The Effect of Competition on Recovery Strategies

Mark E. Ferguson*
College of Management, Georgia Institute of Technology
L. Beril Toktay†
Technology and Operations Management, INSEAD

December 2004

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 model the competition between new and remanufactured products produced by the same firm. The average cost to collect/remanufacture is modelled as an increasing function of the quantity collected/remanufactured, thus capturing a unique aspect of the remanufacturing industry that has not been explored in previous market segmentation research. Our findings provide firms with conditions where the revenue increase from remanufacturing exceeds the detrimental effect of cannibalization. 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 characterize conditions under which each strategy is more beneficial.

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

* Mark E. Ferguson, College of Management, Georgia Institute of Technology, Atlanta, GA 30332. Phone: (404) 894-4330, e-mail: mark.ferguson@mgt.gatech.edu.

† L. Beril Toktay, Technology and Operations Management, INSEAD, Boulevard de Constance, 77305 Fontainebleau Cedex, France. Phone: (33) 1 60 72 44 96, e-mail: beril.toktay@insead.edu.

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 cost to remanufacture plus the fixed cost needed to establish a remanufacturing operation 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, 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 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 average 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 provide conditions 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?

5. How does the OEM's recovery strategy change if the cost of collection and remanufacturing is convex versus linear in the number of units collected and remanufactured?

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 determining 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 collection/remanufacturing cost that increases in the quantity of units collected/remanufactured.

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 (Inderfurth 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 remanufacturable product and price.

Recently, a number of authors have started exploring market-related issues such as market segmentation, competition, and collection incentives. Debo et al. (2004) 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 (2003) 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 (2002) 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 (2002), 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 remanufacturing cost is linear in the total quantity collected and remanufactured. 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 characterizing the equilibrium solution and investigating the impact of various parameters on this solution. Debo et al. (2004), 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.

Several other papers separately address collection issues. Savaşkan et al. (2004) determine the optimal collection channel configuration of a monopolist manufacturer. 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. (2003) 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 cost of collection/remanufacturing increases with the number of units collected/remanufactured. In our analysis, we assume that all product can be collected, but that the average collection (and remanufacturing) cost increases in the volume collected (and remanufactured). We further assume that the original manufacturer has easier access to the used products - its average collection cost is lower than its competitor's.

Our results complement these 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 characterizing under what conditions each strategy is preferable. From a modelling perspective, a novelty is that we incorporate an average collection/remanufacturing cost that increases in volume, thus linking our competition models with the procurement models of Groenevelt and Majumder (2001b), Guide et al. (2003), and Ray et al. (2003). 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 (2002), and Ray et al. (2003).

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 δ 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 of 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' or 'refurbished' 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, refurbished 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 ϕ 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. This construction leads to the following linear inverse demand functions:

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

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

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

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

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 a given quantity level). 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.

Assumption 5. *The average cost of collection/remanufacturing increases in the quantity of the products collected/remanufactured.*

As the firm increases the quantity of used products collected, the average cost of acquiring these cores increases, and so does the average cost of remanufacturing them. The concept of collection or remanufacturing cost being convex increasing in the quantity has been identified in several studies (de Brito and de Koster 2004, Guide 2000, Guide and Van Wassenhove 2001). There are three main drivers behind this relationship: 1) Cores arrive in different states of initial quality so an increase in q_{2r} forces the firm to remanufacture cores of decreasing initial quality levels. An alternative situation, modelled in Guide et al. (2003), is where the firm pays higher prices for higher quality product returns. 2) Transportation cost increases in the collection of cores since the firm loses economies of scale as it moves from collecting cores in densely populated areas to collecting cores in more rural areas. 3) The acquisition cost for the cores increases in q_{2r} 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. (2003) through the use of trade-in rebates. To model this phenomenon, we assume that the total cost to collect x units is $h_c x^2$, giving an average cost to collect x units of $h_c x$. Similarly, the average cost to remanufacture x units is $h_r x$, giving an average collection and remanufacturing cost of hx per unit, where $h = h_c + h_r$. We later compare our results to the case when collection and remanufacturing costs increase linearly in volume (Appendix B).

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_r, is the cost of setting up the remanufacturing 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 $F = F_c + F_r$.

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. At the beginning of the second period, q_1 cores are available to purchase. The quantity of new product the OEM can produce is not capacity constrained, no more than the q_1 cores available can be remanufactured, i.e., $q_{2r} \leq q_1$. 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 new product	c	Cost to produce new product
			δ	Relative willingness-to-pay
			$h_c x$	Average cost to collect x units
			$h_r x$	Average cost to remanufacture x units
			h	$h = h_c + h_r$
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_r	Fixed cost of remanufacturing
			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. (2004) and Ferguson and Koenigsberg (2003) with one important difference: In this model, the average 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.

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

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

The total 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. In this case, the OEM starts the second period with the opportunity to recover 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

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

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

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.*

$Case$	$q^*_{2n}(q_1)$	$q^*_{2r}(q_1)$	$p^*_{2n}(q_1)$	$p^*_{2r}(q_1)$	$\Pi^*_2(q_1) \doteq \Pi_2(q^*_{2n}, q^*_{2r}\|q_1)$
$q_1 \le \bar{q}$	$\frac{1-c}{2} - \delta q_1$	q_1	$\frac{1+c}{2}$	$\frac{\delta(1+c-2q_1(1-\delta))}{2}$	$\frac{(1-c)^2}{4} + c\delta q_1 - (h+\delta-\delta^2)q_1^2$
$q_1 > \bar{q}$	$\frac{1}{2} - (1+\frac{h}{\delta})\bar{q}$	$\bar{q}$	$\frac{1+c}{2}$	$\frac{\delta}{2} + h\bar{q}$	$\frac{(1-c)^2}{4} + \frac{c\delta\bar{q}}{2}$

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

$Case$	$q^*_{2n}(q_1)$	$q^*_{2r}(q_1)$	$p^*_{2n}(q_1)$	$p^*_{2r}(q_1)$	$\Pi^*_2(q_1) \doteq \Pi_2(q^*_{2n}, q^*_{2r}\|q_1)$
$q_1 < \frac{1-c}{2\delta}$	$\frac{1-c}{2} - \delta q_1$	q_1	$\frac{1+c}{2}$	$\frac{\delta(1+c-2q_1(1-\delta))}{2}$	$\frac{(1-c)^2}{4} + c\delta q_1 - (h+\delta-\delta^2)q_1^2$
$\frac{1-c}{2\delta} \le q_1 \le \frac{\delta}{2(\delta+h)}$	0	q_1	$1 - \delta q_1$	$\delta - \delta q_1$	$\delta q_1 - (\delta+h)q_1^2$
$q_1 > \frac{\delta}{2(\delta+h)}$	0	$\frac{\delta}{2(\delta+h)}$	$1 - \frac{\delta^2}{2(\delta+h)}$	$\delta - \frac{\delta^2}{2(\delta+h)}$	$\frac{\delta^2}{4(\delta+h)}$

Under Condition 1, where the OEM prefers to sell both products, as q_1 increases, q^*_{2r} is first constrained by q_1 and then unconstrained. Under Condition 2, as q_1 increases, first the maximum possible amount of remanufacturing takes place, but new products are still manufactured, then the maximum possible amount of remanufacturing takes place, and new products are not manufactured, and finally, only remanufactured products are put on the market, but not all the cores are used. Thus, we infer that the latter case is where the remanufactured product is so profitable that the OEM prefers to put only this product on the market. Since in practice, this case 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 $\delta \le 1-c$, then this is the only case possible, as the condition defining the case holds for any positive h.

Remark 2 *If* $F = 0$, *then remanufacturing in the second period is more profitable than not remanufacturing.*

The profit term $c\delta q_1 - (h+\delta-\delta^2)q_1^2$ increases from 0 to $\frac{c\delta\bar{q}}{2}$ in the interval $q_1 \in [0, \bar{q}]$, and the profit without remanufacturing is $\frac{(1-c)^2}{4}$, 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 needs to exceed F for the firm to consider remanufacturing, i.e. $\Pi_2^*(q_1) - \frac{(1-c)^2}{4} > F$ must hold.

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 3 *Let $F = 0$. If $h < \tilde{h} \doteq \frac{\delta(c-1+\delta)+c\delta(1-\delta)}{1-c}$, then $q_1^* = \frac{1-c(1-\delta)}{2(1+h+\delta(1-\delta))}$, the remanufacturing quantity in period 2 is constrained by q_1^*, and $\Pi^* = \frac{(1-c)^2}{4} + \frac{(1-c(1-\delta))^2}{4(1+h+\delta-\delta^2)}$. If $h \geq \tilde{h}$, then $q_1^* = \frac{1-c}{2}$, the remanufacturing quantity in period 2 is unconstrained by q_1^*, and $\Pi^* = \frac{(1-c)^2}{2} + \frac{c\delta\bar{q}}{2}$.*

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. Note that the expression $\frac{(1-c(1-\delta))^2}{4(1+h+\delta-\delta^2)}$ strictly decreases in h, and so does $\bar{q}$. Therefore, Π^* strictly decreases in h. This observation leads to the following result.

Proposition 4 *There exists a threshold level $\bar{h}$ for the cost of the remanufactured product above which the OEM only sells the new product. When the threshold is reached in the region where $h < \tilde{h}$, it has the form $\bar{h} = \frac{4F(\delta^2-\delta-1)+\delta^2(1-2c+2c^2)+\delta(4c-3c^2-1)}{(1-c)^2+4F}$; when it is reached in the region $h \geq \tilde{h}$, it has the form $\bar{h} = \frac{1}{4}\delta\frac{c^2\delta+4F\delta-4F}{F}$.*

Proposition 4 states that a remanufacturing cost 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 $c = .10$, $h = .005$, $\delta = .8$, 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. We begin by checking the conditions outlined in Proposition 4 to determine if it is profitable for the OEM to remanufacture. Since $\tilde{h}$ is negative, only the second form applies, with $\bar{h} = \frac{1}{4}\delta\frac{c^2\delta-4F+4F\delta}{F} = -0.08$. This means that even for $h = 0$, the fixed cost is too high to allow remanufacturing. Therefore, the OEM should not remanufacture. To check this result, 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 3 since $\tilde{h} = -0.07$, and is $\Pi^* = \frac{(1-c)^2}{2} + \frac{c\delta\bar{q}}{2} - F = 0.395$. Since $\tilde{\Pi}^* > \Pi^*$ our conclusion is verified.

5 OEM's Strategy under the Threat of Remanufacturing Competition

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 the average cost to remanufacture exceeds the threshold given by Proposition 4 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) and 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 analyze the two recovery strategies mentioned. §5.4 compares the two strategies and determines conditions under which each strategy is more profitable.

5.1 OEM 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

$$Max_{q_{2n}} \;\; \Pi_2(q_{2n}|\bar{q}_{2r}) = (p_{2n} - c)q_{2n} = (1 - q_{2n} - \delta\bar{q}_{2r} - c)q_{2n}. \tag{5}$$

The entrant enters the second period with the opportunity to recover 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

$$Max_{\bar{q}_{2r}} \;\; \bar{\Pi}_2(\bar{q}_{2r}|q_{2n}, q_1) = (\bar{p}_{2r} - h\bar{q}_{2r})\bar{q}_{2r} - F = (\delta - \delta q_{2n} - \delta\bar{q}_{2r} - h\bar{q}_{2r})\bar{q}_{2r} - F \tag{6}$$

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

We assume that the threat of an entrant in the second period does not change the OEM's first period behavior. The OEM's only logical first-period response to potential competition in the second period would be to reduce its first-period production quantity so the entrant has less cores to remanufacture in the second period. It is very unlikely that such an action would ever take place in practice. (For completeness, we can characterize conditions under which such a reduction would not take place, and restrict our subsequent analysis to these conditions, but this is omitted for brevity.) With this restriction, we have that the OEM's optimal first-period solution is simply its monopoly quantity $q_1^* = \frac{1-c}{2}$ since this section focuses on cases where the monopolist OEM would not remanufacture. Let the superscript n represent the Nash equilibrium.

Proposition 5 *Let* $\tilde{q} \doteq \frac{(1+c)\delta}{4h+4\delta-\delta^2}$. *If* $q_1^* \geq \tilde{q}$ *then* $(q_{2n}^n, \bar{q}_{2r}^n) = (\frac{2\delta+2h-\delta^2-2c(\delta+h)}{4\delta+4h-\delta^2}, \frac{(1+c)\delta}{4\delta+4h-\delta^2})$, $\Pi_2(q_1^*) = \frac{\left(2\delta+2h-\delta^2-2c(\delta+h)\right)^2}{(4\delta+4h-\delta^2)^2}$, *and* $\bar{\Pi}_2(q_1^*) = \frac{\delta^2(1+c)^2(\delta+h)}{(4\delta+4h-\delta^2)^2} - F$. *If* $q_1^* < \tilde{q}$, *then* $(q_{2n}^n, \bar{q}_{2r}^n) = (\frac{1-c-\delta q_1^*}{2}, q_1^*)$, $\Pi_2(q_1^*) = \left(\frac{1-c-\delta q_1^*}{2}\right)^2$, *and* $\bar{\Pi}_2(q_1^*) = \frac{q_1^*\delta(1+c)-(q_1^*)^2(2h+2\delta-\delta^2)}{2} - F$.

As proven in Proposition 4, 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 δ; 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 5, we can find a similar remanufacturing cost threshold at which 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 δ; 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 $q_1^* = 0.45$. We check whether the entrant is constrained by q_1^* by checking the conditions outlined in Proposition 5. In this case $\tilde{q} = 0.34$, so $q_1^* \geq \tilde{q}$ and the entrant is not constrained. Since the entrant only sells in the second period,

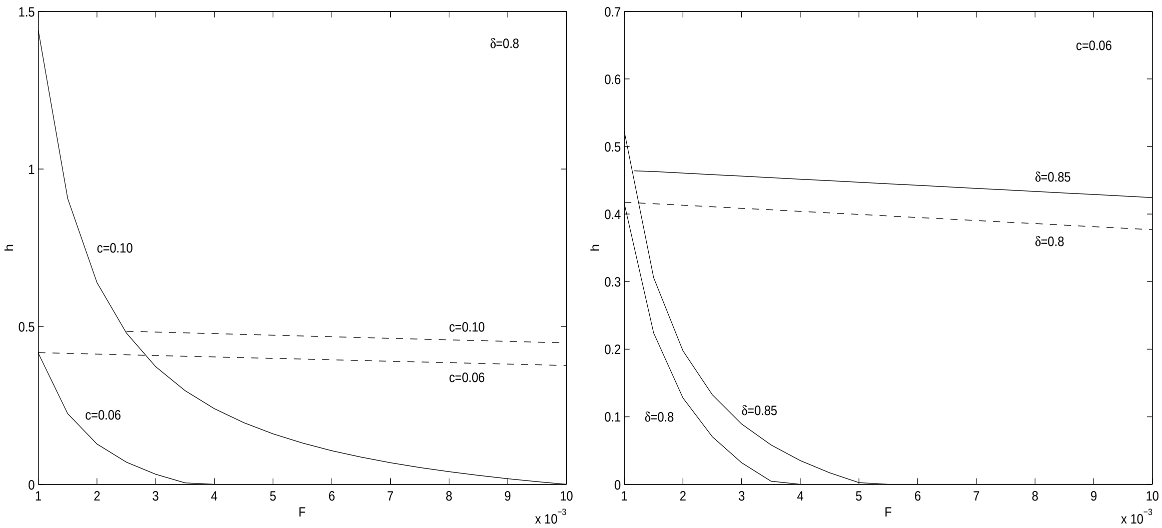

Figure 1: Pairs of OEM (solid line) and entrant (dashed line) indifference curves as a function of h and F. For each pair, in the region between the solid line and the dashed line, a monopolist OEM would not remanufacture, but an entrant would find it profitable to remanufacture.

its profit is $\bar{\Pi}_2(q_1^*) = \frac{\delta^2(1+c)^2(\delta+h)}{(4\delta+4h-\delta^2)^2} - F = .074$. The OEM's profit (under external competition) in the second period is $\Pi_2(q_1^*) = \frac{\left(2\delta+2h-\delta^2-2c(\delta+h)\right)^2}{(4\delta+4h-\delta^2)^2} = 0.099$, 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.

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

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. In addition to keeping the analysis tractable by limiting it to two competing products, this assumption is suitable in many settings: As explicitly modelled in Groenevelt and Majumder (2001a) and Ferrer and Swaminathan (2002), the OEM often enjoys a brand advantage over the entrant that makes it difficult for the entrant to compete when the OEM decides to remanufacture its product. (These authors keep the analysis tractable by assuming that the new and remanufactured products offered by the OEM are indistinguishable, thus also limiting their analysis to two differentiated products - the OEM's and the entrant's).

Under our assumption that the entrant will not find it profitable to offer the same remanufactured product as the OEM, the OEM may choose to remanufacture its product for the sole purpose of discouraging an external firm from doing so. Obviously, the timing of entry is important, but it is reasonable to assume that the OEM has the advantage in terms of entering the market with a remanufactured product. Thus, a strong signal by the OEM that it intends to remanufacture in the second period should be enough to ward off an outside firm from entering the remanufactured product market. The following example (using the same parameter values as Examples 1 and 2) shows that the OEM may indeed choose to remanufacture its product under the threat of competitor entry.

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 try to collect a portion, or all, of the used products and dispose or recycle 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 (e.g. through trade-in rebates) and thus can obtain the cores at the lower end of the quadratic 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 remanufacturing cost does not start at zero as in the original case but rather at hy. Therefore, by collecting cores, the OEM not only reduces the supply available to the entrant, but also makes the operation more expensive.

We introduce a new decision variable, q_c, the number of cores that the OEM decides to collect. 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. Then, the OEM's optimal collection strategy can be 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 optimal collection volume of the OEM in the absence of fixed cost on the entrant's part is presented in Proposition 6; call this volume $\hat{q}_c$. The optimal collection volume q_c^* under a fixed cost for the entrant is then found as follows: Calculate the level $\tilde{q}_c$ that would leave the entrant indifferent between entering the market or not (Algorithm 1 in Appendix A). If $\tilde{q}_c \leq \hat{q}_c$, then $q_c^* = \tilde{q}_c$ and the entrant is deterred; otherwise, $q_c^* = \hat{q}_c$ and the entrant collects and remanufactures used cores, creating competition for the OEM.

Proposition 6 *Let* $q_c^0 \doteq \frac{\delta(1+c)}{4h}$, $b \doteq \min(\frac{1-c}{2}, q_c^0)$, $\bar{q}_c = \frac{(1-c)(4h+4\delta-\delta^2)-2\delta(1+c)}{2\delta(4-\delta)}$, $q_c' = \frac{1-c}{2}\frac{2\delta-\delta^2}{4h_c-\delta^2}$ *and* $q_c'' = \frac{\delta h((1-c)(4\delta+4h)-2\delta^2)}{h_c(4h+4\delta-\delta^2)^2-4\delta^2h^2}$.
(i) $\frac{1-c}{2} \leq \frac{\delta(1+c)}{4h+4\delta-\delta^2}$. *If* $h_c \leq \frac{\delta^2}{4}$, *then* $\hat{q}_c = \frac{1-c}{2}$; *otherwise* $\hat{q}_c = \min(b, q_c')$. *The Nash equilibrium is* $\bar{q}_{2r}^n = \frac{1-c}{2} - \hat{q}_c$ *and* $q_{2n}^n = \frac{1-c-\delta\bar{q}_{2r}^n}{2}$.
(ii) $\frac{1-c}{2} > \frac{\delta(1+c)}{4h+4\delta-\delta^2}$ *and* $\bar{q}_c \geq b$. *If* $h_c \leq \frac{4\delta^2h^2}{(4h+4\delta-\delta^2)^2}$, *then* $\hat{q}_c = b$; *otherwise* $\hat{q}_c = \min(b, q_c'')$. *The Nash equilibrium is* $\bar{q}_{2r}^n = \frac{\delta(1+c)-4h\hat{q}_c}{4\delta+4h-\delta^2}$ *and* $q_{2n}^n = \frac{2\delta+2h-\delta^2-2c(\delta+h)+2\delta h\hat{q}_c}{4\delta+4h-\delta^2}$.
(iii) $\frac{1-c}{2} > \frac{\delta(1+c)}{4h+4\delta-\delta^2}$ *and* $\bar{q}_c < b$. *If* $q_c'' < \bar{q}_c$, *then* $\hat{q}_c = q_c''$; *otherwise, if* $\bar{q}_c \leq q_c' \leq b$, *then* $\hat{q}_c = q_c'$; *otherwise* $\hat{q}_c = b$. *If* $\hat{q}_c < \bar{q}_c$, *then the Nash equilibrium is as in case (ii); otherwise, it is as in case (i).*

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 $h_c = .001$ and $F_c = .005$. We have that $\frac{1-c}{2} = 0.45$, $q_c^0 = 44$, $b = 0.45$, $\bar{q}_c = 0.1098$, and $\frac{\delta(1+c)}{4h+4\delta-\delta^2} = 0.3411$. Therefore, case (iii) applies. Calculating q_c' and q_c'', we find that neither of the first two conditions are satisfied, so $\hat{q}_c = 0.45$. We now calculate $\tilde{q}_c$, the volume that leaves the entrant indifferent. Since we are in case (iii), we determine entrant profits using the Nash equilibrium solution of case (ii) for $q_c < \bar{q}_c$, and that of case (i) otherwise. We find that the entrant profit equals $F = 0.02$ for $q_c = 0.401$. Therefore, $\tilde{q}_c = 0.401$ and $q_c^* = \min(0.401, 0.45) = 0.401$. 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 collection strategy demonstrates the importance of modelling the collection and remanufacturing costs as convex increasing functions of the quantity. If these costs increase linearly in the quantity, the collection strategy becomes less attractive. In particular, when the cost is convex, 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 remanufacturing each 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. For a comparison of our results with those under a linear collection/remanufacturing cost, please refer to Appendix B.

5.4 Which Entry-Deterring 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, which are demonstrated in Figure 2.

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, OEM 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 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 cost of collection versus remanufacturing.

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.

Observation 3. *As relative willingness-to-pay δ 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 δ 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.

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 a cost-effective recovery 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

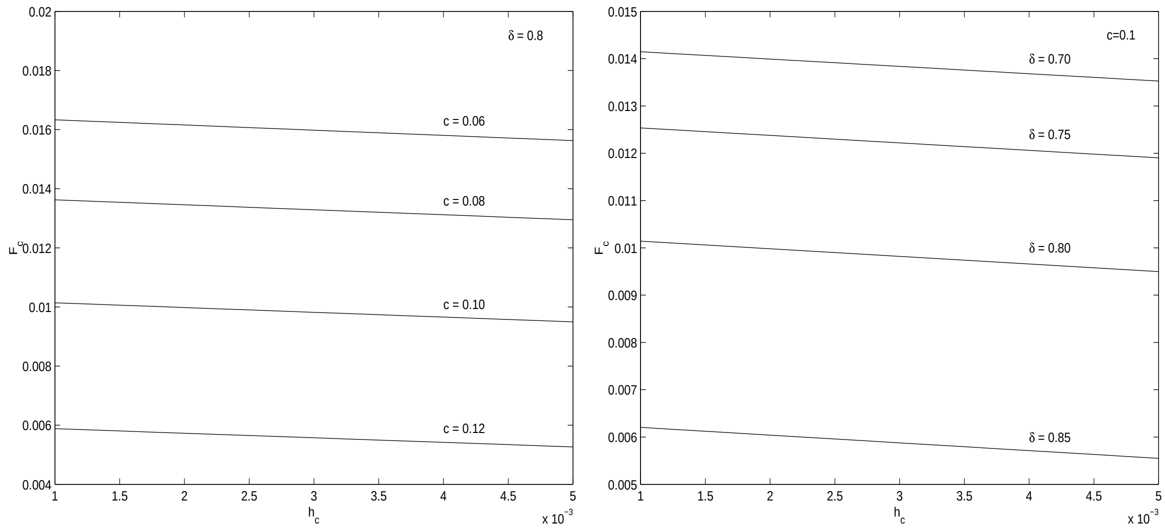

Figure 2: Indifference curves as a function of h_c and F_c for various values of c (left) and δ (right) with $h = 0.005$ and $F = 0.02$. The region to the southwest of each line is the area where collection is preferred to remanufacturing as an entry-deterrent strategy by the OEM.

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. Fixed costs are incurred to set up the collection and remanufacturing operations. The average cost of collection and remanufacturing increases in the quantity collected and 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 common misconception of many 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 although a monopolist OEM would find it more profitable to not 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. 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 remanufacturing. 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 will allow 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.

References

[1] Berko-Boateng, V. J., J. Azar, E. De Jong and G. A. Yander. 1993. Asset Recycle Management – A Total Approach to Product Design for the Environment. International Symposium on Electronics and the Environment, Arlington, VA, IEEE.

[2] Beullens, P., D. Van Oudheusden, L.N. Van Wassenhove. 2004. "Collection and Vehicle Routing Issues in Reverse Logistics," in *Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains*, R. Dekker, M. Fleischmann, K. Inderfurth, and L. N. Van Wassenhove, Eds, Springer Verlag.

[3] de Brito, M.P., M.B.M. de Koster. 2004. "Product Returns: Handling and Warehousing Issues," in *Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains*, R. Dekker, M. Fleischmann, K. Inderfurth, and L. N. Van Wassenhove, Eds, Springer Verlag.

[4] Debo, L., Toktay, B., and L. Van Wassenhove. 2004. "Market Segmentation and Production Technology Selection for Remanufacturable Products," forthcoming in *Management Science*.

[5] Desai, P. 2001. "Quality Segmentation in Spatial Markets: When Does Cannibalization Affect Product Line Design?" *Marketing Science*. 20(3), 265 – 283.

[6] Ferguson, M. and O. Koenigsberg. 2003. "Production and Pricing Decisions: How Should a Firm Manage a Product With Deteriorating Quality," Working Paper, Georgia Institute of Technology.

[7] Ferrer, G. and J. Swaminathan. 2002. "Managing New and Remanufactured Products." Working paper. The Kenan-Flagler Business School.

[8] Fleischmann, M. 2000. *Quantitative Models for Reverse Logistics*. PhD Thesis, Erasmus University, Rotterdam.

[9] Ginsburg, J. 2001. "Once Is Not Enough." *Business Week*. 04/16/2001, Issue 3728, p128-129B.

[10] Groenevelt, H., P. Majumder. 2001a. Competition in Remanufacturing. *Production and Operations Management* 10(2), 125–141.

[11] Groenevelt, H., P. Majumder. 2001b. Procurement Competition in Remanufacturing. Working Paper, Simon School of Business, University of Rochester.

[12] Gutowski, T. G., C. F. Murphy, D. T. Allen, D. J. Bauer, B. Bras, T. S. Piwonka, P. S. Sheng, J. W. Sutherland, D. L. Thurston and E. E. Wolff. 2001. Environmentally Benign Manufacturing. Baltimore, MD, International Technology Research Institute, World Technology (WTEC) Division.

[13] Guide, Jr., V. D. R., R. Srivastava, M. Kraus. 1997. Product Structure Complexity and Scheduling of Operations in Recoverable Manufacturing. *International Journal of Production Research* 35, 3179–3199.

[14] Guide, Jr., V.D.R., S.R. Srivastava. 1998. Inventory Buffers in Recoverable Manufacturing. *Journal of Operations Management,* 16, 551–568.

[15] Guide, Jr., V.D.R. 2000. "Production Planning and Control for Remanufacturing: Industry Practice and Research Needs." *Journal of Operations Management.* 18(4), 467 – 483.

[16] Guide Jr., V.D.R. and L.N. Van Wassenhove. 2001. "Managing Product Returns for Remanufacturing." *Production and Operations Management*. 10(2), 142 – 155.

[17] Guide Jr., V.D.R. and L.N. Van Wassenhove. 2002. "Managing Product Returns at Hewlett Packard," INSEAD Case.

[18] Guide Jr., V.D.R., R.H Teunter and L.N. Van Wassenhove. 2003. "Matching Demand and Supply to Maximize Profits from Remanufacturing." *Manufacturing and Service Operations Management*. 5(4), 303 – 316.

[19] Inderfurth, K., and I. Langella. 2003. "An Overview of Issues Facing Automotive Component Remanufacturers," Presented at the Closed Loop Supply Chain workshop held at Penn State University.

[20] Inderfurth, K.,S.D.P. Flapper, A.J.D. Lambert, C. P. Pappis, T.G. Voutsinas. 2004. "Production Planning for Product Recovery Management," in *Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains*, R. Dekker, M. Fleischmann, K. Inderfurth, and L. N. Van Wassenhove, Eds, Springer Verlag.

[21] Johnson, D. "Beware Cowboys." *Professional Engineering*. 10/31/2001, 14(20), 59.

[22] Kandra A. 2002. "Refurbished PCs: Sweet Deals of Lemons?" From the April 2002 issue of the PC World Magazine.

[23] Katz, M. 1984. "Firm Specific Differentiation and Competition Among MultiProduct Firms." *Journal of Business.* 57 149-166.

[24] Kokkinaki, A., R. Zuidwijk, J. van Nunen, R. Dekker. 2004. "ICT Enabling Reverse Logistics," in *Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains*, R. Dekker, M. Fleischmann, K. Inderfurth, and L. N. Van Wassenhove, Eds, Springer Verlag.

[25] Lund, R. T., F.D. Skeels. 1983. "Start-up Guidelines for the Independent Remanufacturer," Center for Policy Alternatives, Massachusetts Institute of Technology.

[26] Minner, S., G. Lindner. 2004. "Lot Sizing Decisions in Product Recovery Management," in *Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains*, R. Dekker, M. Fleischmann, K. Inderfurth, and L. N. Van Wassenhove, Eds, Springer Verlag.

[27] Moorthy, K. 1984. "Market Segmentation, Self-Selection and Product Line Design." *Marketing Science*. 3(4), 288 – 305.

[28] Moorthy, K. 1988. "Product and Price Competition in a Duopoly." *Marketing Science*. 7(2), 141 – 168.

[29] Mussa, M., S. Rosen. 1978. Monopoly and Product Quality. *Journal of Economic Theory* 18, 301 – 317.

[30] Préjean, M. 1989. *Half-soles, Kettles and Cures, Milestones in the Tire Retreading and Repairing Industry*. American Retreaders' Association.

[31] Ray, S., T. Boyacı, and N. Aras. 2003. Optimal Prices and Trade-in Rebates for Durable Products. Working Paper, McGill University.

[32] Savaşkan, R. C., S. Bhattacharya, L. N. Van Wassenhove. 2004. Closed-Loop Supply Chain Models with Product Remanufacturing. *Management Science*. 50(2), 239 – 252.

[33] Tirole, J. 1988. *The Theory of Industrial Organization*. The MIT Press, Cambridge, MA.

[34] Thorn, B.K. and P. Rogerson. 2002. "Take It Back." *IIE Solutions*. 34(4), 34 – 40.

[35] Toktay, L.B., L.M. Wein, S.A. Zenios. 2000. Inventory Management of Remanufacturable Products. *Management Science*, 46(11), 1412–1426.

[36] Toktay, L.B., E.A. van der Laan, M.P. de Brito. 2004. "Managing Product Returns: The Role of Forecasting," in *Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains*, R. Dekker, M. Fleischmann, K. Inderfurth, and L. N. Van Wassenhove, Eds, Springer Verlag.

[37] U.S Environmental Protection Agency. 1997. "Remanufactured Products: Good As New." WasteWi$e Update. Solid Waste and Emergency Response (5306W). EPA530-N-97-002. May 1997.

[38] U.S. Environmental Protection Agency. 2002. MSW Facts and Figures: State MSW Data. Updated October 29, 2002. <http://www.epa.gov/epaoswer/non-hw/muncpl/mswdata.htm>

[39] U.S. Environmental Protection Agency. 2003a. Municipal Solid Waste. Basic Facts. Updated November 12th, 2003a. <http://www.epa.gov/epaoswer/non-hw/muncpl/facts.htm>

[40] U.S. Environmental Protection Agency. 2003b. Industrial Waste Management. Updated April 22th, 2003. <http://www.epa.gov/epaoswer/non-hw/industd/index.htm>

[41] Valenta, R. 2004. "Product Recovery at Robert Bosch Tools, North America," Presentation at the 2004 Closed-Loop Supply Chains Workshop held at INSEAD, Fontainebleau, France.

[42] van der Laan, E.A., G. Kiesmuller, R. Kuik, D. Vlachos, R. Dekker. 2004. "Stochastic Inventory Control for Product Recovery," in *Reverse Logistics: Quantitative Models for Closed-Loop Supply Chains*, R. Dekker, M. Fleischmann, K. Inderfurth, and L. N. Van Wassenhove, Eds, Springer Verlag.

[43] www.atlex.com. 2003. "About Lexmark's Prebate Program," http://www.atlex.com/lexmark/lexmark-prebate-program.htm; last modified April 10, 2003; accessed December 20, 2004.

Appendix A: Proofs

Proof of Proposition 1.

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

$$s.t. q_{2r} \le q_1,\ q_{2n} \ge 0,\ q_{2r} \ge 0.$$

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

$$\mathcal{L}(q_{2n},q_{2r},\lambda) = (1-q_{2n}-\delta q_{2r}-c)q_{2n} + \delta(1-q_{2n}-q_{2r})q_{2r} - hq_r^2 - \lambda(q_{2r}-q_1) + \mu_1 q_{2n} + \mu_2 q_{2r}.$$

$$\frac{\partial \mathcal{L}}{\partial q_{2n}} = -2q_{2n} + 1 - 2\delta q_{2r} - c + \mu_1$$

$$\frac{\partial \mathcal{L}}{\partial q_{2r}} = -2\delta q_{2n} - 2(\delta+h)q_{2r} + \delta - \lambda + \mu_2$$

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

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

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

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

Table 2a

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

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

Table 2c

The expressions in this table can be simplified:

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

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: $\frac{1-c}{2\delta} > -\frac{\delta c}{2(\delta^2-\delta-h)}$ 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 $q_1 \leq -\frac{\delta c}{2(\delta^2-\delta-h)}$ and $q_1 > -\frac{\delta c}{2(\delta^2-\delta-h)}$, 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 $q_1 < \frac{1-c}{2\delta}$, $\frac{1-c}{2\delta} \leq q_1 \leq \frac{\delta}{2(\delta+h)}$, and $q_1 > \frac{\delta}{2(\delta+h)}$, respectively.

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

Proof of Proposition 3. 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 $c\delta q_1 - (h + \delta - \delta^2)q_1^2$ evaluated at $q_1 = \bar{q}$ 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 $2q_1(\delta^2 - \delta - h) + c\delta$. It should be positive since increasing q_1 relaxes the constraint. Indeed, $2q_1(\delta^2 - \delta - h) + c\delta > 0$ for $q_1 < \bar{q}$, 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 $q_1 > \bar{q}$. 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

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

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

Proof of Proposition 4. Recall $\tilde{h} = \frac{\delta(c-1+\delta)+c\delta(1-\delta)}{1-c}$. For $h < \tilde{h}$, $\Delta_1 \doteq \Pi^* - \tilde{\Pi}^* = \frac{(1-c(1-\delta))^2}{4(1+h+\delta-\delta^2)} - \frac{(1-c)^2}{4}$. 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 Π^* 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 $\bar{h} = \frac{4F(\delta^2-\delta-1)+\delta^2(1-2c+2c^2)+\delta(4c-3c^2-1)}{(1-c)^2+4F}$ (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 5. Maximizing (5) with respect to q_{2n} yields the unique solution $q_{2n}^*(\bar{q}_{2r}) = \frac{1-c-\delta\bar{q}_{2r}}{2}$. Maximizing (6) with respect to $\bar{q}_{2r}$ yields the unique solution $\bar{q}_{2r}^*(q_{2n}) = \min(q_1^*, \frac{(1-q_{2n})\delta}{2(\delta+h)})$. 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 $\frac{(1+c)\delta}{4\delta+4h-\delta^2} < q_1^*$, then this is the Nash equilibrium. Otherwise, $\bar{q}_{2r}^{n} = q_1^*$ and $q_{2n}^{n} = \frac{1-c-\delta q_1^*}{2}$. In the former case, the equilibrium profit is $\frac{\left(2\delta+2h-\delta^2-2c(\delta+h)\right)^2}{(4\delta+4h-\delta^2)^2}$ for the OEM and $\frac{\delta^2(1+c)^2(\delta+h)}{(4\delta+4h-\delta^2)^2}$ for the entrant. In the latter case, the equilibrium profit is $\left(\frac{1-c-\delta q_1^*}{2}\right)^2$ for the OEM and $\frac{q_1\delta(1+c)-(q_1^*)^2(2h+2\delta-\delta^2)}{2}$ for the entrant. ■

Proof of Proposition 6. The second-period profits of the OEM and the entrant including the variable cost of collection (but assuming no fixed cost) are the following:

$$\Pi_2^c = (1 - q_{2n} - \delta\bar{q}_{2r} - c)q_{2n} - h_c q_c^2$$

$$\bar{\Pi}_2^c = (\delta - \delta q_{2n} - \delta\bar{q}_{2r})\bar{q}_{2r} - h(\bar{q}_{2r}^2 + 2\bar{q}_{2r}q_c).$$

Their best responses given $q_c \leq q_1$ are:

$$q_{2n}^*(\bar{q}_{2r}) = (1 - c - \delta\bar{q}_{2r})/2$$

$$\bar{q}_{2r}^*(q_{2n}) = \min\left[q_1 - q_c, \left(\frac{(1-q_{2n})\delta - 2hq_c}{2(\delta+h)}\right)^+\right].$$

Solving these two equations simultaneously assuming that $\frac{(1-q_{2n})\delta-2hq_c}{2(\delta+h)}$ is positive, we find that the Nash equilibrium can take one of two forms:

$$(i)\quad \bar{q}_{2r}^{n,1} = q_1 - q_c, \quad q_{2n}^{n,1} = \frac{1-c-\delta(q_1-q_c)}{2}$$

$$(ii)\quad \bar{q}_{2r}^{n,2} = \frac{\delta(1+c)-4hq_c}{4\delta+4h-\delta^2}, \quad q_{2n}^{n,2} = \frac{2\delta+2h-\delta^2-2c(\delta+h)+2\delta h q_c}{4\delta+4h-\delta^2}.$$

In the first case, the entrant uses all available cores, in the second, not. The optimal solution for the OEM is to collect all cores and drive out the entrant entirely, or collect only a portion of the cores, and let the entrant compete on the same market. The choice will depend on the cost of collection versus loss of profit due to competition.

The first case applies for a given q_c if $q_1 - q_c < \frac{\delta(1+c)-4hq_c}{4\delta+4h-\delta^2}$, otherwise, the second case applies. The proof proceeds by checking which of the two cases applies for different parameter values. As before, we assume that the threat of an entrant in the second period does not change the OEM's first period behavior. Thus, the OEM's optimal first period solution is simply its monopoly quantity $q_1^* = \frac{1-c}{2}$. Therefore, we will take $q_1 = \frac{1-c}{2}$ in what follows. Let $q_c^0 = \frac{\delta(1+c)}{4h}$. Define $b \doteq \min(\frac{1-c}{2}, q_c^0)$. First, we evaluate $\bar{q}_{2r}^{n,1}$ and $\bar{q}_{2r}^{n,2}$, obtaining $\frac{1-c}{2}$ and $\frac{\delta(1+c)}{4\delta+4h-\delta^2}$, respectively. As q_c increases, $\bar{q}_{2r}^{n,1}$ decreases with a slope of 1 and $\bar{q}_{2r}^{n,2}$ decreases with slope of $\frac{4h}{4\delta+4h-\delta^2}$, which is less than 1. Thus, if $\frac{1-c}{2} \leq \frac{\delta(1+c)}{4\delta+4h-\delta^2}$, then $\bar{q}_{2r}^{n,1} < \bar{q}_{2r}^{n,2}$ $\forall q_c \in (0, b]$ and the Nash equilibrium at the optimal value of q_c has the form in case (i). If $\frac{1-c}{2} > \frac{\delta(1+c)}{4\delta+4h-\delta^2}$, we can have two cases: Either $\bar{q}_{2r}^{n,1} > \bar{q}_{2r}^{n,2}$ $\forall q_c \in [0, b]$, and the Nash equilibrium at the optimal value of q_c has the form in case (ii); or $\bar{q}_{2r}^{n,1} > \bar{q}_{2r}^{n,2}$ $\forall q_c \in [0, \bar{q}_c)$ and $\bar{q}_{2r}^{n,1} < \bar{q}_{2r}^{n,2}$ $\forall q_c \in (\bar{q}_c, b]$, and the Nash equilibrium at the optimal value of q_c has the form in case (i) or (ii) depending on which region this value falls in. To find $\bar{q}_c$, we solve for the root of $\bar{q}_{2r}^{n,1} = \bar{q}_{2r}^{n,2}$ and obtain $\bar{q}_c = \frac{(1-c)(4h+4\delta-\delta^2)-2\delta(1+c)}{2\delta(4-\delta)}$.

Now we need to determine the optimal solution $\hat{q}_c$ by maximizing the OEM's second period profits as a function of q_c. Substituting $\bar{q}_{2r}^{n,1}$ and $q_{2n}^{n,1}$ into Π_2^c, we find that Π_2^c strictly increases in q_c if $h_c \le \frac{\delta^2}{4}$, and is maximized at $q_c' \doteq \frac{1-c}{2}\frac{2\delta-\delta^2}{4h_c-\delta^2}$ otherwise. Substituting $\bar{q}_{2r}^{n,2}$ and $q_{2n}^{n,2}$ into Π_2^c, we find that Π_2^c strictly increases in q_c if $h_c \le \frac{4\delta^2 h^2}{(4h+4\delta-\delta^2)^2}$, and is maximized at $q_c'' \doteq \frac{\delta h((1-c)(4\delta+4h)-2\delta^2)}{h_c(4h+4\delta-\delta^2)^2-4\delta^2h^2}$ otherwise.

Combining these results with the cases described at the end of the previous paragraph yields cases (i), (ii) and (iii) in Proposition 6. ■

Algorithm 1. We wish to find $\tilde{q}_c$ that leaves the entrant indifferent between entering the market or not. In the proof of Proposition 6, we characterized the Nash equilibrium in two cases. We can numerically find $\tilde{q}_c$ as follows:

1. Find q_c such that $\bar{\Pi}_2^c = F$ under case (i); call it q_c^1.

2. Find q_c such that $\bar{\Pi}_2^c = F$ under case (ii); call it q_c^2.

3. If the parameters of the problem satisfy case (i) in Proposition 6, then $\tilde{q}_c = (q_c^1)^+$. If they satisfy case (ii), then $\tilde{q}_c = (q_c^2)^+$. If they satisfy case (iii), then $\tilde{q}_c = (q_c^2)^+$ if $q_c^2 \le \bar{q}_c$, and $\tilde{q}_c = q_c^1$ if $q_c^1 \in [\bar{q}_c, b]$.

Appendix B: Impact of Remanufacturing Cost Structure

In our analysis, we assumed the collection/remanufacturing cost to be a convex increasing function of volume (Assumption 5). While we believe that this assumption fits the majority of industrial applications, most previous literature assumes collection and remanufacturing costs that increase linearly in volume, and there may exist applications in practice where this is true. Therefore, we compare our earlier results to this case to see how a firm's optimal decisions may differ when its collection and remanufacturing costs are linear. For brevity, results are stated without proof since the proofs are similar to the ones for the quadratic case.

Monopoly Profits.

Proposition 7 *Assume that the remanufacturing cost is linear, with unit cost h, and $c < 1$. Let $\bar{q} = \frac{\delta c - h}{2\delta(1-\delta)}$. The following three conditions outline the OEM's optimal second-period solution:*

Condition 1. Suppose $h \ge \delta c$. The OEM does not remanufacture and the optimal second-period solution is given by (4). Condition 2. Suppose $\delta c > h > c - 1 + \delta = c\delta - (1-c)(1-\delta)$. The optimal solution is summarized in the table below.

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

Condition 3. Suppose $h \leq c - 1 + \delta$. The optimal solution is summarized in the table below.

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

Under Condition 1, the OEM does not remanufacture. Under Condition 2, the OEM prefers to produce both new and remanufactured units. Under Condition 3, the per-unit remanufacturing cost is so low that the OEM desires to sell only remanufactured product up to the monopoly quantity. Comparing Proposition 7 to the results in Proposition 1, we observe the following.

Remark 8 *If $F = 0$, then the OEM always remanufactures for the convex increasing case but does not remanufacture in the linearly increasing case when $h > \delta c$.*

To understand the condition for not remanufacturing, $h > \delta c$, assume that the OEM chooses its new product price to equal its production cost $p_{2n} = c$. This price represents the lower bound of what it can sell its new product for without losing money on the sale. Given this price for the new product, the maximum a customer is willing to pay for a remanufactured product is $p_{2r} = \delta c$ based on Assumption 4. If the OEM incurs a per-unit remanufacturing cost greater than this price, then each sale results in a negative profit contribution. Thus, $h < \delta c$ is a necessary condition for the OEM to consider remanufacturing, corresponding to Condition 1 above.

In the remainder of this section, as with Proposition 1, we focus on the second condition ($\delta c > h > c - 1 + \delta$). As before, the last condition holds trivially if $\delta < 1 - c$.

Proposition 9 *If $h < \delta(c-1+\delta) + c\delta(1-\delta)$, then $q_1^* = \frac{1-c(1-\delta)-h}{2(1+\delta(1-\delta))}$, the remanufacturing quantity in period 2 is constrained by q_1^*, and $\Pi^* = \frac{(1-c)^2}{4} + \frac{(1-c(1-\delta)-h)^2}{4(1+\delta-\delta^2)}$. If $h \geq \delta(c-1+\delta) + c\delta(1-\delta)$, then $q_1^* = \frac{1-c}{2}$, the remanufacturing quantity in period 2 is unconstrained by q_1^*, and $\Pi^* = \frac{(1-c)^2}{2} + \frac{(c\delta-h)\bar{q}}{2}$.*

Comparing with Proposition 3, we see that the structure of the solution is the same, but that the threshold is lower in the linear case. In other words, for the same parameter h, the second-period is unconstrained for a larger range of remanufacturing costs. This is because for the same value of h, remanufacturing in the linear case is more expensive for all feasible values of q_{2r} (since we normalized the maximum volume to 1). When h is different in the two cases such that the nonlinear case is more expensive for high values of q_{2r}, the opposite effect would be seen for some parameter values.

Profits under Remanufacturing Competition.

Proposition 10 *Let* $\tilde{q} \doteq \frac{(1+c)\delta-2h}{4\delta-\delta^2}$. *If* $q_1^* \geq \tilde{q}$, *then* $(q_{2n}^n, \bar{q}_{2r}^n) = (\frac{2(1-c)-\delta+h}{4-\delta}, \frac{(1+c)\delta-2h}{4\delta-\delta^2})$, $\Pi_2(q_1^*) = \frac{(2(1-c)-\delta+h)^2}{(4-\delta)^2}$, *and* $\bar{\Pi}_2(q_1^*) = \frac{(\delta(1+c)-2h)^2}{\delta(4-\delta)^2}$. *If* $q_1^* < \tilde{q}$, *then* $(q_{2n}^n, \bar{q}_{2r}^n) = (\frac{1-c-\delta q_1^*}{2}, q_1^*)$, $\Pi_2(q_1^*) = \left(\frac{1-c-\delta q_1^*}{2}\right)^2$, *and* $\bar{\Pi}_2(q_1^*) = \frac{q_1^*(\delta(1+c)-2h)-(q_1^*)^2(2\delta-\delta^2)}{2}$.

Again, the structure of the policy is the same as in Proposition 5. Comparing with the quadratic case for the same value of h, the remanufactured product volume is lower and the new product volume is higher in equilibrium under the linear cost case unless $\bar{q}_{2r}^n = q_1^*$ in both cases, in which case the Nash equilibrium is the same. This is again because for h the same, the linear structure is more expensive for all values of q_{2r}. For h large enough in the quadratic case relative to the linear case, the opposite result would hold.

Collection as an Entry-Deterrent Strategy. A significant qualitative difference between the linear and the quadratic cases is observed if collection is used as an entry-deterrent strategy.

Proposition 11 *With linear collection cost* $h < \delta c$, *and* $F = 0$, $\bar{q}_{2r}^n = 0$ *if and only if* $q_c = q_1$.

This proposition focuses on cases where remanufacturing is independently profitable, and says that when the entrant does not have a fixed cost, the only way the OEM can drive out the entrant is to collect all the cores. In contrast, by inspecting Proposition 6, we see that it is possible for the OEM to drive out the entrant via partial collection even if $F = 0$ when the collection cost is nonlinear: In cases (ii) and (iii), if $\hat{q}_c = b < \frac{1-c}{2}$, then $\bar{q}_{2r}^n = 0$. This is because the marginal cost of the first unit it can collect becomes too high for the entrant to consider competing with the OEM by introducing a remanufactured product. Thus, assuming a linear collection cost would result in collection being deemed to be a less effective entry-deterrent strategy than it may truly be.