Submitted to *Management Science*
manuscript MS-09-00479.R2

Is Leasing Greener than Selling?

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Based on the proposition that leasing is environmentally superior to selling, some firms have adopted a leasing strategy and others promote their existing leasing programs as environmentally superior to "green" their image. The argument is that since a leasing firm retains ownership of the off-lease units, it has an incentive to remarket them or invest in designing a more durable product, resulting in a lower volume of new production and disposal. However, leasing might be environmentally inferior due to the direct control the firm has over the off-lease products, which may prompt the firm to remove them from the market to avoid cannibalizing the demand for new products. Motivated by these issues, we adopt a life-cycle environmental impact perspective and analytically investigate if leasing can be both more profitable and have a lower total environmental impact. We find that leasing can be environmentally worse despite remarketing all off-lease products, and greener than selling despite the mid-life removal of off-lease products. Our analysis also provides insights for environmental groups and entities that use different approaches to improve the environmental performance of business practices. We show that imposing disposal fees or encouraging remanufacturing, under some conditions, can actually lead to higher environmental impact. We also identify when educating consumers to be more environmentally conscious can improve the relative environmental performance of leasing.

Key words: Durable goods; sustainable operations; green marketing; environment; servicizing

1. Introduction

Making firms responsible for their products post use has been discussed as a mechanism to improve their environmental performance. The argument is that this may give the firms an incentive to efficiently remarket[1] their recovered products or invest in designing their products to be more durable (White et al. 1999, Hawken et al. 1999, Fishbein et al. 2000, Mont 2002). These actions decrease the demand for new products, reducing the environmental impact of manufacturing and disposal. Thus, environmental groups and agencies recommend that firms voluntarily offer leasing or takeback options (U.S. EPA 2008a, Minnesota Pollution Control Agency 2006, New York City Government 2007, Fishbein et al. 2000). Leasing in particular provides firms with direct control over used products, without requiring them to give consumers any explicit incentives to return these products.[2] Some firms seeking to "green" their image have specifically embraced the "Leasing is Greener" message. For example, Interface Inc., a carpet manufacturer, introduced the Evergreen Lease with the express purpose of reducing the environmental impact of its operations and described it as a "new workable business model for sustainable development" (Olivia and Quinn 2003). Other firms such as IBM, HP, and Xerox also promote their existing leasing programs as being environmentally friendly (IBM 2007, Hewlett-Packard 2009, Charter and Polonsky 1999).

At the same time, the environmental superiority of leasing is not clear. The direct control that a leasing firm exerts on the off-lease units allows it to choose to remove the returned off-lease products from the market, in order to avoid cannibalizing the demand for the firm's new products (Fishbein et al. 2000). Such mid-life removal may result in more new products manufactured and more products disposed than under the selling strategy, potentially causing leasing to be environmentally worse. In this paper, our goal is to analyze the key drivers that determine when leasing is both environmentally superior and more profitable, leading to its voluntary adoption by firms.

In our analysis, we assume that the firm makes the lease-versus-sell choice based on their relative profitabilities and compare the total environmental impact resulting from the profit-maximizing decisions made by the firm. We use a product life-cycle perspective, where the total environmental impact of a strategy is given by the volume of products in each life-cycle phase (production, use and disposal) multiplied with the per-unit environmental impact in that phase, summed over all the life-cycle phases (White et al. 1999). Adopting this profit-maximization perspective is important in the non-regulatory context, since firms will adopt leasing only if it is more profitable than selling. From the firm's perspective, if leasing is more profitable, we analyze the conditions when it can justifiably claim that leasing is the greener strategy. This is valuable in an environment where consumers are sensitive to "greenwashing" and the internet makes information about offenders easy to publicize and access (e.g., through sites such as www.greenwashingindex.com).

[1] In this paper, the term "remarketing" refers to putting the used product on the market.

[2] Other takeback options such as trade-in rebates require a firm to offer explicit financial incentives and only a fraction of the products are recovered.

Our work builds on and contributes to the previous literature on durable goods, closed-loop supply chains and industrial ecology. In the durable goods literature, several issues associated with the profitability of the lease-versus-sell decision faced by a firm have been studied (see Waldman 2003 for an excellent overview). Some of these issues include pricing power (Coase 1972, Bulow 1982), the role of secondary markets and market segmentation (Hendel and Lizzeri 1999, Desai and Purohit 1998, Huang et al. 2001), competition (Desai and Purohit 1999) and channel structure (Desai et al. 2004, Bhaskaran and Gilbert 2009). We make three distinct contributions to this literature. First, our work brings the environmental impact dimension to the comparison of leasing and selling. We explicitly compare the total environmental impact of leasing and selling, and identify conditions when leasing is a win-win strategy. Second, we enrich the comparison of the two strategies by endogenizing the remarketing and disposal decisions, and incorporating disposal costs. Third, we discuss the implications of our results for environmental groups and agencies that utilize different approaches to achieve environmental improvements such as lobbying for landfill bans, regulations imposing disposal fees, encouraging product reuse and remanufacturing, and educating consumers to be more environmentally conscious.

In the closed-loop supply chain literature, a number of papers focus on the joint pricing of new and remarketed products under the selling strategy in a variety of competitive and regulatory environments (Debo et al. 2005, Ferguson and Toktay 2006, Atasu et al. 2008). In these papers, however, there is an assumption that the product has a useful life of only one period and has to be remanufactured or refurbished before it can be used again. This characterization blurs the distinction between leasing and selling, as no consumer-to-consumer trading occurs and the firm has full control of used products even under selling. We complement this literature by considering a firm's disposal and remarketing decisions for a durable product with a useful life of two periods, which makes the distinction between the two strategies particularly salient.

In the industrial ecology literature, conventional life-cycle analysis (LCA) focuses on evaluating the environmental impact of one unit of a specific type of product throughout its life cycle (U.S. EPA 2008c), where assumptions are made on the reuse and disposition decisions of a firm. In contrast, we endogenize these decisions, capturing the contributions of the aggregate demand and effective use duration to the total environmental impact of a strategy.

2. The Model

In this section, we develop a discrete-time, dynamic, sequential, firm-consumer game over an infinite time horizon. Periods are indexed by $t \geq 0$. Vectors are arranged in rows and primes represent transposes. $\mathbf{1}$ denotes a vector of ones. The characters f, c, l and s denote parameters specific to the firm, the consumer, leasing and selling, respectively.

Firm and Product Characteristics. We study a profit-maximizing monopolist that produces a single durable product. The marginal cost of producing a new product is denoted by c. The product depreciates with use and has finite durability. To capture the inter-temporal substitution effect due to product durability while maintaining tractability, we assume the product lasts for two periods (Desai and Purohit 1998, 1999, Huang et al. 2001). We refer to a product in its first period of useful life as *new* (denoted by the subscript n) and in the second period of its useful life as *old* (denoted by the subscript u). Old products can be *off-lease* or *used*, corresponding to whether the product was originally leased or sold. Products that have been used for two periods are called *end-of-life* products, and can only be disposed of (via recycling, incineration or landfilling).

To compare leasing and selling, we focus on pure strategies. If the firm chooses the leasing strategy, it offers one-period operating leases, where the firm maintains ownership of the off-lease units and has the option of remarketing them; it has to dispose end-of-life products. Under the selling strategy, it only sells new products; used products are traded between consumers on the secondary market at the market-clearing price and it is the consumers who dispose of end-of-life products. The firm avoids direct disposal costs, but has to implicitly bear the consumer's disposal cost (if any) and the loss of control over the secondary market. Thus, the presence of disposal costs affects the profitability and the total environmental impact of leasing and selling differently.

If the firm or the consumer disposes of products, they incur a per-unit cost, s_f and s_c, respectively. We allow s_f and s_c to either be positive or negative, reflecting costly or profitable disposal, but for brevity use the term "disposal cost" to refer to both cases. For example, cars can typically be sold to scrap yards, but electronic waste is typically costly to dispose of. We also allow for an asymmetry in the disposal costs in our analysis. For example, federal law on hazardous substances (U.S. EPA 2008b) does not restrict households from throwing their electronic waste in the trash ($s_c < s_f$). On the other hand, even if recycling is profitable, recyclers may only purchase from firms that generate large volumes, and the recycling opportunity may not be available to consumers ($s_f < s_c$). We assume that disposal is not more profitable than the cost of producing a new product, i.e., $s_f, s_c > -c$. We also assume that remarketing or transaction costs are normalized to zero.[3]

Consumer Characteristics. The size of the consumer population remains constant over time and is normalized to size 1. Consumers are heterogeneous in the utility they derive from consumption, and are characterized by their type θ, which is time-independent and finite. We assume that θ is uniformly distributed on $[0,1]$. Consumer θ's utility derived from one-period use of the new, off-lease, used product and remaining inactive is given by $u_n(\theta)$, $u_u^l(\theta)$, $u_u^s(\theta)$ and 0, respectively. Let $u(\theta,i) \doteq (u_n(\theta), u_u^i(\theta), 0)$, where $i \in \{l,s\}$. Ceteris paribus, every consumer (weakly) prefers

[3] Results with positive remarketing costs are qualitatively similar and available from the authors upon request.

a new product to an old (off-lease or used) product, and an old product to remaining inactive; $u_n(\theta) \geq u_u^i(\theta) \geq 0$ for all $\theta \in [0,1]$ and $i \in \{l, s\}$. We adopt the following specification for the consumer utility that satisfies the above conditions and is often used in the literature (Desai and Purohit 1998, Desai et al. 2004): $u_n(\theta) = \theta$, $u_u^l(\theta) = \delta_l\theta$ and $u_u^s(\theta) = \delta_s\theta$, where $\delta_l, \delta_s \in (0,1)$ is interpreted as the relative willingness to pay for the old product compared to the new product. δ represents both the physical and the economic deterioration of the product. For brevity, we will refer to δ as the product durability.

We allow the product durability to be different based on whether the product was originally leased or sold. A leased product may depreciate to a greater extent than a sold product, $\delta_l < \delta_s$, due to moral hazard issues that may lead to a rougher use of a leased product. On the other hand, since a leasing firm may maintain or service the product better than a consumer during the initial lease period or choose to refurbish or remanufacture the off-lease product before remarketing it, we can have $\delta_l \geq \delta_s$ (Desai and Purohit 1998).

Specification of the Game. We develop a dynamic game where in every period, the firm first makes her quantity decisions, followed by the consumers making their purchasing decisions. Under the leasing strategy, the firm chooses the quantity of new and off-lease products to lease. We assume that the remaining off-lease products and all end-of-life products are disposed.[4] Under the selling strategy, the firm only decides the quantity of new products to sell. All players maximize their net present values with a discount factor of $0 \leq \rho < 1$. We assume $c + s_f < 1 + \delta_l$ and $s_c < \delta_s + \frac{2\rho(1-c)}{1+\rho^2}$ to eliminate uninteresting cases where the business is not profitable under leasing and selling.

Environmental Impact of a Product. We consider three life-cycle phases: production, use and disposal. The total environmental impact of a strategy depends on the volume of products in each phase multiplied by the per-unit impact of the product in each phase (White et al. 1999, Thomas 2008). The former depends on the firm's profit-maximizing decisions and the latter depends on the product's per-unit environmental impacts in each phase, which are found using conventional life-cycle analysis (U.S. EPA 2008c). We define the per-unit impact as follows:

Production phase: Let i_p denote the per-unit production impact.

Use phase: The per-period, per-unit use impact of a new and an old product is denoted by i_{u1} and i_{u2} respectively. We allow $i_{u2} \geq i_{u1}$, i.e., as a product depreciates, its use impact may increase. This is commonly observed for products whose efficiency degrades with use, such as refrigerators and automobiles (Intlekofer 2009). We assume that i_{u2} is independent of product durability.[5]

[4] In §4, we discuss the implications of selling the off-lease products in another market instead of disposing them.

[5] If we allow i_{u2} to be a decreasing function of the physical durability of the product, and if physical durability is higher (lower) under leasing, its potential as a win-win strategy is improved (reduced) due to the lower (higher) per-unit impact of old products. See discussion in §3.4.

Disposal phase: Let i_d denote the per-unit impact due to the disposal of a product. We assume that i_d under consumer disposal is equal to that under disposal by the firm.[6]

3. Analysis

We first analyze leasing and selling by focusing on the steady-state firm and consumer strategies and then compare their profitability and total environmental impact. We solve the problem using the common approach of only considering subgame perfect equilibria. We define customer θ's period-t action vector under leasing as $a_l^t(\theta) \doteq (l_n^t(\theta), l_u^t(\theta), i^t(\theta))$ and under selling as $a_s^t(\theta) \doteq (b_n^t(\theta), b_u^t(\theta), i^t(\theta))$ where l_n^t, l_u^t, b_n^t, b_u^t and i^t are indicator variables corresponding to leasing a new product (Ln), leasing an off-lease product (Lu), buying a new product (Bn), buying a used product (Bu), and remaining inactive (I). Finally, we let $r^t \doteq (r_n^t, r_u^t)$ and $p^t \doteq (p_n^t, p_u^t)$ denote the vectors of lease and sales prices at time t.

3.1. Leasing Model

We now solve for the steady-state equilibrium under the leasing strategy. This assumption of restricting attention to steady-state equilibria is commonly used in papers that consider a multi-period durable-goods model (Hendel and Lizzeri 1999, Huang et al. 2001, Debo et al. 2005). With a lease duration of one period, consumers enter each period without a product and their decisions across periods decouple; a consumer's decision in the current period is independent of the consumers' previous actions and solely determined by the firm's period-t decisions. Let L_n^t and L_u^t denote the quantity of new and off-lease products leased by the firm, respectively, and $L^t \doteq (L_n^t, L_u^t)$. The inverse demand functions are derived by solving the consumer's utility maximization problem (see Appendix §A1) and the firm's problem in period t is given by $\Pi_l(L^{t-1}, L^t) = (r_n^t(L_n^t, L_u^t) - c)L_n^t + r_u^t(L_n^t, L_u^t)L_u^t - s_f(L_n^{t-1} - L_u^t) - s_f L_u^{t-1}$, such that $L_n^t, L_u^t \geq 0$ and $L_u^t \leq L_n^{t-1}$.

At the steady-state equilibrium, the firm remarkets only a portion of the off-lease products ($L_u^* < L_n^*$) if and only if $s_f < \frac{1-\delta_l}{2} - c$ (see Appendix §A1), and remarkets all of them otherwise. The condition for partial remarketing to be optimal depends on s_f, c and δ_l in the following manner: Partial remarketing of off-lease products reduces the cannibalization of new product leases, but at the expense of foregoing revenue and generating a disposal cost. Thus, all else being equal, a low disposal cost and a low production cost both promote partial remarketing. As durability increases, consumers value an off-lease product more, making remarketing it more attractive for the firm and favoring full remarketing. The firm' per-period optimal profit is given by $\Pi_l^* = \frac{(1-c-s_f)^2 - \delta_l(1-2(c+s_f))}{4(1-\delta_l)}$ for $s_f < \frac{1-\delta_l}{2} - c$, and $\Pi_l^* = \frac{(1-c-s_f+\delta_l)^2}{4+12\delta_l}$ otherwise. The resulting steady-state, per-period, total environmental impact is given by $E_l = (i_p + i_d)L_n^* + i_{u1}L_n^* + i_{u2}L_u^*$.

[6] If i_d is lower due to firm disposal under leasing, the environmental impact of leasing is lower, improving (but not ensuring) its potential as a win-win strategy (see §4).

3.2. Selling Model

We next describe the model for the selling strategy and solve for its equilibrium. Note that since we consider a product with finite durability in an infinite-horizon setting, the conventional time inconsistency effect is not present (Huang et al. 2001).

Consumer θ's action vector in period t is given by $a_s^t(\theta) = (b_n^t(\theta), b_u^t(\theta), i^t(\theta))$ for all $\theta \in [0,1]$. Under selling, since the consumer can keep his used product and the product lasts for two periods, a consumer's payoff in any given period depends on his action in the previous period and the prices in the current period (see Table 1). Thus, the dynamics are Markovian. We restrict our attention to Markov perfect equilibria, which assumes that strategies only depend on the payoff-relevant history that is summarized by the current state (Fudenberg and Tirole 1991). A Markov-perfect equilibrium in the infinite time horizon is one where all explicit time dependence has dropped out. However, cyclic behaviors are still possible. We focus on an equilibrium in which all decisions are constant in time or a "focal point" (Huang et al. 2001).

Table 1 **Net Utility Matrix $\Pi_\theta[a_s^t(\theta); a_s^{t-1}(\theta), p^t]$ under Selling for Consumer θ in period t.**

$a_s^t(\theta)/a_s^{t-1}(\theta)$	Buy new	Buy used	Remain inactive
Buy new	$u_n(\theta) - p_n^t + p_u^t$	$u_n(\theta) - p_n^t$	$u_n(\theta) - p_n^t$
Buy used	$u_u^s(\theta) - s_c$	$u_u^s(\theta) - p_u^t - s_c$	$u_u^s(\theta) - p_u^t - s_c$
Remain inactive	p_u^t	0	0

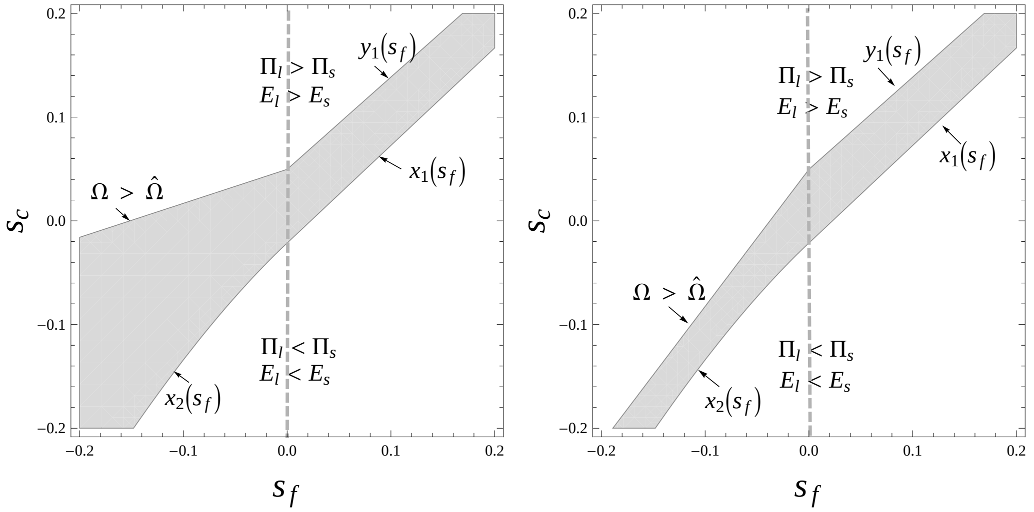
At the focal point, the equilibrium solution is obtained by solving the coupled time-independent Bellman equations of the consumer and the firm, subject to the market-clearance conditions (see Appendix §A2). At the focal point, the inverse demand function for the new products is given by $p_n(S_n) = \frac{2\rho(1-S_n) - s_c(1+\rho^2) + \delta_s(1+\rho^2-2S_n(1+\rho+\rho^2))}{2\rho}$, where S_n is the per-period quantity of new products sold by the firm. The firm's optimization problem reduces to $\max_{S_n \geq 0} \Pi_s(S_n) = (p_n(S_n) - c)S_n$. The equilibrium per-period quantity of new products sold and profit are given by $S_n^* = \frac{\rho(2-2c-\rho s_c+\rho\delta_s) - s_c + \delta_s}{4(\rho+\delta_s(1+\rho+\rho^2))}$ and $\Pi_s(S_n^*) = \frac{(s_c - \delta_s - \rho(2-2c) + \rho^2(s_c-\delta_s))^2}{16\rho(\rho+\delta_s(1+\rho+\rho^2))}$. The resulting steady-state, per-period, total environmental impact is given by $E_s = (i_p + i_d)S_n^* + i_{u1}S_n^* + i_{u2}S_n^* = (i_p + i_{u1} + i_{u2} + i_d)S_n^*$.

3.3. Comparing Leasing and Selling

We now compare the relative environmental impact and the relative profitability of leasing and selling. We illustrate the results from this analysis in Figure 1. For brevity and ease of exposition, the closed-form expressions for the thresholds defined in our results are provided in the Appendix.

PROPOSITION 1. *If full remarketing is optimal ($s_f \geq \frac{1-\delta_l}{2} - c$), leasing is more profitable than selling for $x_1(s_f) < s_c$ and greener than selling for $s_c < y_1(s_f)$. The condition $x_1(s_f) < y_1(s_f)$ holds if and only if $\delta_l > \delta_s w(\rho)$, where $w(\rho) \doteq \frac{1+\rho+\rho^2}{3\rho} \geq 1$.*

Figure 1 In the region to the left of the vertical line, partial remarketing is optimal under leasing, and full remarketing is optimal otherwise. Leasing is more profitable and greener in the shaded regions, which are defined by $x_1(s_f) < s_c < y_1(s_f)$, when full remarketing is optimal, and by $x_2(s_f) < s_c$ and $\widehat{\Omega}(\cdot) < \Omega$, when partial remarketing is optimal. In both panels, $\delta_l = 0.6$, $\delta_s = 0.5$, $c = 0.2$, $\rho = 0.9$ and $w(\rho) = 1.0037$, such that $\delta_l > \delta_s w(\rho)$.



(a) $\Omega = 0.9$ (b) $\Omega = 0.65$

If full remarketing is optimal under leasing, the only differences between leasing and selling arise from the disposal cost or durability. Leasing is more profitable than selling only if the firm's disposal cost is sufficiently lower than the customer's disposal cost ($x_1(s_f) < s_c$). At the same time, leasing is greener than selling only if the firm's disposal cost is not too low ($s_c < y_1(s_f)$). Thus, leasing can be a win-win strategy only if $x_1(s_f) < y_1(s_f)$ holds, which requires that the product durability be sufficiently higher under leasing ($\delta_l > w(\rho)\delta_s$). This is because the consumers then value off-lease products more, making remarketing them more attractive for the firm. This improves profits, while reducing the new production volume, and consequently, the total environmental impact. Thus, remanufacturing the off-lease products before remarketing them or servicing the product during the initial lease period, which both increase the value of the off-lease product, improves the potential of leasing as a win-win strategy.

Proposition 2. *If partial remarketing is optimal ($s_f < \frac{1-\delta_l}{2} - c$), leasing is more profitable than selling for $x_2(s_f) < s_c$. Leasing is greener than selling for $\Omega \doteq \frac{i_{u2}}{i_p + i_{u1} + i_d} > \widehat{\Omega}(s_f, s_c, \delta_l, \delta_s)$.*

If partial remarketing is optimal, leasing is more profitable than selling only if the firm's disposal cost is sufficiently lower than the consumer's disposal cost ($x_2(s_f) < s_c$). We find that leasing can only be greener for products that have sufficiently high values of $\Omega \doteq \frac{i_{u2}}{i_p + i_{u1} + i_d}$. The rationale for this result is as follows: When partial remarketing is optimal, the firm removes $L_n^* - L_u^*$ more old products and puts $L_n^* - S_n^*$ more new products on the market in each period relative to selling.

Thus, leasing reduces the volume of old products in use by $(L_n^* - L_u^*) - (L_n^* - S_n^*) = S_n^* - L_u^*$. Overall, relative to selling, partial remarketing under leasing increases the steady-state production and disposal impacts, increases the steady-state use impact due to new products and reduces the steady-state use impact due to old products. Thus, leasing is greener than selling only if the use impact i_{u2} due to old products is sufficiently high, $i_{u2} > (i_p + i_{u1} + i_d)\widehat{\Omega}(\cdot)$, such that the increase in the total environmental impact due to the greater production, new product use, and disposal volume is dominated by the decrease in the environmental impact due to fewer old products in use. This condition is more easily satisfied for products that have the majority of their environmental impact in the use phase such as printers, photocopiers, washers, and automobiles (Bole 2006, Intlekofer 2009). On the other hand, it is more demanding for products that have the majority of their environmental impact in the production and disposal phases such as laptops, carpets, and cellphones (Kuehr and Williams 2003, Fishbein et al. 2000).

Recall that one of the arguments for the environmental superiority of leasing is that since the firm owns the off-lease units, it has an incentive to remarket them. In contrast, some argue that leasing may be worse for the environment due to the firm's ability to remove recovered off-lease products from the market. Interestingly, we find that leasing may be less green than selling despite full remarketing (from Proposition 1), and greener than selling despite mid-life removal of off-lease products (from Proposition 2). Thus, whether the firm fully remarkets off-lease products or removes some of them from the market is not an accurate indicator of its total environmental impact.

3.4. Implications for Environmental Groups and Agencies.

This section analyzes whether a number of approaches typically used by environmental groups and agencies would be expected to improve the relative environmental performance of leasing.

COROLLARY 1. *The relative environmental impact of leasing ($E_l^* - E_s^*$) increases in the firm's disposal cost (s_f) or durability (δ_l) if $\Omega > 1$ and partial remarketing is optimal ($s_f < \frac{1-\delta_l}{2} - c$), and decreases otherwise.*

Typically, environmental groups and agencies lobby for landfill bans or regulations imposing disposal fees (which increase the disposal cost faced by the firm) or encourage firms to remanufacture their recovered products (which improves the value of the off-lease product), with the intent of reducing total environmental impact. Corollary 1 implies that these are effective strategies in general, but they can sometimes instead lead to an increase in the leasing firm's total environmental impact: When partial remarketing is optimal for the firm, a higher disposal cost or a higher value of the off-lease products results in a higher volume of off-lease products being remarketed. If the product has a sufficiently high use impact (relative to other phases), this larger volume of off-lease products that remain in use leads to an increase in the environmental impact of leasing. This result implies that environmental groups and agencies should focus their attention on increasing the firm's disposal costs or encouraging remanufacturing primarily for products with high disposal and production costs and those that have low use impact such as laptops, carpets, and cellphones.

One of the arguments for the environmental superiority of leasing is that the firm may invest in designing a more durable product. We can generalize our model to allow for product durabilities to be decision variables (set at time $t = 0$), where investing in product durability is costly. While obtaining closed-form expressions for this extension is difficult, we can show using exhaustive numerical optimization that the product durability under leasing is (weakly) higher than that under selling (details are provided in Appendix §A5). The reason for this is as follows: Under leasing, the firm has to recover the off-lease products and thus has an incentive to make them more durable, which increases the profitability of remarketing them. Under selling, however, the firm does not control the secondary market, so increasing the product durability only increases the competition from this market. With this result, Corollary 1 can be interpreted to mean that the design consequences of leasing can be detrimental or beneficial from an environmental impact perspective; depending on the specific product characteristics.

We assumed that the use impact of old products may be higher than that of new products ($i_{u2} \geq i_{u1}$), independent of durability. If the use impact of old products increases in the level of physical deterioration of the product, a higher physical durability would mean a unit of the product is "greener." It is straightforward to extend Corollary 1 to this model and show that a higher physical durability leads to a higher total environmental impact when the use impact of old product is sufficiently high relative to the other phases. In other words, making the product greener on a per-unit basis may lead to a higher total environmental impact.

It is important to note that while environmental groups and agencies typically aim to improve firms' environmental performance, their efforts also influence the firm's profitability, and consequently, influence whether firms adopt leasing. For example, efforts to increase the firm's disposal cost reduces the profitability of leasing. If the disposal cost is sufficiently high, the firm may switch to selling. On the other hand, efforts to increase the product durability increase the profitability of leasing, making it more attractive for the firm to adopt.

Environmentally-conscious Consumers. We now focus on the effect of educating consumers to make them more environmentally conscious on the relative environmental performance of leasing. In order to incorporate environmentally-conscious consumers in our model, we assume that consumers incur a utility loss due to the environmental impact associated with their decisions. Suppose that all consumers are homogeneous in their sensitivity $\beta \geq 0$ to the environmental impact. We assume that if a consumer leases or purchases a new product, she is sensitive to the production, disposal and use impact of the new product, as a consequence of her decision. Similarly, a consumer leasing or buying an old product is simply extending the useful life of an existing product and is only sensitive to the use impact of the old product. We reformulate our model with these modified consumer utilities (see Appendix §A6). Since the consumers are environmentally conscious, the firm's decisions now also depend on the environmental impact of their products (i.e., Ω). We determine the optimal decisions and the resulting per-period, steady-state profit and environmental impact under both strategies. It is straightforward to show that our structural results and insights summarized in Propositions 1, 2 and Corollary 1 still hold. However, analyzing the effect of educating consumers (increasing β) on the relative environmental impact of leasing appears to be intractable for the general case. Nevertheless, simplifying our expressions by assuming $\rho = 1$ allows us to find a sufficient condition for when the relative environmental performance of leasing improves.

COROLLARY 2. *If durability is lower under leasing ($\delta_l < \delta_s$), then the relative environmental impact of leasing compared to selling ($E_l^* - E_s^*$) decreases in the consumer's sensitivity to environmental impact (β).*

The presence of environmentally-conscious consumers exerts a negative pressure on the firm's profits. This leads the firm to reduce its new production (and hence its use and disposal) volume to moderate this detrimental effect, which consequently reduces the firm's total environmental impact under both strategies. However, as consumers become more environmentally conscious, the environmental impact of leasing decreases faster than that of selling when the product's durability is lower under leasing. The reason for this is as follows: If the product durability is lower under leasing (for example, due to moral hazard issues), off-lease products are valued less by the consumers, making remarketing them less attractive. This leads to a higher volume of new products. Thus, in the presence of environmentally-conscious consumers, a lower durability under leasing exerts a larger negative pressure. As a result, the firm reduces its new production volume by a larger amount under leasing, and consequently, a greater reduction in the total environmental impact takes place under this strategy. This implies that as consumers become more environmentally conscious, leasing may become an environmentally superior strategy for a wider range of products (products with lower values of Ω).

4. Conclusions

In this paper, we investigate whether leasing as a form of voluntary product take back can be both more profitable and greener than selling. We also provide guidance on when firms can justifiably promote leasing as the "greener" strategy. The key insights obtained from our analysis are of relevance to both manufacturers and environmental groups, and are discussed below.

Is leasing greener than selling? Our analysis shows that the two main drivers of whether leasing can be both a more profitable and a greener strategy are the product durability and whether it has a high use impact, which depends on the product's type. Leasing can be a win-win strategy for products that have a higher use impact (compared to their production and disposal impacts) and low durability such as personal printers and photocopiers. For products that have a high use impact but higher durability, such as washers, dryers and refrigerators, leasing can be a win-win strategy only if the product durability is higher under leasing. Finally, leasing is more profitable but environmentally worse for products that have a higher production and disposal impact (e.g., laptops and carpets).

The remarketing level or the durability level are not good proxies for environmental impact. We find that leasing may be less green than selling despite full remarketing, and greener than selling despite partial remarketing. We also find that higher durability can lead to leasing being environmentally worse. Thus, the conventional arguments for and against the environmental superiority of leasing based on such simple proxies such as the remarketing level of off-lease products, or whether the product is highly durable or not, can be misleading. This implies that firms such as HP or IBM, who emphasize their remarketing of off-lease products as an argument for the environmental superiority of their leasing programs, could be vulnerable to accusations of greenwashing. In addition, firms such as Pitney Bowes that do not remarket all of their off-lease products (Fishbein et al. 2000) can avoid claims of greenwashing by emphasizing that although they remove functioning off-lease products from the market, their action actually reduces their total environmental impact.

Insights for environmental groups and agencies. We provide several insights for environmental groups and agencies: First, leasing is not always greener than selling and depends on the product type, so care must be taken not to promote leasing without qualification. Second, even when leasing is greener, firms may not have an incentive to adopt it as selling may be more profitable, so its potential as a voluntary mechanism is limited. Third, environmental groups and agencies should focus their attention on increasing the disposal costs through landfill bans or encouraging remanufacturing and higher durability levels only for products with low use impact such as laptops, carpets, and cellphones. Fourth, they should educate consumers to be more environmentally conscious when the product durability is lower under leasing, which makes it greener for a wider range of products.

We conclude with a discussion of the robustness and generality of our results. We assumed that when a leasing firm removes an off-lease product from the market, it disposes of the product. However, in practice, a firm may put these products on a different market. Recall that removing products from the focal market reduces the environmental impact under leasing by removing old products from use. If the products are instead put on a market elsewhere, this benefit is lost, unless these products displace products with sufficiently higher environmental impact in that market. We also assumed that the disposal impact is equal under leasing and selling. If the per-unit disposal impact is lower under leasing, the total environmental impact of leasing is reduced, improving its potential as a win-win strategy. Finally, our analysis was carried out under the assumption that the initial lease period and the use duration for a new product under selling are equal. Since financial accounting rules curtail the length of operating leases to be no more than 75% of the useful life of the product, off-lease products may have higher durability than the used products traded on the secondary market under selling. This makes remarketing off-lease products more attractive and improves profitability under leasing, but the relative environmental impact of leasing will increase for products with high use impact.

To summarize, we offer new insights into a firm's lease versus sell decision by comparing the total environmental impact of each strategy. Thus, we add to the important knowledge base on product leasing that will benefit not only managers, but also environmental groups and agencies. We hope that our research highlights the importance of marketing strategies on the environmental performance of a firm.

Acknowledgments

This paper is based on a chapter from the first author's doctoral dissertation at the Georgia Institute of Technology. The authors thank Preyas Desai, the associate editor and the reviewers for their insightful comments. This research was supported by NSF DMI Grant No. 0620763.

References

Atasu, A., M. Sarvary, L. Van Wassenhove. 2008. Remanufacturing as a Marketing Strategy. *Management Sci.* **54**(10) 1731–1747.

Bhaskaran, S., S. Gilbert. 2009. Implications of Channel Structure for Leasing or Selling Durable Goods. *Marketing Sci.* **28**(5) 918–934.

Blackwell, D. 1965. Discounted Dynamic Programming. *The Annals of Math. Statistics* **36**(1) 226–235.

Bole, R. 2006. Life-Cycle Optimization of Residential Clothes Washer Replacement, Report No. CSS06-03. *Center for Sustainable Systems, University of Michigan* .

Bulow, J. 1982. Durable-Goods Monopolists. *J. of Political Econom.* **90** 314–322.

Charter, M., M.J. Polonsky. 1999. *Greener Marketing: A Global Perspective on Greening Marketing Practice*. Greenleaf Publishing.

Coase, R. 1972. Durability and Monopoly. *J. of Law and Econom.* **15** 143–149.

Debo, L., L.B. Toktay, L. Van Wassenhove. 2005. Market Segmentation and Product Technology Selection for Remanufacturable Products. *Management Sci.* **51**(8) 1193–1205.

Desai, P., O. Koenigsberg, D. Purohit. 2004. Strategic Decentralization and Channel Coordination. *Quant. Marketing and Econom.* **2** 5–22.

Desai, P., D. Purohit. 1998. Leasing and Selling: Optimal Marketing Strategies for a Durable Goods Firm. *Management Sci.* **44**(11) S19–S34.

Desai, P., D. Purohit. 1999. Competition in Durable Goods Markets: The Strategic Consequences of Leasing and Selling. *Marketing Sci.* **18**(1) 42–58.

Ferguson, M., L. B. Toktay. 2006. The Effect of Competition on Recovery Strategies. *Production and Oper. Management* **15**(3) 351–368.

Fishbein, B., L. McGarry, P. Dillon. 2000. Leasing: A Step towards Producer Responsibility. Tech. rep., INFORM, Inc.

Fudenberg, D., J. Tirole. 1991. *Game Theory*. MIT press.

Hawken, P., A. Lovins, L. Lovins. 1999. *Natural Capitalism*. Little, Brown and Company.

Hendel, I., A. Lizzeri. 1999. Interfering with Secondary Markets. *RAND J. Econ.* **30**(1) 1–21.

Hewlett-Packard . 2009. HP Environment: Product Reuse and Recycling. `http://www.hp.com/hpinfo/globalcitizenship/gcreport/productreuse/programs.html`.

Huang, S., Y. Yang, K. Anderson. 2001. A Theory of Finitely Durable Goods Monopoly with Used-Goods Market and Transaction Costs. *Management Sci.* **47**(11) 1515–1532.

IBM. 2007. IBM and its long-term commitment to the Environment: Best Practices in IT Recycling. `ftp://ftp.software.ibm.com/common/ssi/sa/wh/n/gfw03003usen/GFW03003USEN.PDF`.

Intlekofer, K. 2009. Environmental Implications of Leasing, Dissertation, Georgia Institute of Technology.

Kuehr, R., E. Williams. 2003. *Computers and the Environment: Understanding and Managing their Impacts*. Eco- Efficiency in Industry and Science Series, Kluwer Academic Publishers.

Minnesota Pollution Control Agency. 2006. What to do with Waste Electronic and Electrical Products. `http://www.pca.state.mn.us/oea/plugin/index.cfm`.

Mont, O. 2002. Clarifying the Concept of Product-Service System. *J. of Cleaner Production* **10**(3) 237–245.

New York City Government. 2007. Product Stewardship: Strategies. `http://www.nyc.gov/html/nycwasteless/html/in_business/product_stewardship.shtml`.

Olivia, R., J. Quinn. 2003. Interface's Evergreen Services Agreement. Harvard Business School Case 9-603-112, Harvard University, Cambridge, MA.

Thomas, V. 2008. The Environmental Potential of Reuse. Working Paper, Stewart School of Industrial & Systems Engineering, Georgia Institute of Technology, Atlanta, GA.

U.S. EPA. 2008a. eCycling: Buying Green. `http://www.epa.gov/epawaste/conserve/materials/ecycling/basic.html`.

U.S. EPA. 2008b. eCycling: Regulations/Standards. `http://www.epa.gov/epaoswer/hazwaste/recycle/ecycling/rules.htm`.

U.S. EPA. 2008c. Life-Cycle Assessment (LCA). Office of Research and Development, National Risk Management Research Laboratory. `http://www.epa.gov/ORD/NRMRL/lcaccess/`.

Waldman, M. 2003. Durable Goods Theory for Real World Markets. *J. of Econom. Persp.* **17**(1) 131–154.

White, A., M. Stoughton, L. Feng. 1999. Servicizing: The Quiet Transition to Extended Producer Responsibility. Tech. rep., U. S. Environmental Protection Agency, Office of Solid Waste.

Appendix

A1. Derivation of the inverse demand functions and optimal decisions under leasing. Consumer θ's action vector in period t is $a_l^t(\theta) = (l_n^t(\theta), l_u^t(\theta), i^t(\theta))$. Since consumers enter each period without a product, the periods decouple; the consumer's action in the current period depends only on the current-period payoff, which is independent of the consumers' previous actions and solely determined by the firm's period-t decisions. Thus, consumer θ's optimal period-t decision $a_l^t(\theta)^*$ is determined by maximizing his period-t net utility $\Pi_\theta[a^t(\theta); r^t]$ subject to $a_l^t(\theta)\mathbf{1}' = 1$. Here, $\Pi_\theta[(1,0,0); r^t] = u_n(\theta) - r_n^t$, $\Pi_\theta[(0,1,0); r^t] = u_u^l(\theta) - r_u^t$ and $\Pi_\theta[(0,0,1); r^t] = 0$. Since $d(u_n(\theta) - u_u(\theta))/d\theta > 0$, $\Pi_\theta[(1,0,0), r^t] - \Pi_\theta[(0,1,0), r^t]$ and $\Pi_\theta[(0,1,0), r^t] - \Pi_\theta[(0,0,1), r^t]$ are increasing in θ. Thus, in equilibrium, consumers in $\theta \in (\theta_1, 1]$ always lease new products, consumers in $\theta \in (\theta_2, \theta_1]$ always lease used products and consumers in $\theta \in (0, \theta_2]$ are inactive, where $\theta_2 \le \theta_1 \in [0,1]$ such that $u_u^l(\theta_2) - r_u^t = 0$ and $u_n(\theta_1) - r_n^t = u_u^l(\theta_1) - r_u^t$. The aggregate demand for new and off-lease products is given by $L_n^t = 1 - \theta_1$ and $L_u^t = \theta_1 - \theta_2$, respectively. Since we are considering a monopolist and the consumer type θ is uniformly distributed, the inverse mapping $L^t \to r^t(L^t)$ is well defined. We can obtain θ_1 and θ_2 by solving $u_u^l(\theta_2) - r_u^t = 0$ and $u_n(\theta_1) - r_n^t = u_u^l(\theta_1) - r_u^t$ together, where $u_n(\theta) = \theta$ and $u_u^l(\theta) = \delta_l\theta$. Substituting them in $L_n^t = 1 - \theta_1$, $L_u^t = \theta_1 - \theta_2$ and solving for r_n^t and r_u^t, we get $r_n^t(L_n^t, L_u^t) = 1 - L_n^t - \delta_l L_u^t$ and $r_u^t(L_n^t, L_u^t) = \delta_l(1 - L_n^t - L_u^t)$. Recall that we restrict our attention to steady-state equilibria. The firm's per-period problem at steady state is given by $\max_{L_n, L_u}(r_n(L_n, L_u) - c)L_n + r_u(L_n, L_u)L_u - s_f L_n$ such that $L_u \le L_n$ and $L_n, L_u \ge 0$. The Hessian of the per-period profit is given by $\begin{pmatrix} -2 & -2\delta_l \\ -2\delta_l & -2\delta_l \end{pmatrix}$, which is negative definite for $0 < \delta_l < 1$, i.e., the profit function is jointly strictly concave in L_n and L_u. Solving the first-order conditions simultaneously, we get $L_n = \frac{1-(c+s_f)-\delta_l}{2(1-\delta_l)}$ and $L_u = \frac{(c+s_f)}{2(1-\delta_l)}$. We can rule out $L_u = L_n = 0$ as a candidate solution for $c + s_f < 1 + \delta_l$ and $-c < s_f$. It is straightforward to show that if $s_f < \frac{1-\delta_l}{2} - c$, then $L_u^* < L_n^*$, the optimal decisions are given by $L^* = \left(\frac{1-(c+s_f)-\delta_l}{2(1-\delta_l)}, \frac{(c+s_f)}{2(1-\delta_l)}\right)$, and $\Pi_l^* = \frac{(1-c-s_f)^2 - \delta_l(1-2(c+s_f))}{4(1-\delta_l)}$. Otherwise, $L_u^* = L_n^*$ and the optimal decisions are given by $L^* = \left(\frac{1-(c+s_f)+\delta_l}{2+6\delta_l}, \frac{1-(c+s_f)+\delta_l}{2+6\delta_l}\right)$, and $\Pi_l^* = \frac{(1-c-s_f+\delta_l)^2}{4+12\delta_l}$. □

A2. Derivation of the inverse demand functions under Selling. We suppress the selling-specific notation for this proof. Consumer type θ has the following discounted net utility maximization problem given the price path $\{p_t,\ t \ge 0\}$: $V_\theta(a^0) = \max_{\{a^t(\theta), t\ge 1\}} \sum_{t=1}^{\infty} \rho^t \Pi_\theta[a^t(\theta); a^{t-1}(\theta), p^t]$.

Since the per-period net utility is bounded and the strategy space is finite, the above problem can be solved by deriving the Bellman equation for consumer θ using backward induction (Blackwell 1965). The net present value functions $V_\theta^t[a^{t-1}(\theta), p^t]$ are a function of the consumer state $a^{t-1}(\theta)$, which completely specifies the sufficient information, and are defined as $V_\theta^t[a^{t-1}(\theta), p^t] = \max_{a^t(\theta)|a^t(\theta)\mathbf{1}'=1} \Pi_\theta[a^t(\theta); a^{t-1}(\theta), p^t] + \rho V_\theta^{t+1}[a^t(\theta), p^{t+1}]$. Define the reaction function $R_\theta^t[a^{t-1}(\theta), p^t] = a^t(\theta)^*$, where $a^t(\theta)^*$ is the solution to the previous equation.

There are ten potential two-period consumer strategies. Nine of them are as shown in Table 1. The tenth one is to buy a new product, dispose it after one period of use and buy new again (denoted by BnsBn). However, it is easy to see that this strategy will always be dominated by BnBn because a consumer will always obtain more than the disposal value (if any) for the used product when it sells the product on the secondary market. At the focal point, the consumer's time-independent Bellman equation can be written as $V_\theta[a(\theta), p] = \max_{a(\theta)|a(\theta)\mathbf{1}'} \{\Pi_\theta[R_\theta[a(\theta), p]; a(\theta), p] + \rho V_\theta[R_\theta[a(\theta), p], p]\}$. Due to the periodicity of two for all consumer strategies at the focal point, permutations of the same pattern are not distinct. There are only 6 distinct strategies (BnBn, BnBu, BnI, BuBu, BuI and II). Since a product lasts for two periods, a rational consumer who has a state of Bu or I will choose the same action in the current period as it enters the period with no product. This implies that at the focal point $R_\theta[Bu, p] = R_\theta[I, p]$, which implies that BuI can be ruled out.

We next prove that BnI cannot happen. Recall that the reaction function $R_\theta[a(\theta), p]$ is chosen to maximize $U_\theta[s; a, p] \equiv \Pi_\theta[s; a, p] + \rho V_\theta[s, p]$. Let us assume that BnI is a credible strategy, which implies that $R_\theta[Bn, p] = I$ and $R_\theta[I, p] = Bn$ for some $\theta \in [0, 1]$. Note that $R_\theta[Bn, p] = I$ implies that $p_u + \rho V_\theta[I, p] > u_n(\theta) - p_n + p_u + \rho V_\theta[Bn, p]$ or $\rho V_\theta[I, p] > u_n(\theta) - p_n + \rho V_\theta[Bn, p]$. However, the above equation implies that $U_\theta[I; I, p] > U_\theta[Bn; I, p] \Rightarrow R_\theta[I, p] = I$. This violates our assumptions and thus, BnI cannot take place. Thus, there are four possible strategies at the focal point. Consumers who play BnBn have higher θ than those who play BnBu, who have higher θ than those who play BuBu. Consumers playing II have the lowest willingness-to-pay. The net present values for each of the four consumption strategies BnBn, BnBu, BuBu and II at the focal point can be found using the consumer's bellman equation as follows: For $\theta \in BnBn$, solving $V_\theta[Bu, p] = u_n(\theta) - p_n + p_u + \rho V_\theta[Bn, p]$, we get $V_\theta[Bn, p] = \frac{u_n(\theta) - p_n + p_u}{1-\rho}$. For $\theta \in BnBu$, solving $V_\theta[Bu, p] = u_n(\theta) - p_n + \rho V_\theta[Bn, p]$ and $V_\theta[Bn, p] = u_u^s(\theta) - s_c + \rho V_\theta[Bu, p]$ simultaneously, we get $V_\theta[Bn, p] = \frac{u_u^s(\theta) - s_c + \rho(u_n(\theta) - p_n)}{1-\rho^2}$ and $V_\theta[Bu, p] = \frac{u_n(\theta) - p_n + \rho(u_u^s(\theta) - s_c)}{1-\rho^2}$. For $\theta \in BuBu$, solving $V_\theta[Bu, p] = u_u^s(\theta) - p_u - s_c + \rho V_\theta[Bu, p]$, we get $V_\theta[Bu, p] = \frac{u_u^s(\theta) - p_u - s_c}{1-\rho}$. Finally for $\theta \in II$, $V_\theta[I, p] = 0$.

Let the marginal consumer who is indifferent between playing BnBn and BnBu, between BnBu and BuBu, and between BuBu and II, be denoted by Θ_1, Θ_2 and Θ_3, respectively. We can find Θ_1, Θ_2 and Θ_3 by solving $\frac{u_u^s(\Theta_3) - p_u - s_c}{1-\rho} = 0$, $\frac{u_u^s(\Theta_2) - s_c + \rho(u_n(\Theta_2) - p_n)}{1-\rho^2} = \frac{u_u^s(\Theta_2) - p_u - s_c}{1-\rho}$ and $\frac{u_u^s(\Theta_1) - s_c + \rho(u_n(\Theta_1) - p_n)}{1-\rho^2} = \frac{u_n(\Theta_1) - p_n + p_u}{1-\rho}$. Thus, consumers in $\theta \in (\Theta_1, 1]$ play BnBn, consumers in $\theta \in$

$(\Theta_2, \Theta_1]$ play BnBu, consumers in $\theta \in (\Theta_3, \Theta_2]$ play BuBu and consumers in $\theta \in (0, \Theta_3]$ always remain inactive (II), where $\Theta_3 \leq \Theta_2 \leq \Theta_1 \in [0,1]$. The supply of used products on the secondary market is given by $1-\Theta_1$ and the demand for them is given by $\Theta_2 - \Theta_3$. The market-clearing price is implicitly given by $1-\Theta_1 = \Theta_2 - \Theta_3$. Since we are restricting our attention to a focal point, where all firm decisions and consumer strategies remain constant, in any given period, half of the consumers whose strategy is to play BnBu will use their existing product and the other half will have to buy a new product. This implies that the aggregate demand for new products (S_n) in any period at the focal point is $S_n = 1 - \Theta_1 + \frac{\Theta_1 - \Theta_2}{2}$. Since we are considering a monopolist firm and the consumer type θ is uniformly distributed, the inverse mapping $S_n \to p(S_n)$ is well defined. Solving the above set of equations with $u_n(\theta) = \theta$, $u_u^s(\theta) = \delta_s \theta$, $1-\Theta_1 = \Theta_2 - \Theta_3$ and $S_n = 1 - \Theta_1 + \frac{\Theta_1 - \Theta_2}{2}$, we get the inverse demand functions as $p_n(S_n) = \frac{2\rho(1-S_n) - s_c(1+\rho^2) + \delta_s(1+\rho^2 - 2S_n(1+\rho+\rho^2))}{2\rho}$ and $p_u(S_n) = \frac{\rho(\delta_s(2p_n - 1 + \delta_s) - s_c(1+\delta_s))}{\rho + \delta_s(1+\rho+\rho^2)}$. □

A3. Proof of Propositions 1-2. It is straightforward to show that $\Pi_l^* - \Pi_s^*$ is increasing in s_c. Leasing is more profitable if $s_c > x(s_f)$, where $x(s_f)$ is the value of s_c such that $\Pi_l^* = \Pi_s^*$. If $s_f \geq \frac{1-\delta_l}{2} - c$, $x(s_f) = x_1(s_f) \doteq \frac{\delta_s(1+\rho^2) + 2\rho(1-c) - 2(1-c-s_f+\delta_l)\sqrt{\rho(1+3\delta_l)(\rho+\delta_s(1+\rho+\rho^2))}}{(1+3\delta_l)(1+\rho^2)}$. Otherwise, $x(s_f) = x_2(s_f) \doteq \frac{\delta_s(1-\delta_l)(1+\rho^2) + 2(1-c)\rho(1-\delta_l) - 2\sqrt{(1-\delta_l)((1-c-s_f)^2 - \delta_l(1-2c-2s_f))\rho(\rho+\delta_s(1+\rho+\rho^2))}}{(1-\delta_l)(1+\rho^2)}$.

It can also be shown that $E_l^* - E_s^*$ is increasing in s_c. Thus, leasing is greener than selling only if $s_c < y(s_f)$, where $y(s_f)$ is the value of s_c such that $E_l^* = E_s^*$. If $s_f \geq \frac{1-\delta_l}{2} - c$, $y(s_f) = y_1(s_f) \doteq \frac{(1+\rho^2)\delta_s(-1+2c+2s_f+\delta_l) + 2\rho(s_f + \delta_l(2-3c) + \delta_s(-1+c+s_f-\delta_l))}{(1+3\delta_l)(1+\rho^2)}$. Otherwise $y(s_f) = y_2(s_f) \doteq \frac{(1-\Omega)\delta_s(2(1+\rho+\rho^2)(c+s_f) - (1-\delta_l)(1+\rho^2)) - 2\rho(s_f(1-\Omega) + c\delta_l + \Omega(1-2c-(1-c)\delta_l) - \delta_s(1-\delta_l))}{(1+\Omega)(1-\delta_l)(1+\rho^2)}$. This condition can also be written as $\Omega > \widehat{\Omega} \doteq \frac{2\rho(s_f + c\delta_l) - (1-\delta_l)(1+\rho)^2(\delta_s + s_c) + 2\delta_s(1+\rho+\rho^2)(c+s_f)}{s_c(1-\delta_l)(1+\rho^2) - \delta_s(1-2c-2s_f-\delta_l)(1+\rho^2) + 2(-1+s_f+\delta_l+s_f\delta_s + c(2-\delta_l+\delta_s))\rho}$. Finally, if $s_f \geq \frac{1-\delta_l}{2} - c$, then $x_1(s_f) < y_1(s_f)$ holds only if $\delta_l \geq \delta_s w(\rho)$, where $w(\rho) = \left(\frac{1+\rho+\rho^2}{3\rho}\right) \geq 1$. □

A4. Proof of Corollary 1. If $s_f < \frac{1-\delta_l}{2} - c$, $d(E_l^* - E_s^*)/ds_f = \frac{-1+\Omega}{2(1-\delta_l)} > 0$ and $d(E_l^* - E_s^*)/d\delta_l = \frac{(c+s_f)(-1+\Omega)}{2(1-\delta_l)^2} > 0$ only if $\Omega > 1$. Otherwise, $dE_l^*/ds_f < 0$ and $dE_l^*/d\delta_l < 0$. □

A5. Details for product durability as a decision variable. While solving for the closed-form expressions of optimal δ_l and δ_s is difficult, we can numerically optimize the profit function under both strategies to find the profit-maximizing value of δ_l and δ_s respectively. We modify the per-unit cost c under both strategies to $c_0 + \gamma\delta_l^2$ under leasing and $c_0 + \gamma\delta_s^2$ under selling, where $\gamma, c_0 \geq 0$ and $s_f, s_c, \gamma \leq c_0$. This ensures that the production cost is increasing in the product durability. In order to carry out the numerical optimization, we choose 10 equally-spaced levels for c_0, s_c, s_f and γ over their entire theoretical range $[0,1]$ and generate all such possible combinations constrained by the conditions for the business to be profitable under both leasing and selling, and $s_f, s_c, \gamma \leq c_0$. For such combinations of these parameter values, we numerically optimize the profit expressions to find $\delta_l^* \in [0,1]$ and $\delta_s^* \in [0,1]$ under leasing and selling (after substituting the optimal quantity decisions obtained analytically from our earlier analysis). □

A6. Proof of Corollary 2. If a consumer leases or purchases a new product, she incurs a utility loss given by $\beta(i_p + i_{u1} + i_d)$ and if a consumer uses an old product, she incurs a utility loss given by βi_{u2}. Under these modified net utilities, solving for the firm's optimal decisions, we get $L_n^* = \frac{1-c-s_f-\delta_l-\beta(i_p+i_{u1}-i_{u2})}{2(1-\delta_l)}$ and $L_u^* = \frac{\delta_l(c+s_f+\beta(i+p+i_{u1}+i_d)-\beta i_{u2})}{2\delta_l(1-\delta_l)}$ under partial remarketing, $L_n^* = L_u^* = \frac{1-c-s_f+\delta_l-\beta(i_p+i_{u1}+i_d+i_{u2})}{2+6\delta_l}$ under full remarketing, and $S_n^* = \frac{1-c-s_c+\delta_s-\beta(i_p+i_{u1}+i_d+i_{u2})}{2+6\delta_s}$ at $\rho = 1$ (further details available on request). The condition for partial remarketing is $s_f < \frac{\beta i_{u2}(1+\delta_l)+\delta_l(1-2c-2\beta(i_p+i_{u1}+i_d)-\delta_l)}{2\delta_l}$. Substituting these expressions in E_l and E_s, we can show that if $\delta_l < \delta_s$, we have $\partial(E_l^* - E_s^*)/\partial\beta < 0$. □