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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 in order to "green" their image. The argument is that as a leasing firm retains ownership of the off-lease units, it has an incentive to remarket the products, resulting in a lower production and disposal volume. However, some argue that leasing might be environmentally inferior due to the direct control the firm has over the off-lease products, which may prompt their premature disposal to avoid cannibalizing the demand for new products. Motivated by these issues, we adopt a life-cycle environmental impact perspective and analytically investigate if either leasing or selling can be both more profitable for a monopolist and have a lower total environmental impact. We identify conditions where each of these outcomes can occur, depending on the magnitude of the disposal cost, the differential in disposal costs faced by the firm and consumers, and the environmental impact profile of the product. These results provide insights for firms who want to promote their marketing strategy as the "greener" choice.

Key words: Durable goods; green marketing; closed-loop supply chains; environmental impact

1. Introduction

Leasing is a marketing strategy prevalently used by durable goods manufacturers. Academic research in economics and marketing has identified conditions for the profitability of this strategy (Coase 1972, Bulow 1982, Hendel and Lizzeri 1999b, Desai and Purohit 1998, 1999). Recently, researchers in the industrial ecology and environmental strategy fields have promoted leasing as a "green" strategy, claiming that leasing a product rather than selling it results in a lower environmental burden (Hawken et al. 1999, Lifset and Lindhqvist 2000, Fishbein et al. 2000, Mont

2002, Robert et al. 2002). The argument is the following: Since the firm maintains ownership of the product under an operating lease, it has an incentive to efficiently remarket the used product at the end of the lease duration[1]. Remarketing the product as opposed to disposing of it[2] decreases the demand for new products, reducing the environmental impact of manufacturing and disposal.

Some firms seeking to "green" their image in response to growing consumer awareness of environmental issues have embraced the "Leasing is Green" message. For example, Interface Inc., a carpet manufacturer, introduced the Evergreen Lease™ with the express purpose of reducing the environmental impact of its products and described it as a "new workable business model for sustainable development" (Olivia and Quinn 2003). Interface chairman and founder Ray Anderson states "Leasing carpet rather than selling it, and being responsible for it cradle to cradle, is the future" (Anderson 1998). Others promote their leasing programs as being environmentally friendly. According to IBM, "..leasing makes more and more sense for many clients. Clients enjoy the benefits of technology without having to dispose of equipment at the end of its useful life...Combined with the simplicity of returning equipment to IBM at end of lease, IBM essentially uses Best Practice in Asset Management to keep equipment out of the waste stream" (IBM 2007). Indeed, IBM's Global Asset Recovery Services, which is part of IBM Global Financing, remarkets 85% of off-lease machines it receives worldwide (Johnson 2007). HP's environmental sustainability report states "Product reuse programs extend the useful life of equipment, especially at the end of leasing agreements when consumers return products ranging from PCs to data center equipment" (Hewlett-Packard 2009). Xerox named its line of refurbished off-lease products the "Green Line" to emphasize the environmental benefits of their approach (Charter and Polonsky 1999). Several environmental policy-making groups such as the U.S. Environmental Protection Agency, the state of Minnesota and the New York City Government (U.S. EPA 2008a, Minnesota Pollution Control Agency 2006, New York City Government 2007) also recommend leasing as an environmentally superior strategy.

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

[2] In this paper, the term "disposal" refers to taking the used product off the market via recycling, incineration or landfilling.

In contrast, some argue that the environmental superiority of leasing is far from clear (Ruth 1998), and some even argue it is a “fallacy” (Lawn 2001). The reason is the direct control that the firm exerts on the off-lease units. To avoid cannibalizing the demand for the firm’s new products, a leasing firm may remove the returned used products from the market. For example, the majority of Pitney Bowes’ off-lease products are not remarketed (Fishbein et al. 2000), and a computer network equipment manufacturer is known to have prematurely disposed of fully functional products worth more than $700 million (Guide and Van Wassenhove 2009). Such premature disposal may result in a higher manufacturing and disposal volume than selling, causing leasing to underperform from a total life-cycle environmental impact perspective[3].

In this paper, we investigate the validity of the “Leasing is Green” argument. Our goal is to establish when a firm can justifiably claim leasing to be environmentally superior to selling, which 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). We identify conditions under which leasing dominates by being environmentally superior *and* profitable, but also those conditions under which selling is better along both dimensions, providing new support for a selling firm’s environmental positioning.

In comparing the two strategies, we add a new feature to the traditional leasing model by jointly incorporating a disposal cost and allowing for the disposal of off-lease products by the firm. Disposal costs have recently become an important consideration due to increases in landfilling fees and a growing patchwork of legislation governing post-use products (Luther 2008), as well as firms choosing more costly but environmentally preferred methods of disposal to avoid a negative environmental image. The product disposal cost plays a critical role in the volume of products in each life-cycle phase: Under leasing, the firm maintains ownership of the off-lease units, so the remarketing and disposal decisions depend on the disposal cost faced by the firm. Under selling, it

[3] The life cycle of a product consists – at its most basic – of the production, use and disposal phases. We define the total life-cycle environmental impact of a strategy as the volume of products in each phase multiplied with the per unit environmental impact in that phase, summed over all life-cycle phases. Under leasing, the product volumes in each life-cycle phase are determined by the production, remarketing and disposal volumes. Under selling, they are determined by the production volume and the size of the secondary market.

is the consumer who disposes of the product. The firm typically 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 environmental impact of leasing and selling differently and is important to capture in any model comparing the two. Since there is often a differential in disposal costs faced by the firm and consumers, we allow for asymmetry in the disposal costs in our analysis.

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 lease versus sell decision faced by a firm have been studied (for an excellent overview, see Waldman 2003). Some of these issues include pricing power (Coase 1972, Stokey 1981, Bulow 1982, Bagnoli et al. 1989, Karp 1996, Kühn 1998, Hahn 2006), the role of secondary markets and market segmentation (Waldman 1997, Hendel and Lizzeri 1999b, Desai and Purohit 1998, Huang et al. 2001), competition (Desai and Purohit 1999, Huang and Kuzyutin 2002) and channel structure (Purohit 1995, 1997, Desai et al. 2004, Bhaskaran and Gilbert 2009). The main focus of this stream of literature is to analyze the relative profitability of leasing and selling, or to explain the coexistence of these strategies.

We make two distinct contributions to this literature. First, our work brings the environmental impact dimension to the comparison of leasing and selling. Second, we enrich the comparison of the two strategies by incorporating disposal costs faced by both the firm and the consumers and endogenizing premature disposal in this setting. We compare both the profitability and the environmental impact of leasing versus selling and find that all four combinations are possible (selling is more profitable and environmentally superior, leasing is more profitable but selling is environmentally superior, etc.), depending on the inherent durability of the product, the structure of the disposal costs, and which phases of its life cycle contribute the most to the product's environmental impact. Several papers have identified settings where selling may be more profitable: the presence of competition or the threat of entry (Bucovetsky and Chilton 1986, Desai and Purohit 1999), lower durability under selling (Desai and Purohit 1998), the presence of production lead-time and demand uncertainty (Desai et al. 2004), and the presence of complementary goods (Bhaskaran and Gilbert 2005). We identify another setting by showing that selling may be more profitable when a firm faces higher disposal cost than consumers.

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, Heese et al. 2005, Ferrer and Swaminathan 2006, Ferguson and Toktay 2006, Jin et al. 2007, Atasu et al. 2008, Esenduran 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 having a useful life of two periods, which makes the distinction between the two strategies particularly salient. Debo et al. (2005) argue that adding a disposal cost would simply increase the effective cost of production. We formalize this argument, and show that a disposal cost differential leads to cases where selling a durable good can be more profitable than leasing it.

In the industrial ecology literature, the environmental impact of products is evaluated by using conventional life-cycle analysis that focuses on the impact of one unit throughout its life cycle (U.S. EPA 2008c). Firms such as Nokia, Canon and Apple use LCA results to aid decision-making and provide this information to consumers (McLaren and Piukkula 2004, Canon 2009, Apple 2009). LCAs may also form the basis for policy recommendations (European Environmental Agency 1998, Tukker et al. 2005, U.S. EPA 2008c). However, as pointed out by Thomas (2008), focusing on per-unit impact ignores market effects such as demand and use duration that determine total environmental impact. In this paper, we formalize the market effects by including sale, disposal and use volumes in the calculation of the total life-cycle environmental impact of the firm's chosen marketing strategy. As we assume that the product's per unit environmental impact is the same whether it is sold or leased, all the conclusions we draw about relative environmental impact are driven by the market effects.

The rest of the paper is organized as follows: In §2, we discuss our assumptions and develop discrete-time, infinite horizon, dynamic sequential games for the leasing and selling strategies. In §3, we solve for the optimal strategies of a monopolist. In §4, we use the optimal decisions found in the previous section to compare the relative profitability and total environmental impact of the two strategies. Finally, in §5, we conclude by discussing the managerial insights derived from our analysis. All proofs are included in the Appendix.

2. The Model

In this section, we outline our assumptions regarding the product, firm, consumer and market characteristics, and end with the specification of a discrete-time dynamic sequential game over an infinite time horizon. In the remainder of the paper, vectors are arranged in rows and primes represent transposes. $\mathbf{1}$ denotes a vector of ones. Superscripts are used to label time and subscripts are used to label other information. f and c denote firm and consumer specific parameters, respectively.

Firm and Product Characteristics. We study a profit-maximizing monopolist that produces a single durable product. The firm has a constant returns to scale production technology with the marginal cost of producing a new product 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. This assumption has been used extensively in the durable goods literature (Bulow 1982, Hendel and Lizzeri 1999a, Desai and Purohit 1998, 1999, Hendel and Lizzeri 1999b, Huang et al. 2001, Bhaskaran and Gilbert 2005) and does not restrict the generality of the insights obtained. We refer to a product in its first period of useful life as *new* and in the second period as *used*. Subscripts n and u denote new and used products respectively. 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).

The firm uses either a pure leasing strategy or a pure selling strategy. If the firm chooses the leasing strategy, it offers one-period operating leases, where products are returned to the firm after the lease period. The firm may either lease or dispose of the used product, and disposes of end-of-life products; the implications of the firm selling the used products instead of leasing them are discussed in §4. If the firm chooses the selling strategy, it sells new products only; used products are traded between consumers on the secondary market at the market clearing price. Under selling, it is the consumers who dispose of end-of-life products.

If the firm remarkets or the consumer sells the used product, they incur remarketing or transaction costs, $\beta_f \geq 0$ and $\beta_c \geq 0$, respectively. Similarly, if the firm or the consumer disposes of products, they incur a 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.

There are several factors that determine how costly or profitable disposal is. The product type is a primary factor, in particular, whether the product is mainly composed of metal, plastic, glass, etc. and whether it has toxic material content (Van Wassenhove et al. 2004). For example, cars can typically be sold to scrap yards, but electronic waste is typically costly to dispose of. State and federal legislation is another factor. For example, some states ban landfilling and/or incineration of certain materials, requiring either costly processing or transportation over long distances (Luther 2008). In the absence of regulation, a firm may nevertheless undertake costly recycling to avoid a negative environmental perception. For the consumer, disposal can be either costly (paying a fee to remove and dispose a bulky product such as a refrigerator), profitable (selling a product with high value to a recycler) or even free (throwing it in the trash). The disposal cost for a given product need not be the same for the firm and consumers, and can be either higher or lower. 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 for consumers ($s_f < 0 \leq s_c$).

Consumer Characteristics. 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. We assume that θ is uniformly distributed on $[0,1]$. Consumer θ is characterized by the utility vector $u(\theta) \doteq (u_n(\theta), u_u(\theta), 0)$, where $u_n(\theta)$ and $u_u(\theta)$ are the utilities derived from one period use of the new and the used product, respectively, and zero is the utility derived from remaining inactive. $u(\theta)$ is time independent and exogenous. Ceteris paribus, every consumer (weakly) prefers a new product to a used product, and a used product to remaining inactive; $u_n(\theta) \geq u_u(\theta) \geq 0$ for all $\theta \in [0,1]$. It is reasonable to expect that the consumer's utility for a product is finite, i.e., $\exists\, M > 0$ such that $u_n(1) < M$. As in Desai and Purohit (1998), we assume that the drop in utility between using a new and a used product is higher for consumers with a higher type $(d(u_n(\theta) - u_u(\theta))/d\theta > 0)$.

The following assumption satisfying the conditions above is often made in the literature (Desai and Purohit 1998, Desai et al. 2004, Desai and Purohit 1999, Desai et al. 2007):

ASSUMPTION A1. $u_n(\theta) = \theta$ & $u_u(\theta) = \delta\theta$, where $\delta \in (0,1]$ is interpreted as product durability.

Unless otherwise specified, our results are proven for the generic utility function. Assumption A1 is used to obtain closed-form solutions and enable a detailed comparison of leasing and selling. Under Assumption A1, the condition $c + \max(s_c, s_f) + \beta_c < 1$ eliminates uninteresting cases where the business is not profitable for the firm.

Specification of the Game. We develop a dynamic game where the firm and consumers move sequentially in each period. In every period, the firm first makes her decisions, followed by the consumers. Under a leasing strategy, the firm chooses the quantity of new and used products to lease. The remaining used products and all end-of-life products are disposed. Under the selling strategy, the firm only decides the quantity of new products to sell. Observing these decisions, the consumers play the game strategically against the manufacturer. All players in the game are rational and maximize their net present values with a common discount factor of $0 < \rho \leq 1$. All information regarding the cost structures and preferences are common knowledge.

We model the problem as a discrete-time infinite-horizon problem, where periods are indexed by $t \geq 0$. The reasons for this are two-fold: First, at the start of the game, $t = 0$, there are no existing used products, so there is an initial transient time where the supply of used products builds up.

Second, using a finite horizon requires specifying artificial terminal conditions. Consequently, using a finite time horizon would skew the life-cycle based comparison of the two strategies. Thus, we use an infinite time horizon and focus on the steady-state firm and consumer strategies. Our insights are still valid for problems with finite, but sufficiently long horizons.

3. Analysis

In this section, we analyze the leasing and selling strategies. We solve the problem using the common approach of only considering subgame perfect equilibria. Let consumer actions Ln, Lu, Bn, Bu and I denote leasing a new product, leasing a used product, buying a new product, buying a used product, and remaining inactive, respectively. 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 strategies Ln, Lu, Bn, Bu and I, respectively. Since remaining inactive is included in the consumer's action set, we have $a^t(\theta)\mathbf{1}' = 1$ for all t and $\theta \in [0,1]$. 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 for new and used products at time t.

3.1. Leasing Model

In this section, we determine the unique equilibrium under leasing, show that it leads to a steady-state solution and solve for it under Assumption A1. We begin by formulating and solving the consumer's utility maximization problem. The customer's action vector in period t is given by $a_l^t(\theta) = (l_n^t(\theta), l_u^t(\theta), i^t(\theta))$, with initial condition $a_l^0(\theta) = (0,0,1)$ for all $\theta \in [0,1]$. Since consumers enter each period without a product, the periods decouple; the consumer's action in the current period depends only on the payoff in the current period, 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, $\Pi_\theta[(1,0,0); r^t] = u_n(\theta) - r_n^t$, $\Pi_\theta[(0,1,0); r^t] = u_u(\theta) - r_u^t$ and $\Pi_\theta[(0,0,1); r^t] = 0$.

Lemma 1. *In period t, the equilibrium consumer strategies have the following structure: 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 $\theta \in (0, \theta_2]$ remain inactive, where $\theta_2 \le \theta_1 \in [0,1]$ such that*

$$u_u(\theta_2) - r_u^t = 0 \textit{ and } u_n(\theta_1) - r_n^t = u_u(\theta_1) - r_u^t. \tag{1}$$

Turning now to the firm's problem, let L_n^t and L_u^t denote the quantity of new and used products leased by the firm at time t, respectively, and $L^t \doteq (L_n^t, L_u^t)$. The firm's profit in a given period depends on the current and previous period decisions: $\Pi_l(L^{t-1}, L^t) = (r_n^t - c)L_n^t + (r_u^t - \beta_f)L_u^t - s_f(L_n^{t-1} - L_u^t) - s_f L_u^{t-1}$. We define an implementable path P, starting with $L^0 = (0,0)$, as $P \doteq \{L^t,\, t \geq 0 |\, L^0 = (0,0) \,\&\, L^t \geq 0,\, L_u^t \leq L_n^{t-1}\, \forall\, t > 0\}$. Let $V(L^0)$ denote the firm's optimal ρ-discounted infinite-horizon profit starting with initial condition L^0: $V(L^0) = \max_{\{L^t, t\geq 0\}\in P} \sum_{t=1}^{\infty} \rho^t \Pi_l(L^{t-1}, L^t)$.

PROPOSITION 1. *There exists a unique and steady-state policy* $L^* \doteq (L_n^*, L_u^*)$ *for the leasing firm. If Assumption A1 holds,* $L^* \doteq (L_n^*, L_u^*)$ *can be obtained in closed form as follows, where* $s_A(c,\delta,\beta_f) \doteq \frac{\beta_f - \delta c}{\delta}$ *and* $s_B(c,\delta,\beta_f) \doteq \frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta}$*:*

Condition	L_u^*	L_n^*	$\Pi_l(L_n^*, L_u^*)$
$s_f \leq s_A(c,\delta,\beta_f)$	0	$\frac{1-c-s_f}{2}$	$\frac{(1-c-s_f)^2}{4}$
$s_A(c,\delta,\beta_f) < s_f < s_B(c,\delta,\beta_f)$	$\frac{\delta(c+s_f)-\beta_f}{2\delta(1-\delta)}$	$\frac{1-c-s_f+\beta_f-\delta}{2(1-\delta)}$	$\frac{(\delta+\beta_f)}{4\delta} + \frac{2\beta_f^2+(c+s_f)(2\delta(c+s_f)-3\delta(1-\delta)-\beta_f(1+3\delta))}{4\delta(1-\delta)}$
$s_B(c,\delta,\beta_f) \leq s_f$	$\frac{1-c-s_f-\beta_f+\delta}{2+6\delta}$	$\frac{1-c-s_f-\beta_f+\delta}{2+6\delta}$	$\frac{\delta(1-c-s_f-\beta_f+\delta)^2}{(1+3\delta)^2}$

Note that under Assumption A1, the firm prematurely disposes a fraction of the off-lease products ($L_u^* < L_n^*$) if and only if $s_f < s_B(c,\delta,\beta_f)$. This threshold decreases in δ and c, and increases in β_f: Premature disposal reduces the cannibalization of new product leases and avoids remarketing cost, but at the expense of foregoing revenue from off-lease products and generating a disposal cost. Thus, all else being equal, a low disposal cost, a high remarketing cost, and a high margin on the new product promote premature disposal. With respect to durability, the revenue effect dominates the cannibalization effect and high durability inhibits premature disposal.

3.2. Selling Model

In this section, we describe the model for the selling strategy and solve for its equilibrium. The model and analysis is similar to Huang et al. (2001), except that we incorporate disposal cost for customers and the firm, and focus on pure selling.

We start by formulating the consumer's problem. Consumer θ's action vector in period t is given by $a_s^t(\theta) = (b_n^t(\theta), b_u^t(\theta), i^t(\theta))$, with initial condition $a_s^0(\theta) = (0,0,1)$ 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. As in the previous related literature, we restrict our attention to Markov perfect equilibria, which assumes that strategies only depend on the payoff-relevant history that is summarized by their current state (Fudenberg and Tirole 1991).

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.

$a_s^t(\theta)/a_s^{t-1}(\theta)$	Bn	Bu	I
Bn	$u_n(\theta) - p_n^t + p_u^t - \beta_c$	$u_n(\theta) - p_n^t$	$u_n(\theta) - p_n^t$
Bu	$u_u(\theta) - s_c$	$u_u(\theta) - p_u^t - s_c$	$u_u(\theta) - p_u^t - s_c$
I	$p_u^t - \beta_c$	0	0

Consumer type θ has the following discounted net utility maximization problem given the price path $\{p_t,\ t \geq 0\}$:

$$V_\theta(a_s^0) = \max_{\{a_s^t(\theta), t\geq 1\}} \sum_{t=1}^{\infty} \rho^t \Pi_\theta[a_s^t(\theta); a_s^{t-1}(\theta), p^t].$$

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 by backward induction (Blackwell 1965, Stokey and Lucas Jr 1989). The net present value functions $V_\theta^t[a_s^{t-1}(\theta), p^t]$ are a function of the consumer state $a_s^{t-1}(\theta)$, which completely specifies the sufficient information, and are defined as follows:

$$V_\theta^t[a_s^{t-1}(\theta), p^t] = \max_{a_s^t(\theta) | a_s^t(\theta)\mathbf{1}' = 1} \Pi_\theta[a_s^t(\theta); a_s^{t-1}(\theta), p^t] + \rho V_\theta^{t+1}[a_s^t(\theta), p^{t+1}]. \quad (2)$$

Define the reaction function $R_\theta^t[a_s^{t-1}(\theta), p^t] = a_s^t(\theta)^*$, where $a_s^t(\theta)^*$ is the solution to (2). Aggregating over all θ yields the new and used product demand in period t, S_n^t and S_u^t.

Recall $p^t = (p_n^t, p_u^t)$ is the price vector at time t, where p_n^t is determined by the firm and p_u^t is the market clearing price for used goods, which is implicitly determined by equating supply and demand for used products. The optimal prices $p_n^t, t \geq 0$ for a given customer demand path can be derived from the Bellman equation for the firm's problem. The equilibrium solution is therefore obtained by solving for the consumer and firm reaction functions of these coupled Bellman equations, subject to the market clearance conditions in every period. Huang et al. (2001) and Huang and Kuzyutin (2002) note that there is no known general procedure to solve coupled asymmetric Bellman equations, but that since a Markov-perfect equilibrium in the infinite time horizon is one in which all explicit time dependence has dropped out, it is appropriate to focus on an equilibrium in which all prices and aggregate consumer behaviors are constant in time. The fixed point in the strategy space that is associated with this equilibrium will be called the "focal point" following Huang et al. (2001). In order to find such an equilibrium, we need to solve the time-independent Bellman equations. The consumer's time-independent Bellman equation is given by

$$V_\theta[a_s(\theta),p] = \max_{a_s(\theta)|a_s(\theta)\mathbf{1}'=1} \{\Pi_\theta[R_\theta[a_s(\theta),p];a_s(\theta),p] + \rho V_\theta[R_\theta[a_s(\theta),p],p]\} \tag{3}$$

and the firm's problem reduces to the static optimization problem

$$\max_{S_n \geq 0} \Pi_s(S_n) = (p_n(S_n) - c)S_n,$$

where S_n is the aggregate demand for new products.

LEMMA 2. *There are at most four different consumer strategy patterns in equilibrium, for a given constant price vector $p = (p_n, p_u)$: Consumers in $\theta \in (\Theta_1, 1]$ always buy new products (BnBn), consumers in $\theta \in (\Theta_2, \Theta_1]$ buy a new product if their existing product has reached its end-of-life or continue to use their existing product (BnBu), consumers in $\theta \in (\Theta_3, \Theta_2]$ buy used products from the secondary market in every period (BuBu) and consumers in $\theta \in (0, \Theta_3]$ always remain inactive (II), where $\Theta_3 \leq \Theta_2 \leq \Theta_1 \in [0,1]$ and satisfy the following set of equations*

$$\frac{u_u(\Theta_3) - p_u - s_c}{1-\rho} = 0, \ \frac{u_u(\Theta_2) - s_c + \rho(u_n(\Theta_2) - p_n)}{1-\rho^2} = \frac{u_u(\Theta_2) - p_u - s_c}{1-\rho} \ \textit{and}$$
$$\frac{u_u(\Theta_1) - s_c + \rho(u_n(\Theta_1) - p_n)}{1-\rho^2} = \frac{u_n(\Theta_1) - p_n + p_u - \beta_c}{1-\rho}. \tag{4}$$

For a given specification of consumer utility, the inverse demand functions can be calculated using (4). 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

$$1-\Theta_1=\Theta_2-\Theta_3. \tag{5}$$

Since we are restricting our attention to a focal point where all firm and consumer behavior remains constant over time, 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

$$S_n=1-\Theta_1+\frac{\Theta_1-\Theta_2}{2}. \tag{6}$$

PROPOSITION 2. *Under Assumption A1, the equilibrium per-period quantity of new products sold and the firm's per-period profit are*

$$S_n^*=\frac{\rho(2-2c-\beta_c-\rho s_c+\rho\delta)-s_c-\beta_c+\delta}{4(\rho+\delta(1+\rho+\rho^2))} \text{ and } \Pi_s(S_n^*)=\frac{(s_c+\beta_c-\delta-\rho(2-2c-\beta_c)+\rho^2(s_c-\delta))^2}{16\rho(\rho+\delta(1+\rho+\rho^2))}.$$

4. Comparing Leasing and Selling

In this section, we investigate the relative profitability and environmental impact of leasing and selling. For the remainder of the analysis, we assume that Assumption A1 holds. We also assume no discounting ($\rho=1$). Although comparisons with a general value of ρ are not difficult, this assumption simplifies our expressions and helps to isolate the effects of the disposal costs, product durability and remarketing costs. The insights from our analysis remain valid for values of ρ close to 1, which are realistic in practice.

Measuring Environmental Impact. The environmental impact of a strategy depends on the volume of products in each phase of the life cycle (production, use and disposal) and the per-unit impact of the product in each phase (White et al. 1999, Thomas 2008). The former depends on the firm's production, remarketing and disposal strategy under leasing and on the firm's new production strategy in conjunction with consumer trading on the secondary market under selling. The latter depends on the product's environmental impact profile and can be found using a conventional life cycle analysis (U.S. EPA 2008c). Products such as refrigerators, washers, televisions and automobiles have the majority of their environmental impact in the use phase (*high use impact products* for brevity), while products such as carpets, mattresses, cellphones and computers have the majority of their environmental impact in the production and disposal phases (*high non-use impact products* for brevity) (Bole 2006, Quariguasi Frota Neto et al. 2007, MacLean and Lave 1998, Intlekofer et al. 2009, Kuehr and Williams 2003, Fishbein et al. 2000).

In steady-state, comparing the total life-cycle environmental impact of the two strategies reduces to comparing their per-period environmental impact. Under leasing, the per-period production and disposal volumes are both L_n^* and the per-period use volume is $L_n^* + L_u^*$. Under selling, the per-period production and disposal volumes are both S_n^*, and since products are only disposed of after two periods of use, the per-period use volume is given by $2S_n^*$. Similar to Thomas (2008), we assume that environmental impact is independent of whether a product is leased or sold, or whether it is used or new. We also assume that the environmental impact due to consumer disposal is equal to that due to firm disposal. Under the above assumptions, the per-period environmental impact of a durable product is $(i_p + i_d)L_n^* + i_u(L_n^* + L_u^*)$ and $(i_p + i_d)S_n^* + 2i_uS_n^*$ under leasing and selling, respectively, where i_p, i_u and i_d denote the environmental impact of one unit due to production, one period of use and disposal, respectively.

Characterizing Relative Profitability and Environmental Impact. In order to simplify the exposition and to focus on the differential effect of disposal costs, we assume $\beta_f = \beta_c = 0$. The nature of our insights remain the same for non-negative remarketing and transaction costs. We first present a special case, $\delta = 0$, as a building block in understanding the impact of different parameters.

LEMMA 3. *Let $\delta = 0$. If $s_f = s_c$, leasing and selling are equivalent. If $s_f < s_c$, leasing is strictly more profitable but has a higher environmental impact. Otherwise, selling is more profitable but has a higher environmental impact.*

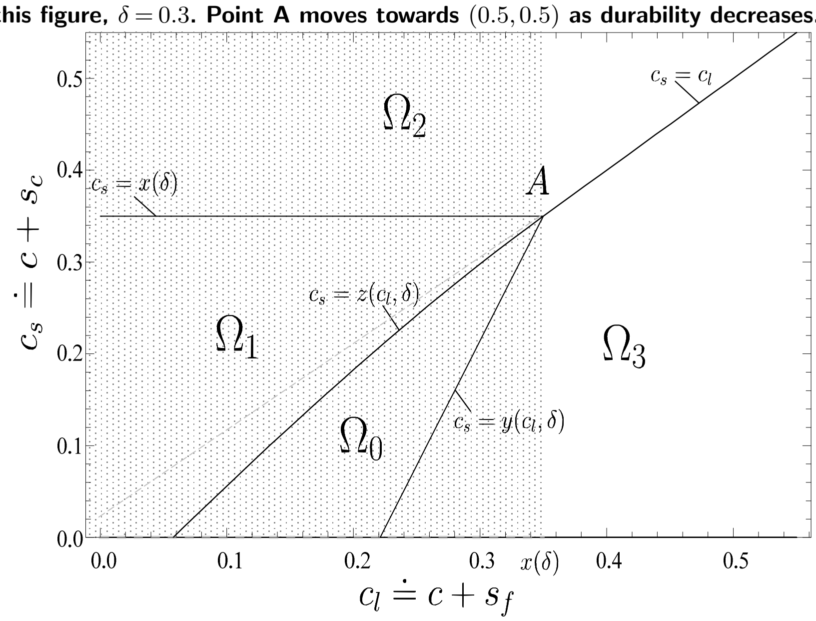
When $\delta = 0$, the product is non-durable. Thus, the selling firm does not face any cannibalization from the secondary market. The only difference between leasing and selling is who incurs the disposal cost. If disposal is cheaper for the firm (or if the salvage value is higher) as compared to the consumer, leasing is more profitable. Since $\delta = 0$, there are no used products and the total environmental impact of leasing and selling are $(i_p + i_u + i_d)L_n^*$ and $(i_p + i_u + i_d)S_n^*$, respectively. When the disposal cost is lower for the firm, the leasing firm produces a larger quantity of products and has a higher environmental impact.

This proposition suggests that it is sufficient to focus on the *effective* cost $c + s$ to compare the relative profitability and the environmental impact of leasing and selling. Let $c_l \doteq c + s_f$ and $c_s \doteq c + s_c$ denote the effective cost (borne by the firm explicitly or implicitly) in leasing and selling, respectively. We find that the relative profitability and environmental impact of leasing and selling can indeed be summarized as a function of c_l and c_s (Figure 1). The thresholds defined in this figure are derived in Propositions 3 - 5.

PROPOSITION 3. *Let $c_l > x(\delta) \doteq \frac{1-\delta}{2}$ (full remarketing is optimal). For $c_l = c_s$, leasing and selling are equivalent; for $c_l < c_s$, leasing is more profitable but has higher environmental impact; otherwise, selling is more profitable but has higher environmental impact.*

Recall we assume $\beta_f = \beta_c = 0$ in this subsection. Then the condition $s_f < s_B(c, \delta, \beta_f)$ derived in Proposition 1 for premature disposal to be optimal reduces to $c_l < x(\delta) \doteq \frac{1-\delta}{2}$. For $c_l > x(\delta)$, the leasing firm remarkets all off-lease products (full remarketing). Since with selling, no product is disposed of by consumers before its end of life, the only difference between the two strategies in this case is the difference in disposal cost (or equivalently, effective cost), as in Lemma 3. Thus, profits and environmental impact are equal if the disposal cost is the same for the firm and the consumer. If $s_f < s_c$, then $c_l < c_s$, and leasing is strictly more profitable. In addition, due to the lower effective cost, the firm produces (and disposes) a larger quantity of products. With full remarketing, this leads to a higher volume of products in use as well, and consequently, a higher total environmental impact. Similarly, if $s_c < s_f$, selling is more profitable and leads to a higher total environmental impact.

Figure 1 **Characterization of the relative profitability and environmental impact of leasing and selling, where $x(\delta) \doteq \frac{1-\delta}{2}$, $y(c_l,\delta) \doteq \frac{c_l(1+3\delta)}{1-\delta} - 2\delta$ and $z(c_l,\delta) \doteq 1+\delta - \sqrt{\frac{(1+3\delta)((1-\delta)(1-2c_l)+c_l^2)}{1-\delta}}$. Dots represent the area where premature disposal is optimal under leasing ($c_l \le x(\delta)$). Selling (leasing) is more profitable in region $\Omega_0 \bigcup \Omega_3$ ($\Omega_1 \bigcup \Omega_2$). The relative environmental impact in regions Ω_0 through Ω_3 is as follows: In Ω_0 and Ω_1, selling has lower environmental impact due to production and disposal, and leasing has lower environmental impact due to use. In Ω_2, selling has lower total environmental impact. In Ω_3, leasing has lower total environmental impact. In this figure, $\delta = 0.3$. Point A moves towards $(0.5, 0.5)$ as durability decreases.**



Proposition 4. *Let $c_l < x(\delta)$ (premature disposal is optimal). Selling and leasing are equally profitable for $c_s = z(c_l,\delta) \doteq 1+\delta - \sqrt{\frac{(1+3\delta)((1-\delta)(1-2c_l)+c_l^2)}{1-\delta}}$, where $z(c_l,\delta) < c_l$. Leasing is more profitable if $c_s > z(c_l,\delta)$. Otherwise, selling is more profitable.*

Recall that with full remarketing, leasing is strictly more profitable if and only if $s_c > s_f$ or if c_s is higher than the threshold c_l. With premature disposal, this threshold is lower ($z(c_l,\delta) < c_l$); the control that the leasing firm has over used products is exercised and reduces the impact of cannibalization, making leasing more competitive.

The conventional result in the durable goods literature is that for a monopolist, leasing is more profitable than selling, since under leasing a firm has control of the used products and does not face reduced demand due to consumers owning a used product (cf., Stokey 1981, Bulow 1982). Propositions 3 and 4 show that that if the consumers face a sufficiently lower disposal cost than the firm, the firm is better off not gaining control over the used products and selling is more profitable.

Proposition 5. *Let $c_l < x(\delta)$ (premature disposal is optimal). For $c_s < y(c_l,\delta) \doteq \frac{c_l(1+3\delta)}{1-\delta} - 2\delta$, leasing is strictly environmentally superior. For $y(c_l,\delta) \le c_s \le x(\delta)$, the total environmental impact in the use phase is lower under leasing and the total environmental impact in the non-use phases is lower under selling. For $x(\delta) < c_s$, selling is strictly environmentally superior.*

Consider the $c_s = c_l$ case, which falls in the intermediate cost range $y(c_l,\delta) < c_s < x(\delta)$ when the premature disposal condition holds. Since the leasing firm finds it optimal to prematurely dispose of used products, cannibalization is mitigated, and the leasing firm produces (and disposes) a larger volume than the selling firm ($S_n^* < L_n^*$). Nevertheless, since the selling firm has no control over used products, while the leasing firm prematurely disposes of them, the volume of products in the use phase is higher for selling ($2S_n^* > L_n^* + L_u^*$). Therefore, under this condition, the total environmental impact of leasing is lower for products with high enough impact in the use phase ($i_u >> i_p + i_d$) and selling is environmentally superior for products with high enough impact in the non-use phases ($i_p + i_d >> i_u$).

As the effective cost faced by the selling firm increases, the volume it produces (and disposes) decreases. When this cost is high enough ($c_s > x(\delta)$), the production volume under selling is low enough such that the total volume in use is also lower ($2S_n^* < L_n^* + L_u^*$). Therefore, under the high cost range, selling is strictly environmentally superior.

As the effective cost faced by the selling firm decreases, the volume it produces (and disposes) increases. If this effective cost is low enough ($c_s < y(c_l,\delta)$), the production and disposal volume under selling is higher than that under leasing ($S_n^* > L_n^*$). In addition, since under selling, this larger volume of products remains in use for their entire life, the volume of products in the use phase is still higher under selling ($2S_n^* > L_n^* + L_u^*$). Therefore, in this low cost range, leasing is strictly environmentally superior.

When is Leasing (or Selling) the Win-Win Choice? The environmental strategy literature has posited that there are many win-win business opportunities in practice that both increase profit and decrease environmental impact (Porter and Van Der Linde 1995). Thus, it is interesting to ask when either leasing or selling can be a win-win choice. Combining Propositions 4 and 5, we see that leasing is both more profitable and has less environmental impact than selling only for high use impact products. This occurs when premature disposal is optimal and the effective cost under selling is neither too high nor too low relative to that under leasing (Region Ω_1). Interestingly, selling can also be a win-win strategy, this time for high non-use impact products. This occurs when premature disposal is optimal and the effective cost under selling is low enough relative to that under leasing (Region Ω_0). As the product durability increases, the threshold $x(\delta)$ decreases. Thus, the area of regions Ω_0 and Ω_1 in Figure 1 decreases, i.e. win-win scenarios take place at lower values of disposal costs faced by the firm and the consumers for more durable products.

Consider products that have high use impact such as cars, washers, dryers, refrigerators and televisions (Bole 2006, Quariguasi Frota Neto et al. 2007, MacLean and Lave 1998). It is reasonable to expect that a firm has better access to recyclers and lower collection or processing costs compared to an individual consumer for such bulky products. It is also reasonable to expect that for products that can be profitably disposed, a firm can recover a higher value from salvaging a unit than an individual consumer. In this case, the effective cost faced by a leasing firm will be lower than that faced by a selling firm. Thus, the conditions defining Region Ω_1 may hold for such products, in which case a leasing strategy will be both more profitable and environmentally superior.

Consider products such as computers, carpets or mattresses that have a high non-use impact (Intlekofer et al. 2009, Kuehr and Williams 2003, Fishbein et al. 2000). For these products, consumers may face a lower disposal cost than a firm, due to stricter legislation for firms as compared to individual consumers. For example, federal law in the U.S. regarding hazardous electronic waste only applies for firms generating more than 220 lbs of such waste (U.S. EPA 2008b). A firm may also voluntarily choose to recycle recovered units due to pressure from environmental groups, while consumers trash the product. For such products, the conditions defining Region Ω_0 may hold, in which case selling will be both more profitable and environmentally superior.

Robustness of Insights to Assumptions. We discuss the implications of relaxing some simplifying assumptions, focusing primarily on their effects on win-win scenarios.

Effect of Remarketing Costs. If we relax the assumption of zero remarketing costs, the structure of Figure 1 remains the same. Under leasing, the presence of a remarketing cost promotes premature disposal of off-lease units, which leads to a higher production and disposal volume and a lower use volume than the $\beta_f = 0$ case. In contrast, under selling, the presence of a remarketing cost inhibits the secondary-market trade, prompting more consumers to hold onto their used product. This leads to a lower demand for new products and consequently, results in lower production, disposal and use volumes than the $\beta_c = 0$ case. Thus, introducing remarketing costs decreases the threshold $y(c_l, \delta)$ and has an indeterminate impact on $x(\delta)$. It is reasonable to expect that a firm is more efficient at remarketing used products ($\beta_f < \beta_c$), since it has economies of scale and is less likely to sufer from adverse selection as compared to consumers (Huang et al. 2001). In this case, the relative profitability of leasing increases ($z(c_l, \delta)$ decreases) when there are remarketing costs.

Effect of Differential Disposal Impact. We assumed that the disposal impact is independent of who disposes the product. In practice, firms may have better access to environmentally superior alternatives (e.g. recycling vs landfilling). All else being equal, the only resulting change will be a reduction in the environmental impact due to disposal under leasing. Therefore, the threshold $y(c_l, \delta)$ will be higher and the area where selling is a win-win strategy (Region Ω_0) will shrink, or may not exist.

Effect of Remarketing Mechanism under Leasing. We restricted our attention to a pure leasing strategy where off-lease products are again leased. If the leasing firm endogenously chooses between leasing and selling off-lease units, the firm will choose to sell them only if the consumers enjoy a lower disposal cost ($c_s < c_l$). This results in a lower effective cost under leasing, which in turn increases both the profitability and the total environmental impact of leasing (thresholds $z(c_l, \delta)$ and $y(c_l, \delta)$ are lower). Therefore, the area of region Ω_1 (where leasing is win-win) is larger, and the area of Ω_0 (where selling is win-win) is typically smaller. Finally, when $c_s < c_l$ and full remarketing is optimal, the profits and the total environmental impact are equal under both strategies. Thus, allowing the firm to endogenously choose between leasing or selling off-lease units makes leasing more profitable, but at the expense of its total environmental impact.

5. Conclusions

Is leasing greener than selling? Articles in industrial ecology and environmental strategy have answered in the affirmative, and have influenced firms, public entities and environmental groups. Whether leasing is greener *and* more profitable is not the concern of the industrial ecology literature, while the environmental strategy literature promotes the win-win argument - that many strategies that are environmentally superior are also more profitable. With this paper, we aim to provide guidance to firms on the viability of promoting leasing as the "greener" strategy. As profit-maximization is the primary objective for firms, we also identify the locus of green and profitable strategies.

To this end, we develop infinite-horizon, sequential dynamic models of pricing, remarketing and disposal for durable products put on the market via leasing or selling by a profit-maximizing monopolist. We characterize the optimal quantity of new and used products observed in equilibrium, and calculate the total volume of products in each life cycle phase (production, use and disposal) under each strategy to compare their total environmental impact. Based on our analysis, we find that the magnitude of the disposal cost, the differential in the disposal costs faced by the firm and consumers, and the environmental impact profile of the product (whether the majority of the impact is in the use phase or the production and disposal phases) are the main drivers of relative profitability and environmental impact (Figure 2). The insights obtained from our analysis are of relevance to manufacturers, environmental groups, and policy makers, and are discussed below.

The remarketing level is not a good proxy for environmental impact. Recall the main argument for the environmental superiority of leasing is that since the firm owns the off-lease units, it has an incentive to remarket them (Hawken et al. 1999, Lifset and Lindhqvist 2000, Fishbein et al. 2000, Mont 2002, Robert et al. 2002). In contrast, Ruth (1998) and Lawn (2001) argue that leasing may be worse for the environment due to the firm's ability to prematurely dispose recovered off-lease products. We find that leasing may be *less green than selling despite full remarketing*, and *greener despite premature disposal*. Market effects (demand volume, use duration) account for these

Figure 2 When is a marketing strategy greener and more profitable? Profit-maximizing and environmentally superior strategies are denoted by "P=" and "E=", respectively. Premature disposal and full marketing are options available to the leasing firm and are driven by the magnitude of the firm's disposal cost.

	Premature Disposal		*Full Remarketing*
	High Non-use Impact	*High Use Impact*	
Moderately Lower Firm Disposal Cost	P = Lease E = Sell X	P = Lease E = Lease √	P = Lease E = Sell X
Moderately Lower Consumer Disposal Cost	P = Sell E = Sell √	P = Sell E = Lease X	P = Sell E = Lease X

results. When the firm's disposal cost is high, but lower than the consumer's, the leasing firm fully remarkets, but leasing has higher environmental impact: Full remarketing may reduce but does not eliminate the incentive for the firm to produce a larger volume of products than with selling to exploit this cost advantage. The larger sales volume in conjunction with full remarketing translates into higher environmental impact. In contrast, when the disposal cost is low enough to make premature disposal optimal, leasing can be greener for high use impact products despite premature disposal. The reason is that premature disposal reduces the contribution of the use phase to the life-cycle environmental impact. We conclude that the remarketing level is not a complete indicator of a firm's total environmental impact.

Selling may be more profitable. We identify asymmetry in disposal cost as the primary driver of the relative profitability of the two strategies. When the firm's disposal cost is higher, selling is more profitable because it transfers disposal responsibility to the consumer. This finding complements the recent literature that identifies settings where selling may dominate leasing (Bucovetsky and Chilton 1986, Desai and Purohit 1998, 1999, Desai et al. 2004, Bhaskaran and Gilbert 2005). It is not unusual for the firm's disposal cost to be higher. Consider Interface's Evergreen Lease. Commercial carpeting, while durable, does not lend itself to reuse and only some of the material can be recycled. Thus, by committing itself to collecting and (partially) recycling the carpet, Interface effectively increased its disposal cost significantly relative to local landfilling by its customers. As our results show, selling is more profitable in this case, and a publicly traded firm such as Interface would find it difficult to deviate from profit maximization as its primary objective. Thus, despite originally being championed at the highest levels of the company, the leasing program was phased out, although the recent spike in oil prices, which makes recycled nylon competitive with virgin nylon, gave the company hope that it could be reintroduced (Ferguson and Plambeck 2008). Interestingly, *selling can even be a win-win choice, but only for high non-use impact products.* This occurs when the volume put on the market is higher with leasing despite a lower consumer disposal cost.

Leasing may be more profitable, but less green. The very reason leasing is more profitable may be the reason why it is not greener. In our model, disposal cost asymmetry in favor of the firm makes leasing more profitable, but also drives volume up, resulting in higher total life-cycle environmental impact when full remarketing is optimal. Therefore, skepticism vis-a-vis claims by firms who lease their products that this is the environmentally superior strategy is warranted. We conclude that to judge the environmental impact of a strategy, a comprehensive assessment, which takes market effects throughout the product life cycle into account, is needed.

Leasing can be a win-win choice for high use-impact products. When premature disposal is optimal, the volume of products in the use phase is reduced. Thus, even when leasing leads to a higher volume put on the market, the total environmental impact of this strategy can be lower for those products that have a high impact during the use phase. For example, leasing photocopiers for Xerox may well be a win-win choice, since photocopiers have high use impact (McIntyre et al. 1998, Sundin et al. 2000), Xerox remarkets only a portion of off-lease products, and enjoys a higher salvage value than consumers, since it harvests spare parts and recyclable materials from off-lease units that are not remarketed.

Leasing is a hard sell. As discussed in §1, several policy-making groups such as the U.S. Environmental Protection Agency, the state of Minnesota and the New York City Government are actively promoting leasing as the greener alternative. In this paper, we provide two main insights for such policy-makers: First, leasing is not always greener than selling, and care must be taken to avoid blanket statements about one strategy being environmentally superior over the other. Second, even if leasing is greener, firms may not have an incentive to adopt it as selling may be more profitable precisely in this case. A better understanding of the drivers of the relative profitability of leasing and selling can enable the design of incentives to encourage the adoption of the environmentally superior strategy.

To summarize, we offer new insights into a firm's lease versus sell decision, and provide an analytical comparison of the total environmental impact (based on total volumes produced, used, and disposed) of each strategy. We show that our qualitative insights are robust to a number of assumptions such as the existence of remarketing costs, asymmetry in the environmental impact of disposal, and the choice of the remarketing strategy. Thus, we add to the important knowledge base on product leasing that will benefit not only managers, but also environmental groups and policy makers. We hope that our paper will promote more research exploring the impact of marketing strategies on the environmental performance of the firm.

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Appendix: Proofs

Proof of Lemma 1. Since $d(u_n(\theta) - u_u(\theta))/d\theta > 0$, we have that $\Pi_\theta[Ln, r^t] - \Pi_\theta[Lu, r^t]$ and $\Pi_\theta[Lu, r^t] - \Pi_\theta[I, r^t]$ are increasing in θ. Thus, in equilibrium, consumers playing Ln will have higher θ than ones playing Lu, who will have higher θ than ones playing I. The values of θ_1 and θ_2 can be found by solving $\Pi_\theta[Ln, r^t] = \Pi_\theta[Lu, r^t]$ and $\Pi_\theta[Lu, r^t] = \Pi_\theta[I, r^t]$, respectively. □

Proof of Proposition 1. Define $Z \doteq \{(z_n, z_u) \in \mathbb{R}_+^2 : z_n + z_u \leq 1\}$. Note that the discount factor is given by $0 < \rho < 1$ and the profit per stage is bounded. Thus, the value function $V(L^0)$ is the unique bounded solution of the following Bellman Equation evaluated at L^0 (Stokey and Lucas Jr 1989):

$$v(x) = \max_y \{\Pi_l(x, y) + \rho v(y)\} \text{ for all } x, y \in Z, \text{ such that } y_u \leq x_n. \tag{7}$$

By construction, we have $L\mathbf{1}' \leq 1$. The action set is compact and all functions are continuous. Thus, there exists an optimal stationary policy (Blackwell 1965). The boundedness and continuity of the per-period function imply that there is a steady-state policy where the optimal decisions remain constant (Flynn 1975).

The Hessian of the per-period profit is given by $\begin{pmatrix} -2 & -2\delta \\ -2\delta & -2\delta \end{pmatrix}$, whose leading coefficient is negative and the determinant $4\delta(1-\delta)$ is positive. Thus, the hessian is negative definite and the per-period profit function is jointly strictly concave in L_n and L_u. This, along with the boundedness of the per-period profit function, ensures the uniqueness of the steady state solution, denoted by $L^* \doteq (L_n^*, L_u^*)$ (Bertsekas 1995).

Now assume that Assumption A1 holds. The inverse demand functions for the new and used product leases can be found by substituting $u_n(\theta) = \theta$ and $u_u(\theta) = \delta\theta$ and solving (1), $L_n = 1 - \theta_1$ and $L_u = \theta_1 - \theta_2$ simultaneously. The firm's per-period problem at steady state is given by

$$\max_{L_n, L_u} (r_n - c)L_n + (r_u - \beta_f)L_u - s_f L_n = (1 - L_n - \delta L_u - c)L_n + (\delta(1 - L_n - L_u) - \beta_f)L_u - s_f L_n \quad (8)$$

$$\text{s.t. } L_u \leq L_n \text{ and } L_n, L_u \geq 0. \quad (9)$$

The Lagrangean is given by

$$\mathbb{L}(L_n, L_u) = (1 - L_n - \delta L_u - c)L_n + (\delta(1 - L_n - L_u) - \beta_f)L_u - s_f L_n - \lambda(L_u - L_n) + \mu_1 L_n + \mu_2 L_u,$$

with first-order conditions

$$\sigma_1(L_n, L_u, \lambda, \mu_1) \doteq \frac{\partial \mathbb{L}}{\partial L_n} = 1 + \lambda + \mu_1 - c - 2L_n - s_f - 2\delta L_u = 0 \text{ and}$$
$$\sigma_2(L_n, L_u, \lambda, \mu_2) \doteq \frac{\partial \mathbb{L}}{\partial L_u} = \delta + \mu_2 - \beta_f - 2\delta(L_n + L_u) - \lambda = 0.$$

Since the per-period profit function is strictly concave in L_n and L_u, the necessary and sufficient conditions for optimality (Kuhn-Tucker conditions) are that the first order conditions (FOC) are satisfied and $\lambda(L_u - L_n) = 0$, $\mu_1 L_n = 0$, $\mu_2 L_u = 0$, $\lambda \geq 0$, $\mu_1 \geq 0$ and $\mu_2 \geq 0$. There are four candidate solutions to the optimization problem defined as cases 1-4 below.

Case 1. $L_n > 0$ and $0 < L_u = L_n$. Then $\mu_1 = 0$ and $\mu_2 = 0$. Solving $\sigma_1(L_n, L_n, \lambda, 0) = 0$ and $\sigma_2(L_n, L_n, \lambda, 0) = 0$ gives $L_n = \frac{1-c-s_f-\beta_f+\delta}{2+6\delta}$ and $\lambda = \frac{2\delta s_f - \beta_f(1+\delta) - \delta(1-2c-\delta)}{1+3\delta}$. $\lambda \geq 0$ and $L_n > 0$ hold for $\frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta} \leq s_f$ and $c + s_f + \beta_f < 1 + \delta$, respectively. Since according to our assumption, $c + \max(s_c, s_f) + \beta_f < 1$ and $\delta > 0$, $c + s_f + \beta_f < 1 + \delta$ clearly holds. Thus, the required condition for this case to apply is $\frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta} \leq s_f$.

Case 2. $L_n > 0$ and $0 < L_u < L_n$. Then $\mu_1 = 0$, $\mu_2 = 0$ and $\lambda = 0$. Solving $\sigma_1(L_n, L_n, 0, 0) = 0$ and $\sigma_2(L_n, L_n, 0, 0) = 0$ gives $L_n = \frac{1-c-s_f+\beta_f-\delta}{2(1-\delta)}$ and $L_u = \frac{\delta(c+s_f)-\beta_f}{2\delta(1-\delta)}$. $L_n > 0$, $L_u > 0$ and $L_u < L_n$ hold for $s_f <$

$1-c+\beta_f-\delta$, $\frac{\beta_f-\delta c}{\delta}<s_f$ and $s_f<\frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta}$, respectively. Since $\frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta}-(1-c+\beta_f-\delta)<0$ for $c+s+\beta_f<1$, if $s_f<\frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta}$ holds, then $s_f<1-c+\beta_f-\delta$ also holds. Thus, the required condition for this case to apply is $\frac{\beta_f-\delta c}{\delta}<s_f<\frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta}$.

Case 3. $L_n>0$ and $L_u=0$. Then $\mu_1=0$ and $\lambda=0$. Solving $\sigma_1(L_n,0,0,0)=0$ and $\sigma_2(L_n,0,0,\mu_2)=0$ gives $L_n=\frac{1-c-s_f}{2}$ and $\mu_2=\beta_f-\delta(c+s_f)$. $\mu_2\geq 0$ and $L_n>0$ hold for $s_f\leq\frac{\beta_f-\delta c}{\delta}$ and $c+s_f<1$, respectively. Since according to our assumption, $c+\max(s_c,s_f)+\beta_f<1$, $c+s_f<1$ clearly holds. Thus, the required condition for this case to apply is $s_f\leq\frac{\beta_f-\delta c}{\delta}$.

Case 4. $L_n=0$ and $L_u=0$. Solving $\sigma_1(0,0,\lambda,\mu_1)=0$ and $\sigma_2(0,0,\lambda,\mu_2)=0$ gives $\mu_1=-1+c+s_f-\lambda$ and $\mu_2=\beta_f-\delta+\lambda$. $\mu_1\geq 0$ holds for $\lambda\leq-(1-c-s_f)$. However, according to our assumption, $c+\max(s_c,s_f)+\beta_f<1$, $(1-c-s_f)>0$. This implies that $\mu_1\geq 0$ and $\lambda\geq 0$ cannot hold together and this case is ruled out.

The three remaining candidate solutions and the required conditions for each of them can be summarized as follows: If $s_f\leq\frac{\beta_f-\delta c}{\delta}$, then $L^*=\left(\frac{1-c-s_f}{2},0\right)$, if $\frac{\beta_f-\delta c}{\delta}<s_f<\frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta}$, then $L^*=\left(\frac{1-c-s_f+\beta_f-\delta}{2(1-\delta)},\frac{\delta(c+s_f)-\beta_f}{2\delta(1-\delta)}\right)$ and if $\frac{\beta_f(1+\delta)+\delta(1-2c-\delta)}{2\delta}\leq s_f$, then $L^*=\left(\frac{1-c-s-\beta_f+\delta}{2+6\delta},\frac{1-c-s-\beta_f+\delta}{2+6\delta}\right)$. □

Proof of Lemma 2. We suppress the selling-specific notation for this proof. There are nine potential two-period consumer strategies as shown in Table 1. At the focal point, the consumer's Bellman equation can be written as

$$V_\theta[a(\theta),p]=\max_{a(\theta)}\{\Pi_\theta[R_\theta[a(\theta),p];a(\theta),p]+\rho V_\theta[R_\theta[a(\theta),p],p]\} \tag{10}$$

Since a product lasts two periods, a rational consumer who has a state of Bu or I, will choose the same action in the current period as they enter the period with no product. This implies that at the focal point,

$$R_\theta[Bu,p]=R_\theta[I,p]\,\text{and}\,V_\theta[Bu,p]=V_\theta[I,p]. \tag{11}$$

Due to the periodicity of two for all consumer strategies at the focal point, permutations of same pattern are not distinct. There are only 6 distinct strategies (BnBn, BnBu, BnI, BuBu, BuI and II). From (11), $V_\theta[Bu,p]=V_\theta[I,p]$ and examining (10), it is easy to see that if a consumer chose Bu or I in the previous period, it will still find it optimal to choose the same strategy in the current period. This implies that BuI cannot happen in equilibrium. Thus, there are only 5 possible strategies left. We next prove that at the focal point, BnI cannot happen.

Recall that the reaction function $R_\theta[a(\theta),p]$ is chosen to maximize

$$U_\theta[s;a,p]\equiv\Pi_\theta[s;a,p]+\rho V_\theta[s,p]. \tag{12}$$

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

$$p_u-\beta_c+\rho V_\theta[I,p]>u_n(\theta)-p_n+p_u-\beta_c+\rho V_\theta[Bn,p] \text{ or } \rho V_\theta[I,p]>u_n(\theta)-p_n+\rho V_\theta[Bn,p]. \quad (13)$$

However, the above equation implies that $U_\theta[I;I,p]>U_\theta[Bn;I,p]\Rightarrow R_\theta[I,p]=I$. Thus, if a consumer plays I when he is in state Bn, then it will be optimal for him to always play I thereafter. This violates our assumptions and thus, BnI cannot take place. Thus, there are four possible strategies at the focal point. Consumers who play BnBn will have higher θ than those who play BnBu, who have higher θ than those who play BuBu. Consumers playing II will 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 are given as follows:

$$V_\theta[Bn,p]=\frac{u_n(\theta)-p_n+p_u-\beta_c}{1-\rho} \text{ when } \theta\in(\theta_5,1] \text{ or } \theta\in BnBn, \quad (14)$$

$$V_\theta[Bn,p]=\frac{u_u(\theta)-s_c+\rho(u_n(\theta)-p_n)}{1-\rho^2} \text{ when } \theta\in(\theta_6,\theta_5] \text{ or } \theta\in BnBu, \quad (15)$$

$$V_\theta[Bu,p]=\frac{u_n(\theta)-p_n+\rho(u_u(\theta)-s_c)}{1-\rho^2} \text{ when } \theta\in(\theta_6,\theta_5] \text{ or } \theta\in BnBu, \quad (16)$$

$$V_\theta[Bu,p]=\frac{u_u(\theta)-p_u-s_c}{1-\rho} \text{ when } \theta\in(\theta_7,\theta_6] \text{ or } \theta\in BuBu, \quad (17)$$

$$V_\theta[I,p]=0 \text{ when } \theta\in(0,\theta_7] \text{ or } \theta\in II. \quad (18)$$

The value of Θ_3 can be found by equating (17) and (18), the value of Θ_2 can be found by equating (15) and (17) and finally, the value of Θ_1 can be found by equating (14) and (15). □

Proof of Proposition 2. Under Assumption A1, it is easy to show using (5) and (6) that the per-period profit function is strictly concave in S_n. Solving for the first-order conditions yields S_n^*.

Proofs of Lemma 3 and Propositions 3-5. These follow directly by comparing the expressions for the optimal decisions and profits obtained in Sections 3.1 and 3.2.

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