturers. The transfer rate (substitution level) from M to C is given by g_M and the transfer rate from C to M is g_C. We assume that $g_M,\ g_C \leq 1$, meaning that only a portion of the consumers shift between the two manufacturers. For simplicity, we also assume that $g_M = g_C = g$. We will later discuss the implications of relaxing this assumption. Similarly, we assume that e_M consumers of M's new product buy the remanufactured product for the loss of 1 consumer and e_C consumers of C's new product buy the remanufactured product for the loss of 1 consumer. Since the valuations of the primary consumers are lower for the remanufactured product, we assume that $e_M,\ e_C \leq 1$. Again, for the sake of analytical tractability we set $e_M = e_C = e$ and later discuss the case when

[3] As we will show later, the upper bound on β depends on the primary segment consumers' valuation for the remanufactured product and the collection rate. Specifically, $\bar{\beta}$ decreases in the primary consumers' valuation of the remanufactured product and increases in the collection rate.

[4] In most real life cases, remanufactured products are cheaper than the new products. One possible explanation is the fair-price perspective. (Ferguson and Toktay 2005) argue that since the remanufactured product is less costly, it has to be lower priced. Another possible explanation they evoke is that the remanufactured products may be perceived as lower quality products.

this does not hold.

With these assumptions, demand in the two periods is represented on figure 1. In period 1, the manufacturer is a monopolist introducing a new product in the market the size of which is normalized to 1. We assume a standard linear demand model (similar to (Ferguson and Toktay 2005),(Heese et.al. 2005)and (Majumder and Groenevelt 2001)):

$$q_1 = 1 - p_1. \tag{1}$$

Having sold q_1 new products in the market, the manufacturer (M) receives remanufacturable returns of size $q_1 c$ in the second period, where we define c as a given collection or reuse rate. The collection rate parameter c can be a function of the manufacturer's remanufacturability selection on the product or the time products spend with the consumers. For a detailed discussion on how this parameter evolves, we refer readers to (Debo et.al. 2004) and (Geyer et.al. 2004).

In the second period, there are multiple products: M's and C's new products and the remanufactured product. Given our assumptions on consumer segment sizes and behaviors, when M remanufactures, her new product sales (q_2), her remanufactured product sales (q_r) and C's sales (q_c) have the following structure (a derivation is provided by (Singh and Vives 1984)), which is common for oligopolistic pricing games with multiple segments (see for example (Padmanabhan and Png 1997)):

$$q_2 = \Delta(1-\beta)\alpha - p_2 + g p_c \tag{2}$$

$$q_c = \Delta(1-\beta)(1-\alpha) - p_c + g p_2 \tag{3}$$

$$q_r = \Delta(\beta) - p_r + e(p_2 + p_c) \tag{4}$$

As mentioned earlier, this demand structure reflects the idea that in period 2, the green segment never considers the new product as its price is always higher than that of the remanufactured product. Note also that the structure of the "no remanufacturing" scenario can be obtained by setting $\beta = e = 0$.

Our last assumption is about remanufacturing and collection costs. For simplicity, we set these to 0. We argue that this is similar to assuming constant marginal costs, which is observed often in the literature. Obviously, above certain cost thresholds, remanufacturing will not be profitable. However, this will not change the intuition we obtain for the factors we investigate. We proceed by stating that existing literature considers the cost issues in remanufacturing in great detail and systematically finds that as long as remanufacturing costs and/or collection costs are below a certain threshold remanufacturing is profitable. For example, (Ferguson and Toktay 2005) derive conditions on the viability of remanufacturing for increasing collection/remanufacturing costs and

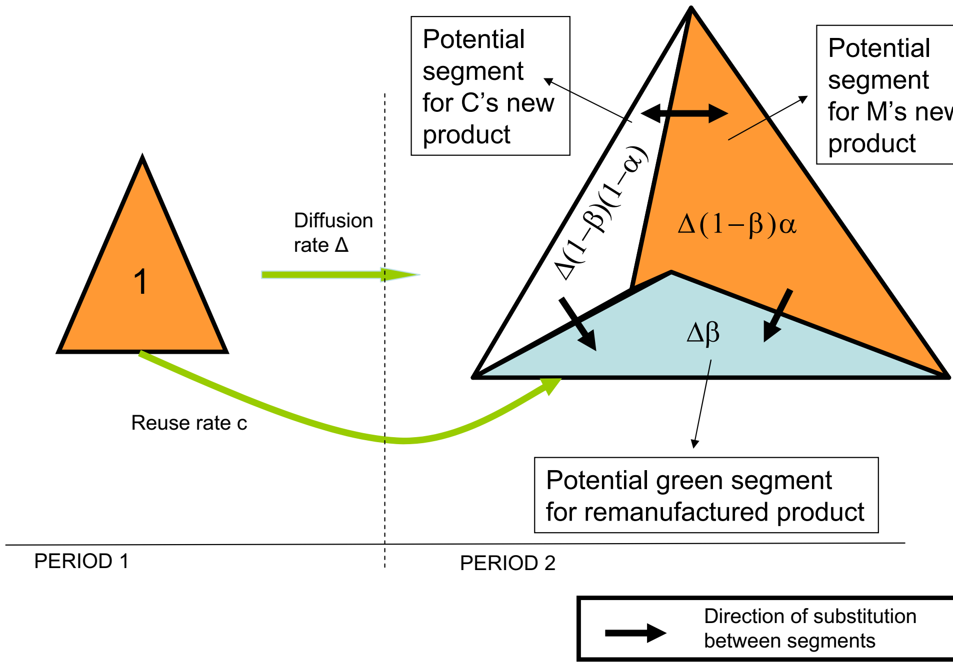


Figure 1: Market potential for competing products under remanufacturing and competition

obtain threshold cost levels below which remanufacturing is profitable. (Debo et.al. 2004) determine the drivers of profitability for remanufacturing and bring conditions on remanufacturing costs for a multi-period model. (Debo et.al. 2005) consider the capacity adjustment costs for a remanufacturing system under diffusion and find that the capacity adjustment costs need to be below a certain threshold for the viability of remanufacturing especially under fast diffusion. Therefore, in order to concentrate on investigating the effects and interactions of diffusion, competition and green segment size on the remanufacturing strategy, we limit our analysis to the case where remanufacturing and collection costs are sufficiently low (i.e. below the relevant thresholds as suggested by the literature).

4 Model Analysis

Having defined our modelling assumptions, our goal is to find when the manufacturer should engage in remanufacturing. Thus, we consider two scenarios: one with remanufacturing and another without remanufacturing. We calculate the optimal profits under both scenarios and compare the two strategies. Let us start with the no remanufacturing scenario.

4.1 The No-Remanufacturing Scenario (n)

If M does not remanufacture in the second period, the green segment will not be cannibalized by the remanufactured product. The sales quantities in period 2 will be given by:

$$q_2 = \Delta\alpha - p_2 + gp_c \tag{5}$$

$$q_c = \Delta(1-\alpha) - p_c + gp_2. \tag{6}$$

Since there is no remanufacturing, price and sales in the first period ($p_1 = q_1 = 1/2$) do not affect the second period decision. Then, M's problem can be written as:

$$\max_{p_2} \qquad \Pi_M^n = 1/4 + p_2(\Delta\alpha - p_2 + gp_c),$$

where $1/4$ is the optimal first period profit and where q_1 and q_2 are given by (1) and (5) respectively. C's problem can be written as:

$$\max_{p_c} \qquad \Pi_C^n = p_c(\Delta(1-\alpha) - p_c + gp_2),$$

where q_c is given by (6).

Proposition 1 *There exists a unique Nash Equilibrium for competition under the no-remanufacturing scenario with prices given by:*

$$p_2^n = \frac{\Delta\ (\alpha\ (2-g)+g)}{4-g^2}$$
$$p_c^n = \frac{\Delta\ (2-\alpha\ (2-g))}{4-g^2}.$$

The manufacturer's two period profit under no remanufacturing is:

$$\Pi_M^n = 1/4 + \frac{\Delta^2\,(\alpha\ (2-g)+g)^2}{(4-g^2)^2}.$$

Using Proposition 1 and setting $\alpha = 1$ and $g = 0$, we obtain the monopolist manufacturer's optimal profits under no remanufacturing.

Corollary 1 *There exists a unique solution to the monopolist's no-remanufacturing scenario with prices, quantities and optimal profit given by:*

$$p_1^n = q_1^n = 1/2, \quad p_2^n = q_2^n = \frac{\Delta}{2}, \quad \Pi_M^n = \frac{1+\Delta^2}{4}.$$

4.2 The Remanufacturing Scenario (r)

The manufacturer's two period decision problem under remanufacturing is:

$$\begin{aligned} \max_{p_1,p_2,p_r} \quad & \Pi_M^r = p_1 q_1 + p_2 q_2 + p_r q_r \\ \text{s.t.} \quad & q_r \le c q_1, \end{aligned}$$

where q_1, q_2 and q_r are given by (1), (2) and (4) respectively. The competitor's decision problem can be written as:

$$\max_{p_c} \quad \Pi_C^r = p_c q_c,$$

where q_c is given by (3).

Proposition 2 *Consider Tables 1 and 2 in the Appendix. There exists a unique Nash Equilibrium under the remanufacturing scenario with equilibrium prices and quantities given as in Table 1 if $c > \bar{c}$ and in Table 2 if $c \le \bar{c}$, where:*

$$\bar{c} = \frac{2\Delta\ (e + \beta\ (2 - e - g))}{4 - e^2 - 2\,g}.$$

Corollary 2 describes the monopolist's optimal decisions under remanufacturing if we set $\alpha = 1$ and $g = 0$:

Corollary 2 *Consider Table 3 in the Appendix. There exists a unique solution to the monopolist's remanufacturing scenario with prices and quantities given as in Table 3.*

As expected, the comparative statics for the remanufacturing scenario show that (see details in the Appendix):

1. q_1 and q_r are increasing in Δ, β and e. For q_r it is trivial that as Δ, β, c and e increase, the optimal q_r also increases. Therefore, for q_1, in order to feed the demand for remanufactured products, one has to sell more new products in the first period, i.e. q_1 also increases with these parameters.

2. q_2 increases in Δ because the market in the second period grows with higher diffusion.

3. For constant Δ, q_2 decreases in β, e and c, since as the optimal q_r increases with those, the green product cannibalizes to some extent the new product.

4.3 The remanufacturing decision

Having identified the manufacturer's optimal decisions for remanufacturing and no remanufacturing scenarios, we are now able to compare them and investigate the impact of the three central parameters: diffusion level (Δ), green segment ratio (β) and competition level (α) on the remanufacturing decision. To set a benchmark, we start by looking at the monopolist's problem. Next, we explore competition.

4.3.1 Monopoly

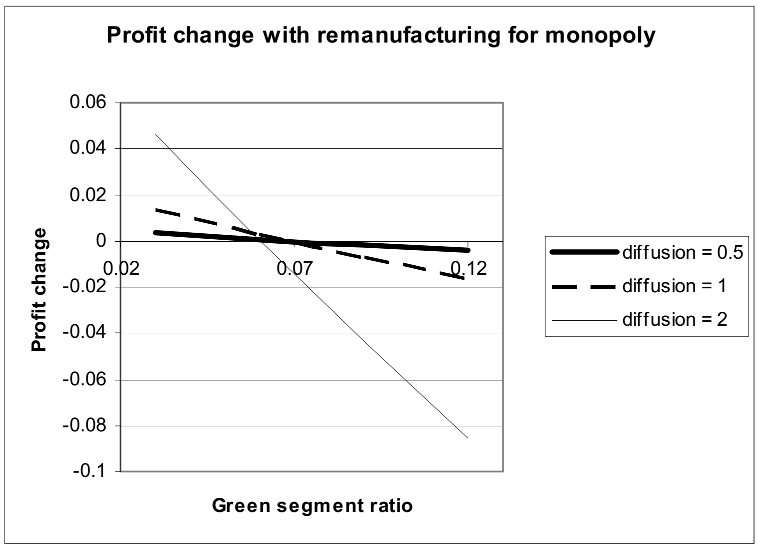


Figure 2: $\Pi_M^r - \Pi_M^n$ as a function of green segment size and diffusion rate for $e = 0.6$, $c = 0.5$

Observation 1 *For a monopolist, remanufacturing decreases profits for higher green segment sizes and more so at higher diffusion levels. If the green segment level is above (below) a certain threshold, remanufacturing brings a loss (profit) and this loss (profit) increases with higher diffusion levels.*

Observation 1 is graphically illustrated on figure 2. The larger the green segment size, the lower profits are under remanufacturing. This result is quite intuitive since higher green segment ratio, by definition, results in higher cannibalization from the primary segment. With increasing green segment sizes, consumers buying the new product are fewer. Since the remanufactured product is a lower valuation product, when the green segment ratio is sufficiently high, the additional profit that comes from the green segment does not compensate the loss from the primary segment.

Figure 2 also illustrates that remanufacturing is more vulnerable to green segment cannibalization for higher diffusion levels. Let us define the threshold green segment level as the green segment level after which remanufacturing brings loss for given values of diffusion, substitution and collection rates. Note that in figure 2, the threshold green segment level when $\Delta = 0.5$ is about 8 %, whereas this reduces to about 5 % for $\Delta = 2$. This shows that, for a monopolist, introducing remanufactured products early in the life cycle (with high diffusion rates) makes sense only if the cannibalization by the green segment is low. If the green segment is expected to be large, delaying the remanufactured product introduction to later stages in the life cycle is more profitable.

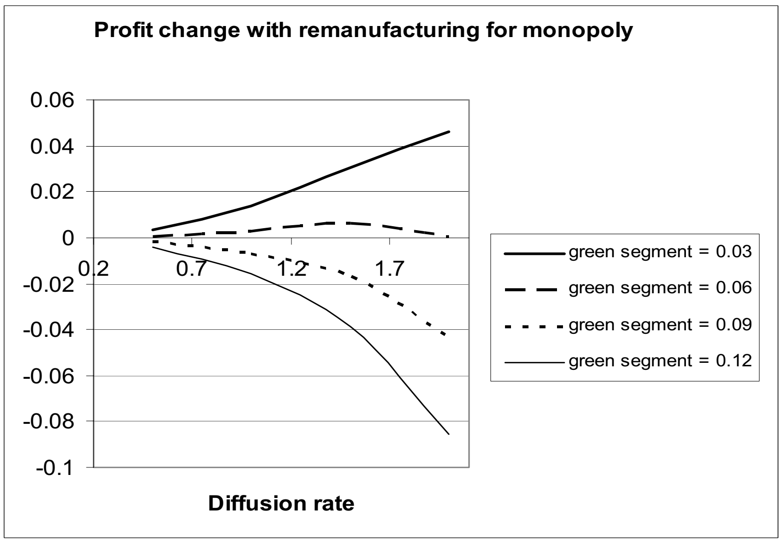


Figure 3: $\Pi_M^r - \Pi_M^n$ as a function of diffusion rate and green segment size for $e = 0.6$, $c = 0.5$

Figure 3 explains this result in a different way. It is easy to see on the figure that when $\beta = 0.03$, it is better to offer the remanufactured products earlier in the life cycle (e.g., when the diffusion rate is high), whereas when $\beta = 0.06$ it is better to offer the remanufactured products somewhere in the middle of the life cycle (e.g., $\Delta = 1.5$). On the other hand, if the green segment level is higher, it is better to delay the introduction of remanufactured products close to the end of the life cycle (e.g., when $\beta > 0.06$ the optimal diffusion rate is close to $\Delta = 0$). We also note that the threshold green segment level below which remanufacturing is profitable is lower for higher diffusion levels, i.e. cannibalization is more dangerous at higher diffusion levels. Although remanufacturing profits increase with diffusion, remanufacturing leads to more cannibalization for high diffusion levels.

As we have stated before, consumer valuations for remanufactured products are also very important for the remanufacturing decision. We expect that remanufacturing be more profitable when the consumer valuations for the remanufactured product are higher.

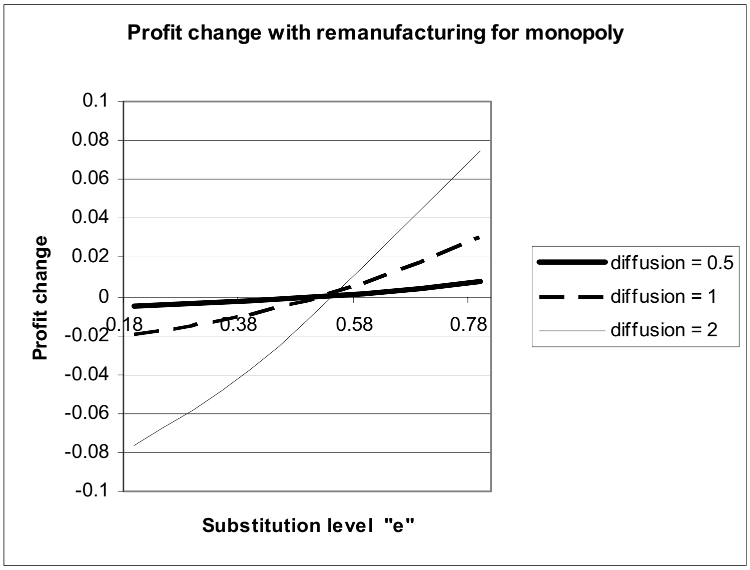


Figure 4: $\Pi_M^r - \Pi_M^n$ as a function of substitution level and diffusion rate for $\beta = 0.05$, $c = 0.5$

Observation 2 *The higher the substitution rate between the new product and the remanufactured product (e), the higher remanufacturing savings are. Remanufacturing profit decreases for lower substitution levels and diffusion increases profit only for certain levels of remanufactured product valuations.*

Observation 2 gives a similar intuition for the effect of green segment size using figure 4, but the interpretation is inverted. Figure 4 illustrates that there exists a consumer valuation level for the remanufactured products above which remanufacturing is profitable. Moreover, this threshold valuation increases for higher diffusion levels. In other words, in order to compensate the cannibalization from the primary segment by selling remanufactured products, consumer valuations for the remanufactured products should be high enough. Note on figure 4 that even for a very small green segment size (i.e., $\beta = 0.05$) the substitution rate should be above 50 % for remanufacturing to be a profitable strategy. Obviously, this consumer valuation threshold should increase for higher green segment levels.

Naturally, as illustrated in figure 5 and by the results of the comparative statics (see the Appendix), when the diffusion level is high, the optimal number of remanufactured products required in the second period should increase. Therefore, at higher diffusion levels, higher collection rates increase profits by providing extra units of returns that can be sold as remanufactured products:

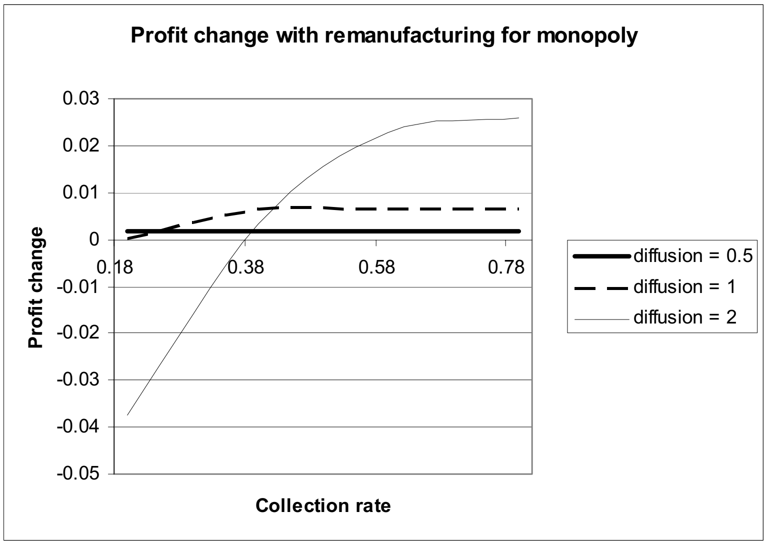


Figure 5: $\Pi_M^r - \Pi_M^n$ as a function of collection and diffusion rates for $\beta = 0.05$, $e = 0.6$

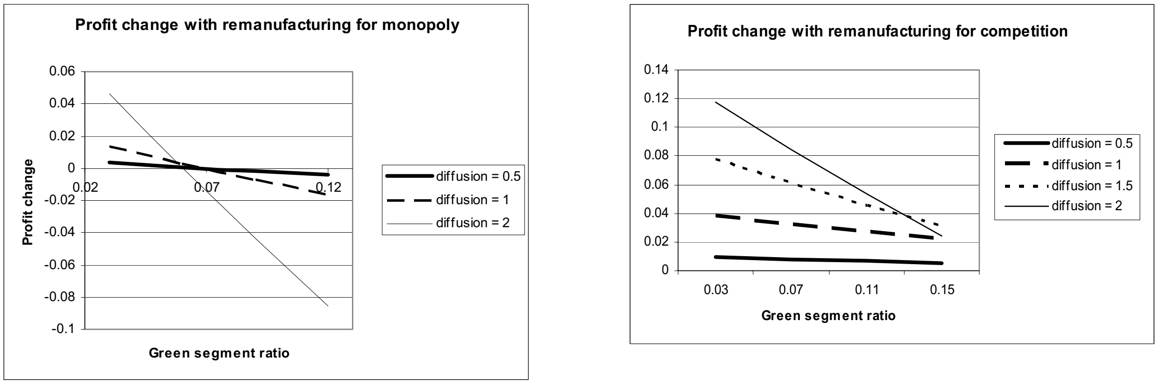
Observation 3 *Remanufacturing profits increase in collection rate up to* $\bar{c}$ *(the maximum collection rate needed) and the rate of profit increase in collection rate is higher for higher diffusion levels.*

4.3.2 Competition

Let us now consider the case where M competes with another OEM (C) in the second period. By assumption, M's market share is higher because M's brand image is higher than C's. Therefore, C has to offer lower-priced products to compete against M.

For the monopoly case, we have seen that remanufactured products cannibalize some portion of the monopolist's market and under certain conditions remanufacturing results in a loss to the manufacturer. However, in the competitive scenario, the manufacturer can use the remanufactured products as a low-priced alternative to its competitor's product. Figure 6b shows the profit change with remanufacturing for different diffusion rates and green segment sizes at a fixed level of competition. Figure 6a represents the monopoly case for a reference. The difference between figures 6a and 6b is the existence of competition. Comparing these figures results in observation 4.

Observation 4 *Remanufacturing is a better strategy under competition than under monopoly. A higher diffusion rate increases profitability (loss) for low (high) green segment levels. Moreover, the negative impact of remanufacturing through cannibalization is lower under competition.*



(a) Monopoly: $\Pi_M^r - \Pi_M^n$ for $e = 0.6$, $c = 0.5$

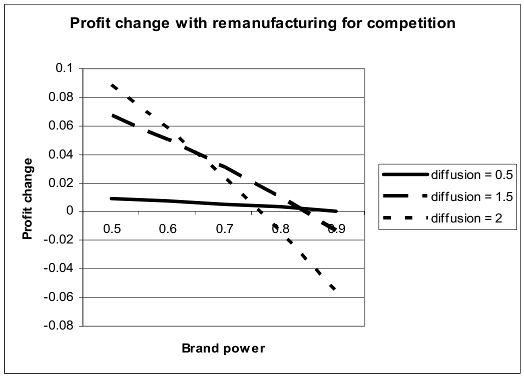
(b) Competition: $\Pi_M^r - \Pi_M^n$ for $e = 0.6$, $c = 0.5$, $g = 0.4$ and $\alpha = 0.7$

Figure 6: Diffusion and green segment effects under competition and monopoly

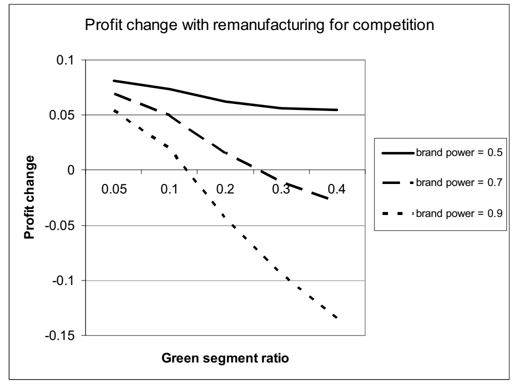
Observation 4 states that the directional impact of green segment and diffusion levels are similar to the monopoly case. However, competition puts the remanufacturing decision in a different context. When we compare figures 6a and 6b, we can observe that under competition, the threshold green segment ratio below which remanufacturing is profitable is higher than in the monopoly case. For example, in the monopoly case, the threshold green segment value for $\Delta = 2$ is about 5 % whereas this threshold is above 15 % under competition. Basically, remanufacturing is a better strategy under competition because it is an efficient way to protect the manufacturer's market share against the competing product. This effect is stronger the larger the green segment size and is accentuated by higher diffusion rates. Notice however, that while a larger green segment size makes remanufacturing more profitable under competition, even without the existence of the green segment the remanufacturing strategy results in more profit making than under monopoly. This can be seen on figure 6 by considering the case of $\beta = 0$.

Observation 5 *Remanufacturing is a more profitable strategy for higher competition levels (lower brand power) and for larger green segment sizes. Higher diffusion rates increase profitability (loss) for high (low) competition levels.*

The intuition for Observation 5 is simple (see figure 7). When the competition level increases (brand power decreases), the market share of the manufacturer decreases. In this case, the manufacturer can make use of the remanufactured products to compete better with C for the low valuation consumers: by providing an alternative product in the market, the manufacturer obtains an additional consumer segment to which she can offer a low-priced product.Notice that



(a) $\Pi_M^r - \Pi_M^n$ for $c = 0.5$, $e = 0.6$, $g = 0.4$ and $\beta = 0.15$



(b) $\Pi_M^r - \Pi_M^n$ for $\Delta = 1.5$, $e = 0.6$, $g = 0.4$ and $c = 0.5$

Figure 7: The impact of competition on the remanufacturing decision

this finding is consistent with the informal rule mentioned before that Bosch Tools is using to decide on remanufacturing. Specifically, based on their intuition they only use such a strategy if their market share is relatively low, i.e., their brand power is relatively weak.

5 Competition in the presence of a local remanufacturer

So far we have considered the remanufacturing decision under monopoly and OEM competition. But as mentioned before, in general, the remanufacturing literature considers the competition with third party remanufacturers (Majumder and Groenevelt 2001, Debo et.al. 2004, Debo et.al. 2005, Ferguson and Toktay 2005). To make our model comparable to this body of literature, we extend it by considering the following. Manufacturer (M) does not collect any returns and does not remanufacture. In the second period, a local remanufacturer (L) remanufactures M's products and competes with M besides the follower OEM (C).

Holding all the other assumptions identical to the previous section's, the manufacturer's problem can be written as:

$$\max_{p_1, p_2} \quad \Pi_M^l = p_1(1 - p_1) + p_2(\Delta(1 - \beta)\alpha - p_2 + gp_c).$$

The competitor's problem is:

$$\max_{p_c} \quad \Pi_C^l = p_c(\Delta(1 - \beta)(1 - \alpha) - p_c + gp_2),$$

while the local remanufacturer's decision problem is:

$$\begin{aligned} \max_{p_r} \quad & \Pi_L^l = p_r q_r \\ \text{s.t.} \quad & q_r \leq c q_1, \end{aligned}$$

where q_r is given by (4).

Proposition 3 *There exists a unique Nash Equilibrium under competition in the presence of a local remanufacturer with prices given by:*

$$\begin{aligned} p_1 &= 1/2 \\ p_2^l &= \frac{(1-\beta)\ \Delta\ (\alpha\ (2-g)+g)}{4-g^2} \\ p_c^l &= \frac{(1-\beta)\ \Delta\ (2-\alpha\ (2-g))}{4-g^2} \\ p_r^l &= \begin{cases} \frac{\Delta\,(e+\beta\,(2-e-g))}{2\,(2-g)} & if\ \ c > \frac{\Delta\,(e+\beta\,(2-e-g))}{(2-g)} \\ \frac{\Delta\,(e+\beta\,(2-e-g))}{(2-g)} - \frac{c}{2} & o/w. \end{cases} \end{aligned}$$

The manufacturer's two period profit is:

$$\Pi_M^l = 1/4 + \frac{(1-\beta)^2\,\Delta^2\,(\alpha\ (2-g)+g)^2}{(4-g^2)^2}.$$

Comparing this case to the situation when M remanufactures directly, we find:

Proposition 4 *When the local remanufacturer is able to enter the market with M's remanufactured products, M is always better off with remanufacturing* ($\Pi_M^r \geq \Pi_M^l$).

This result is not surprising. If M does not remanufacture, then the green segment is lost to the local remanufacturer and M has to deal with competition from both L and C. Moreover, as we have seen in the previous section, M loses the competitive advantage gained against C. Therefore, if both a local remanufacturer and a second OEM exist in the market, M is always better off with remanufacturing.

Figure 8 displays the profit increase ($\Pi_M^r - \Pi_M^l$) with remanufacturing under remanufacturing and OEM competition, for different diffusion and green segment levels. The interpretation of this graph is explained in observation 6.

Observation 6 *When a local remanufacturer is capable of remanufacturing M's products, the benefits from remanufacturing increase for higher diffusion levels even though the remanufactured product cannibalizes primary demand more. Moreover, in contrast to the scenario without the local remanufacturer, the profit increase from remanufacturing increases faster for larger green segment levels.*

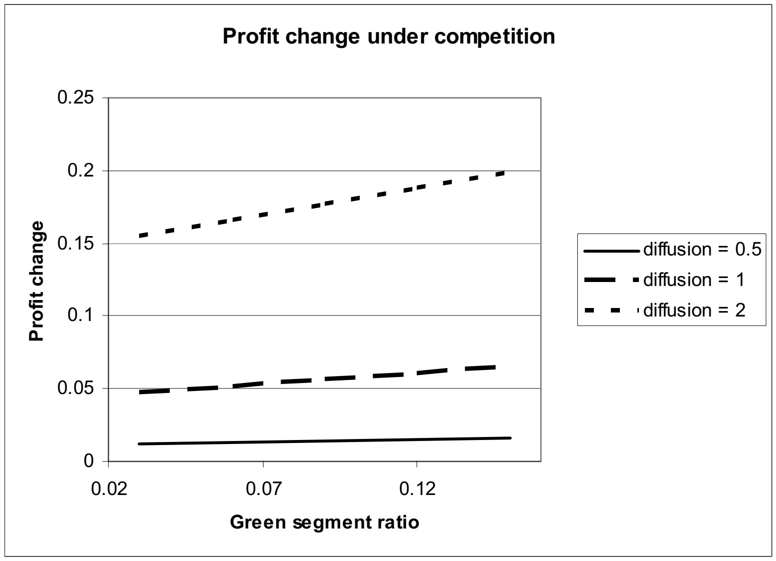


Figure 8: $\Pi_M^r - \Pi_M^l$ as a function of green segment size and diffusion rate for $e = 0.6$, $g = 0.4$,$\alpha = 0.7$, $c = 0.5$

It is an important result that the manufacturer's optimal remanufacturing decision and the dependence of this decision on the model parameters are totally different with or without the existence of a local remanufacturer. When there is no local remanufacturer, the OEM competition level has a significant effect on remanufacturing profitability, whereas without local remanufacturers OEM competition is less significant in terms of remanufacturing benefits. Second, under competition with the existence of a local remanufacturer, higher diffusion levels increase profit under any circumstances, whereas with local remanufacturer, diffusion increases profit only for higher OEM competition levels and below a threshold green segment size. Third, under competition with a local remanufacturer, higher green segment levels increase profit under any circumstances, whereas without local remanufacturer competition, green segment size reduces the profitability of remanufacturing.

It is also important to realize that remanufacturing is not the only entry deterrent strategy. In our extended model, the assumption was that if the manufacturer does not remanufacture, the local remanufacturer remanufactures and gets the entire green segment. This assumption drives the result of proposition 4. However, a simple strategy aimed at avoiding the local remanufacturer's entry could be to collect the returns without remanufacturing them. (Ferguson and Toktay 2005) consider this issue and generate collection cost thresholds under which collection as an entry deterrent strategy makes sense. In contrast, our model assumes negligible collection costs. Therefore, collection without remanufacturing as an entry deterrent strategy boils down to the same model as in section 4. These observations clearly show that remanufacturing strategies should be different depending on the existence of local remanufacturers and their reach on the used product returns.

6 Concluding remarks and future research

Based on a real life example, we have constructed a model in which a manufacturer may collect returns with recoverable value potential and has the option to sell remanufactured products. The manufacturer's remanufacturing decision is driven by factors like environmentalist consumer bases, cannibalization, competition and diffusion. Assuming that the manufacturing/remanufacturing costs are below certain threshold levels (as suggested by the remanufacturing literature), our core result shows that remanufacturing is more beneficial under competition than in a monopoly setting. Specifically, we found that the higher the competition level, the higher are the benefits of remanufacturing. Remanufactured products may help the manufacturer compete for the low valuation consumer segments, that would otherwise be lost to low priced, follower type OEMs. One may suggest that this effect is solely driven by the existence of the green segment. This however, is not true. As it is highlighted after observation 4, remanufacturing is more beneficial under competition than under monopoly even in the absence of the green segment.

Another important result of our analysis is that the product's diffusion rate is a significant driver of remanufacturing decisions. In general, we found that higher diffusion rates accentuate the benefits or drawbacks of remanufacturing because remanufacturing causes more cannibalization when diffusion rates are higher. This means that the remanufacturing decision requires more attention (is more risky) under fast product diffusion.

We have also seen that the effects of diffusion may change depending on the existence of a local remanufacturer. If the local remanufacturer is able to remanufacture the manufacturer's product returns when the manufacturer does not remanufacture, then the potential savings from remanufacturing increase for higher diffusion levels. On the other hand, when no local remanufacturer is capable of remanufacturing (either because of technical difficulties or because of the manufacturer's return collection as an entry deterrent strategy), the diffusion effect is different. For low green segment sizes, remanufacturing increases profit but for higher green segment sizes, remanufacturing profits decrease very fast with higher diffusion rates.

Considering all the issues we have discussed so far, we can now build a practical framework to guide a manufacturer's remanufacturing decision in a competitive setting. Figure 9 summarizes these results by showing the conditions under which remanufacturing is a better strategy. It

	Low competition	High competition
Large green segment	Very low diffusion rate	High diffusion rate
Small green segment	Low diffusion rate	Very high diffusion rate

Figure 9: Green segment size, diffusion rate and competition environment: when is remanufacturing a better option?

considers all three demand-side aspects of the remanufacturing problem: green segment size, competition and the product diffusion rate. For example, the lower right cell of figure 9 shows that when competition is high and cannibalization is low, it is better to start using remanufactured products in the stage of the life cycle when the product has just taken off (i.e. diffusion is fast). In contrast, the upper left cell suggests that when competition is low and cannibalization is high, it is better to delay remanufacturing towards the end of the life cycle (when diffusion is slow).

Our models are based on a number of key assumptions. First, we have assumed that $e_M = e_C = e$, i.e. that the remanufactured product valuations are the same for both M's and C's consumers. The underlying assumption is that being part of the green segment is independent from brand valuations, which is a reasonable assumption. Similarly, our second assumption is that $(g_M = g_C = g)$, which essentially means that M is equally hurt by competition from C as the other way around. One could argue that g_M should be less than g_C, since M is assumed to be having a stronger brand image (i.e. a higher quality product). Note however, that we have taken this into account by specifying that the intercept of M's demand is higher. In other words, in our model, the interpretation of higher quality means that the stronger brand has a higher captive segment (base demand) for its product. While these assumptions simplify the model, our qualitative results do not change if we relax them.

Throughout the analysis, we also assumed that the remanufactured product has a lower price than the new product as in most real life situations. We have verified this assumption for the monopoly case and found that it holds as long as the size of the green segment is not too high. To see this, consider the following more general (monopolistic) model, for which we do not have any restrictions on the green segment level and between-segment substitutions:

$$\begin{aligned} \max_{p_1, p_2, p_r} \quad & \Pi_M^r = p_1 q_1 + p_2 q_2 + p_r q_r \\ \text{s.t.} \quad & q_r \leq c q_1 \end{aligned}$$

where q_1, q_2 and q_r are given by:

$$q_1 = 1 - p_1 \tag{7}$$

$$q_2 = \Delta(1-\beta) - p_2 + g p_c + f p_r \tag{8}$$

$$q_r = \Delta(\beta) - p_r + e(p_2 + p_c). \tag{9}$$

Proposition 5 *The price of the remanufactured product (p_r) for the general monopoly model is lower than the new product's price (p_2) if:*

$$\beta \leq \bar{\beta} = \frac{c^2(2-e) + 2(1-e)}{2(3 + c^2(2-e) - e)}.$$

Moreover, $\bar{\beta}$ is decreasing in e and increasing in c.

This proposition shows that when $\beta \leq \bar{\beta}$ the price of the remanufactured product is always lower than the price of the new product. Therefore, the assumption that potential buyers of the remanufactured product don't buy the new product (i.e. $f = 0$) can be justified. Consider the extreme case that $c = 0.02$ and $e = 0.8$, which is very unlikely to occur. The upper bound in this case can be calculated as $\bar{\beta} = 0.09$, meaning that the ratio of green consumers in the market be below 9 %. We expect this ratio to be much lower in practice, especially when the collection rate is this low (i.e. there are not many environmentally conscious consumers who return their products) and the substitution factor is that high (i.e., the differentiation between the two products is low). Unfortunately, the competitive scenario proved to be untractable analytically but numerical analysis shows that the intuitions obtained from the monopoly case carry through the competitive scenario: $p_r < p_2$ if β is low.

Finally, we have assumed costs away. As mentioned before, this was done to be able to focus on the demand-side issues of remanufacturing. As such our results should be interpreted with the caveat that if any of the relevant costs are too high remanufacturing is not a profitable strategy.

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, some of the exogenous parameters that we used in our models are interdependent. It is likely for instance that diffusion 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. We have mentioned that 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. Future research on these issues warrants interesting new insights for firms that consider remanufacturing.

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7 Appendix A: Proofs

Proof. (Proposition 1)

The first order condition for the manufacturer (M) can be written as:

$$\frac{\partial \Pi_M}{\partial p_2} = \alpha\,\Delta - 2\,p_2 + g\,p_c = 0$$

The first order condition for the competitor (C) can be written as:

$$\frac{\partial \Pi_C}{\partial p_c} = (1-\alpha)\,\Delta - 2\,p_c + g\,p_2 = 0$$

Resulting best response functions are given by:

$$BR^{M,(NR,NL)}(p_c^N) = \frac{\alpha\Delta + g\,p_c^N}{2}$$

Competitor's best response is:

$$BR^{C,(NR,NL)}(p_2^N) = \frac{(1-\alpha)\,\Delta + g\,p_2^N}{2}$$

Solving the best response functions simultaneously, the equilibrium prices are obtained. The uniqueness of equilibrium is immediate by linearity of the best response functions. ■

Proof. (Corollary 1)

The first order conditions can be written as:

$$1 - 2p_1 = 0$$
$$\Delta(1-\beta) - 2p_2 = 0$$

By checking the Hessian for the objective function the Hessian $H^{mon,NR}$ is negative definite. Therefore, the objective function is strictly concave and there exists a unique solution. The rest is straightforward algebra.

$$H^{mon,NR} \quad = \quad \begin{bmatrix} -2 & 0 \\ 0 & -2 \end{bmatrix}.$$

■

Proof. (Proposition 2)

The Lagrangean for manufacturer's (M)problem can be written as:

$$L^M_{p_1,p_2,p_r,\lambda} = p_1 q_1 + p_2 q_2 + p_r q_r - \lambda(q_r - c q_1)$$

The first order condition for the competitor (C) can be written as:

$$\frac{\partial \Pi_M}{\partial p_2} = (1-\alpha)\ (\Delta - \beta\,\Delta) - 2\,p_c + g\,p_2 = 0$$

Thus, competitor's (C) best response is given as:

$$BR_C(p_1^N, p_2^N, p_r^N) = \left\{\ p_2(p_1^N, p_2^N, p_r^N) = \frac{(1-\alpha)\,(1-\beta)\,\Delta + g\,p_2^N}{2}\right. .$$

- **Non-binding collection rate ($\lambda = 0$):**

  The first order conditions for the manufacturer (M) can be written as:

$$\frac{\partial \Pi_M}{\partial p_1} = 1 - 2\,p_1 = 0$$
$$\frac{\partial \Pi_M}{\partial p_2} = \alpha\ (\Delta - \beta\,\Delta) - 2\,p_2 + e\,p_r + g\,p_c = 0$$
$$\frac{\partial \Pi_M}{\partial p_r} = \beta\,\Delta - 2\,p_r + e\ (p_2 + p_c) = 0$$

Resulting best response functions can be written as:

$$BR_M(p_c^N) = \begin{cases} p_1(p_c^N) = 1/2 \\ p_2(p_c^N) = \frac{2\,\alpha\,(1-\beta)\,\Delta+\beta\,\Delta\,e+\left(e^2+2\,g\right)\,p_c^N}{4-e^2} \\ p_r(p_c^N) = \frac{\beta\,\Delta\,(2-\alpha\,e)+e\,\left(\alpha\,\Delta+(2+g)\,p_c^N\right)}{4-e^2} \end{cases}.$$

The equilibrium prices are obtained by solving the best response functions simultaneously.

- **Binding collection rate ($\lambda > 0$)**

The first order conditions for the manufacturer (M) can be written as:

$$\frac{\partial L_M}{\partial p_1} = 1 - c\,\lambda - 2\,p_1 = 0$$
$$\frac{\partial L_M}{\partial p_2} = \alpha\,(\Delta - \beta\,\Delta) - 2\,p_2 + e\,(-\lambda + p_r) + g\,p_c = 0$$
$$\frac{\partial L_M}{\partial p_r} = \beta\,\Delta + \lambda + e\,p_2 - 2\,p_r + e\,p_c = 0$$
$$\frac{\partial L_M}{\partial \lambda} = c - \beta\,\Delta - c\,p_1 - e\,p_2 + p_r - e\,p_c = 0$$

Resulting best response functions can be written as:

$$BR_M(p_c^N) = \begin{cases} \frac{-2+c^2\,\left(-4+e^2\right)+c\,\left(\beta\,\delta\,(2-\alpha\,e)+e\,\left(\alpha\,\delta+(2+g)\,p_c^N\right)\right)}{-4+c^2\,(-4+e^2)} \\ -\left(\frac{-2\,\alpha\,(-1+\beta)\,\left(1+c^2\right)\,\Delta+c\,e+2\,g\,p_c^N+c^2\,\left(\beta\,\Delta\,e+e^2\,p_c^N+2\,g\,p_c^N\right)}{-4+c^2\,(-4+e^2)}\right) \\ \frac{2\,\beta\,\Delta\,(-2+\alpha\,e)-c\,\left(-2+e^2\right)-2\,e\,\left(\alpha\,\Delta+(2+g)\,p_c^N\right)+c^2\,\left(\beta\,\Delta\,(-2+\alpha\,e)-e\,\left(\alpha\,\Delta+(2+g)\,p_c^N\right)\right)}{-4+c^2\,(-4+e^2)} \end{cases}.$$

The equilibrium prices, which are obtained by solving the best response functions simultaneously, are given by Tables 1 and 2.

Table 1: Optimal decisions under competition and remanufacturing when $c > \bar{c}$

Prices	
p_1	$1/2$
p_2	$\frac{\Delta\,\left(e^2+2\,g+\alpha\,(1-\beta)\,\left(4-e^2-2\,g\right)+\beta\,\left(2\,e-e^2-2\,g\right)\right)}{(2+g)\,(4-e^2-2\,g)}$
p_r	$\frac{\Delta\,(e+\beta\,(2-e-g))}{4-e^2-2\,g}$
p_c	$\frac{\Delta\,\left(4-e^2-\alpha\,(1-\beta)\,\left(4-e^2-2\,g\right)-\beta\,\left(4-e^2-e\,g\right)\right)}{(2+g)\,(4-e^2-2\,g)}$
Quantities	
q_1	$1/2$
q_2	$\frac{\Delta\,\left(-e^2+\left(2-e^2\right)\,g+\alpha\,(1-\beta)\,\left(4-e^2-2\,g\right)+\beta\,\left(-2\,g+e\,\left(-2+e+e\,g+g^2\right)\right)\right)}{(2+g)\,(4-e^2-2\,g)}$
q_r	$\frac{\Delta\,(e+\beta\,(2-e-g))}{4-e^2-2\,g}$
q_c	$\frac{(1-\alpha)\,(1-\beta)\,\Delta\,\left(4-e^2\right)+\Delta\,(2\,\alpha\,(1-\beta)+\beta\,e)\,g}{(2+g)\,(4-e^2-2\,g)}$

The threshold collection rate $\bar{c}$ is obtained by calculating the ratio of q_r/q_1 when the Lagrangean $\lambda = 0$.

For an investigation of uniqueness, Facchinei and Pang (Fachinei and Pang 2000), consider the problem of the form

$$\begin{aligned} \max \quad & \pi^i(p_i, p_{-i}) \\ \text{s.t.} \quad & p_i \in X_i \end{aligned}$$

Table 2: Optimal decisions under competition and remanufacturing when $c \leq \bar{c}$

Prices	
p_1	$\frac{2-g+c^2\left(4-e^2-2g\right)-c\Delta(e+\beta(2-e-g))}{2(2-g)+c^2(4-e^2-2g)}$
p_2	$\frac{ce(2+\beta c\Delta(2-e)+c\Delta e)+2(1-\beta)\left(1+c^2\right)\Delta g+\alpha(1-\beta)\Delta\left(4-2g+c^2\left(4-e^2-2g\right)\right)}{(2+g)(2(2-g)+c^2(4-e^2-2g))}$
p_r	$\frac{c\left(-2+e^2+g\right)+2\Delta(e+\beta(2-e-g))+c^2\Delta(e+\beta(2-e-g))}{2(2-g)+c^2(4-e^2-2g)}$
p_c	$\frac{(1-\alpha)(1-\beta)\Delta\left(4+c^2\left(4-e^2\right)\right)+\left(2\alpha(1-\beta)\left(1+c^2\right)\Delta+c(1+\beta c\Delta)e\right)g}{(2+g)(2(2-g)+c^2(4-e^2-2g))}$
Quantities	
q_1	$\frac{2+c\Delta e-g+\beta c\Delta(2-e-g)}{2(2-g)+c^2(4-e^2-2g)}$
q_2	$\frac{\alpha(1-\beta)\Delta}{(2+g)}+\frac{ce(-2+\beta c\Delta(-2+e)-c\Delta e)+(1-\beta)\Delta\left(2+c^2\left(2-e^2\right)\right)g+c(1+\beta c\Delta)eg^2}{(2+g)(2(2-g)+c^2(4-e^2-2g))}$
q_r	$\frac{c(2+c\Delta e-g+\beta c\Delta(2-e-g))}{2(2-g)+c^2(4-e^2-2g)}$
q_c	$\frac{(1-\alpha)(1-\beta)\Delta\left(4+c^2\left(4-e^2\right)\right)+\left(2\alpha(1-\beta)\left(1+c^2\right)\Delta+c(1+\beta c\Delta)e\right)g}{(2+g)(2(2-g)+c^2(4-e^2-2g))}$

and show that, when X_i is a nonempty convex set, π_i is continuously differentiable and concave for every p_{-i}, there exists a unique Nash Equilibrium if $\bigtriangledown_p \pi(p)$ is monotone $\forall p \in X$.

By checking the Hessian of the objective functions, it is easy to see that the objectives for both the manufacturer and the competitor are strictly concave. The feasible set for the manufacturer is linear, therefore convex. Moreover, the derivatives of the objective functions are linear in prices, therefore strictly monotone. Therefore, Nash Equilibrium is unique. ■

Proof. (Corollary 2)

We can formulate the Lagrangean with λ as the dual variable of the collection (or reuse) constraint as follows:

$$L(p_1, p_2, p_r, \lambda) = p_1(1-p_1) + (\Delta(1-\beta) - p_2)p_2 + (\Delta\beta - p_r + ep_2)p_r - \lambda(\Delta\beta - p_r + ep_2 - c(1-p_1))$$

The resulting first order conditions can be written as:

$$\frac{\partial \Pi}{\partial p_1} = 1 - c\,\lambda - 2\,p_1 = 0$$
$$\frac{\partial \Pi}{\partial p_2} = (1-\beta)\,\Delta - e\,\lambda - 2\,p_2 + e\,p_r = 0$$
$$\frac{\partial \Pi}{\partial p_r} = \beta\,\Delta + \lambda + e\,p_2 - 2\,p_r = 0$$
$$\frac{\partial \Pi}{\partial \lambda} = \Delta\beta - p_r + ep_2 - c(1-p_1) = 0$$

By checking the Hessian for the objective function, the Hessian (H) is negative definite ($-8+2e^2 < 0$ since $e \leq 1$). Therefore, the objective function is strictly concave. Moreover, the constraint set is convex linear in prices. Therefore, the solution is unique since a concave function is maximized over a convex set.

$$H = \begin{bmatrix} -2 & 0 & 0 \\ 0 & -2 & e \\ 0 & e & -2 \end{bmatrix}.$$

The threshold collection rate $\bar{c}$ is obtained by calculating the ratio of q_r/q_1 when the Lagrangean $\lambda = 0$.

Simultaneous solution of first order condition results in the given prices. Solving for $\lambda = 0$ gives the prices for non-binding collection rate and solving for $\lambda > 0$ gives the prices for binding collection rate as in Table 3. With straightforward algebra it can be shown that all prices and quantities are nonnegative, except p_1 under binding collection constraint. Naturally, when the collection rate is too low and the diffusion rate

Table 3: Optimal decisions for monopolist under remanufacturing scenario

Price	$c > \bar{c} = \frac{2\Delta(\beta(2-e)+e)}{4-e^2}$	$c \leq \bar{c} = \frac{2\Delta(\beta(2-e)+e)}{4-e^2}$
p_1	$p_1 = \frac{1}{2}$	$1 - \frac{2+c\Delta(e+\beta(2-e))}{4+c^2(4-e^2)}$
p_2	$\frac{2\Delta(1-\beta)+\Delta\beta e}{4-e^2}$	$\frac{2(1-\beta)(1+c^2)\Delta+ce(1+\beta c\Delta)}{4+c^2(4-e^2)}$
p_r	$\frac{2\Delta\beta+\Delta e-\Delta\beta e}{4-e^2}$	$\frac{-2c+2\beta(2+c^2)\Delta+(1-\beta)(2+c^2)\Delta e+ce^2}{4+c^2(4-e^2)}$
Quantity	$c > \bar{c}$	$c \leq \bar{c}$
q_1	$1/2$	$\frac{2+c\Delta(e+\beta(2-e))}{4+c^2(4-e^2)}$
q_2	$\frac{\Delta(2-e^2-\beta(2+e-e^2))}{4-e^2}$	$\Delta(1-\beta) - \frac{2(1-\beta)(1+c^2)\Delta+ce(1+\beta c\Delta)}{4+c^2(4-e^2)}$
q_r	$\frac{\Delta(\beta(2-e)+e)}{4-e^2}$	$\frac{c(2+\beta c\Delta(2-e)+c\Delta e)}{4+c^2(4-e^2)}$

is too high, the manufacturer would prefer selling the new products with negative prices to increase the sales in the first period, in order to guarantee the remanufactured product availability in the second period.
■

Proof. (Proposition 3)

The first order condition for the manufacturer (M) can be written as:

$$\frac{\partial \Pi_M}{\partial p_2} = \alpha\,\Delta\,(1-\beta) - 2\,p_2 + g\,p_c = 0$$

The first order condition for the competitor (C) can be written as:

$$\frac{\partial \Pi_C}{\partial p_c} = (1-\alpha)\,\Delta\,(1-\beta) - 2\,p_c + g\,p_2 = 0$$

The Lagrangean for the local remanufacturer (L) can be written as:

$$L^L_{p_r,\lambda} = p_r\ (\beta\,\Delta + e\,p_2 - p_r + e\,p_c) - \lambda\ (\beta\,\Delta - c\ (1-p_1) + e\,p_2 - p_r + e\,p_c)$$

Resulting best response functions are given by:

$$BR_M(p_c^N) = \frac{\alpha\Delta(1-\beta) + g\,p_c^N}{2}$$

Competitor's best response is:

$$BR_C(p_2^N) = \frac{(1-\alpha)\ (1-\beta)\ \Delta + g\,p_2^N}{2}$$

- **Non-binding collection rate ($\lambda = 0$)**
  Local remanufacturer L's first order condition can be written as:

  $$\frac{\partial \Pi_L}{\partial p_r} = \beta\,\Delta - 2p_r + e\ (p_2 + p_c)$$

  Solving the first order conditions simultaneously, the non-binding equilibrium prices are obtained.
- **Binding collection rate ($\lambda \geq 0$)** Local remanufacturer L's first order condition can be written as:

  $$\frac{\partial \Pi_L}{\partial p_r} = \beta\,\Delta + \lambda + e\,p_2 - 2\,p_r + e\,p_c$$
  $$\frac{\partial \Pi_L}{\partial \lambda} = c - \beta\,\Delta - c\,p_1 - e\,p_2 + p_r - e\,p_c$$

  Solving the first order conditions simultaneously, the binding equilibrium prices are obtained.

The uniqueness of equilibrium is immediate by linearity of the best response functions and the argument in the proof of proposition 2. ■

Proof. (Proposition 4) $\Pi_M^r \geq \Pi_M^l$ since it is easy to see by inspection that manufacturers objective in the (**l**) scenario is a constrained version of the (**r**) scenario (e.g., in (**l**) manufacturer's optimization problem is the same as in (**r**) but q_r is restricted to be zero). ■

Proof. (Proposition 5)

We can formulate the Lagrangean with λ as the dual variable of the collection (or reuse) constraint as follows:

$$L(p_1, p_2, p_r, \lambda) = p_1(1-p_1) + (\Delta(1-\beta) - p_2 + fp_r)p_2 + (\Delta\beta - p_r + ep_2)p_r - \lambda(\Delta\beta - p_r + ep_2 - c(1-p_1))$$

The resulting first order conditions can be written as:

$$\frac{\partial \Pi}{\partial p_1} = 1 - c\,\lambda - 2\,p_1 = 0$$
$$\frac{\partial \Pi}{\partial p_2} = (1-\beta)\;\Delta - e\,\lambda - 2\,p_2 + (e+f)\,p_r = 0$$
$$\frac{\partial \Pi}{\partial p_r} = \beta\,\Delta + \lambda + (e+f)\,p_2 - 2\,p_r = 0$$
$$\frac{\partial \Pi}{\partial \lambda} = \Delta\beta - p_r + ep_2 - c(1-p_1) = 0$$

Simultaneous solution of first order condition results in the given prices. Solving for $\lambda = 0$ gives the prices for non-binding collection rate and solving for $\lambda > 0$ gives the prices for binding collection rate.

- **Binding collection rate:**
  -
  $$p_2 = \frac{c\;(-e+f) - \Delta\;\left(2\;\left(1+c^2\right) + \beta\;\left(2\;(-1+f) + c^2\;(-2+e+f)\right)\right)}{-4 + 4\,e\,f + c^2\;(-2+e+f)\;(2+e+f)}$$
  -
  $$p_r = \frac{-4\,\beta\,\Delta + 2\,\Delta\,e\;(-1+\beta+\beta\,f) + c^2\,\Delta\;(-e-f+\beta\;(-2+e+f)) - c\;(-2+e\;(e+f))}{-4 + 4\,e\,f + c^2\;(-2+e+f)\;(2+e+f)}$$

  By some straightforward algebra we obtain that

  $$p_2 - p_r \propto (1-2\,\beta)\;c^2\,\Delta\;(-2+e+f) + c\;(1+e)\;(-2+e+f) + 2\,\Delta\;(-1+e-\beta\;(-3+e+f+e\,f))$$

  Thus, $p_2 \geq p_r$ if:

  $$(1-2\,\beta)\;c^2\,\Delta\;(-2+e+f) + c\;(1+e)\;(-2+e+f) + 2\,\Delta\;(-1+e-\beta\;(-3+e+f+e\,f)) \geq 0$$

  $$\Rightarrow p_2 \geq p_r \Leftarrow \beta \leq \frac{c\;(1+e)\;(-2+e+f)}{2\,\Delta\;(-3+e+f+e\,f+c^2\;(-2+e+f))} + \frac{2\;(-1+e) + c^2\;(-2+e+f)}{2\;(-3+e+f+e\,f+c^2\;(-2+e+f))}$$

  It is easy to see that this bound is decreasing in Δ. Therefore, a tighter upper bound can be obtained by setting $\Delta \to \infty$

  $$\Rightarrow \beta \leq \beta' = \frac{2\;(-1+e) + c^2\;(-2+e+f)}{2\;(-3+e+f+e\,f+c^2\;(-2+e+f))}$$
  $$\frac{\partial \beta'}{\partial f} = \frac{-\left(\left(2+c^2\right)\;\left(-1+e^2\right)\right)}{2\,(-3+e+f+e\,f+c^2\;(-2+e+f))^2} \leq 0$$

  Thus β' is decreasing in f, and a tighter upper bound can be found at $f = 0$.

  $$\Rightarrow p_2 \geq p_r \Leftarrow \beta \leq \bar{\beta}_b = \frac{c^2\;(-2+e) + 2\;(-1+e)}{2\;(-3+c^2\;(-2+e)+e)}$$

  Note that this upper bound is valid for any value of Δ and f. Moreover,

  $$\frac{\partial \bar{\beta}}{\partial c} = -\left(\frac{c\;\left(c^2\;(-2+e) + 2\;(-1+e)\right)\;(-2+e)}{\left(-3+c^2\;(-2+e)+e\right)^2}\right) + \frac{c\;(-2+e)}{-3+c^2\;(-2+e)+e} \geq 0$$

$$\frac{\partial \bar{\beta}}{\partial e} = \frac{-\left(\left(1+c^2\right)\left(c^2\left(-2+e\right)+2\left(-1+e\right)\right)\right)}{2\left(-3+c^2\left(-2+e\right)+e\right)^2} + \frac{2+c^2}{2\left(-3+c^2\left(-2+e\right)+e\right)} \leq 0$$

Therefore, $\bar{\beta}_b$ is increasing in c and decreasing in e. Moreover $\bar{\beta}_n$ takes values between 0 and 0.4.

- **Non-binding collection rate:**
  - $$p_2 = -\left(\frac{2\,\Delta - 2\,\beta\,\Delta + \beta\,\Delta\,e + \beta\,\Delta\,f}{-4 + e^2 + 2\,e\,f + f^2}\right)$$
  - $$p_r = -\left(\frac{-2\,\beta\,\Delta - (1-\beta)\,\Delta\,(e+f)}{4 - (e+f)^2}\right)$$

  By some straightforward algebra we obtain that

  $$p_2 - p_r \propto (1 - 2\,\beta)\,\Delta\,(2 - e - f)$$

  Therefore, it is easy to see that

  $$p_2 \geq p_r \Leftarrow \beta \leq \bar{\beta}_n = 0.5$$

$\bar{\beta}$ will therefore be given as $\bar{\beta}_n$ when the collection rate is sufficiently high and as $\bar{\beta}_b$ when the collection rate is low.

■

8 Appendix B: Comparative Statics for Monopoly

8.1 Non-binding Collection Constraint

- It is easy to see that if the collection rate is higher than the threshold value c_{th}, q_1 is constant in any of the parameters Δ, β, e or c.

  Let's look at the partial derivatives of q_2 and q_r with respect to Δ, β and e.

- ($*^1$)

  $$\frac{\partial q_2}{\partial \Delta} = \frac{-\left(\beta\,e\right) + (1-\beta)\left(2-e^2\right)}{4-e^2}$$

  The condition for this to be non-negative is that

  $$(1-\beta)(2-e^2) \geq \beta e \Rightarrow \beta < \frac{2-e^2}{2-e^2+e}$$

  Since $0 < e < 1$, this term takes value between 0 and 1.Therefore, q_2 is increasing in Δ only if $\beta < \frac{2-e^2}{2-e^2+e}$, otherwise q_2 is decreasing in Δ. Figure 10 graphically shows the regions in which q_2 is increasing or decreasing in Δ depending on e and β.

- $$\frac{\partial q_2}{\partial \beta} = -\left(\frac{\Delta\,(1+e)}{2+e}\right) \leq 0$$

  Therefore, it is easy to see that q_2 is decreasing linearly in β.

- $$\frac{\partial q_2}{\partial e} = -\left(\frac{\Delta\left(\beta\left(-2+e\right)^2 + 4\,e\right)}{\left(-4+e^2\right)^2}\right) \geq 0$$

  Therefore, q_2 is decreasing in e as expected. By inspection of the second derivative;

  $$\frac{\partial^2 q_2}{\partial e^2} = \frac{2\Delta\left(8(1-\beta) + 12\beta e + 6(1-\beta)e^2 + \beta e^3\right)}{(-4+e^2)^3} \leq 0$$

  The second derivative is always negative, therefore we conclude that q_2 is decreasing concavely in e.

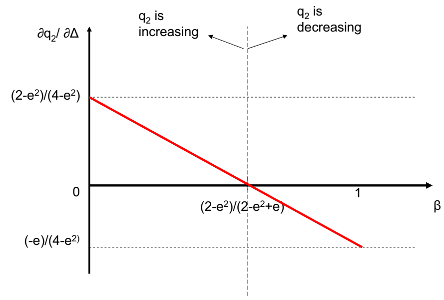

Figure 10: $\partial q_2/\partial\Delta$

- $$\frac{\partial q_r}{\partial \Delta} = \frac{\beta\ (2-e)+e}{4-e^2}$$

  Therefore, q_r is increasing linearly in Δ.

- $$\frac{\partial q_r}{\partial \beta} = \frac{\Delta}{2+e}$$

  Therefore, q_r is linearly increasing in β.

- $$\frac{\partial q_r}{\partial e} = \frac{\Delta\left(4-\beta\left(-2+e\right)^2+e^2\right)}{\left(-4+e^2\right)^2}$$

  This partial derivative is nonnegative only if $\frac{4+e^2}{(e-2)^2} \geq \beta$. Since β and e take values less than 1, this condition is always satisfied(the term on the left hand side is always greater than 1). So, q_r is increasing in e as expected. By inspecting the second derivative:

  $$\frac{\partial^2 q_r}{\partial e^2} = \frac{2\Delta\left(-8\beta-12(1-\beta)-6\beta e^2-(1-\beta)e^3\right)}{(-4+c^2)^3} \geq 0$$

  The second derivative is always positive, so q_r is increasing convexly in e.

8.2 Binding Collection Constraint

If the collection rate is lower than the threshold value c_{th}, optimal prices and quantities are different. Let's look at the partial derivatives of q_2 and q_r with respect to Δ, β, c and e.

- $$\frac{\partial q_1}{\partial \Delta} = \frac{c\ (-\left(\beta\ (2-e)\right)-e)}{4+c^2\ (4-e^2)}$$

  Therefore q_1 is linearly increasing in Δ.

- $$\frac{\partial q_1}{\partial \beta} = \frac{c\,\Delta\ (2-e)}{4+c^2\ (4-e^2)}$$

  So, q_1 is linearly increasing in β.

- $$\frac{\partial q_1}{\partial e} = \frac{c\left(4\,c\,e + \Delta\,\left(4 - \beta\,\left(4 + c^2\,(-2+e)^2\right) + c^2\,\left(4+e^2\right)\right)\right)}{\left(-4 + c^2\,\left(-4+e^2\right)\right)^2} \geq 0$$

  So, q_1 is increasing in e. Inspecting the second derivative:

  $$\frac{\partial^2 q_1}{\partial e^2} = \frac{2c^2\left(-8 - 8c^2 - *\beta c^3\Delta - 12e(\Delta c(1-\beta) + c^3\Delta(1-\beta)) - 6e^2(c^2 + \beta\Delta c^3) - e^3(c^3\Delta(1-\beta))\right)}{(-4 + c^2(+e^2))^3} \geq 0$$

  Therefore, q_1 is increasing convexly in e.

- $(*^3)$

  $$\frac{\partial q_1}{\partial c} = \frac{4\,\Delta\,(-(\beta\,(-2+e)) + e) + 4\,c\,\left(-4+e^2\right) - c^2\,\Delta\,(\beta\,(-2+e) - e)\,\left(-4+e^2\right)}{\left(-4 + c^2\,\left(-4+e^2\right)\right)^2}$$

  The denominator is always positive, if the numerator is positive then q_1 is increasing in c, otherwise q_1 is decreasing in c. By inspecting the numerator we see that q_1 is increasing in c when $c \leq c_2$ and decreasing when $c \geq c_2$, where c_2 can be calculated as:

  $$c_2 = \frac{2}{\Delta(\beta(2-e)+e)}\left(\sqrt{1 + \frac{\Delta^2(\beta(2-e)+e)^2}{4-e^2}} - 1\right)$$

- $(*^2)$

  $$\frac{\partial q_2}{\partial \Delta} = (1-\beta) + \frac{-2\,(1-\beta)\,\left(1+c^2\right) - \beta\,c^2\,e}{4 + c^2\,\left(4-e^2\right)}$$

  The condition for this to be non-negative is that

  $$\beta < \frac{2 + c^2\,\left(2-e^2\right)}{2 + c^2\,e + c^2\,\left(2-e^2\right)}$$

  Since $e < 1$ and $c < 1$, this term takes value between 0 and 1.Therefore, q_2 is increasing in Δ only if $\beta < \frac{2+c^2\,\left(2-e^2\right)}{2+c^2\,e+c^2\,\left(2-e^2\right)}$, otherwise q_2 is decreasing in Δ. Note that this is very similar to the situation in the non-binding collection constraint case.

- $$\frac{\partial q_2}{\partial \beta} = -\left(\frac{\Delta\,\left(2 + c^2\,\left(2+e-e^2\right)\right)}{4 + c^2\,\left(4-e^2\right)}\right)$$

  Therefore, q_2 is linearly decreasing in β.

- $$\frac{\partial q_2}{\partial e} = -\left(\frac{c\,\left(4 + c^3\,\Delta\,\left(\beta\,(-2+e)^2 + 4\,e\right) + 4\,c\,\Delta\,(\beta + e - \beta\,e) + c^2\,\left(4+e^2\right)\right)}{\left(-4 + c^2\,\left(-4+e^2\right)\right)^2}\right)$$

  The denominator is always positive. Thus, if the numerator is positive q_2 is increasing in e otherwise it is decreasing. By inspecting the numerator, it is easily seen that the numerator is always negative. Therefore, q_2 is decreasing in e. The inspection of the second derivative does not help much, while it can be positive or negative for different parameter values, nevertheless we know that q_2 is not necessarily concavely decreasing in e.

- $$\frac{\partial q_2}{\partial c} = -\left(\frac{e\,\left(4 + 4\,c\,\Delta\,(\beta\,(2-e) + e) + c^2\,\left(-4+e^2\right)\right)}{\left(-4 + c^2\,\left(-4+e^2\right)\right)^2}\right)$$

  By inspection, the denominator is always positive and the numerator is always negative. So, q_2 is decreasing in c. The second derivative does not show any special structure, so we are not able to say something about convexity or concavity in c.

- $$\frac{\partial q_r}{\partial \Delta} = \frac{c\,(\beta\, c\,(2-e) + c\, e)}{4 + c^2\,(4-e^2)}$$

  Therefore, q_r is increasing linearly in Δ.

- $$\frac{\partial q_r}{\partial \beta} = \frac{c^2\,\Delta\,(2-e)}{4 + c^2\,(4-e^2)}$$

  Therefore, q_r is increasing linearly in β.

- $$\frac{\partial q_r}{\partial e} = \frac{c^2\left(4\,c\,e + \Delta\left(4 - \beta\left(4 + c^2\,(-2+e)^2\right) + c^2\,\left(4+e^2\right)\right)\right)}{\left(-4 + c^2\,\left(-4+e^2\right)\right)^2}$$

  q_r is increasing in e. By inspecting the second derivative:

  $$\frac{\partial^2 q_r}{\partial e^2} = \frac{2\,c^3\,\left(-8 - 8\,c^2 - 8\,\beta\,c\,\Delta - 8\,\beta\,c^3\,\Delta\right) - 8\,c^3\,\left((1-\beta)\,c\,\Delta + (1-\beta)\,c^3\,\Delta\right)\,e - 12\,c^3\,\left(c^2 + \beta\,c^3\,\Delta\right)\,e^2 - 2\,(1-\beta)\,c^6\,\Delta\,e^3}{\left(-4 + c^2\,\left(-4+e^2\right)\right)^3} \geq 0$$

  Therefore, q_r is increasing convexly in e.

- $$\frac{\partial q_r}{\partial c} = \frac{2\,\left(4 + 4\,c\,\Delta\,(\beta\,(2-e) + e) + c^2\,\left(-4+e^2\right)\right)}{\left(-4 + c^2\,\left(-4+e^2\right)\right)^2}$$

  Note that the part of the numerator in the parentheses, e.g,

  $$4 + 4\,c\,\Delta\,(\beta\,(2-e) + e) + c^2\,\left(-4+e^2\right)$$

  is very similar to the one for $\frac{\partial q_2}{\partial c}$. Therefore, q_r is increasing in c.

8.3 Implications

Table 4: Summary of comparative statics for monopolist under remanufacturing

		Δ	β	e	c
	Collection Threshold	+	+	+	constant
Unconstrained	q_1	constant	constant	constant	constant
	q_2	$(*^1)$	-	-	constant
	q_r	+	+	+	constant
Constrained	q_1	+	+	+	(+) if $c \leq c_2$ o/w (-) $(*^3)$
	q_2	$(*^2)$	-	-	-
	q_r	+	+	+	+

The comparative statics show that q_1 and q_r are increasing in Δ, β and e. The reasoning is simple: as Δ, β, c and e increase, the optimal q_r increases. Therefore, in order to feed the demand for remanufactured products, one has to sell more new products in the first period. Also, note that q_2 decreases in β, e and c, since optimal q_r increases with those and an increase in q_r means a decrease in q_2.

In addition to these, comparative statics bring three interesting observations marked with $(*^1)$, $(*^2)$ and $(*^3)$.

- $(*^1)$ generates a condition on the behavior of q_2 depending on the diffusion rate. Although the market potential for the new products is increasing with Δ, the level of increase in q_2 depends on the interaction between β and e. Condition $(*^1)$ shows that q_2 is increasing with diffusion if :

$$(1-\beta)(2-e^2) \geq \beta e \Rightarrow \beta < \frac{2-e^2}{2-e^2+e} = e_{th}$$

Therefore, q_2 takes nonnegative values and increases in Δ only if $\beta < e_{th}$. It is easy to see that e_{th} takes values in the interval [0.5,1]. Thus, q_2 is always nonnegative since by assumption, $\beta \leq 0.5$.

To understand the basic intuition behind this result, consider the case that $\beta = 0.5$ and $c = 1$, which corresponds to equal primary and green segment sizes and equal valuations for new and remanufactured products. Under these circumstances the optimal new product sales is zero ($q_2 = 0$) and only remanufactured products are sold. The basic reason for this result is the behavioral assumption that green segment consumers buy the remanufactured product when it is offered. This makes the remanufactured product stronger than the new product when consumer valuations are equal. Note that for $\beta = 0.5$ and $c = 1$, $q_r = p_r = \Delta/2$, which is same as the monopolist's no remanufacturing decision. This basically means that the manufacturer uses the remanufactured products only since they cover the whole market. Considering real life examples such as Kodak's single use cameras, we would say that consumer valuations can be equal when the remanufactured product is a perfect substitute of the new product, in which case the products would be the same and and the whole market is covered with a single product, as our $(*^1)$ condition shows.

- $(*^2)$ generalizes the condition $(*^1)$ for lower collection/remanufacturability rates. Under binding collection rate (i.e., $c \leq c_{th}$), e_{th} depends on the collection rate c and is given as:

$$e_{th} = \frac{2 + c^2\left(2-e^2\right)}{2 + c^2\, e + c^2\,\left(2-e^2\right)}$$

Note that, under this condition, e_{th} is bounded in the interval $[0.75, 1]$. Thus, since β is lower than 0.5, under binding collection rates the monopolist always sells a mixture of new and remanufactured products.

- Condition $(*^3)$ states that the optimal sales quantity in period 1 (q_1) depends highly on the interaction between Δ, β, e and c. It shows that for given Δ, β and e, q_1 increases in the collection rate up to a certain level, which we denote by c_2 and then it starts decreasing, where c_2 is given as:

$$c_2 = \frac{2}{\Delta(\beta(2-e)+e)}\left(\sqrt{1+\frac{\Delta^2(\beta(2-e)+e)^2}{4-e^2}}-1\right)$$

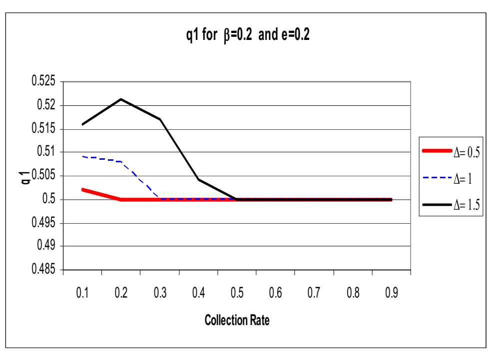

Figure 11: Effect of Collection rate on q_1 for different diffusion levels under Monopoly

This basically shows that the monopolist should tend to increase both the new product sales and the collection/remanufacturing rate when the collection rate is below c_2. But, when the collection rate is above c_2, for increasing collection rates the optimal new product sales in the first period decreases. Moreover, Figure 11 shows that c_2 increases for higher diffusion rates.

It is important to note that the level of reusable return collection has significant effects on the new product positioning decision of the manufacturer, when remanufacturing is a profitable option. Depending on the reusability level, (especially when the reusability rate is low), the pricing and sales decisions of the manufacturer change. Examples from the industry show that reuse rates can vary depending on the industry and product specifications. (Toktay 2003), and Souza et.al (Souza et.al. 2003) report that return rates can vary between 5 to 35 per cent and the reusability rates within those can change between 40 to 93 per cent. Thus, manufacturers performing remanufacturing operations should consider the return availability while introducing new products.

8.4 Collection Threshold

The collection threshold has been calculated as:

$$\bar{c} = q_r/q_1 = \frac{2\Delta(\beta(2-e)+e)}{4-e^2}$$

It is easy to see that the collection threshold is increasing linearly in Δ and β. In order to see the substitution effect on the collection:

$$\frac{\partial c_{th}}{\partial e} = \frac{2\,\Delta\,\left(4+\beta\,(2-e)^2+e^2\right)}{\left(4-e^2\right)^2}$$

Therefore, collection threshold is increasing in e, as well.