

# The Effect of Competition on Recovery Strategies

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## Abstract

Manufacturers often face a choice of whether to recover the value in their end-of-life products through remanufacturing. In many cases, firms choose not to remanufacture, as they are (rightly) concerned that the remanufactured product will cannibalize sales of the higher-margin new product. However, such a strategy may backfire for manufacturers operating in industries where their end-of-life products (cell phones, tires, computers, automotive parts, etc) are attractive to third-party remanufacturers, who may seriously cannibalize sales of the original manufacturer. In this paper, we develop models to support a manufacturer's recovery strategy in the face of a competitive threat on the remanufactured product market. We first analyze the competition between new and remanufactured products produced by a monopolist manufacturer and identify conditions under which the firm would choose not to remanufacture its products. We then characterize the potential profit loss due to external remanufacturing competition and analyze two entry-deterrent strategies: remanufacturing and preemptive collection. We find that a firm may choose to remanufacture or preemptively collect its used products to deter entry, even when the firm would not have chosen to do so under a pure monopoly environment. Finally, we discuss conditions under which each strategy is more beneficial.

Keywords: Remanufacturing, Competition, Pricing, Entry-deterrent Strategies

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# 1 Introduction

Industrialization and population growth have increasingly burdened the environment. To give one of many examples, in 2001, US residents, businesses and institutions produced more than 229 million tons of Municipal Solid Waste, as a result of an almost straight-line increase from the 1960 level of 88.1 million tons; 56% of this waste ends up in landfills (U.S. EPA 2003a). This volume pales in comparison to the waste generated by industry: According to the Environmental Protection Agency, “American industrialized facilities generate and dispose of approximately 7.6 billion tons of industrial solid waste each year” (U.S. EPA 2003b). In 1999, fourteen states had no landfill capacity left, whereas eight states had less than ten years of landfill capacity left (U.S. EPA 2002).

While recycling is the most prevalent activity in diverting waste from landfills (for example, two thirds of municipal solid waste that is not landfilled is recycled), the EPA advocates “source reduction” as the preferred way of reducing the burden on the environment (U.S. EPA 2003a). Source reduction refers not only to using fewer and less toxic materials in manufacturing a product, but also to encouraging reuse, “removing a product or component from a retired system and installing it in another system,” and remanufacturing, “disassembling, inspecting, repairing, replacing, and reassembling the components of a part or product to like-new condition” (Thorn and Rogerson 2002). Remanufacturing reduces both raw material and energy consumption. On average, for each pound of new material used in remanufacturing, five to nine pounds are conserved (U.S. EPA 1997). Remanufacturing auto parts, for example, conserves an estimated 60% of the energy used in making the original product (U.S. EPA 1997).

It is encouraging that there is a market for remanufactured products in the US. For example, by 1997, approximately 73,000 U.S. firms had sold an estimated \$53 billion worth of remanufactured products (U.S. EPA 1997). Examples of remanufactured products include automotive parts, cranes and forklifts, furniture, medical equipment, pallets, personal computers, photocopiers, telephones, televisions, tires and toner cartridges, among others. These products are put on the market by the Original Equipment Manufacturer (OEM) and/or independent remanufacturers.

The Xerox Corporation demonstrated early on that remanufacturing can be a very lucrative prospect (Berko-Boateng et al. 1993). In 1991, they obtained savings of around \$200 million by remanufacturing copiers returned at the expiration of their lease contracts. Kodak is one of the classic examples of an OEM that has created a fully integrated manufacturing-remanufacturing strategy around its reusable Funsaver camera line (Toktay et al. 2000). Caterpillar is shifting its strategy from solely manufacturing and selling construction equipment to a leasing and remanufacturing strategy (Gutowski et al. 2001). This allows Caterpillar to create a new market among contractors who cannot afford to buy a Caterpillar product outright, but instead, lease one when

needed.

Unfortunately from an environmental standpoint, the companies mentioned above represent the exception to the rule; most firms do not adopt the remanufacturing option. In many cases, the choice not to remanufacture is driven by two concerns: cost and internal cannibalization. On the cost side, the combination of fixed and variable costs may be too high to justify remanufacturing. However, even if the remanufactured product is independently profitable, firms may ignore this option due to concerns about cannibalization: If the remanufactured product is sold in the same market as the new product, it attracts the same customer population. If, in addition, it is priced lower than the new product, previously captive customers may choose to buy the remanufactured product instead. Such internal cannibalization is often assumed by firms to be undesirable if the margin on the new product is higher than the margin on the remanufactured product. The degree and effect of demand cannibalization depends on the relative positioning of the new and the remanufactured products, and their relative margins. For this reason, it is important to jointly determine the prices (called “market segmentation”) of the new and remanufactured products to optimize profit.

The question of how to position (or even to offer or not) a remanufactured product is not well understood by the majority of firms today. In the absence of analytical tools to help them, firms often develop rules of thumb such as to never price a remanufactured product more than  $x\%$  of the price of a new product. Bosch Tools division for example, decides what product lines to remanufacture based upon the product’s price and market share. If the market share is below a certain threshold and the new product price is above a given threshold, then the product is remanufactured, otherwise it is not (Valenta 2004).

If the remanufactured product is independently profitable, but the firm chooses not to invest in remanufacturing, independent remanufacturers may enter the market, resulting in external competition rather than internal cannibalization. The threat of external competition through the remanufactured product is a major concern for many firms. To respond to this threat, several strategies are available to the original manufacturer. Two such OEM strategies are (i) entering the remanufacturing market, or (ii) preemptively collecting its used products. For example, independent PC rebuilders abound, taking market share from OEMs, especially on low-budget customers who do not need the latest technology. In response, companies such as Dell and IBM have started taking back used computers for remanufacture and sale through their own distribution channels (Ginsburg 2001). To limit competition from remanufacturers, Lexmark introduced the Prebate program whereby customers who return an empty printer cartridge obtain a discount on a new cartridge; Lexmark does not remanufacture these cartridges, recycling them instead ([www.atlex.com](http://www.atlex.com) 2003). Bosch collects a broader range of products than those it remanufactures (Valenta 2004).

The choice of recovery strategy in the face of competition remains a challenge in practice. In this paper, we develop models to support decision making concerning recovery strategies under external remanufacturing competition. We start by analyzing a monopolist’s pricing decisions for both its new and remanufactured products. We model the (internal) competition between a new and remanufactured product explicitly, as a function of prices and the difference in consumer willingness-to-pay between the products. The variable cost to collect and remanufacture is modelled as an increasing function of the quantity remanufactured, thus capturing a unique aspect of the remanufacturing industry that has not been explored in previous market segmentation research. Our findings provide OEMs with conditions where the cost savings from remanufacturing exceed the detrimental effect of cannibalization. We then explore the implications of an OEM choosing not to remanufacture by modelling the impact of external competition on the OEM’s profit if a new firm enters the market and remanufactures the OEM’s product. We find that an OEM may choose to remanufacture to deter this entry, even when it would not have chosen to do so under a pure monopoly environment. There are also cases where it is more profitable for the firm to collect the used products (cores) but not remanufacture them. In this case, collection is used as a deterrent to avoid competition from external remanufacturers. Finally, we discuss where one deterrent strategy is more profitable than the other. In particular, we provide insights to the following questions:

1. To what extent will the remanufactured product cannibalize sales of new products? Should a firm remanufacture its own product? If yes, how should it price each product?
2. How should the OEM define its recovery strategy if there is a possibility of third-party remanufacturing entrants?
3. What are the conditions that favor remanufacturing versus collection as entry-deterrent recovery strategies?
4. What is the impact of the fixed and variable costs incurred on recovery strategies?

The rest of the paper is organized as follows: In the next section, we position our research in the context of the relevant literature. Our key assumptions and notation are outlined in §3. In §4, we analyze a monopolist manufacturer’s decision concerning whether or not to remanufacture its own product. In §5, we analyze the impact of remanufacturing competition and the effectiveness of entry-deterrent recovery strategies. In particular, §5.1 determines the effect on the firm’s profit if an external entrant remanufactures the firm’s product and sells it in the same market. §5.2 and §5.3 explore remanufacturing and collection as potential entry-deterrent recovery strategies. We conclude our analysis by comparing these two strategies in §5.4 and discuss when each is appropriate. In §6, we summarize our results and conclude with managerial implications. All proofs are provided in Appendix A.

## 2 Literature Review

Our research draws on two separate streams of literature: market segmentation and remanufacturing. In this section, we provide a review of the prominent research in each stream and position our research at the point of their intersection. We begin with an overview of the relevant market segmentation literature.

The literature on market segmentation by a monopoly (Mussa and Rosen 1978, Moorthy 1984) studies the optimal pricing and placement of independent products that are differentiated by quality in a market of heterogeneous consumers. The monopolist faces an increasing cost of quality. Consumers prefer a higher quality to a lower quality but differ in how much they are willing to pay for the quality. The monopolist chooses the quality level and price for each product. Katz (1984), Moorthy (1988), and Desai (2001) extend this research stream to allow for external competition. The major differences between the new product market segmentation research and the remanufacturing problem that we address are: (i) the constraint that the number of remanufactured products must be less than or equal to the number of new products previously produced, (ii) an exogenous relative consumer willingness-to-pay for a remanufactured versus a new product, and (iii) an average variable collection and/or processing cost that increases in the quantity of units collected/processed.

The majority of the existing literature on remanufacturing has focused on operational issues that arise as a result of the return flows of used products. These issues include disassembly (Guide and Srivastava 1998), MRP for product recovery (Kokkinaki et al. 2004), production planning (Indenfurth et al. 2004), scheduling and shop floor control (Guide et al. 1997), inventory management (Toktay et al. 2000, Minner and Lindner 2004, van der Laan et al. 2004), handling and warehousing (de Brito and de Koster 2004), forecasting (Toktay et al. 2004), reverse logistics network design (Fleischmann 2000), and collection and vehicle routing (Beullens et al. 2004). In this stream of literature, price and demand are assumed to be exogenous, and consumers do not differentiate between new and remanufactured products. The focus is on determining the cost-minimizing operating policy or system design for a given remanufactured product and its price.

Recently, a number of authors have started exploring market-related issues such as market segmentation, competition, and collection incentives. Debo et al. (2005) focus on a monopolist who considers selling both new and remanufactured products to a customer base that has a lower willingness-to-pay for the remanufactured product. They determine the monopolist's optimal market segmentation and remanufacturability level decisions in an infinite-horizon setting. In a related paper, Ferguson and Koenigsberg (2005) analyze the stocking and pricing decisions of a monopolist who sells perishable goods. Unsold product from the first period can be sold in the second period

along with fresh product, and is valued less by consumers. Conditions are derived for when the manufacturer should carry over all, some, or none of its leftover product. The market segmentation model used in these papers is the same as ours, and the constraint on sales of remanufactured or old products by past production levels is explicitly modelled. In contrast, our focus is on analyzing and comparing entry-deterrent strategies in the face of potential competition.

Several papers investigate the impact of competition in a remanufacturing setting from various angles. Groenevelt and Majumder (2001a), and Ferrer and Swaminathan (2005) assume that new and remanufactured products offered by the OEM are indistinguishable, but that the entrant's remanufactured product is valued less by consumers. Thus, the external competition model in these papers is one with essentially two products as in ours (apart from the internal OEM decision of how much of its own demand to satisfy through remanufacturing). In these papers, both firms make pricing decisions subject to the availability of used products in a two-period model; the proportion of used products available to each company is exogenously given. In Ferrer and Swaminathan (2005), the OEM collects a fraction of used products for free, and the rest are available to the competitor. The main focus of this paper is characterizing the Nash equilibrium and investigating the impact of various parameters. In Groenevelt and Majumder (2001a), the collection and processing cost is linear in the total quantity collected and processed. Again, a given fraction of used products is at the disposal of the OEM, and the rest is available to the competitor. The authors consider four different scenarios depending on whether one party has access to the unused allocation of the other party. The focus is on characterizing the equilibrium solution and investigating the impact of various parameters on this solution. Debo et al. (2005), in an extension, assume that a perfectly competitive remanufactured product market exists, and investigate pricing and remanufacturability level implications for an OEM who only produces the new product. They find that the remanufacturability level provided by the OEM decreases relative to the base case where the OEM controls the remanufactured product market. Savaşkan and Van Wassenhove (2005) discuss the impact of remanufacturing on competing retail stores.

Several other papers separately address collection issues. Savaşkan et al. (2004) determine the optimal collection channel configuration of a monopolist manufacturer. Galbreth and Blackburn (2005) model the number of cores to collect as a parameter in the overall remanufacturing cost minimization problem. Groenevelt and Majumder (2001b) consider a manufacturer and an independent remanufacturer who are price takers in the product market (perfect competition), but who compete on procurement of used products. Motivated by an example from the cellular phone industry, Guide et al. (2003) determine the optimal quality-dependent take-back price schedule for a remanufacturer. Finally, Ray et al. (2005) study the use of trade-in rebates to encourage the customer's replacement of a product and to provide the firm with additional revenues through

remanufacturing/reuse operations. These papers reinforce the notion that the average variable cost of collection/remanufacturing increases with the number of units collected/remanufactured. In our analysis, we assume that the average variable remanufacturing cost increases in the volume remanufactured. We further assume that the original manufacturer has a first mover advantage in terms of access to collecting the used products.

Our results complement the two streams of literature on competition and collection in a remanufacturing setting by investigating the effectiveness of remanufacturing and collection as entry-deterrent strategies, and discuss under what conditions each strategy is preferable. From a modelling perspective, one of our contributions is that we incorporate a variable collection and/or processing cost that increases in volume, thus linking our competition models with the procurement models of Groenevelt and Majumder (2001b), Guide et al. (2003), Ray et al. (2005), and Galbreth and Blackburn (2005). We also incorporate fixed costs for collection and remanufacturing, which play an important role in the analysis of entry deterrence.

### 3 Key Assumptions and Notation

Before presenting our model, we state and discuss key assumptions specific to our remanufacturing environment. We refer to the firm that originally manufactures the product as the OEM and the firm that remanufactures a product that was originally produced by the OEM as the entrant.

**Assumption 1.** *Key problem dynamics are captured in a two-period model.*

We develop a two-period model with a single-firm, single-product setting in the first period and potential competition in the second period. The competition in the second period (internal or external) is due to product that was sold new in the first period, and is now sold as a remanufactured product. Our objective is two-fold. First, we study how the presence of competition from remanufactured units affects the OEM's new product pricing decisions and its recovery strategy, captured through our second-period analysis. Second, we study how the possibility of remanufacturing in the future affects the OEM's pricing decisions in the present, captured in our first-period analysis. Thus, a two-period model is sufficient and allows us to maintain tractability. Other papers that use a two-period model in a remanufacturing setting include Groenevelt and Majumder (2001a), Ferrer and Swaminathan (2005), and Ray et al. (2005).

**Assumption 2.** *The product has a useful lifetime of only one period.*

We assume that the product has a useful lifetime of only one period although it may be remanufactured after the first period and provide positive utility for some customers in the second period. This assumption is appropriate as long as periods are chosen of sufficient length for the product being analyzed. Because without remanufacturing it, a product bought in the first period

cannot be used in the second period, used products are returned at the end of the first period. Thus, customer purchase decisions are independent across periods.

**Assumption 3.** *Each consumer’s willingness-to-pay for a remanufactured product is a fraction  $\delta$  of their willingness-to pay for the new product.*

This assumption gives rise to a vertical differentiation model where consumers’ valuation for a product characteristic (typically referred to as ‘product quality’) has an agreed order, i.e. all consumers prefer a higher quality product to a lower quality product (Tirole 1988). Note that if  $\delta = 0$ , consumers are not willing to pay anything for the remanufactured product; this eliminates the option of remanufacturing and selling used products. If  $\delta = 1$ , consumers view the new and remanufactured units as being identical and are willing to pay the same amount for either product. Most products fall between the two extremes; we assume  $0 < \delta < 1$ .

The reason for the lower relative willingness-to-pay is either due to customer concerns about quality or because of a ‘fair price’ perspective - if it costs less for the manufacturer to remanufacture the product than to make it, the customer wants that reflected in the price. The first perspective is reflected in the title of the Computer World article (Kandra 2002) – “Refurbished PCs: Sweet Deals or Lemons?” In the tire industry, retreads are perceived to have lower quality than new tires (Préjean 1989). These types of fears are typically unfounded; most remanufactured products perform on par with new products. In fact, some products sold as ‘remanufactured’ are just commercial returns without any performance problems that are put on the market again after some testing (Guide and Van Wassenhove 2002). However, there are also cases where there may be quality problems, especially when independent remanufacturers are in question (Johnson 2001). In our model, we assume the products to be of equal quality; the lower willingness-to-pay is due only to consumer perception.

The implication of the customer’s lower willingness-to-pay is that even a product of the same specification and warranty as the new product may need to be priced lower to attract customers. Indeed, processed PCs are typically priced at 10-30% below the price of a comparable new system (Kandra 2002). Lund and Skeels (1983) also note that the price at which remanufactured automotive components can competitively sell for is 57% of the new item price. We assume that the relative willingness-to-pay is given. There may be cases where the OEM can influence the ‘perceived’ quality of the remanufactured product through a judicious choice of packaging, warranties, marketing, etc. Our assumption can be interpreted as the firm having chosen to operate under an existing bias, possibly achieved as a result of prior advertising.

**Assumption 4.** *Consumer willingness-to-pay is heterogeneous and uniformly distributed in the interval  $[0, 1]$ .*

We assume that consumers’ willingness-to-pay (valuations) are distributed uniformly in the



interval  $[0, 1]$  and that in any period, each consumer uses at most one unit. The market size is normalized to 1. In this vertical differentiation model, a consumer of type  $\phi \in [0, 1]$  has a valuation of  $\phi$  for a new product and  $\delta\phi$  for a remanufactured product. The utility that each consumer derives from purchasing a product is given by the difference of their valuation and the price.

Let  $q_1$  denote the first-period demand for new products, and  $q_{2n}$  and  $q_{2r}$  denote the second-period demand for new and remanufactured products, respectively. We derive the demand functions from consumers' utility functions (Appendix B). This construction leads to the following linear inverse demand functions:

$$p_1 = 1 - q_1 \quad (1)$$

for the first period (since there are no remanufactured units available to sell in the first period, there is only one inverse demand function) and

$$p_{2n} = 1 - q_{2n} - \delta q_{2r} \quad (2)$$

$$p_{2r} = \delta(1 - q_{2n} - q_{2r}) \quad (3)$$

for the second period. The latter functions capture the competition between the remanufactured product and the new product. Note that the relative willingness-to-pay has a different effect on the prices of the new and the remanufactured units (for given quantity levels). As this parameter increases, the price of the remanufactured product increases to take advantage of the increased willingness-to-pay. However, as this parameter increases, the price of the new product decreases as the two products become closer substitutes and there is more competition (the cannibalization effect).

**Assumption 5.** *The variable cost of collection and/or processing increases in the quantity of the products collected/processed.*

Since this assumption is a departure from previous literature, it deserves an extended explanation. For most firms, remanufacturing an item typically involves two steps. First, the used cores must be collected, inspected and sorted from the best to worst condition upon arrival; and second, a subset of the number of cores collected are processed (testing, cleaning, and replacing of parts) in the order of their decreasing arrival conditions. Thus, a decision to remanufacture  $x$  units involves an optimization problem where the firm chooses the number of units  $y : y \geq x$  to collect, with only a proportion,  $0 \leq x/y \leq 1$ , of these units being processed. Suppose the total variable cost of collecting  $y$  units is  $h_c(y)$  and the total variable cost of processing  $x$  of those  $y$  units is  $h_p(x, y)$ . Combining these two variable costs results in an optimization problem where the optimal  $y$  is chosen such that the combined total variable cost to remanufacture  $x$  units is minimized:

$$\Gamma(x) = \min_{x \leq y \leq \gamma q_1} [h_c(y) + h_p(x, y)]. \quad (4)$$

The first constraint on  $y$  ensures that a sufficient number of cores are collected ( $x \leq y$ ). The second constraint ( $y \leq \gamma q_1$ ) places a limit on the number of cores that can be collected based on the first-period production quantity: We assume that at the beginning of the second period, at most  $\gamma q_1$  cores can be collected. The parameter  $\gamma$  captures the fact that not all products can be obtained at the end of their useful lifetime. For example, the return rate for Kodak single-use cameras was less than 60%.

We do not explicitly model the optimization problem (4); the reader is referred to Galbreth and Blackburn (2005) for a thorough treatment of this problem. Instead, let  $\Gamma(x)$  represent the minimum total variable cost to remanufacture  $x$  units (found by solving (4) for the optimal number of cores to collect,  $y^*$ ).  $\Gamma(x)$  is convex increasing in the quantity remanufactured if either the variable collection cost is convex increasing in the collection quantity or the processing cost is convex increasing in the processing quantity, with neither cost being concave decreasing.

There are many cases where the collection cost is convex increasing in quantity. Transportation cost often increases in the number of cores collected since the firm loses economies of scale as it moves from collecting cores in densely populated areas to collecting cores in more rural areas. Agnihotri et al. (1990) describe a refuse collection facility where the cost of collecting is convex increasing in the amount collected. The acquisition cost for the cores may also increase in the number of units as consumers have heterogeneous reservation prices for what it takes to convince them to return their used products. This cost is modelled explicitly in Ray et al. (2005) through the use of trade-in rebates.

Many firms also experience a convex increasing processing cost due to the variance in condition of the returned cores and the fact that the firms process the cores in the best condition (upon arrival) first. The concept of a high variance in the condition of returned products has been identified in several studies (Klausner and Hendrickson 2000, Guide and Van Wassenhove 2001, Guide et al. 2003, and de Brito and de Koster 2004). Ferguson et al. (2004) provide an example where 80% of HP's inkjet printer returns required no significant processing besides cleaning and repackaging. For this reason, most firms sort their returned units and only process a percentage of the total returns with the highest quality. An alternative situation, modelled in Guide et al. (2003), is where the firm pays higher prices for higher quality product returns. Under either of these strategies, the total variable cost of processing is convex increasing in quantity.

For our analysis, we approximate the function  $\Gamma(x)$  with  $hx^\lambda$ , where  $h$  and  $\lambda$  are found from a non-linear least squares fit of:

$$\sum_{x=1}^{\gamma q_1} [hx^\lambda - \Gamma(x)]. \quad (5)$$

When  $\Gamma(x)$  is convex increasing, which is the focus of this paper,  $\lambda > 1$  will be obtained. As

explained later, our quantitative results are obtained for the special case  $\lambda = 2$ . Our qualitative results however, generalize to the less restricted case of  $\lambda > 1$ .

We offer one possible representation of the total variable collection and processing cost as follows:  $h_c(y) = h_c y^\alpha$  and  $h_p(x, y) = h_p \frac{x}{(1-\frac{x}{y})^\beta}$ . For  $\alpha > 1$ , the total variable collection cost is convex increasing in the quantity collected. The special case of  $\alpha = 1$  results in a linear collection cost of  $h_c y$ . For  $\beta > 0$ , the total variable processing cost is convex increasing in the quantity processed. The special case of  $\beta = 0$  results in a linear processing cost of  $h_p x$ . In this representation, our assumption of a convex increasing total variable remanufacturing cost,  $\lambda > 1$ , holds if either  $(\alpha > 1, \beta \geq 0)$  or  $(\alpha \geq 1, \beta > 0)$ . Thus, our assumption holds if either the variable collection or processing cost is convex increasing in the quantity and the other is not concave decreasing. From our experience, it is rare that at least one of these costs are not convex increasing in quantity.

**Assumption 6.** *A firm choosing to remanufacture faces a fixed cost  $F$  consisting of two components. The first component,  $F_c$ , is the cost of setting up the collection system and the second component,  $F_p$ , is the cost of setting up the processing operation.*

We assume that all firms are profit seeking so a firm will not remanufacture if its incremental profit from doing so is below the total fixed cost  $F = F_c + F_p$ .

Based on the assumptions described above, we introduce the remainder of our notation and describe the model. The OEM can produce new units at a price of  $c$  each. The unit cost  $c$  must satisfy  $c < 1$ , since 1 is the maximum willingness-to-pay of consumers for a new product. If this condition were not satisfied, the firm could not profitably manufacture the new product in the first place. We summarize the model's parameters and decision variables in Table 1.

	First Period		Second Period	
	Symbol	Definition	Symbol	Definition
Parameters	$c$	Cost to produce 1 new product	$c$	Cost to produce the 1 new product
			$\delta$	Relative willingness-to-pay
			$\gamma$	Fraction of $q_1$ that can be collected
			$hx^\lambda$	Total variable cost to remanf $x$ units
Decision vars	$p_1$	Price of new products	$p_{2n}$	Price of new products
	$q_1$	New products produced	$q_{2n}$	New products produced
			$p_{2r}$	Price of remanufactured products
			$q_{2r}$	Number of products remanufactured
			$F_c$	Fixed cost of collection
			$F_p$	Fixed cost of processing
			$F$	$= F_c + F_r$

Table 1: Parameters and Variables

## 4 Monopolist's Strategy in the Absence of Remanufacturing Competition

In this section, we answer the question: “Should a monopolist remanufacture its own product and, if so, how should the remanufactured product be priced in relation to the firm’s existing product?” In our setting, a monopolist refers to an OEM that is not under an immediate threat of an entrant offering a remanufactured version of its product. Devoid of this external competition, a monopolist OEM may still decide to recover and remanufacture its product. In doing so however, the remanufactured offering will cannibalize sales of the OEM’s new product. Thus, we model this internal competition to obtain conditions where it is profitable for an OEM to offer both its new product and its remanufactured product in the same market. This is similar to the internal competition models of Debo et al. (2005) and Ferguson and Koenigsberg (2005) with one important difference: In this model, the average variable cost to remanufacture is a function of the volume remanufactured. The results of this section will form the basis for the analysis in later sections concerning OEM strategies under the threat of competitive entry. In §4.1 and §4.2, we calculate optimal OEM profits without and with remanufacturing, respectively. These profits are compared in §4.3 to determine the monopolist OEM’s optimal strategy in the absence of remanufacturing competition. In our analysis, we assume the special case of a quadratic total variable remanufacturing cost ( $\lambda = 2$ ). This is done for illustrative purposes as it allows for closed form expressions of the decision variables and the

corresponding threshold values where the firm's strategy may change. All of our qualitative results hold for any convex increasing variable cost ( $\lambda > 1$ ) as the structure of the solutions remain the same.

#### 4.1 OEM Profits without Remanufacturing

With no remanufacturing, the two periods are independent and identical. The OEM's objective in the first period is

$$Max_{\tilde{q}_1} (\tilde{p}_1 - c)\tilde{q}_1,$$

which is concave in  $\tilde{q}_1$  (tilde denotes the "no remanufacturing" case). Checking first-order conditions yields the familiar monopoly results of

$$\tilde{q}_1^* = \frac{1-c}{2}, \quad \tilde{p}_1^* = \frac{1+c}{2}, \quad \tilde{\Pi}_1^* = \frac{(1-c)^2}{4}. \quad (6)$$

With no competition from a remanufactured product in the second period, the second period decisions are the same as the first period decisions and the combined optimal two-period profit is

$$\tilde{\Pi}^* = \frac{(1-c)^2}{2}.$$

#### 4.2 OEM Profits with Remanufacturing

We now model the scenario where the OEM remanufactures and sells the remanufactured units in the same market as its new units in the second period. We remove the tilde from our notation to distinguish this case from the "no remanufacturing" case. Since the OEM's second-period decisions are dependent upon the amount sold in the first period, we solve the problem in two stages, starting with the second period.

**Second-Period Analysis.** The OEM starts the second period with the opportunity to recover  $\gamma q_1$  cores from product that was sold in the first period. In addition to the new product quantity  $q_{2n}$ , the OEM also chooses the number of units to remanufacture,  $q_{2r}$ . With two products on the market, the inverse demand functions are given by (2) and (3). The OEM's second period objective is

$$Max_{q_{2n}, q_{2r}} \Pi_2(q_{2n}, q_{2r} | q_1) = (p_{2n} - c)q_{2n} + (p_{2r} - hq_{2r})q_{2r}$$

$$s.t. \quad q_{2r} \leq \gamma q_1.$$

First, let us assume that  $F = 0$  and find the optimal solution. A positive fixed cost will be added back at the end of the analysis. Let  $\bar{q} \doteq \frac{\delta c}{2(h+\delta-\delta^2)}$ . Since  $0 < \delta < 1$ ,  $\bar{q} > 0$ .

**Proposition 1** *Condition 1. Suppose  $h > \frac{\delta(c-1+\delta)}{1-c}$ . The optimal solution is summarized in the table below.*

Case	$q_{2n}^*(q_1)$	$q_{2r}^*(q_1)$	$p_{2n}^*(q_1)$	$p_{2r}^*(q_1)$	$\Pi_2^*(q_1) \doteq \Pi_2(q_{2n}^*, q_{2r}^*   q_1)$
$\gamma q_1 \leq \bar{q}$	$\frac{1-c}{2} - \delta \gamma q_1$	$\gamma q_1$	$\frac{1+c}{2}$	$\frac{\delta(1+c-2\gamma q_1(1-\delta))}{2}$	$\frac{(1-c)^2}{4} + c\delta\gamma q_1 - (h + \delta - \delta^2)\gamma^2 q_1^2$
$\gamma q_1 > \bar{q}$	$\frac{1}{2} - (1 + \frac{h}{\delta})\bar{q}$	$\bar{q}$	$\frac{1+c}{2}$	$\frac{\delta}{2} + h\bar{q}$	$\frac{(1-c)^2}{4} + \frac{c\delta\bar{q}}{2}$

*Condition 2. Suppose  $h \leq \frac{\delta(c-1+\delta)}{1-c}$ . The optimal solution is summarized in the table below.*

Case	$q_{2n}^*(q_1)$	$q_{2r}^*(q_1)$	$p_{2n}^*(q_1)$	$p_{2r}^*(q_1)$	$\Pi_2^*(q_1) \doteq \Pi_2(q_{2n}^*, q_{2r}^*   q_1)$
$\gamma q_1 < \frac{1-c}{2\delta}$	$\frac{1-c}{2} - \delta \gamma q_1$	$\gamma q_1$	$\frac{1+c}{2}$	$\frac{\delta(1+c-2\gamma q_1(1-\delta))}{2}$	$\frac{(1-c)^2}{4} + c\delta\gamma q_1 - (h + \delta - \delta^2)\gamma^2 q_1^2$
$\frac{1-c}{2\delta} \leq \gamma q_1 \leq \frac{\delta}{2(\delta+h)}$	0	$\gamma q_1$	$1 - \delta \gamma q_1$	$\delta(1 - \gamma q_1)$	$\delta \gamma q_1 - (\delta + h)\gamma^2 q_1^2$
$\gamma q_1 > \frac{\delta}{2(\delta+h)}$	0	$\frac{\delta}{2\gamma(\delta+h)}$	$1 - \frac{\delta^2}{2(\delta+h)}$	$\delta - \frac{\delta^2}{2(\delta+h)}$	$\frac{\delta^2}{4(\delta+h)}$

We observe a threshold level on  $h$  that determines the OEM product portfolio choice. When  $h$  is low (Condition 2), remanufacturing is very attractive: The OEM prefers to sell only the remanufactured product in the second period, and offers the new product only because it is restricted in its supply of used products to remanufacture. When  $h$  is high (Condition 1), remanufacturing is less attractive and the OEM prefers to sell both products. There is a threshold  $\bar{q}$  on the availability of cores below which  $q_{2r}^*$  is constrained and all available cores  $\gamma q_1$  are remanufactured. In this case, the remanufactured product price depends on the supply of cores. Since in practice, the second condition (where the OEM prefers to sell only the remanufactured product) is not prevalent, we focus on Condition 1 for the remainder of our analysis: We assume that  $h > \frac{\delta(c-1+\delta)}{1-c}$ . Note that if  $\delta \leq 1 - c$ , then this is the only case possible, as the condition defining the case holds for any positive  $h$ .

**Remark** *If  $F = 0$ , then remanufacturing in the second period is always more profitable than not remanufacturing.*

The optimal solution  $q_{2r}^*$  is always positive, as observed in Proposition 1. Thus, if there were no fixed cost associated with remanufacturing used products, then remanufacturing would be undertaken by the manufacturer for any level of  $q_1$ . On the other hand, with a fixed cost  $F$ , the profit differential between the remanufacturing and no remanufacturing strategies needs to exceed  $F$  for the firm to consider remanufacturing, i.e.  $\Pi_2^*(q_1) - \frac{(1-c)^2}{4} > F$  must hold. This result is driven by our assumption of a convex-increasing total variable remanufacturing cost and the fact that we model the number of products as a continuous variable. If the total variable cost is linear in the number of products remanufactured, there exists a threshold on  $h$  above which the OEM would not remanufacture even when  $F = 0$  (see Ferguson and Koenigsberg 2005 for details).

**First Period Analysis.** After characterizing the OEM's optimal second-period decisions given  $q_1$ , we now solve for the optimal first-period quantity decision. We maximize the total two-period

profit  $\Pi(q_1) = (p_1 - c)q_1 + \Pi_2^*(q_1)$  with respect to  $q_1$  to determine  $q_1^*$  and  $\Pi^* \doteq \Pi(q_1^*)$ .

**Proposition 2** *Let  $F = 0$ . If  $h < \tilde{h} \doteq \frac{\delta c - \delta \gamma(1-\delta)(1-c)}{(1-c)\gamma}$ , then  $q_1^* = \frac{1-c+c\delta\gamma}{2(1+\gamma^2(h+\delta-\delta^2))}$ , the remanufacturing quantity in period 2 is constrained by  $\gamma q_1^*$ , and  $\Pi^* = \frac{(1-c)^2}{4} + \frac{(1-c(1-\delta\gamma))^2}{4(1+\gamma^2(h+\delta-\delta^2))}$ . If  $h \geq \tilde{h}$ , then  $q_1^* = \frac{1-c}{2}$ , the remanufacturing quantity in period 2 is not constrained by  $\gamma q_1^*$ , and  $\Pi^* = \frac{(1-c)^2}{2} + \frac{c\delta\bar{q}}{2}$ .*

Note that if  $h$  is high, the first period production quantity is the same as in the monopoly case, and this quantity is sufficient to attain the optimal unconstrained product mix in the second period. When  $h$  is low, and remanufacturing is attractive, the first period production quantity exceeds the monopoly quantity; this is to benefit from the future remanufacturing potential of these sales.

### 4.3 Monopolist's Optimal Strategy

The analysis so far assumed  $F = 0$ . We now introduce a fixed cost  $F$  and determine the optimal strategy for the OEM - whether to only sell new products or to also remanufacture.

**Proposition 3** *There exists a threshold level  $\bar{h}$  for the cost of the remanufactured product above which the OEM only sells the new product.*

Proposition 3 states that a threshold  $\bar{h}$  exists, above which the monopolist OEM chooses not to remanufacture and sells only new product in the second period. Even though the incremental profit from remanufacturing is positive before fixed costs are accounted for, this profit does not make up for the fixed costs needed to establish the remanufacturing operation. The following numerical example illustrates a case where the OEM decides (in the absence of external competition) not to remanufacture in the second period.

**Example 1.** Let  $c = .10$ ,  $h = .005$ ,  $\delta = .8$ ,  $\lambda = 2$ ,  $\gamma = 1$  and  $F = .02$ . The fixed cost is small because we have normalized our market size to one and the fixed cost needs to be of the same order of magnitude to be meaningful. If the OEM does not remanufacture, its profit is  $\tilde{\Pi}^* = \frac{(1-c)^2}{2} = 0.405$ . If the OEM does remanufacture, its optimal profit is calculated from the second case in Proposition 2 since  $\tilde{h} = -0.07$ , and is  $\Pi^* = \frac{(1-c)^2}{2} + \frac{c\delta\bar{q}}{2} - F = 0.395$ . Since  $\tilde{\Pi}^* > \Pi^*$ , we conclude that it is not optimal for the OEM to remanufacture.

## 5 OEM's Strategies under the Threat of an Entrant

There are many situations where the conditions for remanufacturing are not attractive for the OEM (due to the cannibalization effect), but they are attractive for independent remanufacturers. Indeed, many products are remanufactured and sold by companies who do not produce the original

product. Such an entrant creates a competitive environment by capturing sales from the original OEM's customer base.

In this section, we focus on situations where  $h$  exceeds the threshold given by Proposition 3 such that a monopolist OEM would choose not to remanufacture, thus opening itself to the threat of competition by a third-party remanufacturer (the 'entrant'). In this context, we answer the question: "How does the potential entrance of a third-party remanufacturer in the second period affect the OEM's recovery strategy?" In particular, we consider two strategies: The OEM remanufactures to deter entry and the OEM collects cores to preempt entry. While there may be other strategies available to the OEM, these two are prevalent strategies, and demonstrate the usefulness of our models. We start by characterizing the second-period Nash equilibrium and calculating OEM profits when an entrant decides to remanufacture the OEM's product (§5.1), then demonstrate the potential profit loss incurred by the OEM as a result of not having invested in recovery. In §5.2 and §5.3, we propose two possible preemptive strategies and discuss conditions under which each strategy is more profitable in §5.4.

### 5.1 OEM's Profit when the Entrant Remanufactures

Let  $\bar{p}_{2r}$ ,  $\bar{q}_{2r}$  and  $\bar{\Pi}_2$  represent the entrant's second-period remanufactured product price, quantity and profit, respectively. The OEM only makes decisions concerning the new product. The OEM's second-period objective given the entrant's choice of  $\bar{q}_{2r}$  is

$$\text{Max}_{q_{2n}} \Pi_2(q_{2n}|\bar{q}_{2r}) = (p_{2n} - c)q_{2n} = (1 - q_{2n} - \delta\bar{q}_{2r} - c)q_{2n}. \quad (7)$$

The entrant enters the second period with the opportunity to recover  $\gamma q_1$  cores from product that was sold in the first period and faces competition from the OEM's new product. The entrant's objective given the OEM's choice of  $q_{2n}$  is

$$\text{Max}_{\bar{q}_{2r}} \bar{\Pi}_2(\bar{q}_{2r}|q_{2n}, q_1) = (\bar{p}_{2r} - h\bar{q}_{2r})\bar{q}_{2r} - F = (\delta - \delta q_{2n} - \delta\bar{q}_{2r} - h\bar{q}_{2r})\bar{q}_{2r} - F \quad (8)$$

$$s.t. \quad \bar{q}_{2r} \leq \gamma q_1.$$

Let the superscript  $n$  represent the Nash equilibrium in the second period. In the first period, the OEM strategically determines the production quantity in anticipation of the second period interaction; call this value  $q_1^n$ .

**Proposition 4** *Let  $\tilde{q} \doteq \frac{(1+c)\delta}{4h+4\delta-\delta^2}$  represent the threshold level where the entrant is constrained by the availability of the cores.  $q_1^n$  maximizes the total two-period profits  $\Pi_1(q_1) + \Pi_2(q_1)$  where  $\Pi_1(q_1) = (1 - c - q_1)q_1$  and  $\Pi_2(q_1) = \left(\frac{1-c-\delta\gamma q_1}{2}\right)^2$  for  $\gamma q_1 \leq \tilde{q}$  and  $\Pi_2(q_1) = \frac{(2\delta+2h-\delta^2-2c(\delta+h))^2}{(4\delta+4h-\delta^2)^2}$  otherwise. The second period equilibrium production quantities and the entrant's profit are:*



\* If  $\gamma q_1^n \leq \tilde{q}$  the entrant is constrained by the first period production quantity and the Nash equilibrium for the second period production quantities are  $(q_{2n}^n, \bar{q}_{2r}^n) = (\frac{1-c-\delta\gamma q_1^n}{2}, \gamma q_1^n)$ . The entrant's second period profit is  $\bar{\Pi}_2(q_1^n) = \frac{\gamma q_1^n \delta(1+c) - (\gamma q_1^n)^2(2h+2\delta-\delta^2)}{2} - F$ .

\* If  $\gamma q_1^n \geq \tilde{q}$  the entrant is not constrained and the Nash equilibrium for the second period production quantities are  $(q_{2n}^n, \bar{q}_{2r}^n) = (\frac{2\delta+2h-\delta^2-2c(\delta+h)}{4\delta+4h-\delta^2}, \frac{(1+c)\delta}{4\delta+4h-\delta^2})$ . The entrant's second period profit is  $\bar{\Pi}_2(q_1^n) = \frac{\delta^2(1+c)^2(\delta+h)}{(4\delta+4h-\delta^2)^2} - F$ .

As proven in Proposition 3, there is a threshold value of  $h$  above which the monopolist OEM would prefer to not remanufacture. The solid lines in Figure 1 plot this threshold as a function of  $F$  for different values of  $c$  and  $\delta$ ; above the solid line, the monopolist OEM would not remanufacture. However, this leaves the door open to a potential entrant to remanufacture cores and compete with the OEM. Using the equilibrium profit expression for the entrant from Proposition 4, we can find a similar threshold for  $h$  where the entrant is indifferent between entering the remanufactured product market or not. These thresholds, as functions of  $F$ , are represented by dashed lines in Figure 1 for different values of  $c$  and  $\delta$ ; below the dashed line, the entrant profitably remanufactures the OEM's cores. As either the manufacturing cost or the relative willingness-to-pay increases, remanufacturing becomes a more attractive option for both parties, and the indifference curves shift accordingly. The area between each pair of OEM and entrant indifference curves is where the monopolist OEM would choose not to remanufacture, but an entrant would find it profitable to do so, detracting from OEM profits. The following example illustrates such a case, using the same parameter values as Example 1.

**Example 2.** The OEM's first-period production quantity is  $q_1^n = 0.45$ . In this case  $\tilde{q} = 0.34$ , so  $\gamma q_1^n \geq \tilde{q}$  and the entrant is not constrained by the availability of cores. Since the entrant only sells in the second period, its profit is  $\bar{\Pi}_2(q_1^n) = \frac{\delta^2(1+c)^2(\delta+h)}{(4\delta+4h-\delta^2)^2} - F = .074$ . The OEM's profit (under external competition) in the second period is  $\Pi_2(q_1^n) = \frac{(2\delta+2h-\delta^2-2c(\delta+h))^2}{(4\delta+4h-\delta^2)^2} = 0.099$ , and its two-period profit is  $\Pi^{*,n} = \frac{(1-c)^2}{4} + .099 = 0.301$ . Comparing to Example 1, we observe that the OEM is significantly worse off with external competition. Note that 0.45 is also the monopoly production quantity in period 1. Although the OEM acts strategically in period 1, and may set  $q_1^n < q_1^*$ , he does not do so in this case. This is because the OEM would need to reduce first period production by a large amount (and lose significant revenue) before he can affect the quantity the entrant will remanufacture in the second period.

Since competitor entry is detrimental to OEM profits, we next focus on two preemptive strategies designed to discourage an external firm from remanufacturing the OEM's product: remanufacturing and collection.

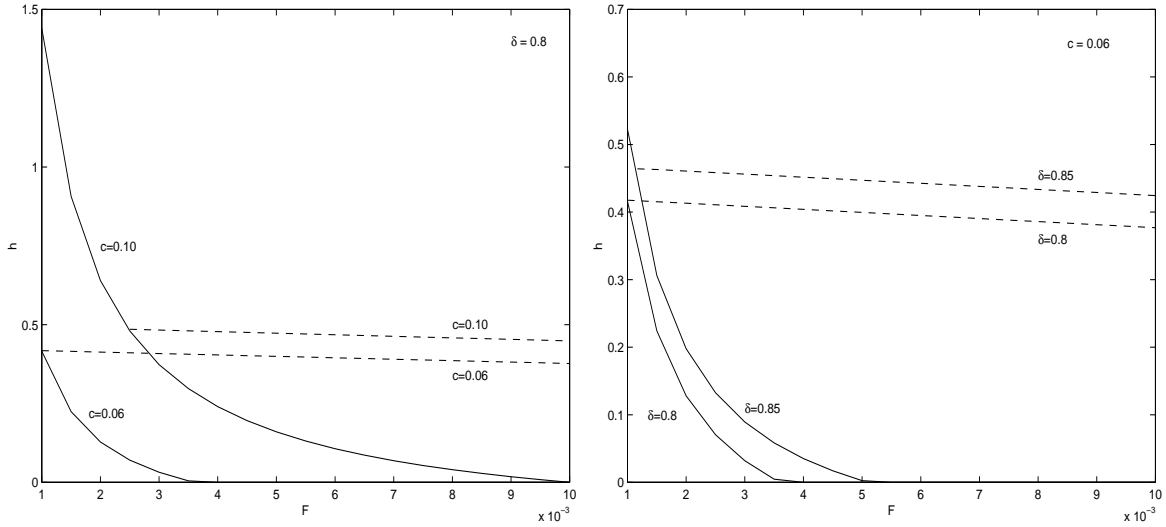


Figure 1: Pairs of OEM (solid line) and entrant (dashed line) indifference curves as a function of  $h$  and  $F$ . For each pair, in the region between the solid line and the dashed line, a monopolist OEM would not remanufacture, but an entrant would find it profitable to remanufacture.

## 5.2 Strategies to Discourage Competition: OEM Remanufactures to Preempt Entry

In our analysis, we assume that a third-party remanufacturer will only consider entering the market if the OEM decides not to remanufacture itself. Thus, we allow at most one firm to remanufacture in the second period; the OEM always sells the new product. This assumption is reasonable when the OEM enjoys a brand advantage for its remanufactured product over the entrant's product or the OEM enjoys a first-mover advantage in the recovery of the cores needed for remanufacturing.

With a brand advantage, the OEM's offering of both a new and a remanufactured product will leave little room for an entrant to sell a product of a perceived lower quality than either of the two offerings of the OEM. If the entrant faces the same remanufacturing cost structure as the OEM, it is only under very rare conditions that the remaining market size (not covered by the OEM's new and remanufactured products) is large enough for the entrant to make enough positive profit to cover its fixed cost. Both Groenevelt and Majumder (2001a) and Ferrer and Swaminathan (2005), discuss situations where the OEM enjoys a brand advantage over the entrant that makes it difficult for the entrant to compete when the OEM decides to remanufacture its product.

With a first-mover advantage, remanufacturing can again be an attractive preemptive strategy. When the OEM has a first-mover advantage, the OEM essentially collects the cores that are the most readily available, thus making it much more expensive for the entrant to remanufacture relative to the OEM. There are many situations where the OEM enjoys such a first-mover advantage. In

general, OEMs already have a relationship with their customers as well as some knowledge about when the product will need to be replaced. OEMs that sell capital goods often also sell maintenance contracts, giving them a clear advantage for recovering the cores once a component or product has expired. Auto manufacturers have a network of dealers that perform regular maintenance on their products, providing them with easy access to the replaced parts. Printer manufacturers sometimes provide postage paid shipping bags with their products so the used printer cartridges can be easily returned and many providers of such items as car batteries and tires provide discounts (sometimes mandated by regulation) if the old product is returned when the new product is purchased.

Assuming one of the assumptions above holds, under most conditions the entrant will not find it profitable to offer a remanufactured product in competition with the OEM's remanufactured product. Thus, the OEM may choose to remanufacture for the sole purpose of discouraging an external firm from doing so. The following example (using the same parameter values as Examples 1 and 2) shows that the OEM may choose to remanufacture its product under the threat of competitor entry although it would not do so in a monopoly setting. In the absence of at least one of the conditions described above, however, remanufacturing is less desirable as a preemptive strategy.

**Example 3.** From Example 2, the OEM's total profit under external competition is  $\Pi^{*,n} = 0.301$ . From Example 1, if the OEM remanufactures, it makes  $\Pi^* = 0.395$ , if it doesn't, it makes  $\tilde{\Pi}^* = 0.405$ . Thus, even though it is not profit maximizing in this case for the OEM to choose to remanufacture in the absence of external competition since  $\tilde{\Pi}^* > \Pi^*$ , it is rational for it to do so to preempt entry by a competitor since  $\Pi^* > \Pi^{*,n}$ .

### 5.3 Strategies to Discourage Competition: OEM Collects Cores but Does Not Remanufacture

The OEM may choose a second strategy to deter entry – collecting a portion, or all, of the used products and disposing or recycling them to limit or prevent remanufacturing by the entrant. There are many examples of companies employing policies meant to recover their product's cores to prevent them from being remanufactured by potential competitors. For example, Lexmark offers a rebate to customers who return their used cartridge, but does not refill it, recycling it instead (www.atlex.com 2003). Bosch collects a broader range of products than those it remanufactures (Valenta 2004). Volkswagen charges an 80% premium on the cost of a replacement engine if the old engine is not returned (Inderfurth and Langella 2003).

To recover the cores, the OEM only incurs the fixed collection cost  $F_c$ ,  $F_c \leq F$  and collection cost  $h_c$ ,  $h_c \leq h$  since it does not use the cores for remanufacturing. The purpose of collection under this scenario is purely strategic; it limits or completely eliminates competition from the entrant. We assume that the OEM has better access to the owners of the cores (as discussed in §5.2) and thus

can obtain the cores at the lower end of the convex increasing cost curve. Another way of saying this is that the OEM has the first choice on what cores to collect and chooses the cores with the lowest collection cost. Thus, if the OEM collects the first  $y$  cores, the entrant's variable remanufacturing cost does not start at zero as in the original case but rather at  $hy$  (for the quadratic cost case). Therefore, by collecting cores, the OEM not only reduces the supply available to the entrant, but also makes the operation more expensive.

An OEM following a collection strategy decides on  $q_c$ , the number of cores to collect but not to process. If enough cores are left that the operation is profitable for the entrant, the entrant will remanufacture; collection does not preclude entry since the OEM does not remanufacture. To understand the OEM's decision, consider a scenario with no fixed cost. In this case, the OEM's optimal collection strategy is to collect part or all of the existing supply. The former decision will be taken when the cost of collecting more cores exceeds the savings obtained by avoiding the cannibalization of the new product; the latter decision will be taken when complete collection is more cost effective than incurring revenue loss due to cannibalization. With a fixed cost for the entrant, the OEM never collects all the cores, at most, the OEM collects up to the point where the profit from remanufacturing the remaining cores does not cover the fixed cost of the entrant's operation.

The following example (using the same parameter values as in the previous three examples) shows that the OEM may deter entry by recovering some of the cores sold in the first period.

**Example 4.** Let  $h_c(y) = h_c y^2 = .001y^2$  and  $F_c = .005$ . Then  $q_c^* = 0.401$ . The OEM does not collect all the cores, but the amount it collects is enough to deter the entrant from collecting and remanufacturing its cores. The OEM profit in the second period after accounting for the fixed and variable cost of collection is 0.1971, giving a total two-period profit of 0.400. Comparing this with a total profit of 0.395 when using remanufacturing as a deterrent, we see that the OEM is better off using a collection strategy. If the fixed cost of collection were the dominant factor, the result would be reversed. For example, if  $F_c = 0.015$ , then the OEM's two-period profit is 0.390 in the collection strategy, but the profit under the remanufacturing strategy is unchanged since  $F = 0.02$  still holds, so remanufacturing is preferable as an entry-deterrent strategy.

The OEM may not always enjoy a first mover advantage in the collection of the cores. For example, local remanufacturers may be able to access used products more easily due to geographic proximity. In this case, the effectiveness of collection as an entry-deterrent strategy decreases. Another factor that may reduce the effectiveness of the collection strategy is a disposal cost charged against units collected but not processed. In Europe, for example, there is legislation imposing a recycling cost for such a case. In Appendix C, we discuss the ramifications of a disposal cost.

The collection strategy demonstrates the importance of accurately modelling the shape of the

variable collection cost curve as a function of the quantity collected. If the cost increases linearly in the quantity, the collection strategy becomes less attractive. In particular, when the cost is convex increasing, even in the absence of a fixed cost for the entrant, it is possible for the OEM to deter entry without collecting all the cores. With a linear cost structure, this is not possible since the cost of collecting and processing each additional unit is equal, and the OEM is unable to impact the economic viability of the cores available to the entrant; its only lever is to limit the available quantity. Thus, inaccurately using a linear collection cost would result in collection being deemed to be a less effective entry-deterrent strategy than it may truly be. In summary, the conditions that are favorable to using a collection strategy to deter entry are when the OEM enjoys a first mover advantage in the collection of the cores needed for remanufacturing and the total variable collection cost is convex increasing in the quantity of cores collected.

#### 5.4 Which Entry-Deterrent Strategy should the OEM Adopt?

Example 4 demonstrates that there are conditions under which the remanufacturing strategy dominates the collection strategy and vice versa. In this section, we explore these conditions more fully. In particular, we ask the following questions: “What is the impact of collection costs on the preferred strategy? How do consumer willingness-to-pay and unit manufacturing cost impact the preferred strategy?” We make three observations.

**Observation 1.** *For a given level of  $h$  and  $F$ , a lower collection cost, either due to the variable component  $h_c$  or the fixed component  $F_c$ , increases the relative profitability of the collection strategy.*

The reason for this result can be explained as follows: First, with  $F$  fixed, it is obvious that a reduction in  $F_c$  would increase OEM profit in the collection strategy but not change it in the remanufacturing strategy since  $F$  is the relevant cost in the latter strategy. Now consider a reduction in  $h_c$ , keeping everything else constant. Again, the OEM’s profit in the remanufacturing strategy would not change. First, suppose that the optimal solution is to collect enough to completely exclude the entrant from the market. As  $h_c$  decreases, this is still optimal and the amount that the OEM needs to collect to deter entry is independent of  $h_c$  and  $F_c$  since entrant profits are a function of  $h$  and  $F$ . The OEM’s profit before collection cost is also independent of these values. Thus, the total OEM profit in the collection strategy monotonically increases as  $h_c$  decreases. Now, suppose that the optimal solution leaves enough cores for the entrant to enter the remanufactured product market. As  $h_c$  decreases, the amount collected increases, the amount remanufactured by the entrant decreases, and that manufactured by the OEM increases, leading to a net increase in OEM profit. This observation provides a basis for categorizing products with respect to whether remanufacturing or collection is the better strategy by looking at the relative variable cost of

collection versus remanufacturing. A product for which collection may be preferred by the OEM is the print cartridge. Since cartridges are often collected by including a prepaid envelope in the new cartridge packaging, the OEM avoids the fixed cost of establishing a sophisticated reverse-flow logistics network. The Lexmark Prebate program is such an example.

**Observation 2.** *As the unit manufacturing cost increases, the relative profitability of the remanufacturing strategy increases.*

The intuition is the following: The unit manufacturing cost influences only the OEM directly. As the unit manufacturing cost increases, making profits from the remanufactured product rather than the new product (as the OEM would under a collection strategy) becomes more attractive since the margin on the new product erodes. In other words, for a low-margin product that is relatively cheap to remanufacture, it may be desirable for the OEM to set up a remanufacturing operation not only to benefit from the residual value in the product but also to preempt entry by third parties into the lucrative remanufacturing market. This is the case, for example, with copiers and automotive parts.

**Observation 3.** *As relative willingness-to-pay  $\delta$  increases, the relative profitability of the remanufacturing strategy increases.*

The reason for this result is the following: An increase in the relative willingness-to-pay advantages any party that undertakes remanufacturing. Thus, the collection effort that the OEM must expend to limit or completely deter the entrant increases in  $\delta$  since the entrant's profitability increases. This decreases the profitability of the collection strategy. At the same time, the profit that the OEM can make from remanufacturing increases, enhancing the profitability of the remanufacturing strategy. Combining the two effects, we conclude that an increased willingness-to-pay for the remanufactured product favors remanufacturing as an entry-deterrent strategy. Thus, market acceptance of the remanufactured product increases the legitimacy of a remanufacturing strategy: Remanufacturing becomes more profitable both in its own right and as an entry-deterrent strategy.

In many industries, commercial buyers are more knowledgeable about the high relative quality of remanufactured products than are consumer buyers. Thus, tire manufacturers offer retreaded tires in their commercial fleet product line but not in their consumer product line, even though there is little difference in the true relative quality levels of the retreaded versus new tires in either line. Bosch Power Tools also follows this strategy by focusing their remanufacturing efforts on the products that are typically purchased by professional contractors. Since the relative willingness-to-pay of the customer is higher if a warranty is offered, we expect to see warranties to go hand in hand with remanufacturing, as with retreaded tires and Bosch Power Tools.

In making this observation, we assumed that consumers value the remanufactured product the same, regardless of whether it is produced by the OEM or the remanufacturer. For some products, consumer confidence in the original manufacturer may be higher. In this case, remanufacturing the OEM's product will be less attractive for an entrant. Thus, an OEM who chooses not to remanufacture will be less likely to have its sales cannibalized. Furthermore, deterring the remanufacturer from entering the market will be easier for the OEM. In particular, the collection strategy will be more effective over a larger set of conditions.

## 6 Conclusion

In this paper, we develop insights for managers who face potential competition from firms remanufacturing their used products, and who wish to deter entry using the most cost-effective strategy. Motivated by examples from industry, we focus on remanufacturing and collection as two potential entry-deterrent recovery strategies. Our model captures some of the key elements driving the choice of recovery strategy; in particular, we focus on market characteristics and cost drivers. We consider a market where a remanufactured product is valued less than a new product and is targeted to the lower end of the market. Remanufactured product volume is constrained by past sales of the new product and fixed costs are incurred to set up the collection and remanufacturing operations. The average variable cost of remanufacturing increases in the quantity remanufactured; this assumption captures a unique aspect of remanufacturing that has not been explored in previous research. Motivated by practice, we also assume that the OEM has easier access to used products and can drive up the effective cost of collection and remanufacturing for the entrant through collection.

Two concerns typically drive the OEM's choice of whether to remanufacture its product: cost and cannibalization. Even if the remanufactured product is independently profitable, firms may ignore this option due to concerns about cannibalization. The decision not to remanufacture in this situation is often made in ignorance, as OEMs lack models to guide them on the financial impact and strategic implications of their decision. Our findings provide OEMs with conditions where the benefits of remanufacturing exceed the detrimental effect of cannibalization.

We also explore the implications of an OEM's decision not to remanufacture. A misconception of some managers is that if remanufacturing is not profitable for the OEM, it is also not profitable for an external firm. We demonstrate the fallacy in this perception by showing that there is a significant range of fixed and variable remanufacturing costs where, even though a monopolist OEM would not find it more profitable to remanufacture, an independent entrant would make profits doing so. In other words, the entrant can profitably remanufacture under conditions where the OEM would prefer not to, despite the fact that the two share the same cost structure. For example, for

a given variable cost of remanufacturing, the entrant will find it profitable to remanufacture for a much larger range of fixed costs. This result is driven by the cannibalization of the OEM's new product by its remanufactured product. Because of this cannibalization effect, the OEM incurs an opportunity cost when selling remanufactured products that the entrant does not, since the entrant has no other competing product. When this opportunity cost is factored in, the profitability hurdle for the remanufactured product is much higher from the OEM's perspective. If guided only by profits, ignoring the threat of competition, the OEM may choose not to remanufacture, but the consequence may be a significant profit drop if an entrant decides to remanufacture its product. We conclude that the choice to remanufacture should be considered as part of an OEM's competitive strategy.

There are other strategies available to OEMs who wish to deter the entry of a third-party remanufacturer. Total remanufacturing cost is a combination of the cost for collecting the used product and the cost to bring the product back up to its original quality level. Some OEMs deter entry by only incurring the cost of collecting their used product, with no intention of remanufacturing it, simply to increase the cost of a potential remanufacturing competitor. The choice of which strategy to choose to deter competition depends on many interrelated factors. The literature to date has analyzed competition and collection in a remanufacturing setting from different angles, but has not evaluated remanufacturing and collection as potential entry-deterrent mechanisms. Our research provides guidance for when an OEM should choose a remanufacturing strategy over a collection strategy or vice versa. Our key results are summarized below.

First, we find that when collection is the major portion of the total remanufacturing fixed and/or variable cost, the OEM is better off remanufacturing. This observation provides a basis for categorizing products with respect to whether remanufacturing or collection is the better strategy by looking at the relative cost of collection versus processing. Second, we find that as the unit manufacturing cost increases, the relative advantage of the remanufacturing strategy increases. Therefore, for a low-margin product, especially if remanufacturing is cheap, it may be desirable for the OEM to set up a remanufacturing operation. This allows the OEM not only to benefit from the residual value in the product, but also to preempt entry by third parties into the lucrative remanufacturing market. Finally, we focus on a market characteristic, consumer acceptance of the remanufactured product, as measured by consumers' relative willingness-to-pay for this product. We find that as market acceptance increases, the relative advantage of the remanufacturing strategy increases. Thus, market acceptance of the remanufactured product increases the legitimacy of a remanufacturing strategy: Remanufacturing becomes more valuable both in its own right and as an entry-deterrent strategy.



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## Appendix A: Proofs

### Proof of Proposition 1.

$$\begin{aligned} \text{Max}_{q_{2n}, q_{2r}} \Pi_2(q_{2n}, q_{2r} | q_1) &= (p_{2n} - c)q_{2n} + p_{2r}q_{2r} - hq_{2r}^2 \\ \text{s.t. } q_{2r} &\leq \gamma q_1, \quad q_{2n} \geq 0, \quad q_{2r} \geq 0. \end{aligned}$$

Here,  $p_{2n} = 1 - q_{2n} - \delta q_{2r}$  and  $p_{2r} = \delta(1 - q_{2n} - q_{2r})$ . The Hessian is  $\begin{pmatrix} -2 & -2\delta \\ -2\delta & -2\delta - 2h \end{pmatrix}$ , whose leading coefficient is negative and whose determinant  $4\delta(1 - \delta) + 4h$  is positive. Thus, the Hessian is negative definite and the profit function is concave in  $(q_{2n}, q_{2r})$ . The Lagrangean is

$$\begin{aligned} \mathcal{L}(q_{2n}, q_{2r}, \lambda) &= (1 - q_{2n} - \delta q_{2r} - c)q_{2n} + \delta(1 - q_{2n} - q_{2r})q_{2r} - hq_{2r}^2 - \lambda(q_{2r} - \gamma q_1) + \mu_1 q_{2n} + \mu_2 q_{2r}. \\ \frac{\partial \mathcal{L}}{\partial q_{2n}} &= -2q_{2n} + 1 - 2\delta q_{2r} - c + \mu_1 \\ \frac{\partial \mathcal{L}}{\partial q_{2r}} &= -2\delta q_{2n} - 2(\delta + h)q_{2r} + \delta - \lambda + \mu_2 \end{aligned}$$

Since the profit function is concave, necessary conditions and sufficient conditions for optimality are that these FOC = 0, as well as  $\lambda(q_{2r} - \gamma q_1) = 0$ ,  $\mu_1 q_{2n} = 0$ ,  $\mu_2 q_{2r} = 0$ ,  $\lambda \geq 0$ ,  $\mu_1 \geq 0$  and  $\mu_2 \geq 0$ .

Case 1.  $q_{2r} = \gamma q_1$ . Then  $\lambda \geq 0, \mu_2 = 0$ . Also take  $q_{2n} > 0$ . Then  $\mu_1 = 0$ . Solving the FOC gives  $q_{2n} = \frac{1-c}{2} - \delta\gamma q_1$  and  $\lambda = 2(\delta^2 - \delta - h)\gamma q_1 + \delta c$ . If  $\gamma q_1 < \frac{1-c}{2\delta}$ , then  $q_{2n} > 0$  holds. The second condition  $\lambda \geq 0$  gives  $2(\delta^2 - \delta - h)\gamma q_1 + \delta c \geq 0$ . The prices are as follows:  $p_{2n} = \frac{1+c}{2}$  and  $p_{2r} = \frac{\delta(1+c-2\gamma q_1(1-\delta))}{2}$ .  $\Pi_2 = (\delta^2 - \delta - h)\gamma^2 q_1^2 + c\delta\gamma q_1 + \frac{(1-c)^2}{4}$ .

Case 2:  $0 < q_{2r} < \gamma q_1$  and  $q_{2n} > 0$ . Then  $\lambda = 0, \mu_1 = 0$  and  $\mu_2 = 0$ . Solving for the first order conditions gives  $q_{2n} = \frac{\delta^2 - \delta - h + c(\delta + h)}{2(\delta^2 - \delta - h)}$  and  $q_{2r} = -\frac{\delta c}{2(\delta^2 - \delta - h)}$ . The prices are as follows:  $p_{2n} = \frac{1+c}{2}$  and  $p_{2r} = \frac{\delta(\delta^2 - \delta - h - ch)}{2(\delta^2 - \delta - h)}$ .  $\Pi_2 = \frac{(1-2c)(\delta^2 - \delta - h) - c^2(\delta + h)}{4(\delta^2 - \delta - h)}$ . We need the conditions  $0 < -\frac{\delta c}{2(\delta^2 - \delta - h)} < \gamma q_1$  and  $\frac{\delta^2 - \delta - h + c(\delta + h)}{2(\delta^2 - \delta - h)} > 0$  to hold for this case to be valid.

Case 3:  $0 < q_{2r} < \gamma q_1$  and  $q_{2n} = 0$ . Then  $\lambda = 0$  and  $\mu_2 = 0$ . Solving the FOC gives  $q_{2r} = \frac{\delta}{2(\delta + h)}$  and  $\mu = \frac{\delta^2 - \delta - h + c(\delta + h)}{\delta + h}$ .  $q_{2r} > 0$  is automatically satisfied. We need  $\gamma q_1 > \frac{\delta}{2(\delta + h)}$  for this case to be valid. In addition, we need  $\delta^2 - \delta - h + c(\delta + h) \geq 0$ . The prices are as follows:  $p_{2n} = 1 - \frac{\delta^2}{2(\delta + h)}$  and  $p_{2r} = \delta \left(1 - \frac{\delta}{2(\delta + h)}\right)$ .  $\Pi_2 = \frac{\delta^2}{4(\delta + h)}$ .

Case 4:  $q_{2r} = \gamma q_1$  and  $q_{2n} = 0$ . Then  $\mu_2 = 0$ . Solving the FOC gives  $\lambda = \delta - 2\gamma q_1(\delta + h)$  and  $\mu_1 = -1 + 2\delta\gamma q_1 + c$ . Non-negativity conditions require  $\gamma q_1 \leq \frac{\delta}{2(\delta + h)}$  and  $\gamma q_1 \geq \frac{1-c}{2\delta}$ . The prices are as follows:  $p_{2n} = 1 - \delta\gamma q_1$  and  $p_{2r} = \delta(1 - \gamma q_1)$ .  $\Pi_2 = \delta\gamma q_1 - (\delta + h)\gamma^2 q_1^2$ .

Case 5:  $q_{2r} = 0$  and  $q_{2n} > 0$ . Then  $\mu_1 = 0$  and  $\lambda = 0$ . Solving the FOC gives  $q_{2n} = \frac{1-c}{2}$  and  $\mu_2 = -\delta c$ . The prices are  $p_{2n} = \frac{1+c}{2}$  and  $p_{2r} = \delta\frac{1+c}{2}$ .  $\Pi_2 = \frac{(1-c)^2}{4}$ . But  $\mu_2 \geq 0$  cannot be satisfied, so this case cannot occur.

Case 6: Both quantities 0. Then  $\lambda = 0$ . Solving the FOC gives  $\mu_1 = c - 1$  and  $\mu_2 = -\delta$ . So this cannot happen unless  $c - 1 > 0$ , or,  $c > 1$ , which we ruled out in §3 since otherwise, no new product would be sold in period 1.

With  $c < 1$ , these last two cases show that  $q_{2r} = 0$  is ruled out. So there are a total of four possible cases, summarized in Tables 2a and 2b below.

Case	$q_{2n}^*$	$q_{2r}^*$	$p_{2n}^*$	$p_{2r}^*$	$\Pi_2(q_{2n}^*, q_{2r}^*   q_1)$
1)	$\frac{1-c}{2} - \delta\gamma q_1$	$\gamma q_1$	$\frac{1+c}{2}$	$\frac{\delta(1+c-2\gamma q_1(1-\delta))}{2}$	$(\delta^2 - \delta - h)\gamma^2 q_1^2 + c\delta\gamma q_1 + \frac{(1-c)^2}{4}$
2)	$\frac{\delta^2 - \delta - h + c(\delta + h)}{2(\delta^2 - \delta - h)}$	$-\frac{\delta c}{2(\delta^2 - \delta - h)}$	$\frac{1+c}{2}$	$\frac{\delta(\delta^2 - \delta - h - ch)}{2(\delta^2 - \delta - h)}$	$\frac{(1-2c)(\delta^2 - \delta - h) - c^2(\delta + h)}{4(\delta^2 - \delta - h)}$
3)	0	$\frac{\delta}{2(\delta + h)}$	$1 - \frac{\delta^2}{2(\delta + h)}$	$\delta - \frac{\delta^2}{2(\delta + h)}$	$\frac{\delta^2}{4(\delta + h)}$
4)	0	$\gamma q_1$	$1 - \delta\gamma q_1$	$\delta(1 - \delta\gamma q_1)$	$\delta\gamma q_1 - (\delta + h)\gamma^2 q_1^2$

Table 2a

Case	Conditions
1)	$\gamma q_1 < \frac{1-c}{2\delta}, 2(\delta^2 - \delta - h)\gamma q_1 + \delta c \geq 0$
2)	$0 < -\frac{\delta c}{2(\delta^2 - \delta - h)} < \gamma q_1, \frac{\delta^2 - \delta - h + c(\delta + h)}{2(\delta^2 - \delta - h)} > 0$
3)	$\gamma q_1 > \frac{\delta}{2(\delta + h)}, \delta^2 - \delta - h + c(\delta + h) \geq 0$
4)	$\gamma q_1 \leq \frac{\delta}{2(\delta + h)}, \gamma q_1 \geq \frac{1-c}{2\delta}$

Table 2b

For Case 2 to exist, we need  $\delta^2 - \delta - h < 0$ , which is always true since  $\delta < 1$ . With this observation, we can rewrite Table 2b as follows:

Case	Conditions
1)	$\gamma q_1 < \frac{1-c}{2\delta}, \gamma q_1 \leq -\frac{\delta c}{2(\delta^2 - \delta - h)}$
2)	$\gamma q_1 > -\frac{\delta c}{2(\delta^2 - \delta - h)}, \delta^2 - \delta - h + c(\delta + h) < 0$
3)	$\gamma q_1 > \frac{\delta}{2(\delta + h)}, \delta^2 - \delta - h + c(\delta + h) \geq 0$
4)	$\gamma q_1 \leq \frac{\delta}{2(\delta + h)}, \gamma q_1 \geq \frac{1-c}{2\delta}$

Table 2c

The expressions in this table can be simplified:

Case	Conditions
1)	$\gamma q_1 < \frac{1-c}{2\delta}, \gamma q_1 \leq -\frac{\delta c}{2(\delta^2-\delta-h)}$
2)	$\gamma q_1 > -\frac{\delta c}{2(\delta^2-\delta-h)}, \frac{\delta}{2(\delta+h)} < \frac{1-c}{2\delta}$
3)	$\gamma q_1 > \frac{\delta}{2(\delta+h)}, \frac{\delta}{2(\delta+h)} \geq \frac{1-c}{2\delta}$
4)	$\gamma q_1 \leq \frac{\delta}{2(\delta+h)}, \gamma q_1 \geq \frac{1-c}{2\delta}$

Table 2d

The second condition in Cases 2 and 3 have only to do with the parameters of the problem. So these cases cannot simultaneously hold. Also, if we compare the two limits in Case 1, we find that the resulting inequality is the same as the second condition in Cases 2 and 3:  $\frac{1-c}{2\delta\gamma} > -\frac{\delta c}{2\gamma(\delta^2-\delta-h)}$  is the same as the condition  $\frac{\delta}{2(\delta+h)} < \frac{1-c}{2\delta}$ . Thus, given the condition  $c < 1$ , the optimal solution can be summarized by two cases, with mutually exclusive and collectively exhaustive regions for the value of  $q_1$ .

Case I:  $\frac{\delta}{2(\delta+h)} < \frac{1-c}{2\delta}$ , or,  $h > \frac{\delta(c-1+\delta)}{1-c}$ . Cases 3 and 4 do not apply. Cases 1 and 2 are  $q_1 \leq -\frac{\delta c}{2\gamma(\delta^2-\delta-h)}$  and  $q_1 > -\frac{\delta c}{2\gamma(\delta^2-\delta-h)}$ , respectively.

Case II:  $\frac{\delta}{2(\delta+h)} \geq \frac{1-c}{2\delta}$ , or,  $h \leq \frac{\delta(c-1+\delta)}{1-c}$ . Case 2 does not apply. Cases 1, 4 and 3 are  $q_1 < \frac{1-c}{2\delta\gamma}, \frac{1-c}{2\delta\gamma} \leq q_1 \leq \frac{\delta}{2\gamma(\delta+h)}$ , and  $q_1 > \frac{\delta}{2\gamma(\delta+h)}$ , respectively.

These cases are tabulated in the statement of Proposition 1 using expressions from Table 2a. ■

**Proof of Proposition 2.** Recall that we are working under the assumption  $h > \frac{\delta(c-1+\delta)}{1-c}$ . First, we need to check that  $\Pi_2^*(q_1)$  is continuous at the boundary  $q_1 = \bar{q}$  of the two regions. Since  $c\delta\gamma q_1 - (h+\delta-\delta^2)\gamma^2 q_1^2$  evaluated at  $\gamma q_1 = \bar{q}$  is  $\frac{c\delta\bar{q}}{2}$ , this is true. The derivative of  $\Pi_2^*(q_1)$  with respect to  $q_1$  for the region  $q_1 < \bar{q}$  is  $2\gamma^2 q_1(\delta^2 - \delta - h) + c\delta\gamma$ . It should be positive since increasing  $q_1$  relaxes the constraint. Indeed,  $2\gamma^2 q_1(\delta^2 - \delta - h) + c\delta\gamma > 0$  for  $\gamma q_1 < \bar{q}$ , which is exactly what defines Region 1. At the boundary, the derivative is 0, so not only is  $\Pi_2^*(q_1)$  continuous, but it is also continuously differentiable since  $\Pi_2^*(q_1)$  is constant for  $\gamma q_1 > \bar{q}$ . Therefore,  $\Pi(q_1) = (1 - q_1 - c)q_1 + \Pi_2^*(q_1)$  is also continuously differentiable. In addition, it is strictly concave in  $q_1$ .

Taking the derivative of  $\Pi(q_1)$  with respect to  $q_1$ , we find

$$1 - c - 2q_1 + (2\gamma^2 q_1(\delta^2 - \delta - h) + c\delta\gamma)I_{\{\gamma q_1 \leq \bar{q}\}}.$$

At the boundary  $\gamma q_1 = \bar{q}$ , the derivative is  $1 - c - 2\bar{q}/\gamma$ . If this is negative ( $\frac{\bar{q}}{\gamma} > \frac{1-c}{2}$ ), it means that the optimum is reached at  $\gamma q_1^* < \bar{q}$ ; if it is positive, the optimum is reached at  $\gamma q_1^* > \bar{q}$ . In the former case,  $q_1^* = \frac{1-c(1-\delta\gamma)}{2(1-\gamma^2(\delta^2-\delta-h))}$  and the remanufacturing quantity in period 2 is constrained by  $\gamma q_1$ ; which gives  $\Pi^* = \frac{(1-c)^2}{4} + \frac{(1-c(1-\delta\gamma))^2}{4(1+\gamma^2(h+\delta-\delta^2))}$ . In the latter case, the optimal solution is  $q_1^* = \frac{1-c}{2}$  and the remanufacturing quantity in period 2 is unconstrained by  $\gamma q_1$ ; which gives  $\Pi^* = \frac{(1-c)^2}{2} + \frac{c\delta\bar{q}}{2}$ . Finally, note that the condition  $\frac{\bar{q}}{\gamma} > \frac{1-c}{2}$  can be rewritten as  $h < \tilde{h} \doteq \frac{\delta c - \delta\gamma(1-\delta)(1-c)}{(1-c)\gamma}$ . ■



**Proof of Proposition 3.** Recall  $\tilde{h} = \frac{\delta c - \delta \gamma (1 - \delta)(1 - c)}{(1 - c)\gamma}$ . For  $h < \tilde{h}$ ,  $\Delta_1 \doteq \Pi^* - \tilde{\Pi}^* = \frac{(1 - c(1 - \delta\gamma))^2}{4(1 + \gamma^2(h + \delta - \delta^2))} - \frac{(1 - c)^2}{4}$ . For  $h \geq \tilde{h}$ ,  $\Delta_2 \doteq \Pi^* - \tilde{\Pi}^* = \frac{c\delta\bar{q}}{2}$ . Thus, the incremental profit as a function of  $h$  (not taking into account fixed costs) is  $\Delta(h) \doteq \Delta_1 I_{\{h < \tilde{h}\}} + \Delta_2 I_{\{h \geq \tilde{h}\}}$ . Since  $\Pi^*$  strictly decreases in  $h$ , we can find a threshold  $\bar{h}$  satisfying  $\Delta(\bar{h}) = F$ . When the threshold is reached in the region where  $h < \tilde{h}$ , it has the form  $\bar{h} = \frac{4F(\gamma^2\delta^2 - \gamma^2\delta - 1) + \delta^2\gamma^2(1 - 2c + 2c^2) + \delta(2c\gamma(1 - c) - \gamma^2(1 - c)^2)}{\gamma^2((1 - c)^2 + 4F)}$  (obtained by solving for  $h$  in  $\Delta_1(h) = F$ ); when it is reached in the region  $h \geq \tilde{h}$ , it has the form  $\bar{h} = \frac{1}{4}\delta\frac{c^2\delta + 4F\delta - 4F}{F}$  (obtained by solving for  $h$  in  $\Delta_2(h) = F$ ). For  $h < \bar{h}$ , it is optimal for the manufacturer to remanufacture its products in period 2; otherwise it is more profitable to only offer new products in period 2. ■

**Proof of Proposition 4.** Maximizing (7) with respect to  $q_{2n}$  yields the unique solution  $q_{2n}^*(\bar{q}_{2r}) = \frac{1 - c - \delta\bar{q}_{2r}}{2}$ . For a given level of  $q_1$ , maximizing (8) with respect to  $\bar{q}_{2r}$  yields the unique solution  $\bar{q}_{2r}^*(q_{2n}) = \min(\gamma q_1, \frac{(1 - q_{2n})\delta}{2(\delta + h)})$ . Under our assumption that  $h > \frac{\delta(c - 1 + \delta)}{1 - c}$ , the two best-response curves intersect exactly once. First consider the lines  $q_{2n} = \frac{1 - c - \delta\bar{q}_{2r}}{2}$  and  $\bar{q}_{2r} = \frac{(1 - q_{2n})\delta}{2(\delta + h)}$ . Their intersection point is at  $\bar{q}_{2r} = \frac{(1 + c)\delta}{4\delta + 4h - \delta^2}$  and  $q_{2n} = \frac{2\delta + 2h - \delta^2 - 2c(\delta + h)}{4\delta + 4h - \delta^2}$ . Therefore, if  $\frac{(1 + c)\delta}{4\delta + 4h - \delta^2} < \gamma q_1$ , then this is the Nash equilibrium. Otherwise,  $\bar{q}_{2r}^n = \gamma q_1$  and  $q_{2n}^n = \frac{1 - c - \delta\gamma q_1}{2}$ . In the former case, the equilibrium profit is  $\frac{(2\delta + 2h - \delta^2 - 2c(\delta + h))^2}{(4\delta + 4h - \delta^2)^2}$  for the OEM and  $\frac{\delta^2(1 + c)^2(\delta + h)}{(4\delta + 4h - \delta^2)^2} - F$  for the entrant. In the latter case, the equilibrium profit is  $\left(\frac{1 - c - \delta\gamma q_1}{2}\right)^2$  for the OEM and  $\frac{\gamma q_1 \delta(1 + c) - (\gamma q_1)^2(2h + 2\delta - \delta^2)}{2} - F$  for the entrant. ■

## Appendix B : Derivation of Inverse Demand Functions

As stated in Assumption 4, we assume consumers' willingness-to-pay (valuations) are distributed uniformly in the interval  $\phi \in [0, 1]$  and that in any period, each consumer uses at most one unit. Therefore, for a total market size of  $M$  consumers, the quantity of product purchased at price  $p_1$  in the first period is  $q_1 = M(1 - p_1)$ . Normalizing the size of the market to 1 gives  $q_1 = 1 - p_1$ . Thus, the inverse demand function for the first period is  $p_1 = 1 - q_1$ .

For the second period inverse demand functions, we follow the lead of Desai and Purohit (1998) and derive them directly from the consumer utility functions. Note that the net utility,  $NU$ , from using a unit in the second period is

$$NU = \delta^m \phi - p_{2z}, \quad (9)$$

where  $m$  is an indicator variable such that  $m = 0$  if the unit is new,  $m = 1$  if the unit is remanufactured, and  $p_{2z}$  is the second period price of new ( $z = n$ ) or remanufactured ( $z = r$ ) units.

Consider the problem facing consumers in period 2. Each consumer has to choose from one of the three following strategies: (i) buy a new unit (N); (ii) buy a remanufactured unit (R); (iii) be inactive (X). In terms of consumer utility, if all three strategies are observed in equilibrium, then

consumers who follow a N strategy value the product more (i.e., have a higher  $\phi$ ) than consumers who follow a R strategy, who value it more than consumers who follow an X strategy.

Now consider the lowest valuation consumer who adopts an R strategy. This consumer is located at a point  $\phi' = 1 - q_{2n} - q_{2r}$  on the  $[0, 1]$  line and is indifferent between following a R and an X strategy. From (9), this consumer's net utility from a R strategy is  $\delta(1 - q_{2n} - q_{2r}) - p_{2r}$ , and the utility from following an X strategy is 0. Equating these two gives a second period price for the remanufactured product of

$$p_{2r} = \delta(1 - q_{2n} - q_{2r}) .$$

Finally, consider the lowest valuation of the consumer who adopts an N strategy. This consumer is located at a point  $\phi'' = 1 - q_{2n}$  and is indifferent between the N and R strategies. The net utility from a N strategy is  $1 - q_{2n} - p_{2n}$ . Similarly, the net utility from buying a remanufactured unit is  $\delta(1 - q_{2n}) - p_{2r}$ . Equating these two utilities gives a second period price of the new product of

$$p_{2n} = 1 - q_{2n} - \delta q_{2r} .$$

## Appendix C: Disposal Cost

In this section we add a disposal cost for units collected but not processed,  $y - x$ . The most likely scenario in this situation is a constant per unit cost that increases linearly in the number of units disposed. Let  $h_d$  represent the per unit cost of disposal. The firm's sub-optimization problem (4) of how many units to collect and what percentage to process is now:

$$\Lambda(x) = \min_{x \leq y \leq \gamma q_1} [h_c(y) + h_p(x, y) + h_d(y - x)] .$$

As before, we approximate the total cost to remanufacture  $x$  units as  $\bar{h}x^{\bar{\lambda}}$  where  $\bar{h}$  and  $\bar{\lambda}$  are found from a non-linear least squares fit of:

$$\sum_{x=1}^{\gamma q_1} (\bar{h}x^{\bar{\lambda}} - \Lambda(x)) .$$

As long as the least squares fit results in  $\bar{\lambda} > 1$  then all conceptual results based on Propositions 1-5 continue to hold but the threshold values that define the regions where remanufacturing is profitable will shift. In other words, as long as the total variable remanufacturing cost remains convex increasing then the OEM and the entrant still face the thresholds levels for  $\bar{h}$  and  $F$ , below which it is profitable to remanufacture. The inclusion of a disposal cost simply shifts these thresholds higher, making remanufacturing less attractive for both the OEM and the entrant. If disposal of the units results in a positive revenue instead of a cost, the thresholds would shift down and remanufacturing becomes more attractive than in the base case (no disposal cost).

For the choice of entry-deterrent strategy, Observations 2 and 3 also continue to hold. With everything else held constant, an increase in the new product manufacturing cost and/or the relative willingness-to-pay increases the attractiveness of the remanufacturing strategy. Observation 1 (a lower collection cost increases the attractiveness of the collection strategy) continues to hold as well, but the magnitude changes with the addition of a disposal cost. A disposal cost for unprocessed units increases both the OEM's collection cost and the entrant's variable remanufacturing cost. Thus, the quantity the OEM needs to collect to deter entry depends on both  $h_p$  and  $h_d$  as opposed to only  $h_p$  in the no disposal cost case.