Economic and Environmental Assessment of Remanufacturing in a Competitive Setting

Abstract

This paper studies the economic and environmental trade-offs of remanufacturing for product+service firms under competition. We use an analytical model and a behavioral study which together incorporate demand cannibalization from multiple customer segments across the competing firms’ product lines. We compare firms’ and industry’s economic performance (measured by profits) and environmental performance (measured by energy consumption in relative and absolute terms) under monopoly and competition and with and without remanufacturing.

Our paper generates two key insights. On the economic side our results shed a new light on the existence of the “green segment” consumers. While we find no consumers who are willing to pay equally or more for refurbished products, some consumers segments are willing to pay more for new products from a firm that refurbishes. Thus while competition decreases prices, the firm that refurbishes suffers less of a price drop and hence is more profitable in the new product market. A price decrease naturally leads to the growth in the total production, which on the environmental side, leads to increase in the absolute environmental impact. What is surprising, however, and this is our second key insight, is that competition worsens not only the absolute, but also the relative environmental performance of both firms and the industry in total. This happens because the refurbished product impacts the product line competition and changes the product mix: increasing the share of the high-end products, with higher environmental impacts, and decreasing the share of the low-end products with lower environmental impacts.

Keywords: remanufacturing, product-line competition, demand cannibalization, eco-efficiency, product+service firms
1 Introduction

Remanufacturing enables firms to extend the useful life of their products, diverts items from the waste stream and allows some consumers to substitute new products with refurbished ones. While all these elements intuitively have environmental benefits, several recent studies suggested that remanufacturing may actually increase firms’ environmental impact. For example, Quariguasi-Frota-Neto and Bloemhof (2011) based on empirical data for personal computers and mobile phones demonstrated that this may be the case when “the life spans of remanufactured products are substantially shorter than the life spans of their new counterparts” (page 101). Ovchinnikov, Blass and Raz (2014), henceforth referred to as OBR14, pointed out that looking at the impact on a per-product basis is incomplete because a remanufactured product may cannibalize not only its parent product sales, but also sales of other products a firm is selling. They considered economic and environmental impact across a product line of a product+service firm and showed that the introduction of a remanufactured product could in some cases result in negative cannibalization, i.e., an increase (rather than a decrease) in the firm’s new unit sales. More importantly, this increase can in many cases result in an increase in the firm’s environmental impact – a negative absolute environmental effect. Interestingly, they showed that the resultant growth was in nearly all cases sustainable: on average products become “greener” (per unit) and profits increase faster than environmental impacts (per dollar) – a situation they called a positive relative environmental effect.

An approach that looks at a firm in isolation (such as the one described in the two papers above, as well as in many other papers in the literature, see Souza 2012 for a review), however, is likewise incomplete because the growth in the firm’s sales could come at the expense of a decline in sales of its competitors and thus the absolute environmental effect could still decrease. Under competition there are two opposite environmental effects: First, if because of remanufacturing firm A sells one more unit to a customer who would otherwise purchase from firm B that doesn’t remanufacture, then while firm A’s impact increases, the total impact on the environment might actually decrease (since some remanufactured units from firm A might be replacing new units of firm B). On the other hand, competition can result in both firms’ lowering their prices so that the total market of both firms can expand. It is not clear which effect will be stronger. More importantly, to have the negative environmental effect, it’s not enough for the market to simply grow; it has to grow enough on the new product’s end to counteract the lower environmental impact of the remanufactured product compared to new. For example, OBR14 showed the negative
cannibalization and market growth in 35% of the cases but only in 27% there was a negative absolute environmental effect. Thus, in this paper, our goal is to examine this impact by performing economic and environmental assessment of remanufacturing in a competitive setting.

An important question is how to model competition in a way that will capture the interaction between remanufacturing and product line competition. Majumder and Gronevelt (2001), Ferguson and Toktay (2006), Mitra and Webster (2008), Örsdemir et al. (2013) and Ovchinnikov et al. (2013) examined competition between an OEM that sells new (and possibly remanufactured) products and a third party that sells only remanufactured products. This setting is not suitable for our goal as we are interested in the impact of a firm’s decision to remanufacture when it is engaged in product-line competition with other firms selling similar products. Heese et al. (2005) examined the case of two identical firms deciding on a take-back program where the remanufactured products are sold in a secondary market and thus do not cannibalize the new products sales. This setting is not suitable for our goal either because it does not take into account cannibalization of new product sales, which is a major concern in many industries and also a major driver for the environmental impact of remanufacturing (See OBR14). In an effort to extend the product line cannibalization in OBR14 to product line competition, we therefore opted for an approach in which the two competing product + service firms\(^1\) are asymmetric: one firm sells only new products (new high- and low-end products as in OBR14) and the other sells only high-end products (new and, if it chooses so, refurbished). This situation existed in practice, for example, when Apple introduced the new iPhone 4S in 2011 and allowed (for the first time) other firms besides AT&T, such as Sprint and Verizon to sell new iPhones, while AT&T (Apple’s original partner) was offering both new and refurbished iPhones. In Israel in 2013, among the three major service providers, only Celcom offered refurbished iPhones (Cellcom web site, 2013) while its competitors, Orange (Orange web site, 2013) and Pelephon (Pelephon web site, 2013) offered new iPhones only. While we acknowledge that this approach is not the only way to model remanufacturing in a competitive setting, we believe that it offers a good balance by capturing a fundamental interplay between remanufacturing and competition, and doing

\(^{1}\) We consider product+service firms primarily to be able to directly compare our results to those from OBR14 for the case of a monopoly. Generally, and as they explain in their paper, many of the firms that practice remanufacturing can be classified as product+service firms, e.g., AT&T offering devices and plans, HP offering printers and consumables for them, and the like. In fact, 11 out of 24 studies of remanufacturing mentioned in Guide and Li (2010) explicitly refer to product+service firms.
so in a way that can be analyzed behaviorally. See further discussion on modeling product-line competition in Section 2 and on behavioral estimation in Section 4.1.

Using this model of competition, we present a data-driven model that captures both the demand and supply dimensions of the problem: On the demand-side, our model captures heterogeneity in consumers’ attitudes towards the price, type of product (new vs. remanufactured), firm, and type of service, using a multi-segment random utility demand model. On the supply side, it captures product-line competition that includes both new (high- and low-end) and refurbished products. Based on demand estimation from the consumer choice data and problem parameters drawn from both the literature and conversations with industry executives, we analyze the competition between the two product+service firms and provide the economic and environmental assessment of remanufacturing in a competitive setting. We note that while the numerical estimates/parameters in our paper are specific to the mobile phones industry/category, the overall approach and framework are general and the results could be generalized to other industries, as discussed in more detail in the Conclusion.

Our paper generates four main results. The first two are rather expected, while the other two are quite surprising. First, we show that competition reduces prices overall, however, in all cases, the profits increased as well, both for the firm that remanufacturers and for the one that does not. As a result of the price decrease, we find that in the majority of instances remanufacturing resulted in a worsened environmental impact (measured by the total energy used throughout the product lifecycle; see Section 3.4). In the absolute terms, for both firms in almost all cases we observe a situation when the total energy consumption increased, same negative absolute environmental effect as in OBR14, although in much higher frequency. As discussed above, this shows that the price competition effect has a higher impact compared to the “market share stealing effect” so even though some of the remanufacturing firm increase in demand might come from the competitor, the price competition effect is dominant enough to cause an overall increase in the absolute environmental impact.

Our third result, is that from an economic perspective, while prices decrease overall, the firm that offers remanufactured products suffers less of a price drop. This sheds a new light on the so-called “green segment.” Our result shows that no consumers are willing to pay equally for new and refurbished products (as is sometimes assumed in the literature, e.g., Atasu et al. 2008). But consumers are giving credit to firms that refurbish which allows those firms to charge higher prices
for their new products. As we show this is due to the fact that some consumer segments have a higher willingness to pay for the firm that remanufactures compared to the one that doesn’t, which results in a higher average utility for the new product of the firm that remanufactures. This finding is also related to Agrawal et al. (2012) who showed that consumer willingness-to-pay for a new product could increase when a third party remanufactures it, but could decrease when remanufacturing is performed by the new product manufacturer. Because we consider product+service firms (such as AT&T) our “firms” from the perspective of remanufacturing are more similar to third parties in their setup, hence the results are directionally consistent.

Our fourth result is that with regard to the environmental perspective, the environmental impact worsens in relative terms as well; recall that in OBR14 the relative impacts were nearly always positive. In this paper, for the firm that did not remanufacture, the per-unit environmental impact was worse in almost all of the cases (by construction no such cases could exist for the firm that did remanufacture). Combining both firms, for the industry as a whole, the relative per-unit environmental impact worsened in almost half the cases. The frequency of negative impacts per-dollar of profit for both firms and the industry as a whole was likewise orders of magnitude higher than that reported in OBR14 for the case of an isolated firm. This striking result is driven by the change in the mix of products within the product line: remanufacturing intensifies competition for high-end products which lowers their prices, hence some consumers instead of purchasing low-end products purchase high-end products which are more profitable for the firm, but have larger environmental impacts.

Overall, our analysis contribute to the sustainable operations literature by offering a more nuanced and comprehensive understanding of the economic and environmental consequences of remanufacturing in a competitive setting. Note that the reason we are able to show the last two results is in the richness of our model with respect to competition, multi-product supply (product lines) and multi-segment demand. The green segment result could not have been seen in models that only examined the monopoly case or a single customer segment. Similarly, the result about the relative environmental effect, cannot be shown in models that only consider a single parent product and its remanufactured version. Only models (like ours) that present multi-firm, multi-product and multi-segment analysis could potentially capture these kinds of phenomena.

This disconnect between an increase in profitability, but with possibly worsened environmental impacts adds a new bend to the long standing environmental claim that
environmental regulations and investments (including those in/about remanufacturing) create a win-win situation for both firms and society. Society benefits from reduced pollution, while firms achieve greater profitability and stakeholder cooperation, recognition and value, Plaza-Úbeda et al. (2009). As our results show this is not always the case because with the introduction of remanufacturing under competition, both firms improve their profits, but at the same time they might increase their environmental footprint, a win-lose situation. While this result may at first seem somewhat discouraging, it is important to note that the current scope of analysis may not capture the entire societal benefit of remanufacturing. For example, the increased market penetration of high-end wireless communication products which due to remanufacturing displace low-end products (as per our results), increases people’s access to mobile communications, internet, and other related services. While beyond the scope of our paper, studying the benefits of those services to society could present an even more nuanced and comprehensive assessment of the impact of remanufacturing.

In the remainder of the paper, Section 2 reviews the literature, Section 3 presents the analytical model and Section 4 describes the behavioral study we used for demand estimation. Section 5 discusses the parameters and results of the numerical simulations. Section 6 summarizes our discussion and concludes the paper.

2 Literature Review

Our paper is related to four streams of literature: first is the literature in Operations Management (OM) that examines the economics of remanufacturing, second is the literature in Operations and Marketing that analyzes green consumers and green tendencies, third is the Operations, Marketing and Economics on product-line competition, and last is the literature in OM and Industrial Ecology that examines the environmental performance of remanufacturing.

Within the first stream (economics of remanufacturing), for brevity, we focus only on the papers that consider competition; for a broader review see Souza (2012). Most OM papers (Majumder and Gronevelt 2001, Ferguson and Toktay 2006, Mitra and Webster 2008, Ovchinnikov et al. 2013, this list is by no means complete) consider Stackelberg-like competition between an OEM and an independent remanufacturer – a setting that, as we argued in the Introduction is not of a particular relevance to this paper.
Atasu et al. (2008) consider a case with asymmetric OEMs engaged in a Nash competition: one offering a new product and possibly its remanufactured version, and another, offering a lower-quality new product. Our setting is similar to theirs in the sense that we too consider asymmetric firms, however our setting is richer because each firm offers a differentiated product-line and no firm is restricted to sell only a lower-quality product. Their result also critically depends on the existence of the green consumers who value new and remanufactured products equally, but to the best of our knowledge all behavioral studies of remanufacturing fail to show the existence of such consumers, see OBR14, Abbey et al. (2014) and our own estimates in Section 4.1.

Heese et al. (2005) consider two symmetric firms but assume that they compete in a Stackelberg-Nash manner: they decide whether to remanufacture sequentially and then set their prices simultaneously once the remanufacturing decisions are irreversible. They show that the resultant equilibrium is often asymmetric so that one firm is remanufacturing and another one does not – in this sense our setting with asymmetric firms of which only one remanufactures could be interpreted as an equilibrium outcome to a higher level sequential-move game much as in their setup. Additionally, they assume that new and remanufactured products are sold on separate markets – an assumption that is true for their rather specific product category (hospital beds), but not for ours (consumer electronics and mobile communications devices), in which new and remanufactured products are sold side-to-side\textsuperscript{2}.

Within the second stream (green consumers and preferences), many papers in the Operations literature focus specifically on remanufacturing (as is natural); papers in the Marketing literature are typically more general: they focus on identifying green consumers and their attitudes towards products and firms. As discussed above as far as we know, all behavioral studies of remanufacturing failed to show the existence of green consumers (e.g. OBR14, Abbey et al. 2014, Michaud and Llerena 2011). Specifically, Abbey et al. (2014) showed that consumer greenness had the weakest relative effect on the remanufactured consumer product attractiveness for any product category. Michaud and Llerena (2011) found no evidence that consumers were willing to pay a premium for remanufactured products, however, they found that providing environmental information to

\textsuperscript{2} Some papers, e.g., Majumder and Gronevelt 2001, consider the case when new and remanufactured products are indistinguishable – an assumption that also does not hold for our product category where by industry norms even a slightly used product undergoes refurbishing and is labeled accordingly, see Ovchinnikov (2011).
consumers generally decreased significantly their WTP for the conventional (and thus most polluting) product. Agrawal et al. (2012) showed that consumer willingness-to-pay for a new product could increase when a third party remanufactures it, but could decrease when remanufacturing is performed by the new product manufacturer. As discussed above, this result is somewhat similar to ours as a product+service firm is more similar to a third party in their context than to a manufacturer.

In the marketing literature many papers focused on identifying socio demographic characteristics of green consumers (e.g. Roberts 1996, Kilbourne and Beckmann 1998, Straughan and Roberts 1999, Laroche et al. 2001, and Diamantopoulos et al. 2003). Diamantopoulos et al. (2003) provide a review of this literature and state that while the multivariate results indicate that socio-demographics are associated with environmental consciousness, their explanatory power is weak. Straughan and Roberts (1999) comment that most findings about the impact of consumers’ demographic characteristics on their environmentally conscious behavior are contradictory, and that demographics are less important than knowledge, values and/or attitude in explaining ecologically friendly behavior. Other papers in the marketing literature focus on the impact of firms green strategies on consumer perception of the firm and its products (Brown and Dacin 1997, Peattie 2001, Sen and Bhattacharya 2001, Pickett-Baker and Ozaki 2008, Manchanda 2013). Manchanda (2013) shows that perceived sustainability practices of a firm activate a prevention (i.e. green) focus on consumers that will then make green inferences about the products of the firm. Pickett-Baker and Ozaki (2008) show that green consumers do not necessarily purchase more green products, however, consumers who are willing to pay a premium price for green products can shift to greener consumption if their beliefs or attitudes can be changed through green marketing strategies. Brown and Dacin (1997) show that Corporate Social Responsibility (CSR) affects consumers via overall firm evaluation, while Sen and Bhattacharya (2001) find that CSR initiatives can have a direct positive (but possibly indirect negative) effects on consumers’ purchase intentions. These papers are related to our finding regarding green preferences, that some segments of consumers would prefer a new product from a firm that remanufactures (the “green” firm) over one that does not.

Within the third stream (product line competition), we emphasize that to the best of our knowledge no sustainable OM paper considers firms that compete with product lines that include remanufactured products; in fact OBR14 is perhaps the only paper that considers remanufacturing
across a product line even in the monopoly setting. Papers that consider product-line competition in other areas of management sciences are also relatively scarce. Mendelson and Parlakturk (2008) is one such example in OM: similar to this paper, the authors by design consider a case with two asymmetric firms. Moorthy (1988) is an example in the Marketing literature that considers symmetric firms in both simultaneous and sequential move games. Chisholm and Normal (2012) is an example in the Economics literature, where the competing firms are also asymmetric in the sense of having a different ability to access competitor’s “home markets”. This list is by no means complete, and several other papers explored various nuances of product-line competition: vertical versus horizontal, Bertrand, Cournot or imperfect, etc. But the overarching theme in those papers is that regardless of the starting assumptions or the domain of application the “multi-product firms would prefer to avoid overlapping their product lines, specializing in particular market niches as a means of softening competition” (Chisholm and Normal 2012). Our modeling construct with asymmetric firms builds on this fundamental logic.

Within the last stream of literature (environmental performance of remanufacturing), the researchers approached the problem from two angles. In OM, the researchers focused primarily on the issue of demand cannibalization: to what extent remanufacturing a unit reduces demand for a new one, and suggested a variety of strategies to decrease cannibalization in order to increase profits. However, effectively by assumption most OM papers considered remanufacturing as “environmentally efficient” (Hesse et al. 2005, p. 143) and having the potential to “benefit the environment by diverting more items from the waste stream” (Ovchinnikov 2011, p. 838). In the Industrial Ecology Literature, researchers focused on the detailed assessment of the environmental impacts of remanufacturing across various stages of the product’s lifecycle, i.e., how “environmentally efficient” it actually is, but for the most part assuming full cannibalization, i.e., that remanufacturing a unit eliminates the need to produce new one completely (Thomas; 2003, Thomas; 2010, Geyer; 2004, Ilgin and Gupta; 2010). A common measure of environmental efficiency in those papers is related to the energy used throughout the life-cycle of the product; we use the same measure as well.

Studies that combine the detailed economic and environmental analysis are very scarce. In fact, to the best of our knowledge, OBR14 is the only such paper. They show that while in isolation remanufacturing is indeed environmentally beneficial, a decision to remanufacture changes firm’s behavior on the new product market, leading to the negative cannibalization and the resultant
increase\textsuperscript{3} in the environmental impact. In this paper we follow the approach in OBR14 and combine the per-unit environmental assessment of remanufacturing (and new product manufacturing) with the changes in the numbers and kinds of units manufactured/remanufactured as a result of the competition between firms and the decision to remanufacture. We present our model next.

3 The Model

3.1 Model Schematic

As discussed in the introduction, our model extends the single-firm model of OBR14 to the case of two product+service firms. Firm 1 sells a product line that consists of a new high-end (\(NH\)) and new low-end (\(NL\)) products, offered with high-end (\(H\)) and low-end (\(L\)) services, respectively, while firm 2 sells an identical new high-end (\(NH\)) product offered with high-end (\(H\)) service and, possibly, a remanufactured high-end (\(RH\)) product offered with either (\(H\)) or (\(L\)) services.

A fundamental feature of remanufacturing is the interaction of multiple product generations. At the beginning of period \(i\), the two firms start selling generation \(i (= 1, 2, \ldots)\) of \(NH\) and \(NL\) that became available due to technological progress, and discontinue the sales of new generation \(i - 1\) products. However, those generation \(i - 1\) products provide cores for the remanufactured products sold in period \(i\). We focus on the economic and environmental assessment along the lifecycle of generation \(i\) of the firms’ products as a representative scenario for the firms’ overall business. At the beginning of period \(i\), firm 1 needs to decide on the prices to charge for products \(NH\) and \(NL\), while firm 2 decides on the prices for \(NH\) as well as on whether to introduce its remanufactured version, \(RH\), and if so, what should be its price. The two firms engage in the product line competition where the prices set for their products affect both their own products’ demand and the demand for their competitor’s products.

The selling horizon of generation \(i\) new products consists of two sub-periods: \(i_1\) and \(i_2\). These capture the fact that levels of remanufacturing range from products that were returned close to the purchase date and therefore need to be only tested and repackaged (these are sometimes referred to as “false returns”; see Ferguson et al. 2006), all the way to products that were in use for months or years and were collected as part of a take-back program, during upgrade or disposal of the product. Thus, in period \(i_2\), firm 2 collects and remanufactures some fraction (the “false returns”

\textsuperscript{3}Quariguasi-Frota-Neto and Bloemhof (2011) is another OM paper that presents a similar qualitative insight but from a very different angle: interplay between the use and the manufacturing phases of the product lifecycle.
whose remanufacturing is typically inexpensive) of NH from generation $i$ sold in period $i_1$. In the subsequent period, $i + 1_1$, firm 2 also collects some NH from generation $i$ (which corresponds to the products that reach the end of their initial use) and remanufactures (at a higher cost than “false returns”) and sells them in period $i + 1_1$. That is, the selling season of RH phones from generation $i$ also consists of two periods: $i_2$ when the firm 2’s product line consists of NH and RH from generation $i$, and period $i + 1_1$ when the product line consists of NH from generation $i + 1$, and RH from generation $i$ (Correspondingly, in period $i_1$ firm 2’s product line also consists of NH products from generation $i$ and RH from generation $i − 1$).

Following OBR14 we make three simplifying assumptions (see their paper for the examples, figures and overall justification of these assumptions):

(A1) The new generation of NH and NL products become available at the same time.

(A2) The product prices are constant throughout generations $i − 1$, $i$, and $i + 1$.4

(A3) The demand for NH and NL from generation $i + 1$ that RH from generation $i$ cannibalizes in period $i + 1_1$, is the same as that cannibalized in period $i_1$ by RH from generation $i − 1$.

The key implication of assumptions A1-A3 is that to assess economic and environmental impact of remanufacturing the firms only need to consider what happens in periods $i_1$ and $i_2$.

Let $\tilde{p}_n$ and $\tilde{c}^{ij}_n$ be the price and cost vectors for firm $n = 1, 2$, and $j = 1, 2$, such that $\tilde{p}_1 = (p_{NH1}, p_{NL}), \tilde{p}_2 = (p_{NH2}, p_{RH})$ and $\tilde{c}^{ij}_1 = (c_{NH}, c_{NL}), \tilde{c}^{ij}_2 = (c_{NH}, c_{RH}^{ij})$, where $c_{NH}, c_{NL}$ are the costs for NH and NL in both period $i_1$ and $i_2$, and $c_{RH}^{ij}$ denote the cost of remanufacturing (including collection, testing, etc.) for the corresponding products and periods $i_j (j = 1, 2)$. Also let $\bar{m}_n$ denote the net present values of the profit margins from service for firm $n = 1, 2$, such that $\bar{m}_1 = (m_H, m_L), \bar{m}_2 = (m_H, m_{RH})$ where $m_H, m_L$ are the profits from the H and L services, and $m_{RH} = \Delta m_H + (1 − \Delta) m_L$. From our discussions with executives at AT&T (2009, 2010), RH can be offered with either L or H service and we therefore define $\Delta$ as the net present value of the probability of an upgrade in the duration of the service contract when the customer starts with L service. This overall setup is consistent with the case when consumers sign a service contract with

4 Note that the pricing policy of service providers such as AT&T and Verizon is consistent with this assumption. For example when introducing the iPhone 4 in June 24, 2010, AT&T charged $199 for the 16GB and $299 for the 32GB version. When introducing the iPhone 4S in October 14, 2011, the prices were identical with the addition of a third version of 64GB at a price of $399.
the firm and pay for service over time, but purchase the product upfront upon signing the contract. Note that since both firms purchase their identical NH product from the same manufacturer, the costs are likely to be the same. With respect to the service margins, while these could be different between the two firms, since our focus in this paper is on the pricing of the product lines, we keep those equal.

With respect to the demand / sales for the products, let \( \vec{D}_{nj}^{ij}(\vec{p}_1, \vec{p}_2) \) and \( \vec{S}_{nj}^{ij}(\vec{p}_1, \vec{p}_2) \) be the demands and sales vectors for firm \( n = 1, 2 \), and the corresponding products and periods, \( i_j \) \((j = 1, 2)\), where \( \vec{D}_{1}^{ij}(\cdot) = (D_{NH}^{ij}(\cdot), D_{NL}^{ij}(\cdot)) \), \( \vec{D}_{2}^{ij}(\cdot) = (D_{NH}^{ij}(\cdot), D_{RH}^{ij}(\cdot)) \), and \( \vec{S}_{1}^{ij}(\cdot) = (S_{NH}^{ij}(\cdot), S_{NL}^{ij}(\cdot)) \), \( \vec{S}_{2}^{ij}(\cdot) = (S_{NH}^{ij}(\cdot), S_{RH}^{ij}(\cdot)) \). Also, we assume that for the new products, the two firms purchase products as needed, so that for products \( k = NH1, NL, NH2 \), demand \( \equiv \) sales. The sales of RH in period \( i_j \) \((j = 1, 2)\) are equal to:

\[
S_{RH}^{ij}(\vec{p}_1, \vec{p}_2) = \min\left[D_{RH}^{ij}(\vec{p}_1, \vec{p}_2), K_{ij}\right] \tag{1}
\]

where

\[
K_1 = \beta_1 \left(S_{NH1}^{i_1}(\vec{p}_1, \vec{p}_2) + S_{NH2}^{i_1}(\vec{p}_1, \vec{p}_2) + S_{NH1}^{i_2}(\vec{p}_1, \vec{p}_2) + S_{NH2}^{i_2}(\vec{p}_1, \vec{p}_2) - S_{RH}^{i_2}(\vec{p}_1, \vec{p}_2) \right) \tag{2}
\]

and

\[
K_2 = \beta_2 \left(S_{NH1}^{i_1}(\vec{p}_1, \vec{p}_2) + S_{NH2}^{i_1}(\vec{p}_1, \vec{p}_2) \right). \tag{3}
\]

Equations (1) – (3) reflect the fundamental feature of remanufacturing: the supply of remanufacturable cores in period \( i_j \), and hence the sales of RH in \( i_j \) \((j = 1, 2)\), is constrained by a multiple of the NH sales in the previous periods. We therefore define \( \beta_j \) to be the multiples for period \( i_j \), where \( \beta_1 \) refers to products that are returned at the end of their use (using the simplifying assumption (A3) so it depends only on period \( i \)) while \( \beta_2 \) refers to “false returns”.

To define the sales of products \( k = NH1, NH2, NL \), consider period \( i_1 \). If \( S_{RH}^{i_1}(\vec{p}_1, \vec{p}_2) = D_{RH}^{i_1}(\vec{p}_1, \vec{p}_2) \), then all remanufactured product demand is satisfied. Otherwise, the first \( \frac{K_1}{D_{RH}^{i_1}(\vec{p}_1, \vec{p}_2)} \) percent of customers will face the choice among the four products (as well as, obviously, the option to buy nothing), while the rest – the overflow, will face the choice between NH1, NL, and NH2.

\footnote{Note that the supply of RH in period \( i_1 \) is the fraction of the total number of generation \( i \) – 1 NH units sold in period \( i \) – 1 net the number of generation \( i \) – 1 RH units sold in period \( i + 1 \). By assumption (A3) the situation is in the steady state so that we can replace \( i \) – 1 by \( i \).}
only. Combining the two cases, the behavior of the first \( \frac{s_{RH}^i(\cdot)}{d_{RH}^i(\cdot)} \) percent of customers is described by the demand vector \( \bar{D}_{ij}^i(\bar{p}_1, \bar{p}_2) \), \( n = 1, 2 \), while the behavior of the remaining \( 1 - \frac{s_{RH}^i(\cdot)}{d_{RH}^i(\cdot)} \), the overflow, is described by a vector of different demand functions which we denote as \( \bar{D}_{kj}^i(\bar{p}_1, p_{NH2}) \), for \( k = NH1, NL, NH2 \). These demand functions account for the fact that consumers’ choice set does not contain the RH product (we discuss this case in Section 3.3).

Therefore the expected sales for the NH1, NL, and NH2 products in period \( ij \) are equal to:

\[
S^i_k(\bar{p}_1, \bar{p}_2) = D^i_k(\bar{p}_1, \bar{p}_2) \times S^i_{RH}(\cdot) + \bar{D}_{kj}^i(\bar{p}_1, p_{NH2}) \times \left( 1 - \frac{s_{RH}^i(\cdot)}{d_{RH}^i(\cdot)} \right)
\]

for \( k = NH1, NL, NH2, j = 1, 2 \), where \( S^i_{RH}(\cdot) \) is given in (1).

3.2 The Firms’ Maximization Problem

Using the vectors of sales, prices, costs and service margins defined above, the profit for firm \( n = 1, 2 \) in period \( ij \) is:

\[
\pi^i_n(\bar{p}_1, \bar{p}_2) = (\bar{p}_n - c^i_n + m_n) \cdot S^i_n(\bar{p}_1, \bar{p}_2),
\]

and the total profit in period \( i \) for firm \( n (= 1, 2) \) is:

\[
\pi^i_n(\bar{p}_1, \bar{p}_2) \equiv \pi^i_{n1}(\bar{p}_1, \bar{p}_2) + \pi^i_{n2}(\bar{p}_1, \bar{p}_2),
\]

where \( \tau \) is the discount factor for the time value of money. Note that the dot operator “\( \cdot \)” in (5) refers to the dot-product of the prices and sales vectors (colloquially known as sum product), while the “\( \times \)” in (6) refers to a regular multiplication of scalars.

The two firms compete in a product-line price competition where the best-response problem of firm \( n (= 1, 2) \) is to select prices that would maximize \( \pi^i_n(\bar{p}_n, \bar{p}_{-n}) \) where \( \bar{p}_{-n} \) refers to the price vector of the other firm. Let \( \bar{p}^*_{-n}(\bar{p}_{-n}) \) denote such a best response. That is,

\[
\pi^i_1(\bar{p}_1^*(\bar{p}_2), \bar{p}_2) \geq \pi^i_1(\bar{p}_1, \bar{p}_2) \forall \bar{p}_1
\]

\[
\pi^i_2(\bar{p}_1, \bar{p}_2^*(\bar{p}_1)) \geq \pi^i_2(\bar{p}_1, \bar{p}_2) \forall \bar{p}_2
\]

Then the Nash equilibrium is the set of two vectors, \( \bar{p}^*_1 \) and \( \bar{p}^*_2 \) such that \( \bar{p}^*_1(\bar{p}_2^*(\bar{p}^*_1)) = \bar{p}^*_1 \).

Generally speaking, whether the best-response functions are “well-behaved” and consequently whether equilibrium exists and is unique cannot be established without specifying
properties of the demand functions. Since this paper draws on the behavioral estimation of demand such properties cannot be guaranteed to hold; thus our approach for the numerical search of the equilibrium takes several pre-cautions to ensure that the reported results correspond to stable and likely unique equilibria; see Section 4.2 for more details.

We also define the resulting sales for each of the firms and products as:

\[
S_k^i(p_1^*, p_2^*) = S_k^{i_1}(p_1^*, p_2^*) + S_k^{i_2}(p_1^*, p_2^*)
\]

for \( k = \text{NH1, NL, NH2, RH} \), and the total sales in the market as:

\[
S_T^i(p_1^*, p_2^*) = \sum_{k=\text{NH1, NL, NH2, RH}} S_k^i(p_1^*, p_2^*).
\]

We finally define the optimal total industry profit given the equilibrium prices as:

\[
\pi_T^i(p_1^*, p_2^*) = \pi_1^i(p_1^*, p_2^*) + \pi_2^i(p_1^*, p_2^*).
\]

The next table summarizes our notation:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_{\text{NH}}, c_{\text{NL}} )</td>
<td>New high-end and low-end product costs</td>
</tr>
<tr>
<td>( c_{\text{RH}}^i, c_{\text{RH}}^i )</td>
<td>Cost of remanufacturing in period ( i_j ) (( j = 1, 2 ))</td>
</tr>
<tr>
<td>( \bar{p}<em>1 = (p</em>{\text{NH1}}, p_{\text{NL}}) )</td>
<td>Price vector for firm 1 (includes prices of new high-end and low-end products)</td>
</tr>
<tr>
<td>( \bar{p}<em>2 = (p</em>{\text{NH2}}, p_{\text{RH}}) )</td>
<td>Price vector for firm 2 (includes prices of new and refurbished high-end products)</td>
</tr>
<tr>
<td>( \beta_1, \beta_2 )</td>
<td>Percentage of products returned in periods period ( i_j ) (( j = 1, 2 )), where ( i ) is omitted</td>
</tr>
<tr>
<td>( \Delta )</td>
<td>Probability of a service upgrade from low to high service for RH customers</td>
</tr>
<tr>
<td>( m_L, m_H )</td>
<td>Net present values of the low / high service plans</td>
</tr>
<tr>
<td>( D_1^{ij} = (D^{ij}<em>{\text{NH}}, D^{ij}</em>{\text{NL}}) )</td>
<td>Demand vector for firm 1 (includes demand of new high-end and low-end products)</td>
</tr>
<tr>
<td>( D_2^{ij} = (D^{ij}<em>{\text{NH}}, D^{ij}</em>{\text{RH}}) )</td>
<td>Demand vector for firm 2 (includes demand of new and refurbished high-end products)</td>
</tr>
<tr>
<td>( S_1^{ij} = (S^{ij}<em>{\text{NH}}, S^{ij}</em>{\text{NL}}) )</td>
<td>Sales vector for firm 1 (includes sales of new high-end and low-end products)</td>
</tr>
<tr>
<td>( S_2^{ij} = (S^{ij}<em>{\text{NH}}, S^{ij}</em>{\text{RH}}) )</td>
<td>Sales vector for firm 2 (includes sales of new and refurbished high-end products)</td>
</tr>
<tr>
<td>( \pi_n^{ij}(\bar{p}_1, \bar{p}_2) )</td>
<td>Profit of firm ( n = 1,2 ) in period ( i_j, j = 1,2 ) given price vectors ( \bar{p}_1, \bar{p}_2 )</td>
</tr>
</tbody>
</table>

**Table 1: Notation Summary**

### 3.3 The No Remanufacturing Benchmark Case

In this subsection we analyze the special case where firm 2 decides not to remanufacture and thus sells only product NH2, while firm 1 sells as before products NH1 and NL. This case is important for two reasons: First, as we saw in the last subsection if the demand for the remanufactured product is higher than the supply of cores, some of the customers face a choice set that includes only NH1,
NL, and NH2. Second, in order to evaluate the environmental impact of remanufacturing under competition we need to compare the case from the previous subsection with a benchmark case where firm 2 does not remanufacture. Let $D_{n}^{ij}(p_1, p_2)$ and $S_{n}^{ij}(p_1, p_2)$ be the demands and sales vectors for firm $n = 1, 2$, and the corresponding products and periods, $i_j (j = 1, 2)$, where $p_1 = (p_{NH1}, p_{NL})$ as before but $p_2 = p_{NH2}$ now, and $D_{1}^{ij}(\cdot) = (D_{NH}^{ij}(\cdot), D_{NL}^{ij}(\cdot))$, $D_{2}^{ij}(\cdot) = (D_{NH}^{ij}(\cdot))$, and $S_{1}^{ij}(\cdot) = (S_{NH}^{ij}(\cdot), S_{NL}^{ij}(\cdot))$, $S_{2}^{ij}(\cdot) = (S_{NH}^{ij}(\cdot))$. The firms’ maximization problem is similar to that in Section 3.2 with the only difference being that for firm 2, its profit in period $i_j (j = 1, 2)$ is now given by

$$\pi^{ij}_{2}(p_1, p_2) = (p_{NH2} - c_{NH} + m_H) \times S_{NH2}^{ij}(p_1, p_2)$$

(11)

The total profit from generation $i$ products without remanufacturing for firm $n (= 1, 2)$ is still given by (6) and the best response functions and the Nash equilibrium are given by (7) where $p^*_2 \equiv p_{NH2}^*$. The resulting optimal sales are given by:

$$S_{k}^{ij}(p_1^*, p_2^*) = S_{k}^{ij}(p_1^*, p_2^*) + S_{k}^{ij}(p_1^*, \tilde{p}_2)$$

(12)

for $k = NH1, NL, NH2$, and the total sales in the market as:

$$\bar{S}^{ij}_{T}(p_1^*, p_2^*) = \sum_{k=NH1,NL,NH2} S_{k}^{ij}(p_1^*, p_2^*)$$

(13)

Similar to (10) we also define the optimal total industry profit for this case as:

$$\bar{\pi}^{ij}_{T}(p_1^*, p_2^*) = \pi^{ij}_{1}(p_1^*, p_2^*) + \pi^{ij}_{2}(p_1^*, p_2^*)$$

(14)

where the equilibrium price vectors are calculated using demand functions $\bar{D}$ and $p_{NH2}^* \equiv p_{NH2}^*$.

### 3.4 The Firm’s Environmental Impact

We measure the environmental impact by the total energy consumption during the life cycle of a product. This approach is common in the academic literature, e.g., Doctori Blass et al. (2006), Geyer (2004), Gutowski et al. (2011), and OBR14, as well as in industry, e.g., McLaren & Piukkula (2004), Apple (2011), Nokia (2011). Figure 1 demonstrates the life cycle stages we considered in our analysis. For the new products these include: raw materials, production and transportation, initial use, and disposal. For the remanufactured products these include: collection and transportation, remanufacturing, secondary use and disposal. It is important to note that the use phase of NH can be either partial, reflecting for example “false returns” ($\beta_2$), or full ($\beta_1$).
Let $E_k (k = NL, NH, RH)$ denote the total energy consumption per unit of product. From this discussion, $E_k$ is the sum of the corresponding life-cycle stages described in Figure 1. Then the total energy, $TE$, is obtained as the sum product of the corresponding per-unit energy $E_k$ and the total unit sales in the general competitive case in Sections 3.1 and 3.2 and the benchmark case of no remanufacturing in Section 3.3:

**General Case:**

$$TE^* = TE_1^* + TE_2^*$$

where

$$TE_1^* = E_{NH} \times S_{NH1}^i(\tilde{p}_1^*, \tilde{p}_2^*) + E_{NL} \times S_{NL}^i(\tilde{p}_1^*, \tilde{p}_2^*),$$

$$TE_2^* = E_{NH} \times S_{NH2}^i(\tilde{p}_1^*, \tilde{p}_2^*) + E_{RH} \times S_{RH}^i(\tilde{p}_1^*, \tilde{p}_2^*).$$

**Benchmark (No Remanufacturing) Case:**

$$\overline{TE}^* = \overline{TE}_1^* + \overline{TE}_2^*$$

where

$$\overline{TE}_1^* = E_{NH} \times \overline{S}_{NH1}^i(\overline{p}_1^*, \overline{p}_2^*) + E_{NL} \times \overline{S}_{NL}^i(\overline{p}_1^*, \overline{p}_2^*),$$

$$\overline{TE}_2^* = E_{NH} \times \overline{S}_{NH2}^i(\overline{p}_1^*, \overline{p}_2^*).$$

Similar to OBR14 we define three measures to assess the environmental impact of remanufacturing:

**Definition:** We define the following environmental impact measures:

(a) The *Absolute* measure, $Env_A = \overline{TE}^* - TE^*$

(b) The *Relative per-unit* measure, $Env_{R/u} = \frac{\overline{TE}^* - TE^*}{\overline{S}_T^l(\overline{p}_1^*, \overline{p}_2^*) - S_T^l(p_1^*, p_2^*)}$

(c) The *Relative per-dollar* measure, $Env_{R/d} = \frac{\overline{TE}^* - TE^*}{\overline{\pi}_T^l(\overline{p}_1^*, \overline{p}_2^*) - \pi_T^l(p_1^*, p_2^*)}$,

where $S_T^l(p_1^*, p_2^*), \overline{S}_T^l(\overline{p}_1^*, \overline{p}_2^*), \pi_T^l(p_1^*, p_2^*),$ and $\overline{\pi}_T^l(\overline{p}_1^*, \overline{p}_2^*)$ are given in (9) – (10) and (13) – (14).

Note that the above measures are defined at the industry level. One can extend this logic and define the firm-level measures. For example, firm 1 absolute environmental impact will be $Env_{1,A} = \overline{TE}_1^* - TE_1^*$. In Section 5.2, we discuss these individual measures, however, we do not define them formally here to avoid adding more notation. It is important to emphasize that although
firm 1 does not remanufacture itself, its environmental impact will change as a result of firm 2’s remanufacturing decision because of firm 1’s response to the actions of firm 2.

We evaluate the impact of remanufacturing in competitive settings along three dimensions: First, we examine how remanufacturing affects the overall environmental impact, of the industry in total and each firm separately. We then examine the environmental impact per-unit sold in the market to separate the impact of growth in total quantity sold from the change in the mix of products in the product line. Finally, we assess environmental impact per-dollar. This eco-efficiency measure evaluates if the firms and the industry are growing in an eco-efficient way by increasing their profit at a higher rate than the environmental footprint.

Next we describe the behavioral study we conducted in order to estimate the demand functions for the two firms and perform numerical analysis with these estimated demands.

4 Parameters and Analysis

In this section we describe the behavioral study conducted in order to estimate the demand faced by the two firms and then discuss the simulation we conducted based on the estimated demands and the parameters drawn from the prior literature and industry sources.

4.1 Behavioral Study

The behavioral study used in this paper ran concurrently to that reported in OBR14 but with the additional attribute for the firm. Subjects were the same in both studies (102 randomly selected employees of a major North-American University) and answered a choice-based-conjoint survey about purchasing items from a product line of a wireless communications firm6. The survey varied the following attributes: product (NH, RH, NL), firm (1, called “N” in the survey and 2, called “M”), plan (voice and voice&data), and price in $50 increments. The survey was implemented and analyzed using the SSI Web system by Sawtooth software.

Note, the NH products of the two firms were described as identical: as mentioned in the Introduction, considering identical NH products but asymmetric firms is important for the internal consistency of our behavioral experiment and demand estimation. Assuming identical firms with identical products, would lead to a Bertrand-like situation when undercutting a rival by a penny would result in a disproportional influx of demand – which is not consistent with observed reality.

---

6 A detailed description of the products is given in Appendix A
(e.g., if Verizon slightly undercuts AT&T it will not steal all AT&T customers) and could not follow from a random utility choice model that we use for demand estimation. Another option is to assume differentiated products, but in this case, small differences cannot be explained to the experimental subjects in a consistent way, while assuming that the new high-end products are significantly different would go against the goal of our paper.

We fit the choice data to a latent class\(^7\) multi-nominal logit (random utility) model using built-in Sawtooth algorithms. We found that the best fit\(^8\) occurred with four latent classes (minimizes Akaike (1974) information criterion). Table 2 presents the results of the estimation – the partworth utilities for different levels of each attribute for each segment.

<table>
<thead>
<tr>
<th></th>
<th>Segment 1</th>
<th>Segment 2</th>
<th>Segment 3</th>
<th>Segment 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>30.1%</td>
<td>18.9%</td>
<td>12.4%</td>
<td>38.6%</td>
</tr>
<tr>
<td>Product = NH1</td>
<td>-0.598</td>
<td>-0.430</td>
<td>1.066</td>
<td>1.122</td>
</tr>
<tr>
<td>Product = NH2</td>
<td>0.406</td>
<td>-0.996</td>
<td>1.476</td>
<td>0.662</td>
</tr>
<tr>
<td>Product = RH</td>
<td>-0.062</td>
<td>-0.001</td>
<td>0.485</td>
<td>-0.129</td>
</tr>
<tr>
<td>Product = NL</td>
<td>0.255</td>
<td>1.427</td>
<td>-3.027</td>
<td>-1.654</td>
</tr>
<tr>
<td>Price = 0</td>
<td>8.031</td>
<td>3.352</td>
<td>0.420</td>
<td>3.099</td>
</tr>
<tr>
<td>Price = 50</td>
<td>7.140</td>
<td>3.300</td>
<td>1.601</td>
<td>2.592</td>
</tr>
<tr>
<td>Price = 100</td>
<td>5.938</td>
<td>2.326</td>
<td>-0.026</td>
<td>2.294</td>
</tr>
<tr>
<td>Price = 150</td>
<td>4.726</td>
<td>1.324</td>
<td>-0.539</td>
<td>1.937</td>
</tr>
<tr>
<td>Price = 200</td>
<td>-5.980</td>
<td>0.284</td>
<td>0.477</td>
<td>0.349</td>
</tr>
<tr>
<td>Price = 250</td>
<td>-5.821</td>
<td>0.593</td>
<td>-0.608</td>
<td>0.444</td>
</tr>
<tr>
<td>Price = 300</td>
<td>-5.779</td>
<td>0.311</td>
<td>-0.061</td>
<td>-0.823</td>
</tr>
<tr>
<td>Price = 350</td>
<td>3.917(^9)</td>
<td>-0.747</td>
<td>-0.454</td>
<td>-1.952</td>
</tr>
<tr>
<td>Price = 400</td>
<td>-6.142</td>
<td>-10.143(^9)</td>
<td>-0.383</td>
<td>-4.274</td>
</tr>
</tbody>
</table>

\(^7\) We also experimented with nested models: for example, that a consumer first decides which product to purchase and then if the product is NH then from which firm. Such models did not increase the quality of fit hence we treated NH1 and NH2 as two distinct products in a consumer choice set.

\(^8\) The overall quality of fit, as measured by the so-called “percent certainty” – improvement in log-likelihood due to the model predictions equals 47.84% (well in line with 48.51% from OBR14).

\(^9\) Note that the utility of price 350 for segment 1 and for price 400 for segment 2 spike dramatically. It is hard to explain this anomaly since the utilities in Table 2 are the output of the Latent-Class module in Sawtooth – an industry-grade conjoint software system. This is the way the data is. However, one speculation for why this could have happened is related to a sampling error. By design, \(p_{RH} \leq p_{NH}\) hence while all \(p_{NH}\) values were uniformly distributed in the conjoint tasks that the subjects were presented with, the distribution of \(p_{RH}\) has more mass at small values and less at large. Hence there is overall less data to estimate utilities at large prices. Our sample size is quite modest (~100 subjects) so the number of subjects in each latent class is between ~12 and ~38. There are clearly many more price combinations that each subject saw, thus it could be that within ~30 segment 2 subjects only 1 or 2 saw a case with \(p = \$350\) and if those 1-2 subjects’ choices were very consistent for this price, but different from other prices, this would result in the anomaly observed. Critically, however, since many comparisons in this paper are with the monopoly results from OBR14, because both papers use the same data, the anomaly is present in both, and thus likely cancels out from the comparison.
Table 2: Partworth Utilities for the Case with and without the Remanufactured Product.

<table>
<thead>
<tr>
<th></th>
<th>Price = 450</th>
<th>-6.030</th>
<th>-0.599</th>
<th>-0.427</th>
<th>-3.666</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan = L</td>
<td></td>
<td>-0.304</td>
<td>0.599</td>
<td>0.250</td>
<td>-0.557</td>
</tr>
<tr>
<td>Plan = H</td>
<td></td>
<td>0.304</td>
<td>-0.599</td>
<td>-0.250</td>
<td>0.557</td>
</tr>
<tr>
<td>None</td>
<td></td>
<td>8.573</td>
<td>1.222</td>
<td>-2.010</td>
<td>0.630</td>
</tr>
</tbody>
</table>

These latent classes correspond to the following characterizations of customer segments:

**Segment 1:** "I don’t really need a phone." For segment 1 the utility of a device or plan is much smaller (in the absolute value) than the utility of purchasing nothing and therefore only if the phone is given for free (price of $0), the utility from buying a phone (achieved for purchasing NH2) is higher than the utility for not getting a phone (0.406 + 8.031 + 0.304 = 8.741 > 8.573).

**Segment 2:** "I want a feature phone (with no data)." For segment 2 the utility of NL is positive and in comparison to the utility of none is much larger than for segment 1. In addition, the utility for the L plan is positive, and thus segment 2 customers want to purchase a phone and prefer feature phones with no data plan.

**Segment 3:** "I want a smartphone and OK with refurbished with or without data." Segment 3 customers have a positive utility for the smartphones but negative for the feature phone and buying nothing. They prefer the new smartphone to refurbished (with slight preference for firm 2 over firm 1), and also (slightly) the voice-only plan to the voice-and-data. Thus, the remanufactured product is most attractive to segment 3 consumers; they would slightly prefer if it was offered with the voice-only plan, but even with the data plan their utility from RH is high, much higher than buying NL or nothing (even at relatively high prices).

**Segment 4:** "I want a new smartphone with data." Segment 4 customers are somewhat similar to those of segment 3, however they prefer more the new devices over the refurbished ones (the utility from RH is actually slightly negative) and would rather have data. In a way, these customers are a mirror image of segment 2 – they want a smartphone with data.

With these segments, consider the firms’ positioning of products. For the three segments that are really interested in a phone, segment 2 should be targeted by firm 1 to sell the low end phone, NL. Segment 3 should be targeted by firm 2 to sell RH, while segment 4 would be targeted by the two firms to sell NH1 and NH2. Segment 1 presents an opportunity for firm 2 to price its product very low and thus win customers in this segment, even if their original inclination is not necessarily to buy the product.
Note that the above model has in total 14 demand functions: For each of the two periods, we have four demand functions for the general case and three for the no remanufacturing benchmark case. Similar to OBR14, we estimate period $i_2$ demand functions (when all products are of generation $i$) directly from the utilities in Table 1 using the latent-class multi-nomial logit (MNL) model, and then adjust them for the technology progress\footnote{To construct period $i_1$ demands in the case with no remanufacturing we assume that $\bar{D}_k^{i_1} = D_k^{i_2}$. This implies that the periods are of equal length and that consumer preferences are not changing throughout the selling horizon of generation $i$ products. To construct period $i_1$ demands in the case with remanufacturing we introduce a parameter, $\gamma$, that adjusts the utility of generation-$i$ RH presented in Table 1 downwards, because in period $i_1$ RH is of generation $i-1$, and thus naturally is less desirable by consumers.} to obtain period $i_1$ demands. For a given segment we calculate the utility of a product $k = NH1, NL, NH2, RH$ given its price and service plan, and then obtain the purchase probability for a given product as a ratio of the exponent of its utility to the sum of exponents of utilities of other alternatives in the choice set. For example, for a segment 4 consumer, if firm 1 offers NH1 at $300$ and NL at $150$, and firm 2 offers NH2 at $300$ and RH at $250$ (with H service) then: the utility from NH1 = $1.122 + 0.557 – 0.823 = 0.856$, the utility from NL = $-1.654 – 0.557 + 1.937 = -0.274$, the utility from NH2 = $0.662 + 0.557 – 0.823 = 0.396$, the utility from RH = $-0.129 + 0.557 + 0.444 = 0.872$, and the utility of None = $0.63$. The corresponding exponents are $2.354$, $0.760$, $1.485$, $2.392$, $1.877$ with the total of $8.869$. Thus the demand share of NH1 = $2.354 / 8.869 = 26.54\%$, of NL = $0.76 / 8.869 = 8.57\%$, of NH2 = $1.485 / 8.869 = 16.75\%$, and of RH = $26.97\%$ and for None = $21.17\%$. Weighing these probabilities and those achieved for the other segments by the size of the segment gives the product’s demand for these prices. In order to find the demand functions for the case when firm 2 does not remanufacture (the tilde demand functions from Section 3.3) we remove the RH product from Table 2 and redistribute its utility in proportion to the absolute values of the utilities of the remaining products so that to preserve their relative attractiveness. This approach reflects the logic discussed earlier: that the choice-set in this case consists of two products and a do-nothing option between which consumers decide.

4.2 The Simulation

Because in part our goal is to compare the competitive case discussed in this paper with the isolated firm studied in OBR14, we used the same parameter ranges as in their paper. We summarize these parameters in Table 3 and refer the reader to the discussion in their paper for the detailed justification of the values used.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Definition</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{NH}$</td>
<td>[$500; 700$]</td>
<td>New high-end product cost</td>
<td>Goldman (2010), The Economist (2011)</td>
</tr>
<tr>
<td>$c_{NL}$</td>
<td>[$150; 300$]</td>
<td>New low-end product cost</td>
<td>AT&amp;T (2010)</td>
</tr>
<tr>
<td>$c_{RH}^{i1}$</td>
<td>[$10; 20$]</td>
<td>Cost of remanufacturing for short use period phones</td>
<td>AT&amp;T (2010), Galbreth and Blackburn (2006, 2010), Zikopoulos and Tagaras (2007), and Ovchinnikov (2011)</td>
</tr>
<tr>
<td>$c_{RH}^{i2}$</td>
<td>[$10; 100$]</td>
<td>Cost of remanufacturing for long term used phones</td>
<td></td>
</tr>
<tr>
<td>$\beta_1$</td>
<td>[15%; 35%]</td>
<td>Percentage of phones returned within a long period from the initial purchase (e.g., a year or two)</td>
<td>Doctori Blass et al (2006), Geyer and Doctori Blass (2010)</td>
</tr>
<tr>
<td>$\beta_2$</td>
<td>[5%; 15%]</td>
<td>Percentage of phones returned within a short period from the initial purchase</td>
<td></td>
</tr>
<tr>
<td>$\Delta$</td>
<td>[50%; 100%]</td>
<td>Probability of a service upgrade from low to high service for RH customers</td>
<td>AT&amp;T (2009)</td>
</tr>
<tr>
<td>$m_v$</td>
<td>[$23; 228$]</td>
<td>NPV of a 24 months voice-only plan Implies monthly margin [$1; 10$]</td>
<td>These ranges were estimated by the authors based on the prices of the voice and data plans with 5% discount rate.</td>
</tr>
<tr>
<td>$m_{v&amp;d}$</td>
<td>[$228; 570$]</td>
<td>NPV of a 24 months voice and data plan Implies monthly margin [$10; 25$]</td>
<td></td>
</tr>
<tr>
<td>$E_{NL}$</td>
<td>154MJ</td>
<td>Total energy in production and use of the NL product</td>
<td>Calculated by authors based on multiple sources (incl. Nokia 2011, Doctori Blass et al. 2006 and Quariguasi-Frota-Neto and Bloemhof 2011). See also the description in Section 5.1 and Table 2 in OBR14</td>
</tr>
<tr>
<td>$E_{RH}$</td>
<td>59.5MJ</td>
<td>Total energy in remanufacturing (incl. collection) and use of the RH product</td>
<td></td>
</tr>
<tr>
<td>$E_{NH}(\beta_2)$</td>
<td>224MJ</td>
<td>Total energy in production and partial use of the NH product, $\beta_2$ returns</td>
<td></td>
</tr>
<tr>
<td>$E_{NH}(\beta_1)$</td>
<td>275MJ</td>
<td>Total energy in production and full use of the NH product, $\beta_1$ returns</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Simulation parameters

We sampled 1,000 parameter combinations with each parameter value drawn at random from the corresponding ranges in Table 3, and for each parameter combination searched for the equilibrium price vectors with and without remanufacturing using the demand functions constructed based on Table 2 in Section 4.1.

We search for the equilibrium price vectors using the iterative best response algorithm, also known as the alternating-move adjustment, see Fudenberg and Tirole (1991) for the general description and Su (2010) for a recent OM application. We went through a sequence of up to 10 best-response iterations in an attempt to converge to an equilibrium. For example, for the case with no remanufacturing, suppose that choosing a price vector of $\tilde{p}_1 = ($100, $50) for firm 1 results in firm 2 reacting with $\tilde{p}_2 = ($200). For this price for NH2, further suppose that firm 1’s best response is to set the price vector $\tilde{p}_1 = ($200, $50) and firm 2’s best response is then to still charge
Thus the equilibrium price vectors in this case are: $p_1^* = ($200, $50)$ and $p_2^* = ($200)$, because firm 1’s best response to $200 for NH2 is $200 for NH1 and $50 for NL, and firm 2's best response to $200 for NH1 and $50 for NL is $200 for NH2.

Two points are worth noting about this procedure. First, since the best-response functions are not guaranteed to have a unique maximum, our optimization routine was such that the vector with lowest prices (in the order of NH1, NH2, RH, NL) would be selected of all the alternative optima. Second, for each of the 1,000 problem instances we searched for the equilibrium twice, starting from a random seed. Our procedure converged to an equilibrium in 779 instances, and in all instances when it converged, it converged to the same equilibrium starting from both seeds. Thus, while technically speaking, this does not guarantee that the equilibrium is unique, there is a reasonable degree of confidence that it is. The fact that the iterative best response failed to always converge is not surprising: theoretically it is not guaranteed to always converge even when equilibrium is known to exist, and in the applications of other authors occasional non-convergence has been reported as well, e.g., Su (2010) reports the failure to converge in 5.4% of scenarios (p. 1138). We hypothesize that one reason for occasional non-convergence in our case could be that we use discrete prices with increments of $50; our procedure could thus cycle around an equilibrium, say with a price of $125. We did not explore this issue further because the 779 cases provide enough data points for our analyses.

5 Results

In this Section we report the results of the simulations we performed in order to assess economic and environmental performance of remanufacturing using the behavioral data. Note that although the results we present are based on parameters and demand estimates for the wireless communications products described in Section 4, the framework we present is general and can be directly applied to other industries and products.

5.1 Economic Results

When analyzing remanufacturing in competitive settings as we do in this paper, there are two interrelated aspects we need to examine: competition and remanufacturing. Thus, there are two benchmarks we compare our results to: First the case when a firm decides to remanufacture in a monopoly analyzed by OBR14, and second, the case of no remanufacturing we discussed in Section
3.3. Therefore, in this section we discuss the economic results of the simulation to answer two major questions:

1. How does the competition change the product line pricing vs. the monopoly case?
2. How are the effects of the introduction of remanufactured products in a competitive environment differ from those with a single firm?

We describe the observations based on 779 cases (out of 1000 cases) where the model converged to a Nash equilibrium solution as discussed in Section 4.2. The results presented refer to the base case where the technology choice parameter is initially set to $\gamma = 1$ to reflect that there is some change between the generations of the product, but yet to keep remanufactured product a viable alternative.

As expected, we find that under competition the high-end products’ prices are lower than those under a monopoly. Interestingly, the decline in prices is not identical for the two firms:

**Observation 1:** Prices for new high-end product for firm 2 (which also offers remanufactured products) were slightly higher than for firm 1.

As Figure 2 shows, firm 2, i.e., the firm that refurbishes, is able to charge higher prices for its NH product than firm 1, even though these products are identical by design. While in most cases both firms charge the same price (e.g. for 258 cases both firms charge a price of $250) in some cases firm 2 charges more (e.g. in 44 cases firm 2 charges $450 while firm 1 charges $300). This is quite interesting since OBR14 as well as other papers in the literature (Abbey et. al 2014) show that in the monopoly case, the existence of the green segment is in question. OBR14 showed that no customers are willing to pay more for the refurbished product compared to the new one (a traditional interpretation of the green segment in the sustainable operations literature, e.g. Atasu et al. 2008). Abbey et al. (2014) showed that consumer greenness had the weakest relative effect on the remanufactured consumer product attractiveness for all product categories they considered (including consumer electronics). Similarly, in this paper, using the data in Table 2, we cannot show that under competition any of the segments prefer the refurbished product to the new one.

However, by the data in the table it is possible to show that some segments (Segments 1 and 3) prefer the new product from the firm that refurbishes (NH2), while others (segments 2 and 4) prefer the one from the firm that sells only new products (NH1). Since the preference of NH2 over NH1 for segments 1 and 3 is stronger than that of NH1 over NH2 for segments 2 and 4 (even though...
their weight is lower), we get that the average utility for NH2 in Table 2 is higher than that for NH1, which causes NH2 to have a higher price in equilibrium.

There are two explanations for this phenomena: The first is that consumers might regard the service provider that refurbishes as being more capable. For example, in the open text remarks we gathered after the behavioral experiment, we received comments such as “If they refurbish I am tempted to assume that they know their products better”. As discussed in the Introduction, this explanation is consistent with Agrawal et al. (2012) who showed using a behavioral study that remanufactured products sold by a third party have a positive effect on the perceived value of new products. The second explanation is that segments 1 and 3 give credit to the firm that refurbishes allowing it to charge more for its new product. For example, in the open text remarks we received comments such as “(the company / product) is more sustainable and better for the environment”. This point suggests that “green consumers” do in fact exist in the remanufacturing context, but they just don’t behave the way some of the earlier studies assumed. Note that this result could not have been seen in models that only examined the monopoly case or a case where two competing firms remanufacture (as is common in the literature) but only in a differentiated competitive model such as the one we use where one firm is green (remanufactures) and the other is not.

![Figure 2: NH prices under competition for the two firms](image)

For the case of a monopoly, OBR14 demonstrated negative cannibalization due to the introduction of the remanufactured product. As the next observation shows this result carries over
to the competitive setting, and in fact competition increases the negative cannibalization effect by driving the prices of the new high-end products for both firms to almost zero.

**Observation 2**: Under remanufacturing:

a) Competition drives down the prices of new high-end products to near zero in the majority of cases. Furthermore, the prices of new low-end products in many cases are higher than for new high-end products. (See Figure 3)

b) Both firms’ profits increase.

![Figure 3: Prices with and without remanufacturing under competition. The numbers inside circles denote the number of cases for a given price pair](image-url)
Observation 2(a) shows that remanufacturing in competitive settings will result in the prices for both NH products (both from firm 1 and from firm 2) to go to 0 and thus often be lower than the prices for the NL product (see Figure 3). This might happen because in the case of high-end products, the service provider can charge for data services that are very profitable and reduce the price of the product itself, while for low end products, the profit margin is much more limited. Additionally, the observation is driven by the consumer segmentation with respect to products and plans: indeed, from Section 4.1 some 19% of consumers are not willing to pay for the data plan that comes with the high-end product, preferring a low-end product instead.

Observation 2(b) shows that in all cases the profits of both firms increased despite the decrease in prices. This is because the price of NH drops down much steeper than that of NL increasing the share of high-end products’ sales. Since high-end products provide better margins (through service), the total profits increase as well.

5.2 Environmental Results

As discussed in Section 3.4, we evaluate the impact of remanufacturing in competitive settings in both absolute (the effect of remanufacturing on the overall environmental impact, of the industry in total and each firm separately) and relative terms (examining the impact both per unit and per dollar profit). By the results below the environmental impact of the firm worsens in both measures. While the absolute measure might be somewhat expected from the pricing result (Observation 2a), the relative measure results are quite surprising and were not shown before in the literature.

Observation 3: In almost all cases, the firms and the market exhibit a negative absolute environmental effect.

By Observation 3, with the introduction of remanufacturing under competition, in almost all cases (99.9% for firm 1 and 96.9% for firm 2) we observe the negative absolute environmental effect; where with the introduction of remanufactured products by firm 2, both firms improved their profits, but at the same time they increased their environmental footprint, a win-lose situation (Plaza-Úbeda et al., 2009). These percentages are much higher compared to the base case of monopoly, where as per OBR14 only 26.2% of the cases yielded this win-lose situation. That is, returning to the discussion in the introduction, while it was theoretically possible that the sales from one firm will increase at the expense of the other firm, our results show that under competition both...
firms reduce their prices and thus the overall demand almost always increases under competition. Further, this increase in the overall sales is larger than the environmental savings from substituting some of the new products with refurbished ones. That is what causes the negative absolute environmental effect. What is even more interesting is the environmental effect in relative terms which is examined in the next observation.

Observation 4:
(a) In 87.9% of the cases we observed a **negative relative (per-unit) environmental effect** for firm 1 (see Table 5 below), however, there were zero\(^{11}\) cases for firm 2. Taking into account the overall effect on the market, in 49.3% of the cases, there was a negative relative (per-unit) environmental effect.

(b) Firm 1 had 16.8% cases and firm 2 had 6.8% cases of **relative (per-dollar) environmental effect**. While this effect is less prevalent than the per unit effect, both of these percentages are much higher compared to the 0.3% in the monopoly case from OBR14.

<table>
<thead>
<tr>
<th># of cases</th>
<th>% of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/Unit</td>
<td>Energy/$ Profit</td>
</tr>
<tr>
<td>Monopoly (from OBR14)</td>
<td>7</td>
</tr>
<tr>
<td>Competition, Firm 1</td>
<td>685</td>
</tr>
<tr>
<td>Competition, Firm 2</td>
<td>0</td>
</tr>
<tr>
<td>Total market</td>
<td>384</td>
</tr>
</tbody>
</table>

**Table 4: Relative negative environmental effect**

The negative relative environmental effects we see above are based on the changing mix of products within the product lines for each of the firms and the market as a whole. They are direct results of the increase in share of high-end phones in the market, as demonstrated in Figure 4 below. When firm 2 decided to remanufacture it needed to increase the supply of RH and thus decreased the price of NH2, which in turn caused firm 1 to respond by decreasing the price of NH1 as well, further increasing the supply of RH. This increase in the quantity of high-end products comes at the expense of the NL product, whose quantity declines: from Figure 4, the average share of NL over the 779 cases we considered dropped from 34.7% to 16.1%, while the share of RH is only 5.1%. In other words, the share of the new high-end products increased from 65.3% to 78.8%. Since the environmental impact of NL is smaller than of NH, this change in the mix (more high-end and less

\(^{11}\) Zero cases of relative per-unit negative effects is a natural outcome in our model because by construction only firm 1 sells NL products. Hence firm 2 per unit cannot get any worse than selling NH.
low-end products) leads to the negative relative environmental effects. Note that this result could not have been seen in a competition models that only examined a high-end product and its refurbished version in the product line (as in most of the previous literature) as shown in the fact that for firm 2, there is no relative effect. This result can happen only in a model like ours that included a richer product line competition where one firm sells both high-end and low-end products.

Figure 4: Breakdown of industry total sales by product before (a) and after (b) the introduction of the remanufactured product.

6 Discussion and Conclusions

This paper provides a data-driven assessment of the economic and environmental aspects of remanufacturing for product+service firms under competition. When analyzing remanufacturing in competitive settings, there are two interrelated aspects we need to examine: competition and remanufacturing. Thus, in order to understand the economic (measured by the optimal profits) and environmental (measured by energy consumption) impacts of remanufacturing we compare our results to two important benchmarks: First the case when a firm decides to remanufacture in a monopoly (analyzed by OBR14) and second, the case of no remanufacturing under competition we discussed in Section 3.3.

For the economic assessment, as expected, we show that competition reduces prices overall. But unexpectedly, the firm that offers remanufactured products suffers less of a price drop for the new products. Our results thus sheds new light on the behavior of the “green segment” who, as we
show, are not willing to pay equally for new and refurbished products (as is sometimes assumed in the OM literature) but have a preference for firms that refurbish which allows those firms to charge higher prices for their new products. This result is a combination of two factors: the remanufacturing firm is being perceived as more capable (as in Agrawal et al. 2012) and consumers preferring the firm due to their green tendencies (as shown in some of the marketing literature, e.g. Sen and Bhattacharya 2001). We also find that while remanufacturing decreased the prices of the new products, in all cases, it increased the profits of both firms (the one that remanufactured and the one that did not).

With regard to the environmental assessment, we show that in most cases (over 95% of the cases for each firm and overall) remanufacturing resulted in a worsened environmental impact: a negative absolute environmental effect. The increase in absolute terms was much higher than the monopoly case and disproved the presumption that competition could lead to better outcomes since the growth in the firm that remanufactures will come through a decrease in demand for the competing firm. When introducing a remanufactured product, a firm is interested in increasing the supply of cores, which motivates it to decrease the new product’s price, in response to which the competing firm reduces its price as well. Thus while the remanufactured product indeed cannibalizes some of the new product’s sales (and by doing so decreases environmental impact), the associated increase in the new production more than offsets this decrease, amplifying the negative cannibalization and consequently making the negative absolute effects more prevalent.

Most importantly, we find that unlike the monopoly case, under competition, the environmental impact worsens also in the relative terms. For the firm that did not remanufacture, the per-unit environmental impact was worse in 88% of the cases, and thus even though the firm that remanufacture had a better environmental outcome (by construction), the relative per-unit environmental impact of the industry as a whole worsened in 49% of the cases. The frequency of negative impacts per-dollar of profit was lower (16.8% of the cases for the firm that did not manufacture, 6.8% for the firm that did, and 7.7% for the industry overall) but still significant compared to the case of a monopoly where almost no such cases existed. This result is driven by the change in the mix of products within the product line since the share of high-end products increased with remanufacturing, decreasing the share of the low-end products thus causing an increase in environmental impact on the relative basis as well.
It is important to note that while the numerical estimates/parameters in our paper are specific to the wireless communication industry/category, the overall approach and framework are general and the results could be generalized to other industries. Recall that the main driver for the relative environmental effect is the multiple products in the firm’s product line that causes people to move from low end products to refurbished and new high-end products. These characteristics are true in many other product categories but as described above were not measured this way since most research that examines environmental effect looked only at the effect of the refurbished product on its parent product and not on other products in the product line. Raz et al. (2013) categorizes products into ones where the manufacturing stage environmental impact is higher than the use stage impact (such as wireless communication devices) versus others where the opposite occurs (e.g. fashion products due to the laundry effect or computer servers due to electricity use). While our results here apply to the wireless communications products and services, they could be even stronger in products where the use stage environmental impact is higher than the manufacturing stage one, because for those products even the move from low-end products to high-end refurbished products could cause higher environmental impact (because environmental impact during the use stage dominates). It is also important to note that the service aspect in our paper is helpful, but not necessary as the results could still happen if there was no service. In this case the firms would be able to reduce their prices only up to the cost and not to nearly zero as we find optimal when firms can recoup their losses from selling products through services. We would still expect that without the remanufactured product the market would have a lower market size and thus the negative relative environmental effect could happen. Future research could look at quantifying the negative environmental effect for different categories of products in order to compare where it is strongest.

Another avenue for future work is to expand the scope of analysis from only capturing the environmental and economic impact of remanufacturing to the overall societal impact. For example, specific to the wireless communications example we considered in this paper, since remanufacturing leads to displacing low-end products and increasing market penetration of high-end wireless communication products, it also increases people’s access to mobile communications, internet, and other related services. It would be interesting to assess the impact of remanufacturing when including the societal benefits from those services as well.
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Appendix A: Description of the products in the behavioral study

The subjects in the study were given the following descriptions\(^\text{12}\) for the products:

A NEW SMARTPHONE with a Voice and Data plan: A smartphone is a high-end mobile communication device, such as, for example, iPhone, BlackBerry or Palm. It has multiple PC-like features, including a miniature keyboard, a touch screen or a scroll-pad, a built-in camera, contact management, an accelerometer, built-in navigation hardware and software, the ability to read business documents, media software for playing music, browsing photos and viewing video clips, high-speed (3G) internet browsers, full-featured e-mail capabilities and a complete personal organizer.

A NEW FEATURE PHONE with a Voice only plan: This product is a new and fully functioning camera phone, but with the smaller set of features than a smartphone. It has a smaller keyboard, a smaller screen, and a slower processor. It is not suitable for high-speed data-intensive tasks; but basic data features, such as text messaging, are supported.

A REFURBISHED SMARTPHONE: This is a fully functional device with the same set of features as in the Smartphone described above, but it is not new. It has been sold before, used by another consumer and then returned for unspecified reason. It has been tested and refurbished by an authorized service provider to meet original factory specifications. The product may have observable cosmetic blemishes, however it is fully functional. Standard new smartphones warranty and return policy applies to this product.

The descriptions for the plans were:

VOICE only: A substantial number of minutes for a total monthly fee of $40. Other features include: per-second billing, no long-distance fees, and free nation-wide roaming.

VOICE and DATA: The above voice plan, plus an unlimited high-speed (3G) data for a total monthly fee of $70.

In addition, the following statements were added regarding plans and firms:

With each plan you are signing a two-year contract that you cannot terminate, unless a significant penalty is paid.

Suppose that there are two manufacturers of the phones:

1) Company N: Makes NEW SMARTPHONE and NEW REGULAR PHONE, but it does not refurbish

2) Company M: Makes NEW SMARTPHONE, and refurbishes its own smartphones. That is, company M does not offer regular phone, but it does offer REFURBISHED SMARTPHONE

\(^{12}\)These descriptions are a blend of descriptions of several devices and plans from AT&T’s website, as well as the corresponding Wikipedia pages.