Economic and Environmental Assessment of Remanufacturing Strategies for Product + Service Firms

Anton Ovchinnikov

Darden School of Business, University of Virginia, Charlottesville, Virginia 39040, USA, aovchinnikov@darden.virginia.edu

Vered Blass

Faculty of Management, Tel Aviv University, Tel Aviv, Israel, vblass@post.tau.ac.il

Gal Raz

Darden School of Business, University of Virginia, Charlottesville, Virginia 39040, USA, razg@darden.virginia.edu

This article provides a data-driven assessment of economic and environmental aspects of remanufacturing for product + service firms. A critical component of such an assessment is the issue of demand cannibalization. We therefore present an analytical model and a behavioral study which together incorporate demand cannibalization from multiple customer segments across the firm's product line. We then perform a series of numerical simulations with realistic problem parameters obtained from both the literature and discussions with industry executives. Our findings show that remanufacturing frequently aligns firms' economic and environmental goals by increasing profits and decreasing the total environmental impact. We show that in some cases, an introduction of a remanufactured product leads to no changes in the new products' prices (positioning within the product line), implying a positive demand cannibalization and a decrease in the environmental impact; this provides support for a heuristic approach commonly used in practice. Yet in other cases, the firm can increase profits by decreasing the new product's prices and increasing sales—a negative effective cannibalization. With negative cannibalization the firm's total environmental impact often increases due to the growth in new production. However, we illustrate that this growth is nearly always sustainable, as the relative environmental impacts per unit and per dollar rarely increase.

Key words: remanufacturing; demand cannibalization; product + service firms; environmental impact
History: Received: June 2012; Accepted: February 2013 by Daniel Guide, after 2 revisions.

1. Introduction

For remanufacturing to be truly sustainable, it must achieve two goals: increase the firm's profits and decrease its environmental impact. In this article, we analyze economic and environmental impacts of remanufacturing to understand when these two goals align. We present a general framework for such an analysis in the context of a product line offered by a product + service firm and conduct a detailed data-driven analysis motivated by the following example.

On June 24th, 2010, Apple, Inc. launched its much anticipated iPhone 4. This was the fourth generation of the iPhone (following the original iPhone, iPhone 3, and iPhone 3GS), and, together with its carrier partner, AT&T, Apple took preorders for 600,000 iPhone 4 handsets on the first day preorders were available, the highest one-day preorder volume it has ever taken

(Ogg 2010). For AT&T this meant that in the fall of 2010, it was offering a product line that consisted (among other things) of the new iPhone 4—a "high-end" device—new "low-end" devices such as the Pantech Breeze II, as well as various voice and data plans that accompany these devices, reflecting the product + service nature of firms like AT&T. But in addition to these new devices, AT&T also faced a stream of used products: the previous generation iPhones from customers who wanted to upgrade their devices to iPhone 4 as well as the returns from some of the iPhone 4 customers who for various reasons were not satisfied with their recent purchase. The former clearly needed some refurbishing, since they were in use for typically close to 2 years, but, according to industry norms (Ovchinnikov 2011), even the latter nearly new devices could only be sold as refurbished.[1] In either case, the speed of technological

innovation was so fast that those used items were not near the end of their physical life (Kogan 2011) and could be profitably resold. An important question is: How should AT&T integrate these refurbished devices in its product line of new products in a way that balances profits with environmental impact?

Interestingly, there is no obvious definition of what constitutes a good balance between profits and environmental impact. In the ideal situation, the firm's profit increases but its total environmental impact decreases; we refer to this case as the *absolute* positive environmental effect. The problem, though, is that if the increase in profits comes from growth (e.g., manufacturing and selling more units), then the firm's total environmental impact might actually increase, creating an absolute negative environmental effect. Hence, we also consider two *relative* measures of the balance between profits and environmental impact: relative per unit and relative per dollar. Such relative measures provide additional insight into the balance between profits and environmental impact by evaluating if the firm's growth is sustainable as they disentangle the growth in the volume of the firm's sales from the effect of substituting products within the product line.

Economic and environmental assessment of remanufacturing has been the focus of both Operations Management and Industrial Ecology literatures; see section 2 for review. Researchers in these disciplines agree that the central issue in such an assessment is that of *demand cannibalization*. Our article expands the analysis of demand cannibalization along two important dimensions: multiple demand segments (demand side) and cannibalization along a product line (supply side).

On the demand side, we consider a multi-segment random utility demand model, which allows us to capture heterogeneity in consumers' attitudes toward the price, type of product (new vs. remanufactured), and type of service. The latter is particularly salient for product + service firms like AT&T: such firms sell not only products but also services that accompany those products[2]; hence, introduction of remanufactured products could be an effective strategy for targeting customer segments that are not willing to pay a premium price for new high-end (*NH*) products, but are willing to pay for a high-end service. On the supply side, we consider not only demand cannibalization of the "parent" new product—a setup analyzed in most previous works—but also demand cannibalization along the product line that consists of new and remanufactured high-end products and a new low-end (*NL*) product offered with high- or low-end services, respectively.

In our model, the firm optimizes the composition of the product line (with or without the remanufactured

product), and the prices of the products in the product line. We investigate two pricing strategies: *global optimization*—a comprehensive approach where the firm possibly adjusts the prices of the new products when the remanufactured product is introduced—and a heuristic, when the firm first optimizes the prices of the new products as if there is no remanufactured product, and then given those prices, it optimizes the price of the remanufactured product. Such a heuristic, although potentially suboptimal, appears to be a rather common approach in practice; see Ovchinnikov (2011).

We estimate the demand model from consumer choice data and, on the basis of the problem parameters drawn from both the literature and conversations with industry executives (AT&T 2009, 2010), perform a series of numerical simulations, documenting the resulting optimal prices, production/remanufacturing quantities, profits, and environmental impact.

For the economic assessment, we find that remanufacturing was profitable in all instances we considered. The heuristic was frequently optimal; that is, it was profitable to introduce the remanufactured product into the firm's product line, but it was not optimal to change the new products' prices. In such cases, remanufactured product cannibalized some new product sales. When the heuristic was suboptimal, however, the firm was able to obtain higher profits by re-optimizing the product line and changing the new products' prices. Interestingly, in most such instances, the quantity of the new products manufactured/sold *increased* when the remanufactured product was introduced—the effect we refer to as the *negative effective cannibalization* and explain in section 5.2.

For the environmental assessment, we find that in the majority of instances remanufacturing resulted in a positive absolute environmental effect—a "win-win" situation when profit increased and environmental impact decreased, also known as the absolute decoupling; see section 2. These instances include all the cases when the heuristic was optimal and some of the cases with negative effective cannibalization. Yet in other instances, we observed a negative absolute environmental effect caused by the growth in the firm's sales: an increase in the new production as a result of the negative effective cannibalization. What is very important, however, is that in nearly all instances the growth was sustainable: the energy use per unit of the product as well as the energy per dollar of profit decreased—positive relative environmental effects, also known as relative decoupling.

We finally examine the sensitivity of the above-mentioned effects to various model parameters and observe that the absolute effects are most sensitive to the recovery rates and technological progress, while the relative effects are most sensitive to the changes in

energy consumption at various stages in the products' life cycle.

Overall, our findings reveal that from an eco-efficiency optimization perspective, remanufacturing is usually a highly beneficial activity: it increases the firm's profits and in most cases decreases its total environmental impact. Our results also demystify two common assertions: we see no support for the existence of green segment consumers (who prefer refurbished products based on their assumed environmental benefits), yet show that an introduction of a remanufactured product could lead to an increase in the new products' sales—a negative effective cannibalization. Our results also suggest that remanufacturing may not always lead to a decrease in the firm's total environmental impact: because of the negative effective cannibalization, remanufacturing may lead to a significant growth; however, as we show, this growth is nearly always sustainable as the environmental impacts per unit of the firm's product or per dollar of profit decrease.

We finally note that while the numerical estimates/parameters in our article are specific to the cell phone industry, the overall approach and framework are quite general and can be applied to analyzing economic and environmental aspects of remanufacturing for other industries.

In the remainder of the article, 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 presents a sensitivity analysis. Section 7 summarizes our discussion and concludes the article.

2. Literature Review

Remanufacturing (or refurbishing) is a practice of collecting and reprocessing used products to the "like new" condition and then selling such products in the marketplace (see Ferguson and Souza 2010 for a comprehensive discussion of remanufacturing). Although initially viewed as a cost-center addressing the need to deal with product returns, today many practitioners and academics view remanufacturing as an innovative business strategy that combines elements of marketing (Atasu et al. 2008), product-line design (Krishnan and Lacourbe 2010), and environmental strategies (Orsato 2009). Studies of remanufacturing span both Operations Management and Industrial Ecology bodies of literature, which with some overlap cover its economic and environmental performance. Because both bodies of literature are very large, we only review works that are directly relevant to ours.

For the economic assessment of remanufacturing, "[t]he central question manufacturers seem to face is,

'When do benefits from remanufacturing outweigh losses from cannibalization?'" (Atasu et al. 2008). Guide and Li (2010) echo this statement by writing that the "managers at OEMs that offer remanufactured products revealed that they concede cannibalization may occur," while also stating that "[w]hether cannibalization actually decreases the overall profitability of the firm is a subject of much debate."

Demand cannibalization is a broad issue that manifests itself far beyond remanufacturing and was examined in depth in the marketing literature; for example, see Van Heerde et al. (2010) and references therein. As they conclude, while managers are typically aware of the possibility of cannibalization, they are "less clear on how to quantify the size of the cannibalization" because in practice both within-category and between-category demand cannibalization must be considered as well as brand switching and the actual new demand. Van Heerde et al. present an econometric model that decomposes product's demand into these sources. Using an application of their model to the introduction of a new RX300 Luxury SUV to Lexus' existing product line, they show that while 26% of the new SUV demand cannibalized sales of other Lexus vehicles, the other 74% of its buyers were new to Lexus, making the RX300 a huge success. The authors also elaborate on what competition could have done to reduce demand cannibalization, with suggestions ranging from quantifying the necessary price decreases to increases in competitors' advertising. Our approach is quite in line with this literature: by studying/quantifying cannibalization across a product line, we too allow for within- and between-category cannibalization and conclude that cannibalization from introducing a remanufactured product could be profitable for the firm overall.

Within the operations management literature on remanufacturing, demand cannibalization has been implicitly incorporated by many authors using the extended Hotelling (1929) line model, in which consumers have valuation $v \in U$ [0, 1] for the new product and δv for the remanufactured product. Agrawal et al. (2011) estimate δ using a behavioral experiment; they also estimate a change in the valuation of the new product once the remanufactured product is introduced. Abbey et al. (2011) discuss consumer perceptions for remanufactured products. Guide and Li (2010) estimate cannibalization using eBay auctions, while Ovchinnikov (2011) estimates it via a behavioral experiment. The latter two papers find that at the optimal prices cannibalization is rather small. Our article extends the cannibalization analysis along two dimensions: first, we consider a multi-segment random utility demand model, which is much more realistic than the Hotelling line demand model used

by most researchers, and, second, we consider cannibalization along a product line.

The estimation of cannibalization is also important from an environmental perspective, since displacement of new production is the core assumption in calculating environmental gains of remanufacturing (for example, EPA 2006, Kerr and Ryan 2001). Therefore, with little cannibalization, the environmental gains might be questioned. Most Operations Management papers take a somewhat simplified view without detailed analysis of the environmental impact. For example, Thierry et al. (1995) write that "the potential benefits of remanufacturing are… a reduction in the overall environmental impact" and Atasu et al. (2008) argue that "[b]ecause it [remanufacturing] reduces both the natural resources needed and the waste produced, remanufacturing helps reduce the environmental burden." These authors take as given that the more that is remanufactured the better is the environmental performance. A more comprehensive approach, the one used in this article and some others, is to explicitly assess the environmental impact along the life cycle of the product: the Life-Cycle Assessment (LCA) approach.

One such work is Quariguasi-Frota-Neto and Bloemhof (2011), who compared the eco-efficiencies of new and remanufactured mobile phones and computers. To do so, they estimated what they called "cumulative energy demand" based on the published LCA studies from the early 2000s. Our measure, total energy consumption, is equivalent to theirs, but we use more recent industry LCA data. They found that remanufactured products reduce the amount of energy used compared over their life span when the second lifetime of the product is smaller than the first. From an eco-efficiency perspective combining economic and environmental views, they argue that remanufactured products are not always more eco-efficient—a finding consistent with our negative environmental effect, but derived from a different perspective. Agrawal et al. (2011) also integrated a more comprehensive LCA-based approach to environmental assessment, but their work is focused on leasing modeling and not in the context of remanufacturing.

Environmental assessment of remanufacturing is also addressed in the Industrial Ecology literature, for example, Thomas (2003, 2011) and Geyer (2004). That literature, however, for the most part makes a somewhat simplistic assumption about demand cannibalization, assuming that a remanufactured product displaces the need to produce a new one; that is, they assume 100% cannibalization. More recent research in that area, for example, Gutowski et al. (2011), looked at the environmental benefits of remanufacturing from the use phase perspective, suggesting that remanufacturing does not always improve the energy

savings. This was found to be true especially when improvements in energy efficiency during the use phase of the new products exceed the energy saving from saved materials and the manufacturing process of remanufactured products. We make a very conservative assumption in this regard, assuming in the base case that the efficiency during the use phase is the same, and then present sensitivity analyses with respect to energy estimates.

The Industrial Ecology literature also emphasizes the concept of decoupling economic growth from resource use and environmental impact, so far mainly at the economy/sector level. It measures decoupling in two ways: relative decoupling refers to "when the growth rate of the environmentally relevant variable is positive, but less than the growth rate of the economic variable" (OECD 2001, UNEP 2011) and absolute decoupling, the situation when the "resource use declines, irrespective of the growth rate of the economic driver" (UNEP 2011). In the Operations Management literature, as far as we know, decoupling has been used only in Raz et al. (2013). It is easy to see that the positive environmental effects we discuss and decoupling are conceptually identical, except that we (and Raz et al. 2013) consider environmental effects on the firm level and not on the level of the entire economy or sector. Hence, to avoid possible confusion, we will use the term environmental effect and not decoupling throughout the article.

3. The Model

3.1. Model Schematic
Consider a product + service firm with a product line that consists of *NH* and *NL* products, offered with high-end (*H*) and low-end (*L*) services, respectively. For example, AT&T offers Apple iPhone (*NH*) with voice & data (*H*), and Pantech Breeze (*NL*) with just voice (*L*) plans. We assume (as is the case of AT&T), that the *NL* product cannot be offered with the *H*-service for technical reasons, while the *NH* is not offered with *L* for economic reasons.

Because of technological progress, newer (faster, better, etc.) versions of *NH* and *NL* become available periodically. We refer to such new versions as *generations* and denote them by $i = 1, 2, \ldots$. We assume that the firm sells generation i products until generation $i + 1$ becomes available, at which point the sales of new generation i products discontinue and sales of new generation $i + 1$ products begin. In this article, we focus on the economic and environmental assessment along the life cycle of generation i of the firm's products as a representative scenario for the firm's overall business. The major decision that we study in this article is whether in addition to *NH* and *NL* the firm should also offer a remanufactured version of

NH, which we denote as *RH*, in its product line with either *H*- or *L*-service and how it should price it. In the context of our article such a decision represents a strategic choice for the firm rather than a tactical one: it either engages in remanufacturing across multiple generations or not (as opposed to a tactical decision that can be generation specific). In practice, to succeed in reverse logistics, firms need to establish multiple operational capabilities from designing products that are easy to remanufacture to collecting used items all the way to marketing remanufactured products, etc., and our approach reflects such strategic choices.

Levels of remanufacturing range from products that were returned close to the purchase date and therefore only need to be tested and repackaged 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. In either case, there is some lag between the sales of *NH* and *RH*. To offer a unit of *RH*, the firm must acquire a unit of previously sold *NH*, which we refer to as the *remanufacturable core*. To capture this lag, we assume that the selling horizon of generation *i* new products consists of two sub-periods: i_1 and i_2. In period i_2, the firm collects and remanufactures some fraction of *NH* from generation *i* sold in period i_1. These products likely correspond to false returns (Ferguson et al. 2006), remanufacturing of which is typically inexpensive. In the subsequent period, $i + 1_1$, the firm also collects some *NH* from generation *i*, (which now correspond to the products that reach the end of their initial use) and remanufactures them (at a higher cost

than false returns) and sells 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's product line consists of *NH*, *RH*, and *NL* from generation *i*, and period $i + 1_1$, when the product line consists of *NH* and *NL* products from generation $i + 1$ and *RH* from generation *i*. Correspondingly, in period i_1 the firm's product line also consists of *NH* and *NL* products from generation *i* and *RH* from generation $i-1$. Figure 1 illustrates the above discussion as well as provides justification for our model setup based on the snapshot of the product line of AT&T.

Before we proceed with formal model definitions, we make two simplifying assumptions which help to avoid cumbersome notation later in the article without impacting insights:

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

(A2) The product prices are constant throughout generations $i-1$, i, and $i + 1$. (Note that the pricing policy of AT&T depicted in Figure 1 is consistent with this assumption).

3.2. The No-Remanufacturing Case

Let p_{NH}, p_{NL} and c_{NH}, c_{NL} denote the prices and costs of the corresponding products, and let m_H, m_L denote the net present values of the profit margins of the *H*- and *L*-services. This setup is consistent with the case when consumers sign a service contract with the firm and pay for service over time, but purchase the product upfront upon signing the contract. Let $D_{NH}^{ij}(p_{NH}, p_{NL})$, $D_{NL}^{ij}(p_{NH}, p_{NL})$ and $S_{NH}^{ij}(p_{NH}, p_{NL})$,

Figure 1 Model Schematic
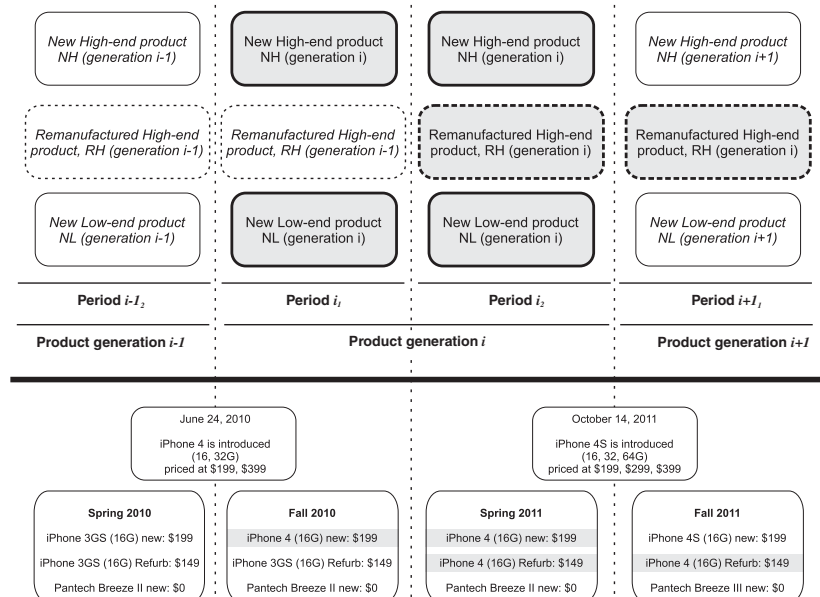
$S_{NL}^{i_j}(p_{NH}, p_{NL})$ be the respective demands and sales in period i_j ($j = 1, 2$). We assume that the firm manufactures/procures products as needed, so that in the case without remanufacturing, demand $\equiv$ sales. Then the firm's profit in period i_j, $j = 1, 2$, is

$$\pi^{i_j}(p_{NH}, p_{NL}) = (p_{NH} - c_{NH} + m_H)S_{NH}^{i_j}(p_{NH}, p_{NL}) \\ + (p_{NL} - c_{NL} + m_L)S_{NL}^{i_j}(p_{NH}, p_{NL}). \quad (1)$$

Finally, the total profit from generation i products without remanufacturing is

$$\pi^i(p_{NH}, p_{NL}) \equiv \pi^{i_1}(p_{NH}, p_{NL}) + \tau \times \pi^{i_2}(p_{NH}, p_{NL}), \quad (2)$$

where τ is the discount factor for the time value of money.

3.3. The Remanufacturing Case
Let $\bar{p}_k$, $\bar{D}_k^{i_j}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH})$, $\bar{S}_k^{i_j}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH})$, for $k = NH, RH, NL$ denote the prices, demands,[3] and sales and let $c_{RH}^{i_j}$ denote the cost of remanufacturing (including collection and testing) for the corresponding products and periods, $j = 1, 2$. As before, let m_H, m_L denote the net present values (NPVs) of the profit margins of the H- and L-services. Further, if RH is initially offered with an L-service, let Δ be the NPV of the probability of an upgrade in the duration of the service contract; the "net present value" indicates that an upgrade can happen at an uncertain moment in the duration of the service contract—a model feature that was emphasized in our discussions with executives at AT&T (2009, 2010).

As discussed earlier, a fundamental feature of remanufacturing is that the supply of remanufacturable cores in period i_j, and hence the sales of RH in i_j ($j = 1, 2$), is constrained by some multiple of the NH sales in the previous periods. Specifically, from Figure 1, for remanufactured products in period i_1 (which are of generation $i-1$), the supply is constrained by the total sales of generation $i-1$ NH net the quantity remanufactured in period $i-1_2$, while for remanufactured products in period i_2 (which are of generation i), the supply is constrained by the generation i NH sales in period i_1. Let β_j be such multiples[4] for period i_j.

Then the sales of RH in period i_j ($j = 1, 2$) are equal to the following:

$$\bar{S}_{RH}^{i_j}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}) = \min\left[\bar{D}_{RH}^{i_j}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}), K_j\right], \quad (3)$$

where, reflecting the above discussion,

$$K_1 = \beta_1 \Big(\bar{S}_{NH}^{i-1_1}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}) + \bar{S}_{NH}^{i-1_2}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}) \\ - \bar{S}_{RH}^{i-1_2}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}) \Big), \quad (4)$$

and

$$K_2 = \beta_2 \bar{S}_{NH}^{i_1}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}). \quad (5)$$

Consider period i_1. If $\bar{S}_{RH}^{i_1}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}) = \bar{D}_{RH}^{i_1}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH})$, then all remanufactured product demand is satisfied. Otherwise, the first $\frac{K_1}{\bar{D}_{RH}^{i_1}(\cdot)}$ percent of customers will face the choice among the three products (as well as, obviously, the option to buy nothing), while the rest—the overflow—will face the choice between NH and NL only. The purchasing behavior of the overflow customers, *and this is critical*, is described by the demand functions from the case without remanufacturing because they choose between two and not three products (since RH is sold out). Combining the two cases, the behavior of the first $\frac{\bar{S}_{RH}^{i_1}(\cdot)}{\bar{D}_{RH}^{i_1}(\cdot)}$ percent of customers is described by the remanufacturing case functions demand functions $\bar{D}_k^{i_1}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH})$, $k = NH, RH, NL$, while the behavior of the remaining $\left(1 - \frac{\bar{S}_{RH}^{i_1}(\cdot)}{\bar{D}_{RH}^{i_1}(\cdot)}\right)$, the overflow, is described by the corresponding no-remanufacturing case demand functions $D_k^{i_1}(\bar{p}_{NH}, \bar{p}_{NL})$, for $k = NH, NL$.

Therefore, the expected sales for the NH and NL products in period i_j are equal to the following:

$$\bar{S}_k^{i_j}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}) = \bar{D}_k^{i_j}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}) \times \frac{\bar{S}_{RH}^{i_j}(\cdot)}{\bar{D}_{RH}^{i_j}(\cdot)} \\ + D_k^{i_j}(\bar{p}_{NH}, \bar{p}_{NL}) \times \left(1 - \frac{\bar{S}_{RH}^{i_j}(\cdot)}{\bar{D}_{RH}^{i_j}(\cdot)}\right) \quad (6)$$

for $k = NL, NH$, $j = 1, 2$, where $\bar{S}_{RH}^{i_j}(\cdot)$ is given in Equation (3).

The firm's profit in period i_j ($j = 1, 2$) is, therefore, as follows:

$$\bar{\pi}^{i_j}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}) = (\bar{p}_{NH} - c_{NH} + m_H) \\ \times \bar{S}_{NH}^{i_j}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}) \\ + (\bar{p}_{RH} - c_{RH}^{i_j} + \Delta m_H + (1 - \Delta)m_L) \\ \times \bar{S}_{RH}^{i_j}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}) \\ + (\bar{p}_{NL} - c_{NL} + m_L) \\ \times \bar{S}_{NL}^{i_j}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}). \quad (7)$$

So that the total profit in the case with remanufacturing is

$$\bar{\pi}^i = \bar{\pi}^{i_1}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}) + \tau \times \bar{\pi}^{i_2}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}), \quad (8)$$

where τ is the discount factor for the time value of money.

3.4. The Firm's Profit Maximization Problem

For the case with no remanufacturing, and given assumptions A1 and A2, the firm's optimization problem is to select the prices p_{NH}^*, p_{NL}^* which maximize $\pi^i(p_{NH}, p_{NL})$. For the case with remanufacturing, the firm's problem is significantly more involved. Generally speaking, because generation i RH overlaps with NH and NL products from generation $i + 1$, the effects of the introduction of a remanufactured product in one generation propagate throughout *all* future generations.[5] At the same time, when the remanufacturing decision is made for generation i the firm likely does not have perfect foresight on what will happen in generation $i + 1$. Hence, it is plausible to assume that the technological progress will impact consumer preferences for RH product from generation i when it will be offered together with NH and NL products from generation $i + 1$ in the same way as when RH from generation $i-1$ was offered with NH and NL from generation i. In our model terms this logic translates into the following assumption:

$$(A3) \quad \bar{D}_k^{ij}(p_{NH}, p_{NL}, p_{RH}) = \bar{D}_k^{i-1_j}(p_{NH}, p_{NL}, p_{RH}) \text{ for } k = NH, RH, NL.$$

With this assumption, the firm's problem becomes separable across generations: 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 $i-1$. This fact combined with (A2) implies that if remanufacturing is profitable for one generation, it is then profitable for all generations. That is, with assumptions A1–A3, to assess economic and environmental impact of remanufacturing the firm only needs to consider what happens in periods i_1 and i_2. Thus, we can redefine K_1 accordingly so that Equation (4) becomes

$$K_1 = \beta_1 \big(\bar{S}_{NH}^{i_1}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}) + (\bar{S}_{NH}^{i_2}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH}) \\ - (\bar{S}_{RH}^{i_2}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH})\big). \quad (9)$$

Thus, the profit in period i_1 in Equation (7) can be expressed only in terms of generation i products such that the sales of RH in period $i + 1_1$ and the associated cannibalization of generation $i + 1$ NH, NL products are both correctly accounted for in period i_1. The profit function for period i_2 in Equation (7) depends only on generation i products and is therefore not affected by this assumption.

Let p_K^* and $\bar{p}_K^*$ for $k = NH, NL, RH$ be the optimal prices in the cases without and with remanufacturing, respectively. The economic assessment of remanufacturing is then given by the following:

DEFINITION 1. The firm will remanufacture if

$$\bar{\pi}^i(\bar{p}_{NH}^*, \bar{p}_{NL}^*, \bar{p}_{RH}^*) \geq \pi^i(p_{NH}^*, p_{NL}^*). \quad (10)$$

Note that our model considers the situation in which, when the firm decides to introduce the remanufactured product, it also may decide to re-optimize the prices of the new products—that is, the firm strategically optimizes its entire product line as a result of the introduction of remanufactured product. We refer to this case as the *globally optimal* solution.

There is some evidence, however, that some firms may not view remanufacturing as a strategic initiative and not change the new products' prices as a result of the introduction of a remanufactured product. For example, the mini-case study reported in Ovchinnikov (2011) states that "remanufacturing operations had no effect on the [firm's] pricing, procurement, or other decisions about the new products." This means that the firm first optimizes $\pi^i(p_{NH}, p_{NL})$ over p_{NH} and p_{NL} and then uses these "optimal" new product prices, p_{NH}^*, p_{NL}^* to maximize $\bar{\pi}^i(p_{NH}^*, p_{NL}^*, \bar{p}_{RH})$ over $\bar{p}_{RH}$. Such an approach is clearly suboptimal, and we refer to it as the *heuristic*, because it replaces firms' global profit maximization with a two-step sequential local optimization. We compare these two approaches in section 5.2.

3.5. The Firm's Environmental Impact

To assess the environmental impact of remanufacturing, we utilize the total energy consumption/use/demand during the life cycle of a product. The energy consumption metric is a common measure used in the literature as a proxy for environmental impact, especially in the context of remanufacturing; see Doctori Blass et al. (2006), Geyer (2004), and Gutowski et al. (2011). In a recent paper, Quariguasi-Frota-Neto and Bloemhof (2011) used the "cumulative energy demand (CED)" as their metric for the environmental impact; CED is identical to our total energy consumption metric. Total energy consumption is also a common metric used in the industry, for example, McLaren and Piukkula (2004), Apple (2011), Nokia (2011).

Figure 2 demonstrates the life-cycle stages we considered in our analysis. For new products these include raw materials, production and transportation, initial use, and disposal. For 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 product returns, β_1), or full (β_2).

The total energy consumption per unit of product, $E_k(k = NL, NH, RH)$, is the sum of the corresponding life-cycle stages described in Figure 2. We estimate

Figure 2   Life-Cycle Flow: New and Remanufactured Products
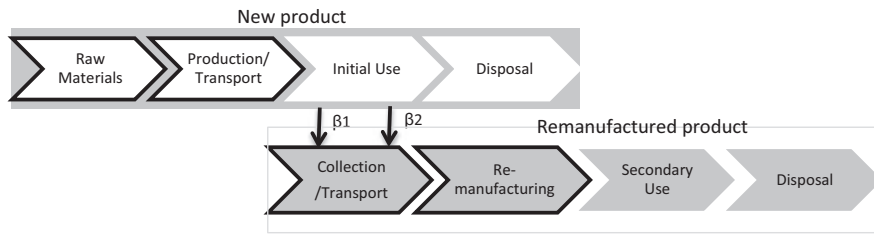
the energy consumption at each state in section 5.1. Then, the total energy, *TE*, is obtained as the sum product of the corresponding per unit energy E_k and the total unit sales:

Without remanufacturing:

$$TE^* = E_{NH} \times \left(S_{NH}^{i_1}(p_{NH}^*, p_{NL}^*) + S_{NH}^{i_2}(p_{NH}^*, p_{NL}^*) \right)$$
$$+ E_{NL} \times \left(S_{NL}^{i_1}(p_{NH}^*, p_{NL}^*) + S_{NL}^{i_2}(p_{NH}^*, p_{NL}^*) \right)$$

With remanufacturing:

$$\bar{T}E^* = E_{NH} \times \left(\bar{S}_{NH}^{i_1}(\bar{p}_{NH}^*, \bar{p}_{NL}^*, \bar{p}_{RH}^*) + \bar{S}_{NH}^{i_2}(\bar{p}_{NH}^*, \bar{p}_{NL}^*, \bar{p}_{RH}^*) \right)$$
$$+ E_{NL} \times \left(\bar{S}_{NL}^{i_1}(\bar{p}_{NH}^*, \bar{p}_{NL}^*, \bar{p}_{RH}^*) + \bar{S}_{NL}^{i_2}(\bar{p}_{NH}^*, \bar{p}_{NL}^*, \bar{p}_{RH}^*) \right).$$
$$+ E_{RH} \times \left(\bar{S}_{RH}^{i_1}(\bar{p}_{NH}^*, \bar{p}_{NL}^*, \bar{p}_{RH}^*) + \bar{S}_{RH}^{i_2}(\bar{p}_{NH}^*, \bar{p}_{NL}^*, \bar{p}_{RH}^*) \right)$$

With this we define three measures to assess the environmental impact of remanufacturing:

DEFINITION 2.   If the firm remanufacturers (condition (10) holds), we define the following environmental impact measures:

(a) The *absolute* measure, $Env_A = TE^* - \bar{T}E^*$
(b) The *relative (per unit)* measure,

$$Env_{R/u} = \frac{TE^*}{S_T^i(\bar{p}_{NH}^*, \bar{p}_{NL}^*)} - \frac{\bar{T}E^*}{S_T^i(\bar{p}_{NH}^*, \bar{p}_{NL}^*, \bar{p}_{RH}^*)}$$

where $S_T^i(\bar{p}_{NH}^*, \bar{p}_{NL}^*, \bar{p}_{RH}^*) = \sum_{k=NL,NH} \left(S_k^{i_1}(\bar{p}_{NH}^*, \bar{p}_{NL}^*) + S_k^{i_2}(\bar{p}_{NH}^*, \bar{p}_{NL}^*) \right)$, and
$S_T^i(\bar{p}_{NH}^*, \bar{p}_{NL}^*, \bar{p}_{RH}^*) = \sum_{k=NL,NH,RH} \left(S_k^{i_1}(\bar{p}_{NH}^*, \bar{p}_{NL}^*, \bar{p}_{RH}^*) + S_k^{i_2}(\bar{p}_{NH}^*, \bar{p}_{NL}^*, \bar{p}_{RH}^*) \right).$

(c) The *relative (per dollar)* measure, $Env_{R/d} = \frac{TE^*}{\pi^i(\bar{p}_{NH}^*, \bar{p}_{NL}^*)} - \frac{\bar{T}E^*}{\bar{\pi}^i(\bar{p}_{NH}^*, \bar{p}_{NL}^*, \bar{p}_{RH}^*)}$, where π^i and $\bar{\pi}^i$ are given by Equations (2) and (8).

By Definition 2, we evaluate remanufacturing along three dimensions: first, we examine how remanufacturing affects the firm's overall environmental impact. We also examine the firm's environmental impact per unit of the product line (measured as the weighted average of energy across the product line mix) 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 the firm's environmental impact per dollar. This eco-efficiency measure evaluates if

the firm is growing in an eco-efficient way by increasing its profit at a higher rate than its environmental footprint. Or, in other words, does the firm use less energy for every dollar of profit?

Next, we estimate the demand functions, the key elements of the above model, using a behavioral study and perform a numerical analysis using these behavioral estimates of demand.

4. Demand Estimation

The above model has in total 10 demand functions: for each of the two periods, we have either two demand functions (for the case of no remanufacturing) or three (if the firm decides to remanufacture). We estimate period i_2 demand functions (when all products are of generation i) directly, and then adjust them for the technology progress to obtain period i_1 demands.

4.1.   Behavioral Study

To estimate period i_2 demands, we used a web-based choice-based conjoint study of consumer behavior with respect to the choice between new and remanufactured products. We implemented the study using SSI Web system by Sawtooth software. The subjects in the study were a panel of 102 randomly selected employees of a major North American university representing diverse age groups and income levels. The objects in the study are items in a product line of a wireless communications firm, such as AT&T, where the *NH* (*RH*) product is a "new (refurbished) smartphone," *NL* product is a "new feature phone," *L*-service is "voice only," and *H*-service is a "voice and data" plan. The subjects were given the following descriptions[6] 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; however, basic data features, such as text messaging, are supported.

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 statement was added regarding plans:

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

Subjects first performed 12 choice-based tasks for the no-remanufacturing case, that is, with three alternative choices: *NH*, *NL*, and none with one attribute,

price, that ranged $0, $50, …, $450 for *NH* and $0, $50, …, $250 for *NL*. Note that the product price is paid once, while the service cost is paid monthly; this was emphasized on each choice-task screen. Subjects then performed 12 choice tasks for the case with *RH*, that is, with four alternatives: *NH*, *RH*, *NL*, and none, and two attributes: price and *RH* plan. Price ranges for *NH* and *NL* were the same; price for *RH* varied between $0 and up to the price for *NH*; *RH* plan took two values: *L* and *H* descriptions were as we discussed above. The following description[7] for *RH* was provided:

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.

We fit the choice data to a latent-class multi-nomial logit model using built-in Sawthooth algorithms. We found that, without remanufacturing, the best fit occurred with three latent classes, while with remanufacturing, the model with four latent classes has the best fit [minimizes Akaike 1974 information criterion]. Table 1 presents the results of the estimation[8] — the partworth utilities for different levels of each attribute for each segment.

Table 1 Partworth Utilities for the Case with and without the Remanufactured Product

	Without Remanufacturing			With Remanufacturing			
	Segment 1	Segment 2	Segment 3	Segment 1	Segment 2	Segment 3	Segment 4
Size (%)	40.5	22.5	37.0	30.6	15.8	25.2	28.4
Product = *NH*	1.005	−0.793	3.089	0.688	−0.972	3.427	1.4
Product = *RH*				−0.027	0.255	1.031	1.061
Product = *NL*	−1.005	0.793	−3.089	−0.661	0.717	−4.458	−2.461
Price = 0	7.557	9.635	3.076	8.244	4.214	6.33	1.431
Price = 50	6.487	8.602	2.473	7.427	3.072	4.639	1.501
Price = 100	4.481	8.567	2.213	6.147	4.309	3.787	1.098
Price = 150	4.702	−0.078	1.931	−4.654	2.838	2.89	0.643
Price = 200	4.070	−1.350	1.130	−5.879	0.82	1.328	0.216
Price = 250	3.367	−2.200	0.135	−5.261	1.885	0.869	−0.063
Price = 300	−14.503	−2.576	−1.539	−6.253	1.644	−0.515	−0.964
Price = 350	−1.806	−3.094	−2.427	3.482	−0.364	−1.238	−0.957
Price = 400	1.225	−4.176	−3.368	3.618	−9.095	−8.245	−1.245
Price = 450	−15.580	−13.329	−3.623	−6.871	−9.323	−9.844	−1.66
Plan = *L*				0.84	1.194	−0.241	0.203
Plan = *H*				−0.84	−1.194	0.241	−0.203
None	6.484	−1.25	−0.413	8.093	−1.071	3.983	−1.931

These latent classes correspond to the following characterizations of customers.

Segment 1: "I do not really need a phone." For segment 1, the utility of device or plan is much smaller (in the absolute value) than the utility of purchasing nothing. Only when the price is very low ($50 or below) does the utility of phone and price become marginally larger than purchasing nothing. Thus, segment 1 customers are effectively indifferent between getting a new smart phone device for $50 or less, a new feature phone for free, or not purchasing anything.

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. Further, in the case with remanufacturing, the utility for the *L* plan is positive. Thus, segment 2 customers want to purchase a phone and prefer feature phones with no data plan.

Segment 3: "I want a new smartphone with data." For segment 3, observe that the utility of *NH* is positive and large. The utility of *H* is also positive in the case with remanufacturing. Such customers, therefore, are a mirror image of segment 2—they want a smartphone with data.

In the absence of remanufactured products, the segment sizes are approximately 40.5%, 22.5%, and 37%. When the remanufactured product is introduced, the same three segments emerge in the estimation (with respective sizes of 30.6%, 15.8%, and 25.2%), but in addition a new segment emerges with the size of 28.4%. Examining its utilities, this new segment corresponds to the following customer profile.

Segment 4: "I want a smartphone and OK with refurbished with or without data." Segment 4 customers have a positive utility for the smartphones, but negative for the feature phone and buying nothing. They prefer the new smartphone to refurbished and also the voice-only plan to the voice-and-data. However, those are weak preferences: additional utility from a new smartphone vs. refurbished is <0.4 compared to the additional utility from buying any smartphone vs. buying nothing, which is >3. As such, the remanufactured product is most attractive to segment 4 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).

With these segments, consider the firm's positioning of products. In the absence of the remanufactured product, the firm should naturally target segment 3 with *NH* and segment 2 with *NL*. With the remanufactured product, the firm's goal is to keep the same positioning for *NH* and *NL* and reach out to segment 4 customers with *RH*. Most importantly, though, of the 28.4% of consumers that comprise the refurbished product's "target" segment 4, only 11.8% come from cannibalizing *NH*'s demand (size of segment 3 decreases from 37% to 25.2%); the remaining 16.6% come from upgrading *NL* consumers (some 7% come from segment 2) and bringing in new consumers (some 10% come from segment 1). That is, while some cannibalization of the "parent" new product occurs, over 60% of the *RH* demand comes from other sources.

Note that we do not see evidence for the existence of the more environmentally conscious segment, that is, "green segment that values remanufacturing": in all four segments, the utility for *RH* is smaller than the utility of the preferred new product (*NH* or *NL*).

4.2. Construction of Demand Functions

We construct period i_2 demands directly from the utilities in Table 1 using the latent-class multi-nomial logit (MNL) model. For a given segment, we calculate the utility of a product $k = NH, NL, RH$ 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[9] of exponents of utilities of other alternatives in the choice set. Weighing such probabilities by the size of the segment gives the product's demand.

To construct period i_1 demands in the case without remanufacturing, we assume that $D_k^{i_1} = D_k^{i_2}$. This implies that the periods are of equal length and that consumer preferences are not changing throughout the selling horizon of generation i products. This assumption is made to simplify exposition and can be easily relaxed by introducing a coefficient capturing the length of the period and change in preferences; doing so will not change the insights of the article.

To construct period i_1 demands in the case with remanufacturing, we introduce a parameter, γ, 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 to consumers. In the MNL model, such an adjustment will have two effects: demand for generation $i-1$ *RH* (in period i_1) will be smaller than for generation i *RH* (in period i_2), while the demands for *NH* and *NL* will be larger in period i_1 than in i_2.

Figure 3 illustrates the demand functions. Panel a depicts demand for *NH*: the dotted line is the demand function in the case without remanufacturing, D_{NH}^i, the solid line is the demand function in period i_1, $\bar{D}_{NH}^{i_1}$, with $\gamma = 1$, and the dashed line is the demand function in period i_2, $\bar{D}_{NH}^{i_2}$, both for the case with remanufacturing. Two observations are evident: first, the introduction of *RH* decreases the demand for *NH*; second, the *NH* demand is increasing in γ (note that

Figure 3   Example of the Demand Curves for *NH* (a) and *RH* (b)

(a)

(b)
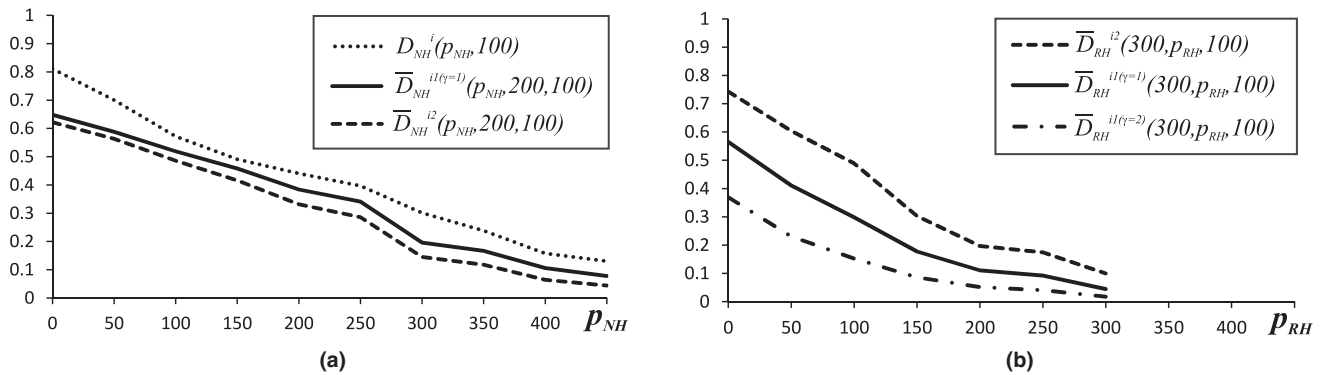
$\gamma = 0$ in period i_2). Panel b depicts demand for *RH*: it is evident that demand for *RH* is decreasing in γ. The latter two observations are natural: *NH* and *RH* are (imperfect) substitutes; thus, the more technologically superior the generation i *NH* is, the lesser demand will generation $i-1$ *RH* attract; hence a larger fraction will demand *NH*.

5. Analysis and Results

In this section, we perform numerical simulations for the economic and environmental assessment of remanufacturing using the behavioral data obtained above. We begin by discussing the parameters used in the simulation, which we obtained from both the literature and from conversations with industry executives (AT&T 2009, 2010). We note that although the results we present are based on parameters and demand estimates for the wireless communications products, the framework we present is general and can be directly applied to other industries and products.

5.1. The Simulation
We sampled 1000 parameter combinations, with each parameter value drawn at random from the ranges below, and for each parameter combination optimized the prices with and without remanufacturing using the demand functions estimated in section 4. We used the following parameter values in the simulation:

- $C_{NH} \in [\$500; \$700]$. Goldman (2010) states that "[s]martphones generally cost carriers around \$500 per unit," while arguing that "the hotter the phone, the more a carrier will pay to buy it." Similarly, *The Economist* (2011) provides an estimate of \$560 for the cost of an iPhone. Note that $c(\cdot)$ parameters refer not to the costs of manufacturing a device but rather to the wholesale price that a product + service firm pays the manufacturer of the product.

- $C_{NL} \in [\$150; \$300]$; $C_{RH}^{i_1} \in [\$10; \$20]$, $C_{RH}^{i_2} \in [\$10; \$100]$. These ranges were provided to us by executives at AT&T (2010). They noted, however, that the variance in costs of the feature phones is larger than for the smartphones. Similarly, there is a significant variance in the cost of remanufacturing due to variable conditions of the remanufacturable cores; for example, see Galbreth and Blackburn (2006, 2010), Zikopoulos and Tagaras (2007), and Ovchinnikov (2011) for further discussion.

- $\beta_1 \in [5\%; 15\%]$, $\beta_2 \in [15\%; 35\%]$. These ranges were used based on industry averages of reuse rates in the secondary cell phone market (Doctori Blass et al. 2006, Geyer and Doctori Blass 2010). As explained above, to be more accurate and cover different types of refurbished products, we distinguish between products that were returned within a short period from the initial purchase (β_1) and products that were used for a longer time (e.g., a year or two) before the initial user decided to upgrade to a newer model (β_2).

- $\Delta \in [50\%; 100\%]$: This range was estimated from the discussion with AT&T executives (AT&T 2009). They discourage consumers from purchasing smartphones without the data plans to "save consumers from themselves": consumers without a data plan may by accident use cellular data and incur significant costs. Further, an upgrade can happen at an uncertain point in the duration of the service contract; Δ is therefore less than 100%.

- $mv \in [\$1; \$10]$; $m_{V\&D} \in [\$10; \$25]$ monthly cost on a 24-month contract, which are standard in the industry. These ranges are estimated by the authors based on the prices of the voice and data plans. We used a 1% discount rate per month to compute the net present values of the margins.

Table 2   Parameter Estimates for Energy Consumption

Life-Cycle Stage	NH	NL	RH
Raw materials + manufacturing + transport	222 MJ	105 MJ	
Partial initial use β_1, assuming 1 month of initial use	2 MJ		
Full initial use	53 MJ	49 MJ	
Collection			5 MJ
Refurbishing			1.5 MJ
Secondary use			53 MJ

- Energy consumption parameters E_k for new products, that is, $k = NH$, NL are estimated based on the ranges of values from the product eco-profiles by Nokia (2011). We identified the models that correspond to the high-end NH products, e.g., E7-00, and the models that correspond to the low-end NL products, e.g., 100/101/700. The eco-profiles for these products present the total LCA estimates for energy use, for example, 278 MJ for the Nokia E7-00 model, as well as the percentage breakdown of the energy use for different life-cycle stages[10] as per Figure 2. Energy estimates for the remanufactured product, E_{RH}, are based on Doctori Blass et al. (2006) and on the assumption that the energy consumption during the secondary use is the same[11] as in the initial use. Table 2 presents the resulting estimates.

We note that our energy estimates are somewhat different from those used in Quariguasi-Frota-Neto and Bloemhof (2011). The differences are due to the timing of the estimates; their estimates are based on studies from 2003 to 2006, suggesting that the actual data collection happened perhaps in 2000–2003. Our data are from 2011 and thus are different in two ways. First, smartphones ("high-end" products in our study) as a category did not exist in 2000; hence, their "mobile phones" are more like our NL products. Second,

the manufacturing technology improved and the physical weight of NL products decreased, thus decreasing the energy consumption. In fact, adjusting for the weight (70 g for our typical NL vs. 90–135 g in their data), our estimates are rather similar to theirs.

- 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 (observe that the utilities for RH in Table 1 are on the order of one).

5.2. Economic Results
We start by discussing the economic results of the simulation. As discussed in section 3, we consider two approaches: global optimization, where the prices of new and remanufactured products are optimized jointly, and heuristic optimization, when the firm first optimizes the prices of new products as if there is no remanufacturing and then, given those new product prices, optimizes the price of the remanufactured product. Our first observation is on how the two relate:

Observation 1: Remanufacturing was profitable in all 1000 cases: In 63.7% of the instances, the heuristic and the globally optimal solutions were identical. In the remaining 36.3%, the firm was able to obtain higher profits by adjusting the new product prices when the remanufactured product was introduced.

By observation 1, in a majority of the cases, following the heuristic was in fact optimal. In the remainder of the cases, the average profit shortfall as compared with the globally optimal solution was 4.4%; however, the maximal profit loss that we observed exceeded 16%. Thus, firms should be aware of the potential opportunity losses when following such a heuristic.

Observation 2: In 35% of the cases (96% of those when the heuristic was suboptimal), we observed *negative effective cannibalization*; that is, the quantity of

Figure 4   Negative Effective Cannibalization
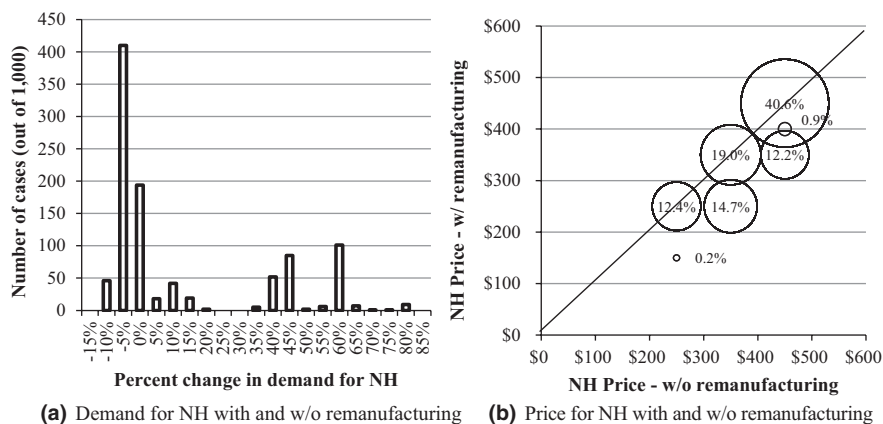
(a) Demand for NH with and w/o remanufacturing   (b) Price for NH with and w/o remanufacturing

NH increased as a result of introducing the remanufactured product.

Figure 4 illustrates the negative effective cannibalization (overall, over both periods, the result in each period is effectively identical to the overall). As can be seen in Figure 4a, while when positive cannibalization occurs, the demand for *NH* is decreased by at most 10%, when the negative cannibalization occurs, the increase in the demand for *NH* with remanufacturing can be as high as 80%. As we will see in the next subsection, when the negative cannibalization is relatively high, this will correspond to cases in which the energy use overall was higher.

Negative effective cannibalization may seem puzzling: indeed, from the discussion in section 4.2 and Figure 3, demand for *NH* decreases when the remanufactured product is introduced. But that discussion and figure correspond to the situation when the price of *NH* does not change, that is, a heuristic optimization approach.[12] Under the global optimization, the firm is free to decrease the price of *NH*, causing an increase in demand due to a price drop that is larger than the decrease due to *RH*; for example, from Figure 4b, in 14.7% of the cases the optimal price of *NH* dropped from $350 to $250, causing an increase in demand depicted in Figure 4a. But how and why can this be profitable? The reason is based on the connection between the new product sales and the availability of remanufacturable cores. If the firm can make money on remanufactured product and associated service, then it wants to do more of it. But supply of remanufacturable cores is limited by the multiple β_i of new product sales. To increase the supply of cores and the number of remanufactured products, the firm overall finds it profitable to lower the price of *NH*, increase the sales quantity of *NH*, and consequently increase the supply of cores and the quantity of *RH*.

5.3. Environmental Results

Observation 3: In 72.9% of the cases, we observed a *positive absolute environmental effect* ($Env_A > 0$); that is, by deciding to remanufacture the firm improved its profits and decreased its environmental footprint.

This observation is certainly encouraging—it suggests that remanufacturing is efficient in achieving the "win–win" situation in which the firm's economic and environmental goals are congruent. These 729 cases include all the cases when the heuristic was optimal (in which the positive environmental effect should be expected because the new products' production is non-increasing and remanufacturing uses less energy) as well as some of the cases with negative effective cannibalization.

But this observation also suggests that in 27.1% of the cases we observe the negative absolute environmental effect: profit increases but so does the total energy use of the firm. These cases all correspond to the instances with negative effective cannibalization, and the negative absolute effect is a result of the firm's sales growth[13]: because of the negative effective cannibalization the new production increases, thus using more energy. But as the next observation shows, this growth is in almost all cases still sustainable.

Observation 4: In 99% of the cases, we observed a *positive relative (per unit) environmental effect* ($Env_{R/u} > 0$), and in all cases we observed the positive relative (per dollar) environmental effect ($Env_{R/d} > 0$).

Figure 5 illustrates the absolute environmental effects; the shaded bars correspond to the cases with increase in the energy use (negative effects), and the non-shaded bars represent the cases with a decrease in energy use (positive effects).

The negative environmental effects may also appear puzzling; indeed, remanufacturing a unit requires much less energy as opposed to that needed to produce a new one. So why does the negative effect occur? The answer is related to the intricacies of

Figure 5   Absolute and Relative Environmental Effects of Remanufacturing

(a) Absolute Effect

(b) Relative Effects
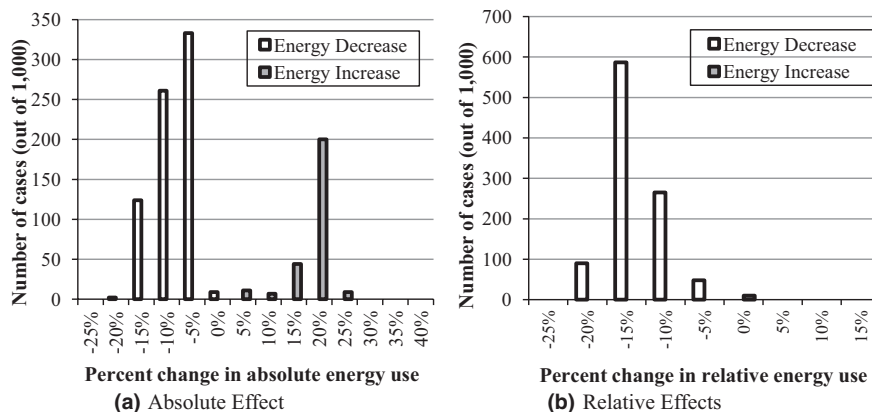
demand cannibalization across the product line. Under the "usual" logic, demand cannibalization implies that the quantity of the new product manufactured/sold decreases when a remanufactured product is introduced; that is, a positive quantity is cannibalized. As seen in observation 2, in 350 cases the quantity of *NH* manufactured/sold increased after a remanufactured product was introduced: the quantity "cannibalized" is therefore negative. By observation 3, the increased quantity of *NH* led to an increase in the firm's overall energy consumption and the negative absolute environmental effect in 271 of 350 such cases. By observation 4, even when we measure the relative effect per unit (mitigating the impact of the quantity increase), we still obtain (very few) cases where the firm's environmental impact per unit increases. The reason for this is the change in the product mix. When the firm remanufactures, the product mix changes to include the remanufactured products (with a lower per unit energy consumption), fewer *NL* products but more *NH*. Since the energy consumption of *NH* is higher than that of *NL*, this change can cause the relative per unit impact to increase as happens in 1% of the cases with very large negative cannibalization.

Overall, our results show that in most cases remanufacturing provides both economic and environmental benefits. Our results validate the heuristic approach used by many firms, as it is frequently optimal and leads to environmental improvements in all cases. We also show, however, that in the cases when the heuristic is suboptimal, a firm has a potential to grow because of the negative effective cannibalization, which may result in an increased total environmental impact for this specific firm. However, this growth is nearly always sustainable: the environmental impact per unit of product or per dollar of profit is almost always lower when a firm remanufactures than when it does not.

6. Sensitivity Analyses of the Environmental Effects

In this section, we test the sensitivity of the environmental effects to various parameters of the model. To do so, we take one parameter at a time and extend the range of its values beyond what was used in the main simulation, while keeping the other parameters' ranges unchanged. We measure the frequency of observing the positive environmental effects.

Table 3 summarizes the insights from the sensitivity analyses (for brevity we do not present the detailed sensitivity analysis in the article, but they are available upon request).

Table 3 Results of Sensitivity Analyses

		Frequency of Cases with Positive Environmental Effect		
Model Parameter	Testing Range	Absolute	Relative per Unit	Relative per Dollar
Sensitivity to costs				
c_{RH}, c_{NL}	$[0, c_{NH}]$	Moderate decrease (from $\approx$ 70% to 50%)	Negligible change	
c_{NH}	$[200, 800]$	Bimodal: almost 100% when cost is very low or very high, lowest at $\approx$ 70% when $c_{NH} = 650$		
Sensitivity to service margins and upgrade probability				
m_v, $m_{V\&D}$, Δ		Inverse of the sensitivity to costs	Negligible change	
Sensitivity to recovery rates				
β_1	$[0, 100\%]$	Bimodal (lowest at $\approx$ 40% when $\beta_1 = 60\%$)	Negligible change	Negligible change
β_2	$[0, 500\%]$	Increases to 100% when $\beta_2 > 250\%$		Minor decrease when $\beta_2 < 50\%$
Sensitivity to technological progress				
γ	$[0, 2]$	Increases from $\approx$50% when $\gamma = 0$ to $\approx$80% when $\gamma = 2$	Negligible change	
Sensitivity to energy parameters				
E_{NH} increases	2–4 times	Negligible change	Minor decrease (to 95%)	Negligible change
E_{NL} decreases	2–4 times		Moderate decrease (to 80%)	Negligible change
E_{NH} increases and E_{NL} decreases	2–4 times each		Moderate decrease (to 80%)	Minor decrease (to 95%)
Use phase energy increases over (re)manufacturing for all products	2–4 times	Negligible change	Negligible change	No change
Use phase energy increases over manufacturing and *RH* use energy increases over *NH* use	2–4 times		Minor decrease (to 95%)	Negligible change

Table 3 reveals several interesting observations regarding the impact of the economic and environmental parameters on the environmental effects:

Observation 5: The impact of the economic parameters is as follows:

- The absolute environmental effect and the negative effective cannibalization that underlines it are driven by the ability of the firm to decrease the new product's price. When C_{NH} is low, the optimal price is already low, and, consequently, the firm has a very limited ability to decrease it further; likewise when C_{NH} is high, price can be decreased but it is not profitable: hence the dependency is bimodal—both low and high costs result in nearly 100% positive effects.

- The absolute environmental effect and the negative effective cannibalization are also critically driven by the constrained supply of remanufacturable cores. As explained in section 3, our model is flexible to accommodate the cases when the firm is collecting the remanufacturable cores which correspond to the new units sold by other firms in the market (e.g., if the firm with a 50% market share collects 60% of its own *NH* and 60% of *NH* sold by other firms in the market, then $\beta_2 = 1.2$). Our results indicate that when β_2 becomes large enough, the positive absolute effects occur in 100% of the cases because the firm's own sales of *NH* are no longer a constraint on its remanufacturing operations; the firm can procure the cores from others.

- The positive relative effects (per unit and per dollar) are rather insensitive to the economic-related model parameters.

Observation 6: The impact of the environmental parameters is as follows:

- The absolute environmental effect and the negative effective cannibalization are insensitive to the energy parameters.
- The frequency of the positive relative effects declines as the difference in energy consumption between the high- and low-end products grows, which happens because of the substitution of the low-end products with a mix of new and remanufactured high-end ones in the product line.
- Interestingly, neither the absolute nor the relative effects are particularly sensitive to the balance between the energy used in the production vs. use phases of the product's life-cycle changes as well as to changes in the new generation products' energy efficiency: increasing the differences in production/use and new/old by a factor of four led to at most a 20% decrease in the frequencies of the relative effects and a negligible change in the absolute effects. In this sense, our results provide a counter-example to those of Quariguasi-Frota-Neto and Bloemhof (2011) and Gutowski et al. (2011), who considered products for which use phase was much more energy consuming relative to manufacturing/remanufacturing and found that the negative effects can be quite common for such products.

7. Discussion and Conclusions

This article provides a data-driven assessment of the economic and environmental aspects of remanufacturing for product + service firms—a business model that appears to be relatively common in the industries in which remanufacturing is practiced (e.g., 11 of 24 studies in Guide and Li 2010 consider product + service firms.) A critical component of such an assessment is the issue of demand cannibalization. Advancing the previous research, on the supply side we consider a case where the remanufactured product is not only cannibalizing the sales of its new "parent" product but also the other products in the firm's product line (multi-product supply). On the demand side, we consider a random utility consumer choice model with multiple consumer segments. We estimate the sizes of these segments and their purchasing behavior using a choice-based conjoint study and fit the data to the multi-nomial logit model with three or four latent classes (multi-segment demand).

Integrating the multi-product supply with an assessment of multi-segment demand, we performed extensive numerical simulations for one specific industry/product category: mobile phones. It is critical to note that while the numerical estimates/parameters in our article are specific to that industry/category, the overall approach and framework are general, and our approach could be easily replicated for other industries. And while the frequencies of the effects we describe would change (because they are driven by the industry-specific demand, cost, and energy estimates), the fundamental relationships would not.

To understand the economic and environmental impacts of remanufacturing, we compared the resulting optimal profits (which is our measure of the economic performance) and energy consumption (which is our measure of the environmental impact).

We found overwhelming support for the eco-efficiency of remanufacturing: it was profitable in all cases we considered, and, in a majority of cases (73%), it also resulted in a decrease in the total energy use—a positive absolute environmental effect (absolute decoupling). Further, while in the remain-

ing cases remanufacturing resulted in an increase in the energy use, that happened because of the firm's growth. As we showed, in some 35% of all cases, an introduction of a remanufactured product led (at optimality) to an increase in the quantity of the new product sold—the negative effective cannibalization. Because of this effect, remanufacturing leads to more new production and hence an expected increase in the total energy: the firm's sales simply grow. But what is important, we show that this growth is sustainable: the firm's relative energy consumption per unit of product decreased in 99% of the cases, and energy consumption per dollar of profit decreased in all of the cases we considered—positive relative environmental effects per unit and per dollar (relative decoupling).

Testing sensitivity, we found that the relative effects are rather insensitive to the economic parameters, while the absolute effects are not sensitive to the energy parameters. The absolute positive environmental effect becomes less pronounced when the firm has no ability to procure cores sold by other firms, the new product's cost is moderate, or when because of the technological progress there is a significant difference in demand between the current generation new product and previous generation refurbished. The relative positive effects become less pronounced when the difference in energy between the low- and high-end products increases, but even in those cases the relative positive effects still occur in over 80% of the instances we considered.

We conclude the article by mentioning three interesting extensions that are subjects of our future work: competition, recovery improvements, and product design. First, competition will impact both economic and environmental performance. In particular, if the additional demand that the firm serves with remanufactured product might come from reducing the new product's demand of a competing firm, then the positive environmental effects could occur with increased frequency. Second, recovery rate is assumed exogenous in this article, but in practice the firm could decide to invest in increasing recovery if it is profitable or if there are regulations in place that provide incentives for improving recovery. A major challenge in analyzing such a case is obtaining reliable cost estimates for improving recovery; as an industry executive pointed out to us "we are constantly looking for ways to collect more, but have just not found a way to do it profitably." One such way could be to design products that (once collected) can be easily remanufactured and upgraded. All these extensions can shed additional light on the balance between firms' economic and environmental goals and are of interest for future research.

Notes

[1] As is common in the literature we use "refurbished" and "remanufactured" as synonyms.

[2] For example, AT&T sells phones and voice and data plans, HP sells printers and cartridges, BOSCH sells power tools and consumables for those tools; in fact 11 of 24 studies of remanufacturing mentioned in Guide and Li (2010) explicitly refer to product + service firms.

[3] We emphasize that in general $p_{NH} \neq \bar{p}_{NH}$, and $p_{NL} \neq \bar{p}_{NL}$. More importantly, $D_k^{ij}(p_{NH}, p_{NL})$ and $\bar{D}_k^{ij}(\bar{p}_{NH}, \bar{p}_{NL}, \bar{p}_{RH})$ are different functions. We use the single bar notation, such as $\bar{p}$, to refer to the case with remanufactured product to differentiate it from the case without remanufacturing.

[4] Note that our model is oblivious to whether the firm is selling a differentiated product sold by no one else or it sells a commodity that other firms sell as well. In the former case β_j, $j = 1, 2$ should be interpreted as recovery fraction implying that $\beta_j \in [0, 1]$. But in the latter case, β_j could be above 1; for example, if a firm with a 50% market share collects 60% of its own and 60% of its competitor's product sales, then $\beta_j = 1.2$. Note also that β_j can be decision variables and the firm can decide to invest in order to acquire more remanufacturable cores. In this article, we assume β_js are exogenous and test sensitivity to their values. The case when recovery rates are determined endogenously is of interest for future research; see section 7.

[5] Sales of RH in period $i + 1_1$ cannibalize the NH sales from generation so fewer remanufacturable cores are available in period $i + 1_2$; hence RH from generation $i + 1$, if offered in period $i + 1_2$ cannibalizes fewer sales of NH from generation $i + 1$, which means that more cores are available in period $i + 2_1$, and so on.

[6] These descriptions are a blend of descriptions of several devices and plans from AT&T's website as well as the corresponding Wikipedia pages.

[7] This description also is a blend of the language used by AT&T and the description used in Ovchinnikov (2011).

[8] The overall quality of fit, as measured by the so-called "percent certainty"—improvement in log-likelihood due to the model predictions equals 56.41% and 48.51% for the cases without and with remanufacturing.

[9] For example, for a segment 4 consumer, if the firm offers NH at \$450, RH at \$350 (with H-service), and NL at \$200, then the utility of $NH = 1.4 - 1.66 - 0.203 = -0.463$, the utility of $RH = 1.061 - 0.957 - 0.203 = -0.098$, the utility of $NL = -2.461 + 0.216 + 0.203 = -2.042$, and the utility of None $= -1.931$. The corresponding exponents are 0.629, 0.906, 0.129, and 0.145, with the total of 1.810. Thus, the demand share of $NH = 0.629/1.810 = 34.7\%$, the demand share of $RH = 0.906/1.810 = 50.05\%$, and similarly for $NL = 7.17\%$ and for None $= 8.01\%$.

[10] We omitted the disposal and recycling stages since the energy consumption in those stages is small in magnitude (2–3 MJ), and it is not clear how many products end up being recycled vs. landfilled and when.

[11] There is no clear evidence for how the initial and secondary use phase energy consumptions compare; on one hand, the older generation product can be more energy intensive, but on the other the secondary use phase may

be shorter (Quariguasi-Frota-Neto and Bloemhof 2011). We effectively assume that these two effects cancel each other.

[12]Non-coincidentally, there are no negative effective cannibalization cases among the 637 cases in which heuristic solution was optimal. The heuristic prevents the firm from decreasing the price of *NH*, always resulting in the (positive) demand cannibalization.

[13]DISCLAIMER. As mentioned earlier, the unit of analysis in this article is a firm. Hence, our negative absolute effect only suggests that the environmental impact of the specific firm under consideration increased. This article provides no insight into whether the overall impact on the environment increased; in particular, if the new demand that the firm attracted with its remanufactured product came from decreasing new production at a competitor, then the cumulative impact (of these two firms) on the environment could well decrease; see section 7.

References

Abbey, J. D., V. D. R. Guide Jr., M. G. Meloy, S. Atalay. 2011. Consumer perceptions of multiple lifecycle products. Working paper, Pennsylvania State University, Pennsylvania.

Agrawal, V., A. Atasu, K. van Ittersum. 2011. The effect of remanufacturing on the perceived value of new products. Working paper, Georgetown University, Washington, DC.

Akaike, H. 1974. A new look at the statistical model identification. *IEEE Trans. Autom. Control* **19**(6): 716–723.

Apple. 2011. iPhone environmental reports for various models downloaded from apple.com. Available at http://images.apple.com/environment/reports/docs/iPhone_3GS-Environmental-Report.pdf, http://images.apple.com/environment/reports/docs/iPhone4_Product_Environmental_Report_2011.pdf, http://images.apple.com/environment/reports/docs/iPhone4S_Product_Environmental_Report_2011.pdf, http://images.apple.com/environment/reports/docs/iPhone5_product_environmental_report_sept2012.pdf (accessed date November 16, 2012).

AT&T. 2009. Phone interview with Erika Thompson-Kemp, VP, AT&T, December 11, 2009.

AT&T. 2010. Phone interview with Phil Bienert, VP, att.com, February 5, 2010.

Atasu, A., M. Sarvary, L. N. Van Wassenhove. 2008. Remanufacturing as a marketing strategy. *Manage. Sci.* **54**(10): 1731–1746.

Doctori Blass, V., L. Favret, M. Fuji, S. Mahdavi, R. Miller, J. Neira. 2006. *End-of-Life Management of Cell Phones in the United States.* Master's thesis, Donald Bren School of Environmental Science and Management, University of California, Santa Barbara, CA.

EPA. 2006. *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*, 3rd edn. Available at http://www.epa.gov/climatechange/wycd/waste/downloads/fullreport.pdf (accessed date September 1, 2011).

Ferguson, M., G. C. Souza, eds. 2010. *Closed Loop Supply Chains: New Developments to Improve the Sustainability of Business Partners.* CRC Press, Boca Raton, FL.

Ferguson, M. E., V. D. R. Guide Jr., G. C. Souza. 2006. Supply chain coordination for false returns. *Manuf. Serv. Oper. Manag.* **8**(4): 376–393.

Galbreth, M. R., J. D. Blackburn. 2006. Optimal acquisition and sorting policies for remanufacturing. *Prod. Oper. Manag.* **15**(3): 384–392.

Galbreth, M. R., J. D. Blackburn. 2010. Optimal acquisition quantities in remanufacturing with condition uncertainty. *Prod. Oper. Manag.* **19**(1): 61–69.

Geyer, R. 2004. Environmental and Economic Evaluation of Supply Loops and Their Constraints, PhD Thesis, Centre for Environmental Strategy, University of Surrey, Guildford, UK.

Geyer, R., V. Doctori Blass. 2010. The economics of cell phone reuse and recycling. *J. Adv. Manuf. Technol.* **47**: 515–525.

Goldman, D. 2010. Why all smartphones are $199. cnn.com. Available at http://money.cnn.com/2010/09/01/technology/smartphoneprice/index.htm (accessed date September 5, 2010).

Guide, V. D. R., J. Li. 2010. The potential for cannibalization of new products sales by remanufactured products. *Decis. Sci.* **41**(3): 547–572.

Gutowski, T. G., S. Sahni, A. Boustani, S. C. Gravesa. 2011. Remanufacturing and energy savings. *Environ. Sci. Technol.* **45**: 4540–4547.

Hotelling, H. 1929. Stability in competition. *Econ. J.* **39**: 41–57.

Kerr, W., C. Ryan. 2001. Eco-efficiency gains from remanufacturing: A case study of photocopier remanufacturing at Fuji Xerox Australia. *J. Cleaner Prod.* **9**: 75–81.

Kogan, K. 2011. Second-hand markets and intrasupply chain competition. *J. Retailing* **87**(4): 489–501.

Krishnan, V. V., P. Lacourbe. 2010. Designing Product Lines with Higher Aggregate Environmental Quality. Working paper, UCSD.

McLaren, J., N. Piukkula. 2004. Life cycle assessment of a 3rd generation Nokia handset, Proceedings of EGG 2004, 6–9 September 2004, Berlin, Germany.

Nokia. 2011. Nokia. Available at http://www.nokia.com/global/about-nokia/people-and-planet/sustainable-devices/eco/eco-profiles/ (accessed date April 16, 2012).

OECD. 2001. Executive summary report on decoupling. Available at http://www.oecd.org/dataoecd/0/52/1933638.pdf (accessed date February 28, 2011).

Ogg, E. 2010. Apple: 600,000 iPhone 4 preorders on first day. Available at www.news.cnet.com/8301-31021_3-20007906-260.html (accessed date April 16, 2012).

Orsato, R. J. 2009. *Sustainability Strategies: When Does It Pays to Be Green?* INSEAD Business Press, Palgrave Macmillan, U.K.

Ovchinnikov, A. 2011. Revenue and cost management for remanufactured products. *Prod. Oper. Manag.* **20**(6): 824–840.

Quariguasi-Frota-Neto, J., J. Bloemhof. 2011. An analysis of the eco-efficiency of remanufactured personal computers and mobile phones. *Prod. Oper. Manag.* **21**(1): 101–114.

Raz, G., Druehl C., V. Blass. 2013. Design for the environment: Life cycle approach using a newsvendor model. *Prod. Oper. Manag.* **22**(4): 940–957.

The Economist. 2011. Slicing an Apple. Available at http://www.economist.com/node/21525685 (accessed date August 10, 2011).

Thierry, M., M. Salomon, J. Van Nunn, L. N. Van Wassenhove. 1995. Strategic issues in product recovery management. *Calif. Manag. Rev.* **37**(2): 114–135.

Thomas, V. M. 2003. Demand and dematerialization impacts of second-hand markets: Reuse or more use? *J. Ind. Ecol.* **7**(2): 65–78.

Thomas, V. 2011. The environmental potential of reuse: An application to used books. *Sustainability Sci. J.* **6**: 109–116.

United Nations Environmental Programme (UNEP), International Resource Panel. 2011. Decoupling natural resource use and environmental impacts from economic growth. Available at http://www.unep.org/resourcepanel/Portals/24102/PDFs/

DecouplingENGSummary.pdf (accessed date September 22, 2011).

Van Heerde, H. J., S. Srinivasan, G. M. Dekimpe. 2010. Estimating cannibalization rates for pioneering innovations. *Mark. Sci.* **29**(6): 1024–1039.

Zikopoulos, C., G. Tagaras. 2007. Impact of uncertainty in the quality of returns on the profitability of a single-period refurbishing operation. *Eur. J. Oper. Res.* **182**(1): 205–225.