Revenue and Cost Management for Remanufactured Products

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Abstract

This paper studies joint pricing and remanufacturing strategy of a firm that decides to offer both new and remanufactured versions of its product in the market. In making this decision, the firm balances the additional revenue from selling remanufactured products, the demand cannibalization of new product sales, and the cost of remanufacturing. We present the model of the firm's decisions and complement it with a study of consumer behavior regarding the choice between new and remanufactured products. Our model does not rely on knowing consumers' willingness to pay (WTP), but rather on knowing the fraction of consumers who switch from the new to the remanufactured product. In the behavioral study, we find that the switching fraction has an inverted U-shape, and thus, the underlying consumer behavior cannot be modeled using the WTP approach.

Combining theoretical and behavioral results, we find that the firm follows one of three strategies – remanufacture nothing, remanufacture everything, or resell falsely returned products. We characterize the optimality conditions for each strategy and relate them to the underlying product and market parameters (consumer behavior, price, demand elasticity, and others).

We find that the firm that incorporates the inverted-U-shaped consumer behavior in its pricing and remanufacturing strategy could be receiving the incremental profit from remanufacturing that is up to two times higher than the firm that makes its decisions based on the WTP only. This happens because with the inverted-U, the firm remanufactures under broader conditions, charges a much lower price, and typically remanufactures more units. The latter suggests that a better understanding of consumer behavior has the potential, in addition to increasing profits, to benefit the environment by diverting more items from the waste stream. Lastly, we find that the size of the low-price market segment plays an important role because the firm reacts to it differently than the WTP-based logic would suggest.

1 Introduction

In many cases, firms that consider remanufacturing are rightly concerned that these remanufactured products offered at lower prices will cannibalize the sales of the higher-margin new products. As a result, many if not most firms do not offer remanufactured products together with new ones. For example, Dell has a separate Web site (www.delloutlet.com) where it sells its refurbished computers and accessories. At the same time, offering remanufactured products together with new ones allows firms to better segment their demand and capture sales to the "low-end" customers who will not purchase the new product. Therefore, even if some sales of the new product would be cannibalized, offering both new and remanufactured products could be profitable for the firm overall, provided that the price and the quantity of remanufactured products are selected properly.

The goal of this paper is to analyze the operations and pricing strategy for a firm that is considering putting remanufactured products on the market *together* with new products. We begin by providing the short case study that motivated our work.

1.1 Mini Case Study: R

This work was motivated by discussions with the management of company R (name disguised for confidentiality purposes) – a major wireless carrier in North America. R sells telephones, PDAs, and data devices as well as mobile voice and data plans that accompany these devices. R has an extensive network of retail outlets; it also sells its products and services online. In particular, in the spring of 2007, its Web site offered both new and refurbished* versions of a number of devices. For example, a popular PDA was offered at $399 new and $139 refurbished. Interestingly, with the default sort by price (ascending), R's customers saw the refurbished product well before seeing the new one.

With such a big price difference, the remanufactured product could be cannibalizing some sales of the new one. Yet R had both products available. This led us to study its marketing and operations with respect to remanufacturing. As a result, we learned that

*In the electronics industry "refurbished" and "remanufactured" are used as synonyms and we also use these terms interchangeably throughout the paper.

there are several key facts that differ from what is typically assumed in the literature.

First, R's remanufacturing operations had no effect on the pricing, procurement or other decisions about the new products. R's management noted that the pricing and procurement of new products is generally affected by such factors as the overall composition of R's product line, competitive moves, seasonal and regional promotions, and so on, the total of which bore a far greater weight on R's strategy than remanufacturing activities. They further noted that consumers have a negative perception of refurbished products, and pricing refurbished products too low can be interpreted by some consumers as a further negative signal about a product quality or popularity. At the same time, there exist other more price-sensitive and less quality-sensitive consumers who will "upgrade" to a refurbished version of an expensive product from a different lower-level new product. Thus R's goal in refurbished product pricing was to achieve a delicate balance with customer perceptions.

Pricing of refurbished products, however, was not R's primary concern; rather, it was the quantity of remanufactured products R wanted to put on the market. Underlying this was a decision about the number of remanufacturable cores[†] to acquire. The interplay of these two decisions is explained by the contractual arrangement of R's remanufacturing operation, described below.

R's remanufacturing activity is done by a third party (partly owned by R). R specifies both the number of cores to acquire and test (for which it pays a flat rate per core) and the number of units to refurbish. Refurbishing is priced on a tier-based scale. Refurbishing a tier-1 core costs R about three times the cost of testing, and tier-1 cores correspond to about 60% of the number of cores procured. Refurbishing a tier-2 core costs about nine times that of testing. Together, tier-1 and tier-2 cores account for more than 90% of all cores. There also exist tier-3 and tier-4 cores, the remanufacturing of which is much more costly. Interestingly, R's management was unable to say what, exactly, it would

[†]A "core" is a returned product that cannot be immediately resold as new – possibly opened, used, and/or defective product. By R's standards, which it believes are used industry-wide, a device with less than three minutes of airtime (most devices have a built-in lifetime timer that records total use time since the device was made) can be sold as new. Devices with more than three minutes of airtime, even if they look new and are fully functional, can only be sold as refurbished.

cost to remanufacture tier-3 and -4 cores, an indication how infrequently this happens in practice.

The different tiers reflect the heterogeneity in the condition of the cores. Indeed, the number of procured cores corresponds to so called false failure returns – the returns of effectively new products that "have no verifiable functional defect" (Ferguson et al. 2006). For example, think of a consumer who bought a fancy PDA and then discovered that the buttons were a bit too small for his somewhat larger-than-average fingers. The box is opened, some of the packaging is destroyed, but otherwise the product is fully functioning. That would be a tier-1 core. Once all such cores are exhausted, the remaining cores have something broken, e.g., parts or software. But still, it is often possible to find cores that have a combination of working parts that can be assembled into a working product. For example, if one telephone has a broken keyboard, and another has a broken screen, then taking the screen from the first one and putting it into the second results in a working telephone. Such a device would correspond to tier-2. Swapping the screens involves some labor and extra testing, and thus tier-2 rebuilds are more expensive. The remaining device (with keyboard and screen both broken) is much more expensive to refurbish, since new parts have to be bought: that would be tier-3 or -4.

The key implication of this tiered cost structure is that the marginal cost of remanufacturing could be decreased by acquiring more cores. This is indeed often done by R's management, which deliberately orders more cores than it plans to remanufacture.

In sum, with respect to remanufacturing a particular product, R is making three decisions: how many remanufacturable cores to acquire, how many products to remanufacture (of these acquired cores), and how to price them relative to the given price of the new product.

Beyond R, the features of the remanufacturing problem we described in this mini case study seem to be applicable rather generally. One could reasonably expect that in their remanufacturing activities, firms in many cases deal with at least some confirmation of the tiered cost structure, collection and remanufacturing decisions, no desire to "mess" with the new product's price, and consumers' judging quality from price.

These characteristics of R's problem, however, do not fit the existing models of remanufacturing well. On the revenue side, the interplay between quality perception and price (to our knowledge) has not been studied within the remanufacturing domain. On the cost side, tiered structure cost adds complexities beyond what most models assume (see Section 2 for literature review). R's problem calls for the development of a new model that integrates revenue and cost management components, and this paper presents such a model.

1.2 Contributions of the paper

This paper presents a new stylized model of how a firm makes remanufacturing decisions, one that more accurately describes the revenue and cost components of remanufacturing, and is supported by the study of consumer behavior with respect to the choice of new versus remanufactured products. The approach in this paper is distinguished from previous research (see Section 2) on both modeling and behavioral/empirical basis.

From the modeling perspective, our key contributions are the following. First, we separate the decisions about the number of cores to acquire and the number of units to remanufacture, and consider a nonlinear cost of remanufacturing where the marginal cost of remanufacturing a unit increases in the number of units to remanufacture, but decreases in the number of available cores (reflecting the tiered structure in the case of R). Second, with respect to consumer behavior, we do not rely on knowing the distribution of consumer willingness to pay (WTP), but rather suggest a construct where the firm's decisions are guided by estimating the fraction of consumers who, for a given price difference, would switch from the new to the remanufactured product. An implicit assumption behind any model that bases consumer choice on WTP is that "the cheaper, the better," i.e., that a consumer is willing to purchase the product at any price below his or her WTP. With respect to remanufactured consumer products, however, this assumption is not consistent with observed behaviors. In particular, consumers may judge the quality of the product from its price. A very low price may signal that the product is of an inferior quality, thus decreasing the number of consumers willing to purchase it. Such a relationship between price and perceived quality is well known in the marketing literature, for example, see Rao and Monroe (1989) or Völckner and Hofmann (2007). We also observe it in our behavioral study. Our model does not rely on knowing WTP and is therefore capable of accommodating such complex and realistic consumer behavior.

Further, estimating consumer behavior *relative* to the price and demand for the new product is arguably more robust: the behavior may be relatively stable as the firm changes its selling strategy for the new product in response to the general market environment (not related to remanufacturing). We discuss modeling assumptions in Section 3.

From the behavioral/empirical perspective, this paper is among the first to report a study of actual consumer behavior with respect to remanufactured products and analyze a firm's remanufacturing strategy based on both an analytical model and empirical data. In our study we estimate the fraction of consumers that for a given price difference would switch from purchasing new to purchasing remanufactured product; this fraction plays a central role in our analytical model. We do so in three steps: first, we conduct focus groups to determine the factors consumers consider in making a switching decision; second, we perform conjoint analysis to understand the relative importance of these factors; and third, controlling for the key nonprice factors, we isolate the effect of price and obtain the needed estimate through a survey.

We find that consumers have substantial uncertainty in terminology: Are returned/ refurbished/ remanufactured/ rebuilt/ reprocessed et cetera products actually the same, or is there a difference? This uncertainty is magnified by not knowing the product's history: Why was it returned, When, Where, What was wrong? and so forth. As our study shows, consumers would benefit if an independent third party would collect and provide such information (as Carfax does in the auto industry); consumers would then be more willing to purchase refurbished products.

In the study, we find that in the absence of such information, consumers use price to judge product quality. As a result, the fraction of consumers who switch from the new to the remanufactured product has an inverted U-shape – at a very low price, consumers suspect low product quality, and therefore few switch. Note that this behavior cannot be observed if one considers only WTP.

Combining the model and behavioral study, our main findings are the following. First, we show that considering switching behavior and incorporating convex cost that decreases in the number of acquired cores can and often does lead to an optimal solution where the firm procures many more cores than it ends up remanufacturing. We note that this qualitative conclusion (i.e., that the firm procures cores it does not remanufacture) has been discussed in the literature from cost minimization perspective (e.g., Galbreth and Blackburn 2006), and from the perspective of deferring competitive entry (e.g., Ferguson and Toktay 2005): the firm was acquiring cores in order to deter the entry of a third party (re)manufacturer. Our results demonstrate that firms have economic reasons beyond cost minimization and competitive threats for following such a strategy, thus enhancing its appeal to managers.

Second, we show how various attributes of products and their respective markets (price versus cost of collection and remanufacturing, percentage of falsely returned units, etc.) affect the remanufacturing strategy of the firm, thus providing firms with managerially relevant guidelines regarding their remanufacturing strategies.

Third, we estimate consumer switching behavior and show that it has an inverted U-shape. Most importantly, this implies that by charging a lower price for the remanufactured product, a firm may actually *decrease* consumer switching and hence minimize high-end demand cannibalization, while at the same time attracting more low-end price sensitive consumers. It is beneficial for the firm that consumers are uncertain about the quality of remanufactured products and infer quality from price. Otherwise, the firm would have to charge a higher price for the remanufactured product, and with the same degree of new product demand cannibalization, sell fewer remanufactured products to low-end consumers.

Fourth, we compare the solutions for the case when the firm correctly estimates consumer behavior to be inverted-U-shaped (firm-U) and the case when the firm (mistakenly) estimates that consumer behavior is driven by WTP (firm-W). We find that the incremental profit that firm-U receives from remanufacturing activities could be up to *two times higher* than that of firm-W (the difference is largest when the cost of new product is small, or, equivalently, when the decision about new product procurement is done independently of remanufacturing; as in the case of R). This happens because firm-U remanufactures under broader conditions, charges a much lower price, acquires more cores and remanufactures more units. The latter suggests that a better understanding of consumer behavior has the potential, in addition to increasing profits, to benefit the environment by diverting more items from the waste stream. We also find that, quite surprisingly, firms -U and -W react to the size of the low-end segment in the opposite manner: Whereas it is optimal for firm-U to increase its price as low-price demand grows, firm-W decreases its price. In fact, a firm may behave according to a "hybrid" of the two strategies and have discontinuities in its pricing strategy. We stress that these comparisons and intuition are unique to our work, because the described effects cannot be captured if one models consumer behavior using WTP only.

The paper is organized as follows. In Section 2 we position our work in the body of existing literature. In Section 3 we introduce the model and discuss its main assumptions. Section 4 presents the analysis of the remanufacturing strategy (the relationship between the number of cores to acquire and the number of units to remanufacture). Section 5 presents the study of consumer behavior and shows that the behavior has inverted-U shape. Section 6 studies joint pricing and remanufacturing strategy and discusses the implications of the inverted-U behavior. Section 7 summarizes the paper and discusses opportunities for future work. The paper is also accompanied by three online Appendices.

2 Literature Review

This work draws on three streams of literature: (i) collection of remanufacturable cores and cost minimization, (ii) market segmentation, competition and cannibalization in remanufacturing, and (iii) behavioral research in operations management in general and remanufacturing in particular.

Collection issues were the focus of early works on remanufacturing, which studied the design and operations of supply chains for reverse logistics, see, for example, Fleischmann et al. (1997) for a review of this earlier literature. More recently, however, collection decisions have been effectively ignored by remanufacturing researchers: in most works, the collection operation is presented as a constraint on the availability of remanufacturable cores, e.g., Ferguson and Toktay (2005). At the same time, as argued by Guide et al. (2003) and Galbreth and Blackburn (2006, 2010), whose work, like ours, is motivated by the cell-phone industry, the supply of remanufacturable cores from third-party brokers is essentially unlimited. Collection, therefore, is a decision, rather than a constraint (as is in the case of R discussed above). In Guide et al. (2003) the firm determines the price it will pay for a core of a certain tier (in our terminology), and thus the firm decides simultaneously on both the number and the quality of cores to acquire. The firm also chooses the price of the remanufactured product and maximizes profit, but in doing so, it oversimplifies market segmentation and cannibalization of new product sales. Galbreth and Blackburn (2006, 2010), like us, consider the number of cores to acquire as a separate decision. Their work, however, is framed as a cost minimization problem, where demand for remanufactured products is given exogenously. In contrast, we consider endogenous demand and pricing by linking the acquisition, remanufacturing and pricing (market segmentation) decisions.

Market segmentation, competition and cannibalization have been studied from a number of angles. For example, Majumder and Groenevelt (2001) and Ferrer and Swaminathan (2005) assume that refurbished products are indistinguishable from new ones and focus on the external competition. Debo et al. (2005), Ferguson and Toktay (2005), Jin et al. (2007) and Souza et al. (2007) assume that consumers value refurbished products less and, as a result, refurbished products are internal competitors to the new product. In addition, some papers also consider external competition from a third-party (re)manufacturer who may also collect the firm's used products, refurbish them, and offer them on the market, thus cannibalizing the firm's sales of the new product externally. Their main finding is that the firm may choose to remanufacture or preemptively collect used products to prevent competitive entry, even when the firm would not do so if it would be a monopoly. These works do not consider acquisition decisions, and further assume a fixed marginal cost of remanufacturing.[‡] Atasu et al. (2008) consider more elaborate demand patterns by including a "green segment" – the consumers who may be willing to pay more for the remanufactured product because of its environmental benefits. We do not consider a green segment, and, as the majority of researchers do, we assume that customers are willing to pay less for the refurbished product; however, we carefully consider the acquisition decisions and allow the cost of remanufacturing to depend upon the number of acquired cores, as suggested by Galbreth and Blackburn (2006, 2010) and

[‡]An exception is Ferguson and Toktay (2005) who, like us, consider a convex cost of remanufacturing. They, however, do not consider acquisition and do not capture the effect described in Galbreth and Blackburn (2006, 2010) as well as in our study of R, where the marginal cost decreases in the number of acquired cores.

the case study of R.

Ferguson and Koenigsberg (2007), even though they do not talk about remanufacturing per se, address the management of deteriorating inventory. In their two-period model, the firm in the second period may face an inventory of leftover product, for which customers are willing to pay less than what they would pay for the new product, which is similar to the firm's putting a refurbished product on the market. They find that the price of the new product is independent of the quality of leftover product (which in their model determines the differential of consumer willingness to pay for it). Motivated by the case of R, we assume a fixed price for the new product, which is consistent with their finding. We note that the majority of works consider pricing of the new product endogenously, which contradicts our experience with R.

Ferguson et al. (2006) consider the management of falsely returned items. In particular, they look at supply chain mechanisms that could reduce false return rates. We do not consider such mechanisms and focus on a single firm, but our remanufacturing cost function incorporates false returns.

Zikopoulos and Tagaras (2007) consider remanufacturing strategy (including collection at possibly more than one site) under the uncertainty in the condition of returns; Galbreth and Blackburn (2010) consider condition uncertainty as well. Our cost structure also represents heterogeneity in the conditions of cores, but since this uncertainty is not a primary focus of our paper, we substitute the distribution of conditions with the average outcome[§] (i.e., instead of considering that a core can be tier-2 with probability β we assume that a fraction β of cores are tier-2). Like some authors mentioned earlier Zikopoulos and Tagaras document that it may be optimal to collect more cores than firms end up remanufacturing. They discuss the drivers of this strategy and provide some managerial intuition (linking it to the transportation and sorting costs and quality distributions), but nevertheless note that in their model "... this behavior is coincidental." In our setting it is not coincidental: we rigorously prove that a firm may deliberately collect more than it ends up remanufacturing, thus strengthening the managerial appeal of such a strategy.

[§]This assumption is also supported by the findings of Galbreth and Blackburn (2010), who note that under some conditions the solution to their model with uncertain condition is "... very similar to that of a simple model that ignores condition uncertainty."

Our paper is also related to the literature that discusses the relationship between price and perceived quality. Such literature is abundant both in academic marketing, and in general business press. For example, the *Economist* writes[¶] "... retailers know that people will sometimes turn their noses up at a cheap version of a more expensive product, even if the two are essentially the same." Survey papers Rao and Monroe (1989) and Völkner and Hofmann (2007) cite over 100 works on this topic. Völkner and Hofmann (2007) conclude that "Managers must be aware that price-quality inferences remain important aspects of consumers behavior and consider them when setting prices... Managers should therefore be cautious when using discounts ... consumers likely make negative price-quality inferences and begin to doubt the quality of the product." Our paper, as far as we know, is the first work to consider price-perceived quality dependence in a remanufacturing context (and perhaps in operations management in general).

Finally, with respect to behavioral research in operations management, the body of behavioral work is growing, e.g., Bendoly et al. (2006) and Wu and Katok (2006). A survey of the bodies of knowledge for behavioral operations management is provided in Bendoly et al. (2008). The works involving remanufacturing, however, are very scarce. To our knowledge, Guide and Li (2009), who study cannibalization based on online auctions for computer networking equipment, is the only other work that considers a behavioral experiment in a remanufacturing context. In this paper, we report the results of consumer behavior research (focus groups, conjoint analysis and a survey study) with respect to purchasing remanufactured electronics, and comment on how this research integrates with the modeling results.

3 Model

We assume that there are two products: new (product 2) and remanufactured (product 1). These products are sold at prices p_2 and p_1, respectively. Price p_2 is fixed, as we discussed in the introduction and in the case study of R; price $p_1 \leq p_2$ is a decision variable.

In the absence of remanufactured product, the demand for the new product, to which we refer as the high-end demand, is D_2, which we assume to be known deterministically.

[¶]http://www.economist.com/displaystory.cfm?story_id=10530119

Given, however, that there is a remanufactured product on the market (which is cheaper but of lower quality) a fraction $\alpha(p_1) \in [0; 1]$ of the new product's demand switches to purchase the remanufactured product instead, provided that it is available.

By offering a remanufactured product at price p_1, the firm also attracts $D_1(p_1)$ new customers (to which we refer as the low-end demand), who would not purchase the new product; these customers would otherwise choose a different product/brand with lower price. We assume that the new product's price is selected "optimally" in the sense of $p_2 D_2 \geq p_1 D_1(p_1)$ for all $p_1 \leq p_2$. Managerially, this condition implies that if the firm decides not to remanufacture then simply decreasing the new product's price is suboptimal.

If the demand for remanufacturing units exceeds their supply, then these units are allocated on proportion (i.e., on a first-come, first-served basis) between the high-end customers who switch from new product and the low-end customers. As a result of this allocation, some switching customers (who were not allocated their most desirable product) – the overflow – continue shopping and purchase the new product.

The firm decides how many units of the new product it collects, $y \geq 0$, how many units it remanufactures, $x \in [0, y]$, and the price of the remanufactured units, $p_1 \in [0, p_2]$.

For a given (x, y, p_1), the revenue of the firm consists of the following three components:

initial sales of the new product $p_2(1 - \alpha(p_1))D_2$;

sales of the remanufactured product $p_1 \min[x, D_1(p_1) + \alpha(p_1)D_2]$;

sales of new product to the overflow customers $p_2\alpha(p_1)D_2\big(1 - \frac{\min[x, D_1(p_1)+\alpha(p_1)D_2]}{D_1(p_1)+\alpha(p_1)D_2}\big)$

where the expression for overflow sales reflects the proportional first-come-first-served allocation of the remanufactured units. This overflow component of the model is similar to the simplified model in Ovchinnikov and Milner (2010); please refer to their paper for more detailed discussion. For notational convenience, let $A(p_1) = D_1(p_1) + \alpha(p_1)D_2$ represent the total demand for remanufactured products. As is commonly assumed, demand $A(p_1)$ is a nonincreasing function; i.e., $\partial D_1/\partial p_1 + D_2 \partial\alpha/\partial p_1 \leq 0$. This condition obviously holds if α is itself a decreasing function.

We assume that collecting cores involves a fixed per-unit cost, c, and remanufacturing x units, given that y cores have been collected involves a total cost $r(x, y)$. The per-unit cost of new product is n. Then the total profit of the firm is:

$$\begin{aligned} g(x,y,p_1) &= (p_2-n)(1-\alpha(p_1))D_2 + p_1 \min[x, A(p_1)] \\ &\quad +(p_2-n)\alpha(p_1)D_2\big(1-\frac{\min[x,A(p_1)]}{A(p_1)}\big) - cy - r(x,y) \\ &= (p_2-n)D_2 + p_1\min[x,A(p_1)] - (p_2-n)\alpha(p_1)D_2\frac{\min[x,A(p_1)]}{A(p_1)} \\ &\quad -cy - r(x,y). \end{aligned} \tag{1}$$

We note that this formulation assumes that the firm realizes that remanufactured product will cannibalize some new product sales and thus will procure less new product. That may not always hold: in the case study of R, for example, *"remanufacturing operations had no effect on the pricing, procurement or other decisions about the new products."* Such cases can be incorporated within the above formulation by setting $n = 0$ and subtracting the (fixed) cost of procuring new products.

We assume that the remanufacturing cost function $r(x, y)$ is increasing convex in x and decreasing in y. We note that this assumption is a generalization of the majority of the previous literature, which considered a linear cost of remanufacturing with a constant marginal cost. An exception to this is the work of Ferguson and Toktay (2005), who consider a power and, specifically, a quadratic cost function.

In particular, we assume a piecewise linear cost function. Such a function represents the case of false returns and reflects the tiered cost structure in the mini-case of R that we discuss in the introduction. Let β be a fraction of false returns; we assume that it costs nothing to remanufacture the first βy units; the extension to a nonzero tier-1 marginal cost is trivial. Remanufacturing the remaining units involves a marginal cost r, leading to the following piecewise linear cost function:

$$r(x,y) = \begin{cases} 0, & \text{if } x \le \beta y; \\ r \times (x - \beta y), & \text{otherwise.} \end{cases} \tag{2}$$

As discussed in the introduction, the fundamental starting point for this paper is that the margin for the new product is higher than for the refurbished. Although this may not be true for all products, the concern about demand cannibalization implies that the higher-margin product's demand is cannibalized. From (2), observe that the average "optimized" per-unit cost of remanufactured product is $\min[c/\beta, c + (1-\beta)r]$. Thus assuming that the margin for the new product is higher implies that $p_2 - n \geq p_1 - \min[c/\beta, c + (1-\beta)r]$, which we assume to hold for the rest of the paper.

Next we discuss the solution(s) to the above model, estimate the functional form of its key component – switching function α – and discuss managerial implications.

4 Analysis of the Firm's Remanufacturing Strategy

By the remanufacturing strategy we mean the relationship between the optimal number of units acquired, y^*, and the number remanufactured, x^*. In this section we show that this relationship holds under some very general conditions, in particular, for any switching function, $\alpha(p_1)$. In the next section we estimate the switching function and determine the values of the remanufacturing strategy parameters, x^* and y^*, as well as the price of the remanufactured product, p^*. These values clearly depend on the α function, but the relationship between them does not, as we discuss next.

Theorem 1 *At optimality, the firm follows one of the three strategies: remanufacture nothing (with $x^* = y^* = 0$), remanufacture everything (with $x^* = y^* > 0$), or resell falsely returned units (with $x^* = \beta y^* > 0$). Further, if the firm remanufactures, i.e., $x^* > 0$, then $x^* = \beta y^*$ if $c \leq \beta r$, and otherwise $x^* = y^*$.*

Proof: Observe that g is nonincreasing in x for $x \geq A(p_1)$. Thus $x^* \leq A(p_1^*)$.

Consider an arbitrary pair (p_1, y). Observe that if $\beta y > A(p_1)$, then these (p_1, y) cannot be optimal, since by collecting $y' = A(p_1)/\beta$ units, the firm would save $(y - A(p_1)/\beta)c > 0$. Therefore $\beta y^* \leq A(p_1^*)$. In this case, observe from (1) that

$$x^*(p_1, y) = \begin{cases} 0, & \text{if } p_1 - \frac{D_2(p_2-n)\alpha(p_1)}{A(p_1)} < 0; \\ \beta y, & \text{if } 0 \leq p_1 - \frac{D_2(p_2-n)\alpha(p_1)}{A(p_1)} \leq r; \\ A(p_1), & \text{if } p_1 - \frac{D_2(p_2-n)\alpha(p_1)}{A(p_1)} > r. \end{cases} \quad (3)$$

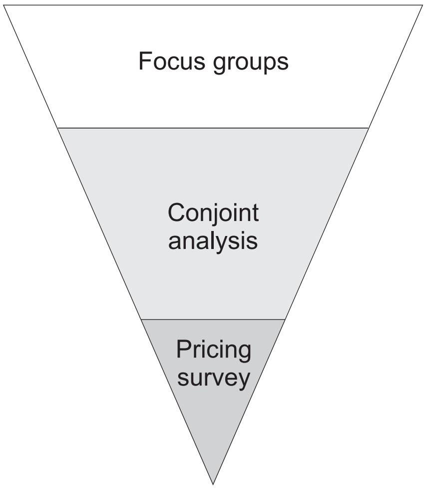
Suppose that the optimal price, p_1, is such that $x^* = \beta y^* < A(p_1)$. Then from (1), $g(\beta y, y, p_1) = (p_2 - n)D_2 + \beta y \left(p_1 - \frac{D_2(p_2-n)\alpha(p_1)}{A(p_1)}\right) - cy$, which is a linear nondecreasing function of p_1 (notice the optimality condition for $x^* = \beta y^*$). Therefore, such p_1 cannot be optimal, and since $A(p_1)$ is decreasing, it is thus optimal to increase p_1 so that $\beta y^* = A(p_1^*) = x^*$.

Finally, suppose $x^* = A(p_1^*) \geq \beta y$. Then $g = (p_2 - n)D_2 + p_1^* A(p_1^*) - cy - r \times (A(p_1^*) - \beta y)$, and so $\partial g / \partial y = -c + \beta r$. Thus if $c \leq \beta r$ then $x^* = \beta y^*$ and otherwise $x^* = y^*$. ■

The above theorem has important implications, both analytical and managerial. From the analytical perspective, it implies that provided the firm remanufactures, the decisions about acquisition of cores and remanufacturing/pricing are in fact separable. The firm first decides on how many remanufacturing units to put on the market and how to price them, and then it selects acquisition strategy to minimize the cost of collection and remanufacturing. From the managerial perspective, and again, provided that the firm offers remanufactured units on the market, the theorem implies that if acquiring cores is not expensive, the firm acquires enough cores so that there are sufficiently many false returned items to satisfy market demand, otherwise it acquires only the number of cores it needs and remanufactures all units that are not false returns. Returning to the case of R, in the former case R acquires many more cores than it needs, and then selects tier-1 units and resells them (technically speaking it does not do any remanufacturing, just collecting and sorting); in the latter, it actually remanufactures all tier-2 cores.

The results of the Theorem are in agreement with the earlier work of Galbreth and Blackburn (2006) who also showed that the firm may be better off by collecting many more units than it plans on remanufacturing even in the absence of a competitive threat. There is, however, a major difference: Galbreth and Blackburn considered a cost minimization problem and therefore started with the case when the firm remanufactures. Before this decision (to remanufacture or not) is made, however, the acquisition and remanufacturing/pricing decisions are clearly not separable, and further, cannot be made without explicitly considering the firm's revenue. Our paper considers both revenue and cost management and therefore shows that the strategy of acquiring more cores than needed is valid, not just as a cost minimization strategy (which is implied by Galbreth and Blackburn), but also as an overall profit maximization strategy. It therefore has an even stronger managerial appeal.

From the above, the decision of whether to remanufacture or not, and ultimately the firm's joint pricing and remanufacturing strategy, depends on both revenue and cost components. The revenue, in turn, critically depends on the consumers' switching behavior. We therefore turn to analyzing this behavior.



Goal(s)	Method	Subjects
Identify factors that consumers consider when deciding whether to purchase new or refurbished product	Focus groups interviews	Three random subsets of business school constituencies (students, staff, faculty), 28 subjects overall
Twofold: 1) understand the interplay between price- and non-price factors 2) demonstrate the existence of two segments: high-end and low-end	Web-based choice-based conjoint survey, designed, administered and analyzed using Sawtooth Software Inc's suit of products. Hierarchical Bayesian estimation was performed	97 MBA for Executives students
Estimate the switching behavior of high-end consumer segment with respect to certified refurbished product	Pricing survey suggested by Monroe (1990) specifically to estimate the price - perceived quality trade-offs	A subset of 17 students from the above 97 that were classified as the high-end in conjoint analysis

Figure 1: Brief description of the behavioral study.

5 Study of Consumer Behavior

Consumer behavior with respect to the choice between the new and the remanufactured product plays a central role in the firm's pricing and remanufacturing strategy. Despite its importance, however, little is known about such behavior. The purpose of this section is to fill this gap, in particular, in relation to the model we proposed earlier. Specifically, we have two goals:

1. Demonstrate that there indeed exist two customer segments, as we assumed: quality-sensitive high-end consumers and price-sensitive low-end consumers

2. Estimate the behavior of the high-end, which, in our model it is given by the function $\alpha(p_1)$: both the functional form and the actual fit

To accomplish these goals our study proceeds in three steps: focus groups, conjoint analysis and specialized pricing survey; see Figure 1 for brief description of these steps. We discuss these steps in sequel below:

Focus Groups. Three focus groups were conducted. Discussions were moderated following a common plan: factors influencing the purchasing of a new consumer electronics products were discussed first, and then a remanufactured option was introduced following the discussion of the factors that the group members deemed important in choosing between the new and remanufactured products.

The findings from the focus-group stage are the following. There are many terms that are commonly applied to remanufacturing: refurbished/ remodeled/ reconditioned/ remanufactured or simply used. Respondents were not sure if these terms meant the same thing or there was a difference. This uncertainty adds to the overall negative perception of remanufactured products, which are believed to be of inferior quality. Participants believe remanufactured products are old or used products that have been rebuilt; as one respondent put it, "I do not want a device that has been used by someone else." There is even skepticism about the "previously opened but never used" products. Respondents believe that there could be something wrong with the products, but the manufacturer/seller is hiding it. This skepticism leads to an interesting finding, that the degree of uncertainty about remanufactured products could be significantly reduced if there were an independent third party that would provide information about the product's history: when it was bought, why it was returned, what was wrong, etc. Respondents pointed to the existence of such services, for example, in the automotive industry (Carfax), but not in consumer electronics. There was a common belief that if such history information were available, that would reduce the uncertainty about remanufactured products and make them a more viable alternative to new products. Product warranty was another important element, as were brand and channel. Respondents were more open to considering a remanufactured product backed by a large warranty, in particular if this warranty came directly from a manufacturer they know and trust. With respect to brand, interestingly, respondents tended to correlate the quality of new products with uncertain quality of remanufactured products (e.g., if brand X has problems even with the new products, then X's remanufactured products are perceived to be of even lower quality). These findings are true for all three focus groups.

Conjoint Analysis. Based on the above findings, for the conjoint analysis, we decided to concentrate on a specific product/brand that is very familiar to subjects: Dell laptop computers; most subjects purchased Dell laptops as part of the computer bundle with specific software used during their studies. Further, because subjects in the focus groups correlated product quality with history, we selected three levels of product condition attribute:

OOTB – "out-of-the-box" – systems never used, canceled orders or returns that were never fully booted. This system may have been powered on by a customer before and has been tested and repackaged at the manufacturer's outlet center.

CR – "certified refurbished" – fully refurbished systems which are retested and repackaged to meet original factory specifications. This system may have been powered on by a customer before, used by a consumer before being returned, shipped out to another customer before or may have observable cosmetic blemishes.

S&D – "scratch-and-dent" – cosmetic blemishes that do not impact performance. This system may have been powered on by a customer before, used by a consumer before being returned, shipped out to another customer before or may have observable and/or considerable cosmetic blemishes.

We had two more attributes: warranty with levels 1,2, and 3 years, and discount with levels 0%, 10%, ..., 90%. Note that although our analytical model is worded in terms of refurbished price p_1, since the price of the new product, p_2, is fixed, there is a one-to-one correspondence between the discount, $(p_2 - p_1)/p_2$, and price p_1. In the behavioral study we used discounts rather than absolute prices because focus groups showed that participants were thinking primarily in terms of a percentage discount.

We administered an online choice-based conjoint study using the SSI Web system by Sawtooth Software Inc. (http://www.sawtoothsoftware.com/). Each respondent faced 20 choice tasks, and in each task he or she had to choose among two remanufactured alternatives and a new alternative with no discount and a one-year warranty. We used Sawtooth's complete enumeration method to generate random choice task designs; this method ensures minimal overlap, good level balance and near perfect orthogonality. The conjoint survey was supplemented by several general questions controlling for age, gender, and perception of and previous experience with remanufactured products, as well as the questions about what car subjects drive, how they finance their studies, the size of their company and how many levels below CEO they are.

We performed Hierarchical Bayes estimation of the individual partworth utilities using Sawtooth's CBC/HB add-on[‖]. For each respondent and each attribute, we calculated the

[‖] We treated Sawtooth system effectively as a "black box." Sawtooth is one of the leading software products for conjoint analysis, it is used by some of the world's best consumer marketing firms.

		Attribute Importance			Average Partworth Utilities for Discount					
Segment	Size	Condition	Warranty	Discount	40%*	50%	60%*	70%*	80 %*	90 %*
High-end	17.5%	53.3	8.92	37.77	1.05**	1.34**	1.94	1.50	1.01**	1.24**
Low-end	82.5%	22.52	12.21	64.27	0.16	1.51	3.15	4.49	6.10	6.98

Table 1: Statistics for the two customer segments. Asterisk at a certain discount level means that the difference between the segments' utilities is significant at the 95% confidence level. Double asterisk at a certain high-end utility means that the difference between that utility and the peak utility (at 60% discount) is significant at 95% confidence level (see Appendix B for complete conjoint output).

attribute importance. For 17 respondents, we observed that the importance of condition was higher than the importance of discount; that is, those respondents correspond to the quality-sensitive and price-insensitive consumers that we defined earlier as high-end. For the remaining 80 respondents the reverse is true, and we therefore classified them as the low-end segment.

Table 1 presents some statistics of interest for the two segments; the complete conjoint output for the two segments is presented in Appendix B. Our main observation is that these segments are fundamentally different with respect to sensitivity to discount. In particular, while for discounts of up to about 60% both segments' utilities are increasing in discount (i.e., the larger is the discount, the more willing the respondents are to purchase refurbished product), for discounts above 60% high-end respondents utilities decline; see Table 1. In many ways this already illustrates the central finding of the study: for a subset of respondents, a decrease in price of refurbished product below a certain level does not necessarily translate into an increase in the likelihood of purchase. These respondents are quality-conscious high-end consumers who perceive low-priced remanufactured products as being of low quality and therefore choose to purchase new product.

Note that the segments are nearly identical with respect to the importance of warranty. Also, membership in a segment is not correlated with any of the general questions we asked; p-values>0.16. Regressing the utilities themselves to the general questions also in most cases led to insignificant results; in only two cases did we find significant dependency: perception of remanufactured products was significant in predicting CR condition utility (p-value$=0.0328$) and the utility of purchasing the new product (p-value<0.0001). For consciences, however, we do not present the results of these regressions since they are not used anywhere else in the paper.

For the final element of our study, we administered the following pricing survey to the respondents that were classified as high-end above.

Pricing Survey. We use the methodology of Monroe (1990), which was specifically designed to capture the dependency between price and perceived quality and is therefore most appropriate for our purposes. For further discussion of this and alternative methodologies refer to the survey by Ofir and Winer (2002). The key element in Monroe's methodology is that consumers are assumed to have two price thresholds: upper and lower. The upper threshold (question 4 below) is familiar to most operations management researchers as the willingness to pay (WTP): it is the price level above which the product is not worth the money. A rather typical assumption in operations management models is that any price below the WTP leads to a purchase. Monroe argued, however, that at a very low price consumers may suspect product quality and refuse to purchase, therefore implying the lower threshold. Monroe suggested asking five questions to estimate these thresholds:

1. At what price would you consider this product to be so inexpensive that you would have doubts about its quality?
2. ... still feel that this product was inexpensive, but have no doubts about its quality?
3. ... begin to feel this product is expensive, but still worth buying because of its quality?
4. ... feel that this product is so expensive that regardless of its quality it is not worth buying?
5. What price would be most acceptable to pay?

We rephrased these questions in terms of the discount offered rather than price[**] and provided radio-buttons for each discount level 0, 10%,...90%. For questions 1 and 2 we also provided the "No doubts" options. Given that the number of respondents is small (17 high-end respondents as identified by conjoint), we focused on the CR condition with

[**]That is, the first question said *"At what discount would you feel that the refurbished product was so inexpensive that you would have doubts about its quality?"* and similarly for the rest.

1 year warranty. The full data set with responses to the survey is presented in Appendix C. The dataset is analyzed as follows.

Let $s^i(p_1)$ be the proportion of respondents who selected discount level $\frac{p_2-p_1}{p_2}$ in response for question i. Let $q^i(p_1) = \sum_{p=0}^{p_1} s^i(p)$ be the cumulative proportion of respondents who selected discount levels higher than $\frac{p_2-p_1}{p_2}$ in response for question i. Then as Monroe suggested:

$$\alpha(p_1) = q^4(p_1) - q^2(p_1) \tag{4}$$

That is, the fraction of the high-end customers who switch from a new to remanufactured product is the percentage of respondents who on one hand do not find the remanufactured product overly expensive, yet on the other do not have doubts about its quality due to discount.

To facilitate the comparison of the optimal policies of the firm that knows the correct estimate of α function, given by (4), and the firm that incorrectly believes that the fraction of switching customers is driven only by their willingness to pay, we differentiate between the true α, to which we refer to as the α^U (i.e., $\alpha(p_1) \equiv \alpha^U(p_1)$) and the WTP-based estimate $\alpha^W(p_1)$. From the above $\alpha^W(p_1) = q^4(p_1)$.

Figure 2 presents both α^W and α^U functions as per the results of the survey, as well as their 90% confidence intervals[††]. The striking difference between the two is evident: α^W is decreasing in price (equivalently, increasing in the discount level $(p_2 - p_1)/p_2$), α^U has an inverted-U shape: it first increases and then decreases. The reason for this difference is in the way high-end consumers use price to judge about quality: for example, at 40% discount, 82% of subjects found the product's price below their WTP. A "traditional" WTP-based approach would suggest that 82% of customers would switch; hence $\alpha^W = 0.82$; however, 39% of subjects doubt product quality: *If this is indeed a fully functional product, then why is the firm selling it at 40% discount?* As a result, only 43% switch; hence $\alpha^U = 0.43$.

We note that there is a minor upswing in the α^U at very high discount levels; observe that a similar upswing also exists in the conjoint estimates, Table 1. It happens because

[††]The Lower (Upper) bound of the 90% confidence interval for discount $\frac{p_2-p_1}{p_2}$ is the Probability such that the chance that at least (no more than) $\alpha(p_1) \times 17$ respondents from 17 are switching is 95% (5%) respectively; i.e., that cdf Binomial($\alpha(p_1) \times 17$, 17, Probability)=0.95 (0.05).

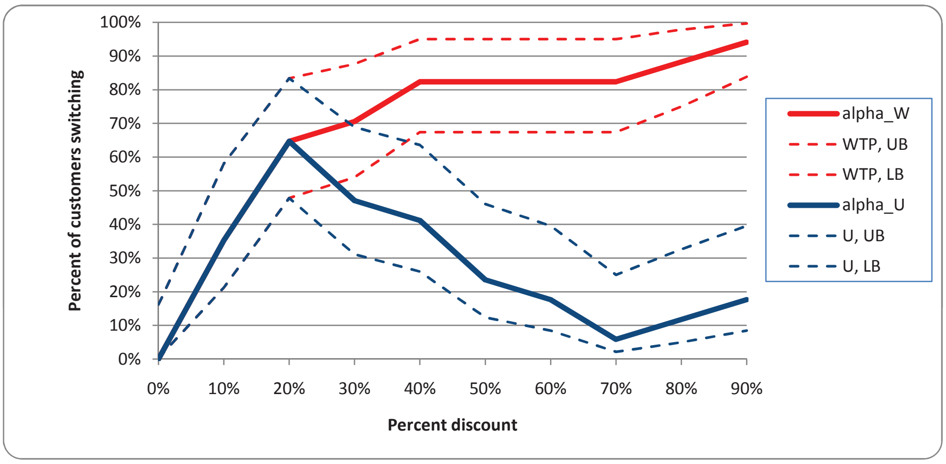


Figure 2: Estimates for functions α^U and α^W (solid lines), and upper (UB) and lower (LB) boundaries of 90% confidence interval (dashed lines) for the corresponding estimate.

at very high discount levels consumers may buy the refurbished products even if they have quality concerns, just because it is so ultra-cheap. As some respondents pointed out, in such cases they would more likely buy two products (e.g., new for him/herself and an 80% discounted for her child). Capturing multiple unit purchases, however, is outside the scope of our paper. Despite its existence, this upswing has minor effect on the policy of the firm: such high discount levels cannot be optimal, because they correspond to lower price and higher cannibalization.

Observation 1 below summarizes the main differences between α^U and α^W, which are evident from the above discussion, the definitions of α^U and α^W, Figure 2 and Table 1:

Observation 1 *The following relationships hold for all potentially optimal p:*

(a) $\alpha^W(p) \geq \alpha^U(p) \geq 0$*;*

(b) $\alpha^W(p)$ *is decreasing in p, $\alpha^U(p)$ has an inverted-U shape;*

(c) $\partial \alpha^U / \partial p \geq \partial \alpha^W / \partial p$.

In the remainder of the paper we discuss the implications of knowing and incorporating the inverted-U behavior *as compared to* the WTP-behavior; we first study these implications analytically, and then perform numerical simulations.

6 Joint pricing and remanufacturing strategy and implications of the inverted-U consumer behavior

In this section we discuss the value of recognizing that consumer behavior has an inverted-U shape. To do so we compare the optimal joint pricing and remanufacturing decisions for two firms. Firm-U believes that high-end consumer behavior is inverted-U-shaped and is described by function α^U; firm-W believes that the high-end behavior is described by α^W (while it is actually α^U). Otherwise the firms face identical problems; specifically, the low-end behaves according WTP in both cases. We use superscripts U and W to differentiate between these firms throughout the section.

We start by discussing when firms-U and -W remanufacture.

Theorem 2 *Either of the following conditions are sufficient for firm-U to remanufacture:*

a) *If there exists* $\overline{p_1} \geq \min[c/\beta, c + (1-\beta)r]$ *for which* $\alpha^U(\overline{p_1}) = 0$*, but* $D_1(\overline{p_1}) > 0$*;*

b) *If there exist* $p_1^* \in [0, p_2)$ *such that* $p_2 - n = p_1^* - \min[c/\beta, c+(1-\beta)r]$ *and* $D_1(p_1^*) > 0$*.*

Proof: For part a): Suppose that firm-U charges the price $\overline{p_1}$ and decides to offer $A(\overline{p_1})$ remanufactured units. Since $\alpha^U(\overline{p_1}) = 0$, $A(\overline{p_1}) = D_1(\overline{p_1})$. From the proof of Theorem 1, if the firm remanufactures, then its acquisition decision, y^*, is separable, and can be expressed as $y^*(x, p_1)$. Thus $g_U^*(x_U^*, y_U^*, p_{1U}^*) \geq g(D_1(\overline{p_1}), y^*(D_1(\overline{p_1}), \overline{p_1}), \overline{p_1}) = (p_2 - n)D_2 + D_1(\overline{p_1})(\overline{p_1} - \min[c/\beta, c + (1-\beta)r]) > (p_2 - n)D_2$, i.e., the firm's profit is higher that the do-nothing profit of $(p_2 - n)D_2$ and hence it is optimal to remanufacture.

For part b): Suppose that firm-U charges the price at which the margins on the new and remanufactured products are equal, i.e., $p_1^* = p_2 - n + \min[c/\beta, c + (1-\beta)r]$, and remanufactures $x^* = A(p_1^*)$ units. Then from (1) its profit equals to $(p_2 - n)D_2 + (p_1^* - \min[c/\beta, c+(1-\beta)r]) \times (A - \alpha D_2) = (p_2 - n)D_2 + (p_1^* - \min[c/\beta, c+(1-\beta)r]) \times D_1(p_1^*) > (p_2 - n)D_2$; i.e., the firm's profit is higher that the do-nothing profit of $(p_2 - n)D_2$ and hence it is optimal to remanufacture. ■

These two sufficient conditions have the following interpretation. Part (a) states that if there exists a low enough price at which the firm is able to perfectly discriminate high- and low-end demand, then it will remanufacture. Although not met exactly, this condition

	Condition 1	Condition 2	Solution
1	$\frac{c}{2\beta} + (p_2 - n)\frac{d+2bD_2}{2(d+bD_2)} \leq r$	$\frac{c}{\beta} \leq \frac{d(p_2-n)}{d+bD_2}$	$x_1^* = \frac{d(p_2-n)-c/\beta(d+bD_2)}{2}$, $y^* = x^*/\beta$, $p_1^* = \frac{p_2+c/\beta}{2} + \frac{bD_2(p_2-n)}{2(d+bD_2)}$
2		$\frac{c}{\beta} \geq \frac{d(p_2-n)}{d+bD_2}$	$x^* = 0$, $y^* = 0$, p^* is arbitrary
3	$\frac{c}{2\beta} + (p_2 - n)\frac{d+2bD_2}{2(d+bD_2)} \geq r$	$\frac{c}{\beta} \geq r$ and $c + (1-\beta)r \leq \frac{d(p_2-n)}{d+bD_2}$	$x^* = \frac{d(p_2-n)-(c+(1-\beta)r)(d+bD_2)}{2}$, $y^* = x^*$, $p_1^* = \frac{p_2+c+(1-\beta)r}{2} + \frac{bD_2(p_2-n)}{2(d+bD_2)}$
4		$\frac{c}{\beta} \geq r$ and $c + (1-\beta)r \geq \frac{d(p_2-n)}{d+bD_2}$	$x^* = 0$, $y^* = 0$, p^* is arbitrary
5		$\frac{c}{\beta} \leq r$	$x^* = \frac{dp_2+bnD_2-r(d+bD_2)}{2}$, $y^* = x^*/\beta$, $p_1^* = \frac{p_2+r}{2} + \frac{bD_2(p_2-n)}{2(d+bD_2)}$

Table 2: Solutions to the firm-W problem (assuming linear demand and switching).

is nearly met in the lower bound case at 70% discount with $\alpha^U = 0.002$, and the firm nearly always remanufactures (Table 3). Part (b) states effectively the opposite: if there exists a high enough price at which the margins on the new and remanufactured products are equal, then charging such a price and remanufacturing the number of units to satisfy remanufactured product demand is better than doing nothing. Such price, however, can be infeasible: e.g., if the cost of collection and/or remanufacturing is very high then to maintain equal margin the firm would have to set $p_1^* > p_2$ which is not feasible in our model and unrealistic in practice.

For firm-W, in order to provide similar result we assume that $\alpha^W(p_1)$ is a linear function. Note that $\alpha^W(p_1) \leq 1$ and thus in practice it is at best piecewise linear. However, p_1 so low that $\alpha^W(p_1) = 1$ clearly cannot be optimal because $p_2 D_2 \geq p_1 D_1$. Thus linearity is a reasonable assumption for p_1 such that $\alpha^W(p_1) < 1$. Further, since by definition $\alpha(p_2) = 0$, we can therefore assume $\alpha^W(p_1) = b(p_2 - p_1)$ for some coefficient b. For simplicity, we will also assume that D_1 is linear, and further, because $D_1(p_2) = 0$ we assume that $D_1(p_1) = d(p_2 - p_1)$ for some coefficient d. We assume linearity of D_1 for the rest of the paper. This allows us to solve firm-W pricing and remanufacturing problem in closed form. Table 6 and Theorem 3 present the results (the proof of the Theorem is in Appendix A).

Theorem 3 *The optimal price, number of cores acquired and number of remanufactured units put on the market for firm-W are presented in Table 6.*

Therefore, for firm-W there are four different solutions that correspond to five different intervals for the parameters of the model (a do-nothing solution appears twice). What do these solutions mean, and why is a particular solution optimal for the corresponding intervals of parameters?

Observe that condition 1 for solutions 1 and 2 implies that the the firm is dealing with a product that is cheap to collect (c is small), but expensive to remanufacture (r is large). Condition 2 for solution 1 corresponds to the case when the percentage of false returns is high (β is large), whereas for solution 2, it corresponds to the reverse case, when the percentage of false returns is low. With this intuition, solutions 1 and 2 seem quite natural: if the firm is dealing with a product that is cheap to collect but expensive to remanufacture, then, if the percentage of false returns is high, the firm should collect many units (since it is cheap to do so) and not remanufacture any units (since it is expensive), but rather resell those that were falsely returned. Since there are many such units, collecting and reselling is beneficial for the firm. If, however, there are few such units (low percentage of false returns in solution 2), then reselling them does not cover the cost of collecting substantially more units, and so the firm does nothing.

On the contrary, condition 1 for solutions 3 to 5 says that the firm's product is expensive to collect but cheap to remanufacture. Furthermore, condition 2 for solution 3 says that the product is also expensive (p_2 is high). In this case, the firm can sell remanufactured units at a higher price, and so it chooses to remanufacture all units it collects (solution 3). If, on the other hand, the product is not expensive, then the firm chooses to do nothing (solution 4). Finally, solution 5 presents the case with balanced costs, where the firm engages in the same reselling strategy as in solution 1, but it resells fewer units at a higher price since the units are more expensive to collect (observe how solution 1 compares to solution 5 in light of condition 2 for solution 5).

In sum, Theorems 2 and 3 discuss the optimal solutions to firm-U and firm-W problems. Next, we compare these solutions and emphasize the value of knowing that consumer switching behavior is inverted-U. We start by showing that at optimality, firm-U necessarily receives higher profit than firm-W.

Theorem 4 $g_U^* \geq g_W^*$.

Proof: Observe that at $x = A(p_1)$, g decreases in α (for a fixed p_1 at which firm still remanufactures): $\partial g/\partial\alpha = -(p_2 - n)D_2 + (p_1 - \min[c/\beta, c + (1-\beta)r])D_2 \leq 0$ (note that if firm remanufactures then p_1 is larger than the expression in the min operator, but by the margins assumption $p_1 - \min[c/\beta, c + (1-\beta)r] \leq p_2 - n$).

Consider the optimal decisions of firm-W, (x_W^*, y_W^*, p_{1W}^*), and suppose that firm-U decides to charge price p_{1W}^*. If firm-W does not remanufacture w.l.o.g. we can assume $p_{1W}^* = p_2$ and the result of the Theorem is trivial. If firm-W remanufactures, then $p_{1W}^* < p_2$. Further, in that case from the proof of Theorem 1 acquisition decision, y_U^*, is separable, and can be expressed as $y_U^*(x_U, p_{1U})$, where the optimal price and quantity of firm-U satisfy $A(p_{1U}^*) = x_U^*$. That is, if firm-U decides to charge price p_{1W}^* then it remanufactures $A^U(p_{1W}^*) = D_1(p_{1W}^*) + \alpha^U(p_{1W}^*)D_2$ units.

Because $\alpha^U(p) \leq \alpha^W(p)$ for all p and because g is decreasing in α for a p that satisfies $x = A(p)$, $g_W^* \leq g_U(A(p_{1W}^*), y_U^*(A(p_{1W}^*), p_{1W}^*), p_{1W}^*) \leq g_U^*$. ■

From the above proof firm-U receives higher profits even if it charges the same price as firm-W, p_{1W}^*. This happens because firm-U recognizes that at price p_{1W}^* it will cannibalize less of the new product's demand, and hence its overall demand for remanufactured units will be smaller. Firm-U therefore puts fewer remanufactured units on the market, and both sells more new products (at the higher price and margin), and saves on remanufacturing and acquisition costs. At the same time, firm-U can clearly do even better if it charges a different price, p_{1U}^*, as we discuss next.

Theorem 5 $p_{1U}^* \leq p_{1W}^*$.

Proof: It is easy to observe that at a given price p_1,

$$\frac{\partial g_W}{\partial p_1} - \frac{\partial g_U}{\partial p_1} = \left(\frac{\partial \alpha^W}{\partial p_1} - \frac{\partial \alpha^U}{\partial p_1}\right)(-(p_2 - n)D_2 + (p_1 - \min[c/\beta, c + (1-\beta)r])D_2) \geq 0$$

because the first expression is negative by Observation 1 and the second is also negative because by the margins assumption $p_1 - \min[c/\beta, c + (1-\beta)r] \leq p_2 - n$.

Further, because by assumption α^W and D_1 are linear (and by definition decreasing),

$$\frac{\partial^2 g_W}{\partial p_1^2} = 2\left(\frac{\partial D_1}{\partial p_1} + \frac{\partial \alpha^W}{\partial p_1} D_2\right) \leq 0,$$

i.e., g_W is concave in p_1. Thus, from the former, at the optimal price p^*_{1U}, $\partial g_W/\partial p_1 \geq 0$, and from the latter $\partial g_W/\partial p_1$ is decreasing. Hence $\partial g_W/\partial p_1 = 0$ at the price greater than p^*_{1U}, i.e., $p^*_{1U} \leq p^*_{1W}$. ■

Contrasting the results of Theorems 4 and 5, from the former, firm-U can get higher profit than firm-W because if firm-U charges the same price as firm-W it will remanufacture less and hence save on cannibalization and remanufacturing cost. But from the former, firm-U will in fact not charge the same, price; rather, it will charge a lower price. By doing so firm-U can decrease cannibalization even further (e.g., observe that α^U goes to almost zero for some discount levels on Figure 2), and more effectively discriminate between the high-end new product's customers, to whom it will sell at new products at price p_2, and the low-end remanufactured-product-only customers, to whom it will sell remanufactured products at price p_1.

It is interesting to note that nothing can be said (in general) about the relationship between x^*_{1U} and x^*_{1W} (correspondingly y^*_{1U} and y^*_{1W}). This is because even though $p^*_{1U} \leq p^*_{1W}$ and $\alpha^U(p) \leq \alpha^W(p)$, we also know that α^U is first increasing and then decreasing. Thus it is not clear whether $\alpha^U(p^*_{1U}) \leq \alpha^W(p^*_{1W})$ or not; if this relationship holds then $x^*_{1U} \geq x^*_{1W}$, and otherwise $x^*_{1U} \leq x^*_{1W}$. We note that in our numerical simulations we observe both cases (Table 3).

6.1 Numerical Simulations

To further facilitate comparison between firm-U and firm-W we perform a series of numerical simulations. We fix $p_2 = 100$ and $D_2 = 100$; this can be done w.l.o.g. because of scaling. We set $D_1(p_1) = d(p_2 - p_1)$ and vary $d = \{0.05; 0.1; 0.2; 0.3; 0.5; 1; 1.5; 2; 3\}$. With respect to the costs, for the new product cost we set $n = \{0, 25, 50, 75\}$, and for the remanufactured product we consider $c = 1, 3$, $r = c \times \{2; 5; 8\}$ and $\beta = \{0.1; 0.2; 0.3; 0.4; 0.5\}$. This leads to 270 combinations of remanufactured cost and demand parameters for each of the 4 levels of the new product cost.

We perform two kinds of tests. First we use the functions α^W and α^U as in Figure 2 and solve for the optimal p^*, x^*, y^* and the corresponding revenue. We discuss how the two solutions contrast and provide managerial intuition for the implications of the inverted-

U behavior. Second, we perform sensitivity tests to the α functions. We use complete enumeration search with $p_1 \in \{0, 1, 2, ...100\}$ and $y \in \{1, 2, ...400\}$, and $x = \{1, 2, ..., y\}$. Computation is implemented in VBA on a standard laptop PC. Table 3 summarizes the results.

First we observe when firms-U and -W remanufacture. In our simulations, firm-U always remanufactures in more cases than firm-W. The policies are different in the cases when low-end demand is small and inelastic. From Theorem 3 and Table 6 these are the cases 2 and 4 (see condition 2) for which it is optimal for firm-W to do nothing. Overall, however, the different way firms-U and -W react to the size of the low-price segment is interesting, and we discuss it separately. Another observation is that the number of cases when firms remanufacture increases with the cost of new product, n: this happens because the do-nothing alternative becomes less attractive as the cost of new product increases.

Second, we observe the difference in prices and quantities. To have a "fair" basis for comparison, we only consider the cases when corresponding firm-W remanufactures. There are several interesting observations. When the cost of new product is high ($n = 50, 75$) then both firms charge the same price – that in fact is the price at which the margins of the two products are equal. The quantities are different: as per the discussion following Theorem 4 firm-W overestimates demand cannibalization and thus collects and remanufactures more product than necessary (the difference could be nearly twofold, 84 vs. 157 in the $n = 75$ case), and thus receives smaller profit. When the new product cost is low ($n = 0, 25$) firm-U charges a much lower price. Firm-W is not charging a lower price because it is afraid of cannibalizing new product's demand. Visually, it is operating on the left side of the plot on Figure 2. To the contrary, firm-U knows that it can combat cannibalization by a drastic price reduction. Visually, it operates on the right side of the α^U curve, where price is small. By doing so it more effectively segments the market and sells new product at a high price to the high-end new product consumers, and sells remanufactured product at a low price to low-end consumers. Observe, however, that the quantities of remanufactured products, and as a result, the quantities of acquired cores, are not necessarily higher for firm-U; that supports our argument following Theorem 5.

Third, as Theorem 4 suggests, firm-U must receive a higher profit. To that extent we have two observations. The profit of either firm increases with the new product cost:

	Remanufacture	Cores	Units	Price	Over Do-Nothing	Over corresp. WTP
$n = 0$, WTP	186	70.08	44.83	86.72	9.85%	
$n = 0$, U	189	94.44	61.32	41.17	20.48%	108%
$n = 25$, WTP	241	182.58	93.65	76.80	20.82%	
$n = 25$, U	241	175.48	91.06	64.53	23.82%	14%
$n = 50$, WTP	242	227.49	130.32	54.34	42.31%	
$n = 50$, U	257	149.93	79.47	54.34	44.60%	5.4%
$n = 75$, WTP	231	251.93	157.19	29.23	61.37%	
$n = 75$, U	264	146.53	84.32	29.23	68.78%	12%
$n = 0$, WTP, LB	211	69.96	44.67	85.15	11.19%	
$n = 0$, U, LB	233	90.6	57.74	38.13	19.94%	78%
$n = 0$, WTP, UB	113	70.01	44.82	83.02	11.51%	
$n = 0$, U, UB	113	83.05	55.54	58.92	18.95%	65%

Table 3: Summary of the optimal decisions for the behaviors given by α^W and α^U, and the corresponding upper (UB) and lower (LB) bounds of the 90% confidence intervals.

by the same logic as above as the new product cost goes up, remanufacturing becomes relatively more profitable overall (the increase over do-nothing goes up from 10–20% to over 60%). The relative advantage of firm-U, however, decreases with the new product cost. As per the proof of Theorem 5 the advantage comes from firm-U charging a lower price, thus the improvement over firm-W is largest when the prices are most different. For the $n = 0$ case, firm-W by optimizing its remanufacturing activities increased its profit on average by 9.85% over a do-nothing profit. Firm-U was able to increase profits by 20.48% on average. That is, knowing that consumer behavior has an inverted-U shape and optimizing pricing and remanufacturing accordingly could effectively *double* the benefits of remanufacturing.

Finally, we perform several kinds of sensitivity analysis. In those analysis we assume $n = 0$; as discussed in Section 3 this reflects the situation when the decision about the procurement of new product is done independently of the remanufacturing operations, as is in the case of R.

Sensitivity analysis with respect to α functions. To do so we repeat the above simulations with lower and upper bounds of the corresponding functions. Table 3 summarizes the results. If less demand is cannibalized (LB cases) then the firm remanufactures in more scenarios and prices lower. Its average profit is smaller only because some of those additional scenarios correspond to the small low-end demand, which were previously excluded because the firm did nothing. If more demand is cannibalized (UB cases),

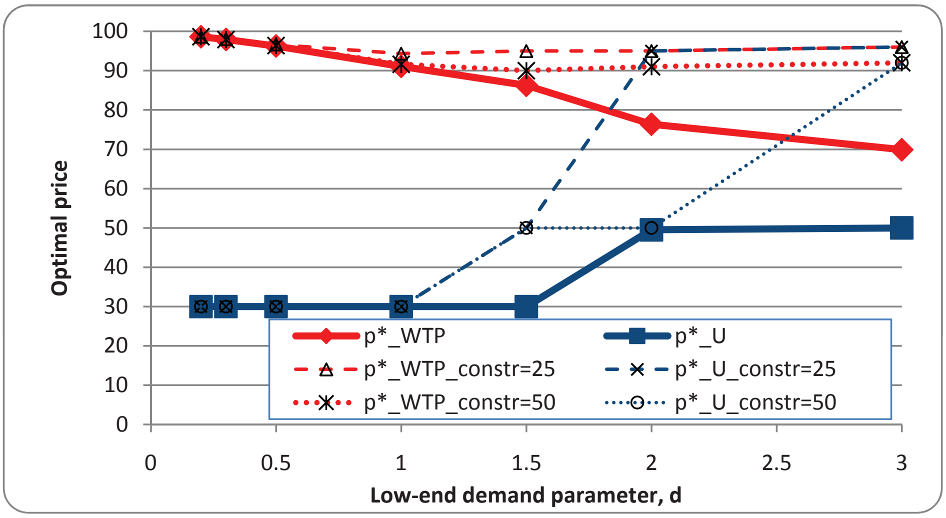


Figure 3: Average prices for firm-U and firm-W as a function of the low-price demand parameter, d.

then the ability to capitalize on the inverted-U behavior decreases and hence the firm remanufactures in fewer cases and prices higher.

In either case, though, firm-U does substantially better than firm-W, which emphasizes the importance of our results. The primary reason for that is pricing, and more specifically, it is the drastically different reaction to low-end segment.

Sensitivity to the size of low-end segment. Consider Figure 3. In the "base case" (solid lines W and U) observe that as the size of low-price demand segment increases, firm-W decreases its price, while firm-U increases its price. This happens because of the inverted-U behavior: firm-U can obtain the same cannibalization by either giving a small discount or a large one–for example, from Figure 2, about 40% of consumers will switch at discounts of either 15% or 42%. But by giving a large discount, firm-U attracts more low-end bargain-hunting consumers who would not buy its new product at all. Therefore, with the inverted-U consumer behavior, the firm can choose the lower price, and while obtaining the same cannibalization, bring more low-end consumers.

Thus, when there are few low-end customers (i.e., parameter d is small), in order to capture most of them, firm-U charges a very low price (simultaneously decreasing high-end demand cannibalization). Firm-W cannot charge a low price since it is afraid to cannibalize all of its new product's demand and hence does nothing. Visually, the starting point for firm-U is at the right of the inverted-U curve on Figure 2, and the starting point for firm-W is at the left. As d increases, firms move in the opposite directions. Firm-W decreases the price, brings in some low-end customers and cannibalizes some new product demand, but it sells remanufactured products at a high price. Firm-U is increasing the price, losing the proportion of the low-price demand it serves, but because the number of low-price customers increases, it may be actually gaining the low-end demand. It also increases cannibalization, but at a smaller rate than firm-W. Finally, it also increases the price, so the increase in cannibalization is offset by an increase in per-unit revenue.

Sensitivity to potential limited supply of cores. Throughout the paper we assumed that the supply of remanufacturable cores is unlimited. This setup is supported by the discussions with the management of R and several academic references and may indeed be close to reality when the firm is selling a commodity-like product; then it can arguably source cores sold by other firms. In some cases, however, the firm may be selling a differentiated product that is not sold by other firms. In that case one must consider a constraint that the supply of remanufacturable cores is bounded by some fraction, called the recovery rate, of the new product sales.

We tested the constraint with 25% and 50% recovery rate. First and foremost, knowing and incorporating inverted-U behavior still proves to be valuable: firm-U gets 18% and 38%, respectively, higher profit than firm-W. This difference clearly comes from pricing (quantity in most scenarios is determined by the binding supply of cores). Firm-W hardly changes its pricing strategy: it prices high and decreases price as low-end demand becomes larger; see dashed lines on Figure 3. Firm-U, however, employs a "hybrid" strategy: when low-end segment becomes large it starts behaving as firm-W. This is because of the interplay between the inverted-U consumer behavior and the limited supply of cores: firm-U can achieve the same level of high-end demand cannibalization by either charging a high or a low price. In the former case it sells few remanufactured products, but has a high margin on each sale; in the latter case it sells many units, but with a low margin. Unconstrained firm finds the second approach more profitable because it can remanufacture more; with constraint, however, the firm cannot sell more units than it has cores, and so the high-price option dominates.

To conclude the numerical analysis, we highlight a striking similarity between what the firm R mentioned in the introduction actually did in practice, and what our numerical simulations show. Recall that R charged \$139 for refurbished vs. \$399 for new (a 65% discount). That is nearly identical to the discount of about 50-70% that firm-U charges in our simulations(!), but is drastically different from the 10-30% discount that firm-W offered. This once again emphasizes the very significant difference in the firm's decisions caused by knowing about the inverted-U behavior and incorporating it into firm's pricing and remanufacturing strategy.

7 Conclusions

This paper considers firms' joint pricing and remanufacturing strategy from two perspectives – modeling and behavioral/empirical. In the model, we consider the revenue component, where the firm selects the price and quantity of remanufactured products in the market to balance the cannibalization of new product sales with the additional sales of remanufactured products. We also consider the cost component, where the firm balances the acquisition of remanufacturable cores with the number of remanufactured products it wishes to put on the market.

The central role in the revenue component of the model is played by the fraction of consumers who, for a given price difference, switch from the new to the remanufactured product. We argue that using such a fraction provides more flexibility than the standard approach of using willingness to pay (WTP). Further, we present the behavioral study where we show that the realistic consumer behavior cannot be explained by the WTP alone–rather, when the remanufactured product's price is very low consumers infer product quality from price and few decide to switch (the WTP approach would suggest that there should be many switching customers when the price is low). In the cost component of the model, we assume a convex cost that decreases in the number of acquired cores – this modeling setup reflects heterogeneity in acquired products' conditions and was motivated by the case study that we present in the introduction.

We solve the model and discuss how various attributes of the products and their respective markets (price vs. cost of collection and remanufacturing, percentage of falsely returned units, etc.) affect the remanufacturing strategy of the firm. This provides firms with intuitive and managerially relevant guidelines with respect their remanufacturing strategy. We show that in all cases the firm's strategy is either to "remanufacture nothing," "remanufacture everything that was collected," or "resell falsely returned products." The latter strategy, under which the firm procures many more cores than it ends up remanufacturing, was known in the literature, but it was motivated by either cost minimization (in the models that did not consider revenue component), or by the fear of competitive entry – the firm was acquiring the cores in order to deter the entry of a third-party (re)manufacturer. As our paper shows, however, firms may have economic reasons beyond cost minimization and competitive threats for following such a strategy, which from a managerial perspective, strengthens its practical appeal.

Complementing the model, we present the behavioral study and estimate the switching consumer behavior. We show that the switching fraction has an inverted U-shape. This implies that by charging a lower price for the remanufactured product, the firm can decrease consumer switching, and hence minimize demand cannibalization of the new product; at the same time it can attract more low-end consumers. Our results also shed a new light on the importance of the low-price segment for the pricing and remanufacturing strategy. Indeed, the above can be done only if by charging a lower price the firm can attract sufficiently many new low-price-only customers. Otherwise, the firm must charge a higher price for the remanufactured product, and with the same degree of new product demand cannibalization, sell fewer units. This implies that the optimal strategy of the firm can be drastically different depending on the size/elasticity of the low-price segment, which in turn implies that firms should dedicate more effort in researching that segment.

Based on both the model and the empirical study we compare the solutions for the firm that correctly estimates its inverted-U-shaped consumer behavior (firm-U) with the solutions for the firm that (incorrectly) believes that its consumers behave according to the WTP (firm-W). We find that knowing that consumer behavior is inverted-U and optimizing pricing and remanufacturing accordingly, has the potential to effectively double the benefits of remanufacturing. The increase in profitability is particularly large when the cost of new product is small; equivalency, when procurement of new products is done independently of remanufacturing. Firm-U generally remanufactures under broader conditions, charges a much lower price for remanufactured products and acquires more cores and remanufactures more units. The latter suggests that a better understanding of consumer behavior has the potential, in addition to increasing profits, to benefit the environment by diverting more items from the waste stream.

We also find that, quite surprisingly, firms -U and -W's react to the size of the low-price segment in the opposite manner: whereas it is optimal for firm-U to increase its price as low-price demand grows, firm-W decreases its price. In fact, a firm may behave according to a "hybrid" of the two strategies and have discontinuities in its pricing strategy (the price can jump from a high W-like price to a low U-like price). We stress that these comparisons and intuition are unique to our work, because the described effects cannot be captured if one models consumer behavior using only WTP.

In terms of the future work, this paper offers several possibilities. The first extension could consider competition. For example, if firms-U and -W as defined in this paper were competitors, would knowing inverted-U consumer behavior provide even more value? Another extension could consider demand uncertainty and substitution. Extensions dealing with supply chain implications might also be considered, as well as extensions dealing with products beyond consumer electronics.

It could also be interesting to consider introduction of remanufactured products as a mechanism to create/change product lines. For example, returning to the case study of R, a $139 remanufactured version of a $399 PDA could be cannibalizing not only the sales of this PDA, but also the sales of the "regular" telephones priced around $139. At the same time, since much of R's revenue comes from sales of voice and data plans, it could be that consumers who purchase refurbished PDAs are more likely to spend more, for example, on data plans. Thus cannibalizing regular telephone sales could be in fact profitable for R overall. Studying such dynamics could be also of interest for future research.

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Appendix A

First, consider a simplified case with linear cost, $x = y$ and $r(x, y) = rx$, i.e., all collected units are remanufactured and remanufacturing additional unit incurs a constant marginal cost (rate) $r \geq 0$ per unit. For notational convenience we omit the y variable in this initial discussion.

As we discuss throughout the paper,

$$x^*(p_1) = \begin{cases} 0, & \text{if } p_1 - \frac{(p_2-n)\alpha(p_1)D_2}{A(p_1)} - r \leq 0; \\ A(p_1), & \text{otherwise.} \end{cases} \tag{5}$$

Substituting (5) into (1) and rearranging with $x = y$ in mind, we obtain

$$g^*(p_1) = (p_2 - n)D_2 + \big((p_1 - r)A(p_1) - (p_2 - n)\alpha(p_1)D_2\big)^+. \tag{6}$$

Let $\Delta(p_1) = (p_1 - r)A(p_1) - (p_2 - n)\alpha(p_1)D_2$. From (5) and (6) the firm engages in remanufacturing if $\Delta(p_1) \geq 0$. This condition can be rewritten as

$$(p_1 - r)D(p_1) \geq ((p_2 - n) - (p_1 - r))\alpha(p_1)D_2, \tag{7}$$

and therefore has a simple managerial explanation. It states that the firm will remanufacture if the revenue potential from new customers who would purchase only remanufactured product offsets the cannibalization of the sales of the new product caused by introducing the remanufactured product, corrected for the costs of remanufacturing, r and purchasing new product, n.

From (6) maximizing $g^*(p_1)$ is identical to maximizing $\Delta(p_1)$. Observe that $\Delta'' = 2D_1' + (p_1 - r)D_1'' + 2D_2\alpha' - ((p_2 - n) - (p_1 - r))D_2\alpha'' \leq 0$ since $D_1' \leq 0$, $\alpha' \leq 0$ and $D_1'' = \alpha'' = 0$ by linearity assumption. Therefore $\Delta(p_1)$ is concave and so the optimal price of remanufactured product, p_1^*, satisfies the first-order condition

$$A(p_1^*) + (p_1^* - r)D_1'(p_1^*) - ((p_2 - n) - (p_1 - r))D_2\alpha'(p_1^*) = 0. \tag{8}$$

Finally, if $\Delta(p_1^*) > 0$ then the firm remanufactures (and collects) $y^* = x^*(p_1^*) = A(p_1^*) = D_1(p_1^*) + \alpha(p_1^*)D_2$ units and offers them for sale at price p_1^*. Otherwise the firm does not remanufacture, $x^* = y^* = 0$ and p_1^* is irrelevant.

Utilizing the assumption that $D_1(p_1) = d(p_2 - p_1)$ and $\alpha(p_1) = b(p_2 - p_1)$ we can obtain closed-form solutions. Solving FOC (8) we obtain

$$p_1^* = \frac{p_2 + r}{2} + \frac{bD_2(p_2 - n)}{2(d + bD_2)}, \tag{9}$$

and therefore

$$x^*(p_1^*) = A(p_1^*) = \frac{dp_2 + bnD_2 - r(d + bD_2)}{2}. \tag{10}$$

The above hold whenever the resulting $A(\cdot) \geq 0$; that is, if

$$r \geq \frac{dp_2 + bnD_2}{d + bD_2}, \tag{11}$$

then $x^* = 0$ and the firm does not remanufacture and obtains a "do-nothing" profit D_2p_2.

Now consider general cost. Observe that both the optimal price and the optimal quantity depend on the number of units collected, y. Specifically if no units are collected, i.e., if $y = 0$, then obviously $x = 0$ and the price is irrelevant. Otherwise, the firm collects some units, y, and therefore it could choose to remanufacture. Therefore it has to select the optimal price, $p_1^*(y)$ for the case when $x^*(p_1^*(y), y) = A(p_1^*(y))$ for a given y (we study the problem of selecting the optimal y later).

By linearity of demand and switching, $A(p_1^*(y)) = (d + bD_2)(p_2 - p_1^*(y))$. Substituting it into (1) and differentiating in p_1 we obtain:

$$\frac{\partial g^*(A(p_1), y, p_1)}{\partial p_1} = (d + bD_2)(p_2 - p_1) + bD_2p_2 + (d + bD_2)\frac{\partial r(x, y)}{\partial x}|_{x=A(p_1)} \tag{12}$$

and

$$\frac{\partial^2 g^*(A(p_1), y, p_1)}{\partial p_1^2} = -2(d + bD_2) - (d + bD_2)^2\frac{\partial^2 r(x, y)}{\partial x^2}|_{x=A(p_1)} \leq 0 \tag{13}$$

because $r(x, y)$ is convex in x for all y.

That is, g^* is concave in p_1 for all y when $x^*(p_1^*(y), y) = A(p_1^*(y))$. Therefore, in this case the optimal price $p_1^*(y)$ satisfies

$$(p_2 - n) - 2p_1^* + \frac{bD_2(p_2 - n)}{d + bD_2} + \frac{\partial r(x, y)}{\partial x}|_{x=A(p_1^*)} = 0. \tag{14}$$

Given the (implicit) functions for both the optimal number of remanufactured units, $x^*(p_1^*(y)) = A(p_1^*(y))$, and the optimal price of remanufactured unit, $p_1(y)$, as per (14) both as functions of the number of units collected for remanufacturing, y, we could determine the optimal y by solving the following nonlinear program:

$$\begin{aligned}(y-NLP) \qquad & \max g(x^*(p_1^*(y)), y, p_1^*(y)) \\ s.t. \qquad & A(p_1^*(y)) \leq y \qquad (15) \\ & x^*(p_1^*(y)), y, p_1^*(y) \geq 0 \qquad (16)\end{aligned}$$

where $p_1^*(y)$ is given by (14) and profit function $g(\cdot)$ is given by (1). Finally if $g^* > p_2 D_2$, i.e., the optimal profit from remanufacturing is greater than the do-nothing profit, then the optimal solution holds, otherwise $y^* = x^* = 0$, and p_1 is irrelevant.

As per Theorem 1, if $x^* > 0$ then $x^* = y^*$ or $x^* = \beta y^*$. The former case was analyzed initially, so suppose $x^* = \beta y^*$. By the definition of $A(\cdot)$

$$p_1^*(y) = p_2 - \frac{\beta y}{d + bD_2}. \qquad (17)$$

Substituting these expressions into the profit function and differentiating over y, we obtain:

$$\frac{\partial g^*(y)}{\partial y} = (\beta p_2 - c) - \frac{\beta d(p_2 - n) + 2y\beta^2}{d + bD_2} \qquad (18)$$

and

$$\frac{\partial^2 g^*(y)}{\partial y^2} = -\frac{2\beta^2}{d + bD_2} < 0. \qquad (19)$$

That is, the profit function is concave, and so it is optimal to collect $y^* = \frac{-c(d+bD_2)+\beta(dp_2+bnD_2)}{2\beta^2}$ units. Therefore from (17)

$$p_1^* = \frac{p_2 + c/\beta}{2} + \frac{bD_2(p_2 - n)}{2(d + bD_2)} \qquad (20)$$

$$x_1^* = \frac{d(p_2 - n) - c/\beta(d + bD_2)}{2}. \qquad (21)$$

Since $\beta \leq 1$, this solution automatically satisfies constraint (15), i.e., that the firm cannot remanufacture more units than it collects. For the nonnegativity constraint (16) we must have $y^* \geq 0$ (which implies $x^* \geq 0$) and $p^* \geq 0$. From (20) the latter always holds, while the former demands $c \leq \beta \frac{d(p_2-n)}{d+bD_2}$. Finally, this solution should satisfy the range for prices, i.e., since $0 \leq p_1 - \frac{bD_2(p_2-n)}{d+bD_2} \leq r$ from (3), we must have

$$\frac{c}{2\beta} + (p_2 - n)\frac{d + 2bD_2}{2(d + bD_2)} \leq r. \qquad (22)$$

The condition $0 \leq p_1 - \frac{bD_2(p_2-n)}{d+bD_2} \leq r$, leading to (22), suggests that such a policy would be feasible when it is relatively cheap to collect the units (c is small), but it is expensive to remanufacture them (r is large), while the percentage of false returns, β, is high. Since this is not always the case, we are considering the remaining case where the optimal price p_1^* is such that $p_1^* - \frac{bD_2(p_2-n)}{d+bD_2} \geq r$.

In this case, observe that for a fixed y, the model resembles that with the linear cost of remanufacturing. Therefore from (9) and (10) $p_1^* = \frac{p_2+r}{2} + \frac{bD_2(p_2-n)}{2(d+bD_2)}$ and $x^*(p_1^*) = A(p_1^*) = \frac{dp_2+bnD_2-r(d+bD_2)}{2}$ respectively, so long as $x^* \leq y$. Since these solutions are independent of y, and for given x and p_1 the profit function is linear in y, we obtain $\frac{\partial g(x^*,y,p_1^*)}{\partial y} = -c+\beta r$.

Hence if $c/\beta \leq r$, then the firm would like to collect as many units as possible and so $y^* = A(p_1^*)/\beta$, where p_1^* is given by (9). Otherwise the firm would like to collect as few units as possible, and hence the solution satisfies $x^* = y^*$. In this case by the same logic as initially:

$$p_1^* = \frac{p_2 + c + (1-\beta)r}{2} + \frac{bD_2(p_2-n)}{2(d+bD_2)} \tag{23}$$

and therefore

$$x^*(p_1^*) = A(p_1^*) = \frac{d(p_2-n) - (c+(1-\beta)r)(d+bD_2)}{2} \tag{24}$$

and this solution holds if $x^* \geq 0$, which is equivalent to $c + (1-\beta)r \leq \frac{dp_2}{d+bD_2}$. Otherwise $x^* = y^* = 0$ and p^* is arbitrary.

Appendix B: Complete Conjoint Output

CBC System Multinomial Logit Estimation
Copyright 1993-2010 Sawtooth Software

Name/Description: Logit Run
02:51:08PM Thursday, June 24, 2010

Main Effects
Respondent Filter: Equal to 1 (Variable1 = 1)
Tasks Included: All Random

Total number of choices in each response category:

1	120	35.29%
2	110	32.35%
NONE	110	32.35%

Files built for 17 respondents.
There are data for 340 choice tasks.

Iter	1	Chi Square = 194.99384	rlh =	0.44403
Iter	2	Chi Square = 227.86771	rlh =	0.46603
Iter	3	Chi Square = 232.48275	rlh =	0.46920
Iter	4	Chi Square = 232.72758	rlh =	0.46937
Iter	5	Chi Square = 232.72912	rlh =	0.46937
Iter	6	Chi Square = 232.72912	rlh =	0.46937

Converged.

Log-likelihood for this model = -257.16362
Log-likelihood for null model = -373.52818

Difference = 116.36456

Percent Certainty = 31.15282
Consistent Akaike Info Criterion = 609.93247
Chi Square = 232.72912
Relative Chi Square = 16.62351

	Effect	Std Err	t Ratio	Attribut	Level	t Ratio, diff from 60%	Effect, rescaled for compatibility
1	3.676	0.174	21.132	1	1 Out-of-the-Box		59.260
2	-5.366	0.285	-18.810	1	2 Scratch-and-Dent		-86.503
3	1.690	0.169	9.991	1	3 Certified Refurbished		27.241
4	-0.577	0.139	-4.162	2	1 year warranty		-9.295
5	-0.175	0.135	-1.296	2	2 year warranty		-2.815
6	0.751	0.137	5.472	2	3 year warranty		12.111
7	-6.299	0.489	-12.876	3	1 no discount	20.411	-101.538
8	-1.923	0.307	-6.267	3	2 10% discount	12.852	-30.999
9	-0.440	0.294	-1.494	3	3 20% discount	8.088	-7.087
10	0.567	0.297	1.911	3	4 30% discount	4.649	9.141
11	1.059	0.305	3.474	3	5 40% discount	2.942	17.076
12	1.346	0.289	4.660	3	6 50% discount	2.042	21.695
13	1.941	0.294	6.594	3	7 60% discount	0.000	31.293
14	1.503	0.301	5.001	3	8 70% discount	1.473	24.231
15	1.000	0.306	3.267	3	9 80% discount	3.133	16.124
16	1.245	0.294	4.233	3	10 90% discount	2.367	20.067
17	1.617	0.179	9.011	NONE			26.067

Elapsed time: 0:00:01

CBC System Multinomial Logit Estimation
Copyright 1993-2010 Sawtooth Software

Name/Description: Logit Run
02:53:39PM Thursday, June 24, 2010

Main Effects
Respondent Filter: Equal to 2 (Variable1 = 2)
Tasks Included: All Random

Total number of choices in each response category:

1	652	40.75%
2	669	41.81%
NONE	279	17.44%

Files built for 80 respondents.
There are data for 1600 choice tasks.

Iter	1	Chi Square = 1347.85288	rlh =	0.50793
Iter	2	Chi Square = 1439.48825	rlh =	0.52269
Iter	3	Chi Square = 1446.47527	rlh =	0.52383
Iter	4	Chi Square = 1446.57652	rlh =	0.52385
Iter	5	Chi Square = 1446.57660	rlh =	0.52385
Iter	6	Chi Square = 1446.57660	rlh =	0.52385

Converged.

Log-likelihood for this model = -1034.49136
Log-likelihood for null model = -1757.77966

Difference = 723.28830

Percent Certainty = 41.14784
Consistent Akaike Info Criterion = 2186.27135
Chi Square = 1446.57660
Relative Chi Square = 103.32690

	Effect	Std Err	t Ratio	Attribut	Level	Effect, rescaled for compatibility
1	1.160	0.180	6.443	1	1 Out-of-the-Box	16.436
2	-2.328	0.199	-11.728	1	2 Scratch-and-De	-32.984
3	1.168	0.179	6.526	1	3 Certified Refu	16.544
4	-1.098	0.186	-5.913	2	1 year warranty	-15.557
5	-0.122	0.180	-0.678	2	2 year warranty	-1.728
6	1.220	0.178	6.853	2	3 year warranty	17.284
7	-8.381	0.760	-11.024	3	1 no discount	-118.736
8	-6.423	0.605	-10.623	3	2 10% discount	-91.003
9	-5.416	0.502	-10.796	3	3 20% discount	-76.732
10	-2.198	0.406	-5.412	3	4 30% discount	-31.136
11	0.167	0.374	0.446	3	5 40% discount	2.363
12	1.516	0.365	4.158	3	6 50% discount	21.476
13	3.158	0.373	8.468	3	7 60% discount	44.741
14	4.493	0.395	11.385	3	8 70% discount	63.656
15	6.104	0.411	14.842	3	9 80% discount	86.475
16	6.980	0.447	15.626	3	10 90% discount	98.895
17	-2.537	0.229	-11.084	NONE		-35.946

Elapsed time: 0:00:04

Figure 4: Complete conjoint outputs. Left pane: high-end segment (Respondent filter variable =1). Right pane: low-end segment (Respondent filter variable =2).

Appendix C: Full data set with responses to the Monroe's survey

ID	sys_ InternalRespNum	monroe1	monroe2	monroe3	monroe4	monroe5
1	2	10	7	5	4	8
2	14	6	5	3	1	4
3	17	1	10	10	10	10
4	23	11	11	2	1	4
5	27	9	5	4	2	6
6	34	11	11	5	4	8
7	35	11	11	4	2	10
8	41	6	4	3	2	4
9	53	5	3	3	2	4
10	54	5	6	7	8	7
11	65	5	4	2	1	3
12	67	6	5	1	2	3
13	69	4	3	2	1	2
14	73	6	4	2	1	4
15	75	4	3	4	3	3
16	86	5	7	8	9	3
17	89	4	3	2	1	3

Table 4: Field descriptions: *ID* is a row number, *sys_...* is the respondent number assigned by Sawtooth, *monroe1...5* are the fields for the answers to Monroe's questions, Section 5. Here 1 means that respondent selected the 0% discount level, 2 means the 10%, and so on until 10 that means a 90% discount; response 11 for questions *monroe1* and *monroe 2* means that the respondent selected the "No doubts" option.