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Relicensing as a Secondary Market Strategy

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Secondary markets in the Information Technology (IT) industry, where used or refurbished equipment is traded, have been growing steadily. For Original Equipment Manufacturers (OEMs) in this industry, the importance of secondary markets has grown in parallel, not only as a source of revenue, but also because of their impact on these firms' competitive advantage and market strategy. Recent articles in the press have severely criticized some OEMs who are perceived to be actively trying to eliminate the secondary market for their products. Others have policies that enhance their secondary markets. The goal of this paper is to understand how an OEM's incentives and optimal strategies vis-à-vis the secondary market are shaped contingent on her relative competitive advantage, product characteristics and consumer preferences. The critical tradeoff that we examine is whether the indirect benefit from maintaining an active secondary market (the resale value effect) can outweigh the potentially negative effect of the sales of used products at the expense of new product sales (the cannibalization effect). To that end, we develop a model where the OEM can directly affect the resale value of her product through a relicensing fee charged to the buyer of the refurbished equipment. Moreover, we introduce a measure of the consumers' willingness to return their used products to account for the fact that the higher the price offered by a third-party entrant, the higher the ratio of returned products at their end-of-use. We analyze the OEM's strategy in both the monopoly and the duopoly cases, characterize the optimal relicensing fee set by the OEM, and draw conclusions on the conditions that favor stimulating or deterring the secondary market.

Key words: Cannibalization, Secondary Market, Relicensing Fee, Remanufacturing, Closed-Loop Supply Chain

1. Introduction

Today, Original Equipment Manufacturers (OEMs) in the Information Technology (IT) industry often face difficult decisions when forming strategies involving secondary markets for their products.

In the years before the dot-com bubble of the late 1990s, there was a limited secondary IT market. Some reasons for this lack of demand for refurbished IT equipment included: 1) IT OEMs focused on their primary sales channels and discouraged customers from considering refurbished equipment; 2) buyers of IT equipment were leery of the quality level of a refurbished product; and 3) there was a lack of independent secondary market firms to refurbish, resell, and support IT equipment. Shortages of higher-end IT equipment such as servers and routers during the late 1990s however, led to unmet demand that was often satisfied by a new market of third-party IT equipment brokers and refurbishers[1]. In the years following, the dot-com bust resulted in a large surplus of barely used IT equipment for sale from companies who failed when the bubble burst. The availability of so much inexpensive used IT equipment led to significant price discounts compared to the price of new equipment and even more brokers and refurbishers entering the secondary market (Berinato 2002).

One of the lasting effects from the dot-com era is that major customers of IT equipment have started accepting refurbished IT equipment as a viable alternative to new equipment and a new body of IT refurbishers has entered the market to meet this demand. According to a 2002 survey of 187 IT executives in CIO magazine, 77 percent said they were purchasing secondary market equipment and 46 percent expected to increase their spending on refurbished equipment in the next year by an average of 15 percent (Berinato 2002). In another article, Computer Business Review highlights that "third-party companies have built $100+ million per year businesses in buying used computer equipment, refurbishing it, and selling or leasing it out to someone else" (CBRonline.com 2005). Given the size and growth of the secondary market, the days of ignoring it and only focusing on the sale of new products are over for all major IT OEMs. OEMs may either

[1] Third-party refurbishers do not manufacture their own products, but instead rebuild and reconfigure used OEM products that they buy from IT users who upgrade or no longer need those products. Unlike other markets such as the automotive market, potential customers in the used IT equipment market typically expect the equipment to be refurbished before purchasing; thus the vast majority of the sales in the IT secondary market are between refurbishers and the end-users rather than between the end-users themselves. Following industry usage, we will use the terms "refurbished" and "remanufactured" interchangeably in this paper; for a detailed definition of these terms, see Thierry et al. (1995).

embrace the secondary market or try to eliminate it, but one thing is now evident, they must form strategies to respond to it.

Some of the major OEMs in the IT industry have not only embraced the existence of a secondary market, but also deploy it to obtain competitive advantage over their rivals. IBM and Hewlett Packard, for instance, create high resale values for their used equipment by facilitating the resale process and secondary use (e.g. charging small relicensing fees, offering maintenance and inspection) so that the original customers gain a higher net benefit from their new product purchases. Such a proactive, and in a sense cooperative, relationship with third-party brokers and refurbishers, however, is not a standard policy among all IT OEMs. An alternative strategy is to institute policies and fees that attempt to eliminate the secondary market. For example, Sun Microsystems (Sun), one of the leading firms in the IT server business, was "under fire for deliberately attempting to eliminate the secondary market for its machines worldwide through their new pricing and licensing schemes" (Marion 2004). Cisco is another company that requires each buyer of its refurbished equipment to pay high relicensing fees for the proprietary software that makes the equipment run.

The following excerpts, typical of the IT industry, shed some light on how the relicensing mechanism works. "Cisco adopts a policy of non-transferability of its software to protect its intellectual property rights." What this means is that owners of Cisco products are only allowed to transfer, resell, or re-lease used Cisco hardware and not the embedded software that runs on it. This practice, in effect, eliminates the secondary market and creates customer dissatisfaction. Cisco's response to this criticism was to institute relicensing fees, albeit significant: "As Cisco's installed base of equipment has grown to such large numbers over the years, our customers have become more interested in selling and leasing used Cisco equipment on the secondary market. In order to provide our valued customers and partners with this capability, Cisco is now setting up a program where companies who are interested in buying used equipment, may now purchase a new software license to do so" (Cisco.com 2007).

Despite such statements that a relicensing fee mechanism allows reselling refurbished equipment on the secondary market, many industry observers argue that some OEMs use unreasonably high relicensing fees as a means of limiting the secondary market. In the case of Sun, Marion (2004) highlights the fact that the relicensing fee is deliberately set so high that the overall cost of a unit of refurbished equipment, including hardware and software, reaches that of a new one: "In the end, the potential buyer for the refurbished equipment may have no choice but to return to Sun for a new product." He concludes by stressing another interesting facet of the problem: "End users need to know this and take action to adjust the Sun hardware values reflected on their respective balance sheets to account for the impact that Sun's actions, described above, will have on resale and residual values." In other words, users should be aware that Sun's practices result in very low resale values of used equipment and this information should be factored into their original purchase decision. In fact, many IT consulting companies (e.g. www.computereconomics.com) offer detailed forecasts regarding future resale values of used IT equipment, underlining the critical role of the resale value in the initial IT purchase decision.

From a research perspective, the discussion above raises the fundamental question addressed in this paper. Given the OEM's ability to interfere with the IT secondary market through pricing and relicensing schemes, is limiting this market or, conversely, encouraging its existence, a more profitable strategy? If one strategy is dominant over the other, the winner is currently not clear based on anecdotal evidence alone. Our goal is to understand how the OEM's incentives and optimal strategies are shaped contingent on costs, product characteristics, consumer preferences and the intensity of remanufacturing competition. Motivated by the industry articles concerning Sun, a company that has historically been considered the premium brand in the server market (Sun.com 2007), we also examine whether such a brand premium could justify an aggressive strategy vis-à-vis the secondary market.

We begin our analysis by studying the optimal strategy of an OEM that has a monopoly on the new product market, but faces future competition from a third-party entrant who purchases the used products from the OEM's customers, refurbishes them, and resells them in competition with the OEM's new products. The OEM collects a relicensing fee on every product sold by the entrant; and can effectively "shut down" the secondary market by charging a high enough fee. Our key finding is that it is suboptimal for the OEM to shut down the secondary market when the refurbishing cost is low, even though this means the entrant is more competitive. This seemingly counter-intuitive strategy is driven by the fact that in this cost range, not only can the OEM charge a higher relicensing fee, but she can also benefit from a stronger resale value effect. If customers are not strategic (no resale value effect) or the OEM's second-generation product is technologically superior to the first, however, then the OEM adopts a more aggressive strategy against the secondary market, and may even charge a high enough fee to shut it down completely for any level of refurbishing cost. Similarly, if the OEM decides to enter the secondary market herself (in conjunction with imposing a relicensing fee), she will do so more aggressively when the refurbishing cost is low, exiting the secondary market and benefiting indirectly from its existence at higher values of the refurbishing cost.

We also examine how the OEM's strategy changes as the number of the independent entrants increases, i.e. the secondary market becomes more competitive. We find that both the OEM's profits as well as the size of the secondary market grow with an increase in the number of entrants. Interestingly, the OEM decreases her relicensing fee even as the sales volume of refurbished equipment grows, and the cannibalization of new products increases. This is because an increasing network of resellers strengthens the marginal impact of the relicensing fee on the resale value effect relative to the corresponding impact on the cannibalization effect. As a result, the OEM chooses to lower the relicensing fee, further stimulating the procurement competition among the entrants, and benefits from the higher resale value of her used product.

We conclude by analyzing OEM strategies in a differentiated new product duopoly setting. Our numerical results show the high-end OEM always charges a higher relicensing fee than the low-end OEM, and the difference between relicensing fees can be significant. Thus, a high relicensing fee need not be indicative of an attempt to shut down the secondary market, but rather reflect the brand premium the high-end OEM commands. This result may help explain the significantly different relicensing fees observed in practice. Overall, our research highlights the strategic importance of supporting an active secondary market under a wide range of circumstances, particularly in the presence of strategic consumers and low refurbishing costs.

2. Literature Review

A rapidly growing stream of literature on remanufacturing has focused on the competition between the OEM and independent refurbishers/remanufacturers (Majumder and Groenevelt 2001, Debo et al. 2005, Ferguson and Toktay 2006, Ferrer and Swaminathan 2006), or the role of OEM-initiated remanufacturing in primary market competition between OEMs (Heese et al. 2005, Atasu et al. 2007). We contribute to this literature in the following ways.

First, although the first set of papers provide a theoretical framework for analyzing the competition between the OEM and potential entrants that refurbish and sell the OEM's product, with the exception of an extension in Debo et al. (2005), they do not incorporate the effect of the resale value on the consumers' net utility from purchasing a new product[2]. As a result, they focus only on the cannibalization effect, and therefore, the existence of independent remanufacturers is always detrimental for the OEM's profit. We contribute to this stream by endogenizing the resale value on the secondary market, and more importantly, by linking it to the consumers' willingness to pay for a new product. Thus, competition from an independent refurbisher has both a positive (resale value effect) and a negative (cannibalization of new product sales) impact on the OEM's profit. We show that the resale value effect can dominate and the OEM can benefit from the existence of an entrant.

Second, Debo et al. (2005) find that as the number of remanufacturers increases (cannibalization increases), the OEM's profit decreases despite the positive resale value effect. With the relicensing fee mechanism, we show that a higher competitive intensity in the secondary market can benefit the OEM. This happens because the relicensing fee allows the OEM to directly impact the secondary market: The OEM increases her profits by reducing the relicensing fee and increasing the product's resale value as remanufacturing competition increases.

[2] Heese et al. (2005) model the impact of the resale value as well, but in the context of primary market competition between OEMs while treating it as an exogenous effect on the secondary market.

Third, we show that if the OEM decides to refurbish her own products in conjunction with a relicensing fee mechanism, she will dominate the secondary market at low refurbishing costs, while leaving the secondary market to the entrant at higher levels of refurbishing cost. This is consistent with Heese et al. (2005), who show that an OEM that has a cost or market advantage can enter refurbishing first to deter competing OEMs from doing so, Ferrer and Swaminathan (2006), who show that a higher remanufacturing cost savings means higher participation by the OEM in the secondary market, and Ferguson and Toktay (2006), who find that as the entrant becomes more competitive and the cannibalization threat increases, the OEM should increase her efforts to deter the secondary market. If the OEM makes a strategic determination not to participate in the refurbished product market, however, then she should pursue the diametrically opposed strategy of supporting the secondary market at low levels of the refurbishing cost to exploit the strong resale value effect in this cost range.

While the idea that a secondary market can benefit the OEM is relatively new in the remanufacturing literature, it is well established in the durable goods literature, a thorough review of which can be found in Waldman (2003). Until the early 1970s, the main conclusion regarding the impact of secondary markets on a monopolist's profitability was due to the cannibalization effect between new and used products. In the words of Gaskins (1974), "conventional economic wisdom... contends that the existence of a competitive secondhand market constitutes a major long-run restraint on monopoly power in a primary market." Motivated by the market for diamonds, however, Miller (1974) argues that "the buyer of a newly produced diamond pays a price consistent with what the diamond can be sold for to others including members of later generations" and thus "the initial price captures the present value of all subsequent transactions." In essence, he points out the "resale value effect," arguing that a secondary market might increase the value derived by the consumer, and in turn, the price that the monopolist can charge for it. This argument is also stressed by Benjamin and Kormendi (1974), Liebowitz (1982), Rust (1986), and Levinthal and Purohit (1989), who all argue that whether or not a monopolist has the incentive to eliminate the secondary market is not clear-cut. A limitation of these papers is the assumption that the demand side is modeled by a representative consumer (homogeneous consumer preferences). Anderson and Ginsburgh (1994) argue that in those models, the size of the second-hand market is indeterminate since the representative consumer buys both new goods and used goods each period and essentially sells the used good to herself. By introducing a model in which consumers have heterogeneous tastes, they show that the existence of a secondary market enables the monopolist to achieve price discrimination between high and low valuation consumers who buy new and used products, respectively.

Models allowing consumers to have heterogeneous tastes are refined in further research by Waldman (1996, 1997), Desai and Purohit (1998), Hendel and Lizzeri (1999) and Desai et al. (2004, 2007). Waldman (1996) employs the seminal Mussa and Rosen (1978) analysis of market segmentation and product-line pricing to allow consumers to vary in their valuations of quality. His main result is that because of the substitution effect between new and used products, the price at which old units trade on the secondary market constrains the price that the monopolist can charge for the new units. Therefore, he demonstrates that the monopolist may have an incentive to "shut down" the market by reducing durability to "sufficiently low" values. In a follow-up paper, Waldman (1997) demonstrates that leasing versus selling can be used to eliminate the secondary market, and argues that this motivation might have been the primary reason for many prominent antitrust leasing cases (United Shoe, IBM, Xerox). Hendel and Lizzeri (1999) study leasing and selling strategies under secondary markets when durability is endogenous and the OEM can either allow a fully functioning secondary market (perfectly competitive with no restrictions) or shut down the secondary market completely. They show conditions where the OEM would not want to shut down the secondary market but prefers reducing the durability instead. Finally, Desai and Purohit (1998) and Desai et al. (2004, 2007) include the discounted resale price (resulting from perfect competition in the second period) in the consumer's first-period valuation of the new product, but their primary focus is on evaluating leasing versus selling, solving the time-consistency problem, or evaluating the impact of demand uncertainty, respectively.

We contribute to the literature on interfering with the secondary market along the following dimensions. First, we introduce one more mechanism to this literature – imposing a relicensing fee – and are the first to capture the strategic implications of this widespread mechanism. Unlike previously explored mechanisms that require the OEM to make modifications to her product or market strategies, the relicensing fee mechanism is "costless" in that the OEM can set the fee as high as needed to deter the entrants without any direct repercussions. We show that nevertheless, the OEM should not shut down the secondary market under a wide range of conditions. By treating the relicensing fee as a continuous decision variable, we avoid restricting the OEM to either fully supporting or completely shutting down the secondary market (e.g. as in Hendel and Lizzeri 1999).

Second, we analyze the relicensing fee strategy in depth, by modeling operational elements such as production cost and refurbishing cost, by making a distinction between the inherent durability of the product and the value to the customer after refurbishing, by varying the level of competitive intensity on the secondary market, and by allowing competition in the primary market. We highlight some of these elements below:

We relax the common assumption of perfect competition in the secondary market and allow for a profit-maximizing entrant to collect and refurbish the used products (in the durable goods literature, consumers are allowed to sell the used product to each other, creating a perfectly competitive secondary market, and refurbishing cost is not modeled). The value offered to the consumers for the used product by the entrant is determined as his optimal response to the OEM's decisions. Thus, the purchase price for used units and the prices charged to consumers for new and refurbished products arise as the Nash equilibrium of the game between the OEM and the entrant. This allows us to examine the impact of the production and refurbishing costs on the OEM's strategy. We also study how the relicensing fee strategy changes with respect to the number of entrants.

We also relax the assumption of a monopolist OEM by allowing vertically differentiated new products to compete in the primary market. To our knowledge, we are the first to model differentiated new and refurbished products competing in both the primary and secondary markets. We find that the high-end OEM always charges a higher relicensing fee than the low-end OEM and that the difference between relicensing fees can be significant. Yet, whether a high-end or a low-end OEM has a greater secondary market depends on the market conditions and the relative brand differential between the two OEMs. Our results indicate that even with competition in the primary market, it remains rare for either OEM to eliminate the secondary market, although the total size of the secondary market decreases as the brand premium of the high-end OEM decreases.

We conclude by highlighting a contribution at the intersection of the remanufacturing and durable goods literatures. Prior work on durable goods theory assumes consumers trade among each other, selling the (depreciated) used product as is. In contrast, prior work on remanufacturing assumes that a used product provides no utility unless it is refurbished. Our model captures both aspects, where the product depreciates with use, but it can be refurbished by an entrant to offer a higher utility than if used as is. We are thus able to separate the effect of inherent product durability from the effect of the remanufacturing process. As our analysis reveals, although both effects reduce the demand for new products in the second period, their role on the relicensing strategy is diametrically opposite. In particular, the optimal relicensing fee decreases in the durability of the product, but increases in the value that the customer obtains from the refurbished product. As explained in detail later, the difference stems from the way in which these two features affect the resale value of the product.

3. Key Assumptions and Notation

Our baseline analysis assumes the OEM holds a monopoly in the new product market. We develop a two-period model. In the first period, the OEM sells new products. In the second period, the OEM may again sell new products, and there is a third-party entrant who may refurbish and resell used products bought from the OEM's first-period customers. Thus, in the second period, the OEM's new product sales face competition from the refurbished products offered by the entrant. At the same time, the OEM generates relicensing fee revenues from the refurbished products. Our goal is to examine the OEM's relicensing fee strategy in the face of future competition from refurbished products. We make the following assumptions:

Assumption 1. *Consumer willingness-to-pay is heterogeneous and uniformly distributed in the interval* $[0,1]$.

We assume that consumer types are distributed uniformly in the interval $[0,1]$, where a consumer of type $\theta \in [0,1]$ has a willingness-to-pay of θ for a new product. In any period, each consumer uses at most one unit. The market size is normalized to 1. With this representation, in a single-period problem with only the new product, consumer θ's utility function would be $U_1(\theta) = \theta - p_1$, where U_1 represents consumer utility and p_1 is the price paid for the new product. This would lead to the familiar inverse demand function $p_1 = 1 - q_1$, where q_1 is the quantity of new product sold in the first period. Demand functions for our two-period model are developed in the Analysis section.

Assumption 2. *The product depreciates with use.*

The rate of depreciation of a product depends on its durability, which we parametrize by δ_o. Thus, if the consumer type θ who bought a new product in the first period continues to use that product in the second period, the utility he obtains in that period is $\delta_o\theta$. If $\delta_o = 0$, consumers obtain no utility from their used product in the second period. In this case, the product's useful life (in the absence of being refurbished by the entrant) is effectively only one period. Therefore, all first-period customers re-enter the market in the second period, and can buy another new product or a refurbished product. The majority of remanufacturing papers make this one-period useful product life assumption (Majumder and Groenevelt 2001, Ray et al. 2005, Ferrer and Swaminathan 2006, Ferguson and Toktay 2006, and Atasu et al. 2007).

Assumption 3. *Consumers do not sell their used products directly to each other.*

Used IT equipment, before it can be reused by another party, typically requires some costly refurbishing effort (e.g., updating software, replacing hardware components, testing the equipment). Thus, we assume that consumers cannot sell their used products directly to each other. Instead, a third-party refurbisher buys used products from first-period consumers (return volume depends on the price offered by the entrant), and enters the market in the second period by refurbishing and reselling these products. This assumption reflects the current practice in the used IT market where most used equipment, before it can be resold, requires software updates and the replacement of wearable parts that the consumers do not have the technical capability to perform.

Assumption 4. *Each consumer's willingness-to-pay for the refurbished product is a fraction* δ *of their willingness-to pay for the new product, where* $\delta_o < \delta < 1$.

Under this assumption, a consumer with a willingness-to-pay θ for the new product has a willingness-to-pay $\delta\theta$ for the refurbished one. The nature of competition between new and refurbished units is thus one of vertical differentiation. That is, for the same price, consumers prefer a new product to a refurbished one. This assumption is driven by the evidence that consumers are concerned about the quality of a refurbished product and this is reflected in their willingness to pay for it. Empirical evidence for lower valuation of remanufactured products is offered in Guide and Li (2007), and Subramanian and Subramanyam (2007). This perspective is also reflected in a number of articles in the practitioner and academic literature (Lund and Skeels 1983, Hauser and Lund 2003, Kandra 2002, Debo et al. 2005, Vorasayan and Ryan 2006, Jin et al. 2007). Since refurbishing involves software updates, the replacement of wearable parts, cleaning and testing, the relative utility that a customer would obtain from using a refurbished product is higher than if he just kept using his now-used product that he had purchased in the first period. We capture this by assuming $\delta_o < \delta$.

Assumption 5. *The disutility to a consumer of reselling a used product is a fraction of his original willingness-to-pay for the new product.*

The entrant offers a resale value (denoted by s) to first-period customers to purchase their used products at the end of the first period. We assume that a consumer with a willingness-to-pay θ for a new product will incur a perceived transactional disutility (hereafter disutility) of $\gamma\theta$ (where $0 < \gamma < \delta$) to sell his used product to the entrant (e.g. perceived disutility of searching for IT resellers, removing sensitive data, etc.). Hence, a higher incentive is needed to induce a higher willingness-to-pay consumer to resell his used product. This is consistent with consumer search theory which states that consumers are diversified with respect to how much disutility they perceive from such searching, with wealthy consumers experiencing the greatest loss (Phlips 1983, Mehta et al. 2003). This behavioral characteristic also forms the basis behind the common use of product rebates that allow price discrimination between consumers who will take the time to send in the rebate and those who will not. For example, Gerstner and Hess (1991) argue that "there is a positive association between willingness-to-pay and redemption costs" (Gerstner and Hess 1991, p. 875) since "high-end customers have higher time costs for the activities required to take advantage of the discount" (Gerstner et al. 1994, p. 1438). Obviously, the higher the rebate, the higher the percentage of customers that claim it. Similarly, with this assumption, the higher the price offered by the entrant, the higher the percentage of customers who will sell their used product to the entrant. In line with previous research on reverse logistics and remanufacturing, this assumption ensures that the average cost of acquisition increases in the quantity of the products collected (Guide 2000, Guide and Van Wassenhove 2001, Galbreth and Blackburn 2006, Ferguson and Toktay 2006).

Assumption 6. *Consumers are strategic.*

There is empirical evidence that IT consumers are strategic in their purchasing behavior (Song and Chintagunta 2003, Nair 2004, Plambeck and Wang 2006). Accordingly, we assume that consumers take into account the future resale value s of the product in making their purchase decisions. This is facilitated in practice by the existence of IT consulting companies that offer resale value forecasts.

Assumption 7. *The OEM charges a relicensing fee h in the second period to any consumer who purchases a refurbished product.*

The establishment of a relicensing fee, typically called a Digital License Agreement (DLA), has been widely employed by OEMs as a means of protecting their intellectual property rights. A DLA allows a consumer to re-install the necessary software for the equipment to operate and thus, a refurbished product is of no use without it. OEMs publish list prices for new equipment (that implicitly includes both hardware and software cost) and most publish a separate list where their relicensing policies are explicitly laid out. The relicensing fee, declared in the first period, constitutes an important element of our model, since it affects the resale value offered by the entrant, which is taken into account by strategic consumers of new products. In particular, the utility that each consumer derives from purchasing a refurbished product is given by the difference of their willingness-to-pay and the price plus the relicensing fee.

Assumption 8. *In the second period, the OEM introduces new products technologically equivalent or superior to the ones introduced in the first period.*

The IT industry is characterized by rapid technological change. It is typical for an OEM to introduce an improved version of her existing product not long after the original product introduction. For instance, an upgraded version might have a faster Central Process Unit (CPU) or bigger memory. To capture the increased consumer willingness-to-pay due to this technology improvement, we assume that a consumer with a willingness-to-pay θ for the new product in the first-period has a willingness-to-pay $\alpha\theta$, where $\alpha \geq 1$, for a new second-period product.

4. Analysis: Monopoly in the New Product Market

In this section, we analyze the model with a single OEM who sells a new product in both periods and charges a relicensing fee for refurbished products that are acquired, refurbished and resold by entrants in the second period.

In this competitive setting, the OEM has a significant advantage over the entrants: She controls the relicensing fee that consumers of refurbished products need to pay on top of the purchase price charged by the entrants. As the relicensing fee increases, the cost to consumers of the refurbished product increases, which in turn reduces demand and shifts consumers to the new product. At first sight, a high value for the relicensing fee may seem like a good idea for the OEM, since it eliminates the competition from the refurbished product. Eliminating the secondary market, however, has an important impact on first-period profits. Since consumers can no longer sell their used products to an entrant, the net utility they obtain from the new product decreases. Consequently, the price charged by the monopolist OEM, along with her first-period profits, is lower than it would have been had the consumers foreseen a positive resale value for their used products. Hence, the OEM needs to balance the impact of two opposite forces: A lower relicensing fee leads to competition in the second period, but allows the OEM to charge a premium in the first period that reflects the consumer's ability to resell the product in the second period.

To analyze this trade-off systematically and delineate the impact of various drivers, we start with a baseline model where $\delta_o = 0$ and there is a single entrant. Then we explore the following extensions that shed light on the role of the resale value effect, competition and durability: non-strategic consumers, N entrants, OEM participation in the secondary market and $\delta_o > 0$.

Analysis of the Baseline Model

With the baseline model assumption that the used product offers no utility in the second period ($\delta_o = 0$), two-period consumer strategies decompose into two independent single-period decisions: In period 1, the consumer choices are to buy new or to not buy, and in period 2, the consumer choices are to buy new or refurbished or nothing, regardless of their first-period decision. In addition, first-period buyers decide to sell their product to the entrant or not (depending on the value of s relative to their disutility $\gamma\theta$), which impacts their net first-period utility, but has no impact on their second-period choices.

Derivation of Demand Functions. As discussed above, the two periods decouple in the consumer strategy space. Let us start with the first-period decision of the consumer, to buy a new product or not. The resale value of the product, since it is a consequence of selling the product bought in the first period, needs to be included in the net utility obtained from that product's purchase. Consumer θ will sell the used product to the entrant for a price s only if this value is greater than his disutility $\gamma\theta$. Therefore, a strategic consumer of type θ derives a net utility of $U_1(\theta) = \theta - p_1 + (s - \gamma\theta)I_{(s \geq \gamma\theta)}$ from purchasing a new product in period 1, where $I_{(s \geq \gamma\theta)} = 1$ when $s \geq \gamma\theta$ and 0 otherwise.

As shown in Figure 1, contingent on their type, first-period consumers fall in one of three segments. If $\theta \leq \frac{p_1 - s}{1-\gamma}$, consumers do not purchase the new product, while for $\frac{p_1 - s}{1-\gamma} < \theta \leq \frac{s}{\gamma}$, consumers purchase the new product and subsequently resell it. Finally, for $\frac{s}{\gamma} < \theta \leq 1$, consumers purchase the new product and do not resell it. Therefore, the total sales quantity in period 1 is $q_1 = 1 - \frac{p_1 - s}{1-\gamma}$, or, $p_1 = (1-\gamma)(1-q_1) + s$, and the total number of units acquired by the entrant is given by $q_u =$

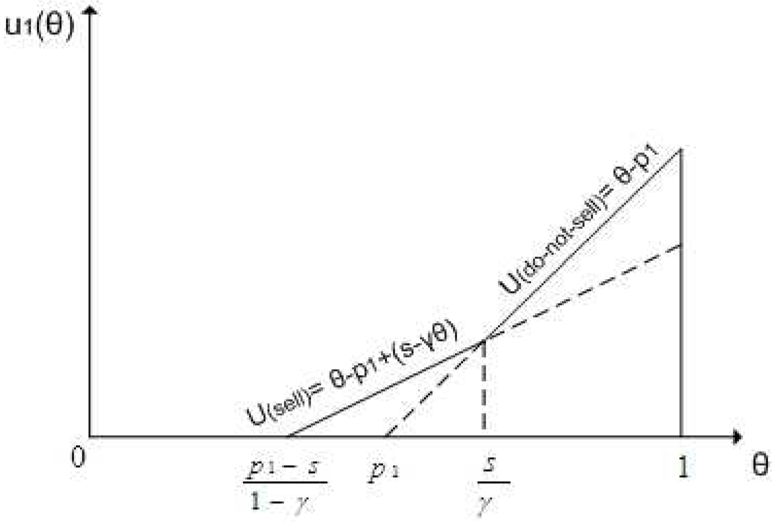

Figure 1 Consumer state space and corresponding utilities from selling versus not selling the used product.

$\frac{s}{\gamma} - \frac{p_1 - s}{1-\gamma}$. Note that the entrant would never set $s > \gamma$, as $s = \gamma$ is sufficient to ensure all consumers sell their used products ($q_u = q_1$).

We now turn to the second period. Let p_2 and p_r denote the second-period prices of new and refurbished products, respectively. Following our previous discussion, the corresponding consumer utilities obtained by consumer type θ from purchasing each type of product in the second-period are $U_2(\theta) = \alpha\theta - p_2$ for the new product and $U_r(\theta) = \delta\theta - p_r - h$ for the refurbished product. From these utility functions, and letting q_2 and q_r represent the second-period quantities of new and refurbished product respectively, the inverse demand functions are

$$p_2 = \alpha(1 - q_2) - \delta q_r$$
$$p_r = \delta(1 - q_r - q_2) - h.$$

Analysis of the Second-Period OEM-Entrant Competition. We solve the problem by backward induction, starting with the second period. Let Π_2 and Π_e denote the OEM's and the entrant's second-period profit, respectively. At this stage, the OEM decides the quantity of new products that she will sell in the market, while the entrant decides the price s that he will offer to the consumers to obtain their used products, as well as the quantity of refurbished products that he will make available in the market, denoted by q_r. We assume that the unit production cost is $c < 1$, and the unit refurbishing cost is $c_r < c$.

The OEM's second-period objective given the entrant's choice of q_r is

$$Max_{q_2}\ \Pi_2(q_2|q_r) = (p_2 - c)q_2 + hq_r = (\alpha - \alpha q_2 - \delta q_r - c)\, q_2 + hq_r \quad s.t.\ q_2 \geq 0. \tag{1}$$

The first part of (1) captures the profit obtained from selling q_2 units of new products while the second part represents the profit from the relicensing fee (h), obtained from the q_r customers who purchase the refurbished units from the entrant. The quantity of new products to sell is the only decision variable for the OEM in the second period as the relicensing fee is set in the first period.

The entrant's corresponding objective given the OEM's choice of q_2 is

$$Max_{q_r,s}\ \Pi_e(q_r, s|q_2) = (p_r - c_r)q_r - sq_u \quad s.t.\ 0 \leq q_r \leq q_u \tag{2}$$

$$\text{where } q_u = \frac{s}{\gamma} - \frac{p_1 - s}{1-\gamma}.$$

The constraint in (2) ensures the quantity of refurbished product is no greater than the number of units collected from the consumers at a resale price of s, given by $q_u = \frac{s}{\gamma} - \frac{p_1 - s}{1-\gamma}$ (see Figure 1). In practice, the amount collected falls far short of the volume of existing used products, so we do not explicitly model the constraint $q_u \leq q_1$ and limit the analysis to parameters where $q_u^* < q_1^*$ in equilibrium. Where appropriate, the potential effect of this constraint is discussed. The following lemmas characterize the price the entrant will pay for the used units.

LEMMA 1. *At optimality, the entrant has no incentive to collect more units than the ones he intends to sell in the market. That is, the constraint $q_r \leq q_u$ is binding and the optimal resale price offered by the entrant satisfies*

$$s^*(q_r) = \gamma(1-\gamma)q_r + \gamma p_1. \tag{3}$$

All proofs are provided in the Appendix.

LEMMA 2. *For equilibria where both new and refurbished products co-exist in period 2, the equilibrium resale value is given by $s^*(q_1, h) = \gamma \frac{[2\gamma\alpha(\gamma-1)+\delta(\delta-4\alpha)]q_1 + [5\delta+2\gamma(1-\gamma)-2(h+c_r)]\alpha+\delta c-\delta^2}{2\gamma\alpha(2-\gamma)+\delta(4\alpha-\delta)}$ while the corresponding second-period quantities are $q_2^*(q_1, h) = \frac{\delta h - \gamma\delta q_1 - \delta(\delta-\gamma)+\delta c_r - (\alpha - c)[\gamma(\gamma-2)-2\delta]}{2\gamma\alpha(2-\gamma)+\delta(4\alpha-\delta)}$ and $q_r^*(q_1, h) = \frac{2\alpha(\gamma q_1 - h - \gamma - c_r)+\delta(\alpha+c)}{2\gamma\alpha(2-\gamma)+\delta(4\alpha-\delta)}$.*

The second lemma reveals two interesting properties of the equilibrium resale value. First, s^* decreases in the quantity of new products sold in the first period. This observation is consistent with the resale values we observe in practice: Whenever a large supply of a specific used model becomes available, its resale value drops dramatically. Second, s^* increases as the relicensing fee h decreases: A low value of h means a higher profit potential from the secondary market, thus the entrant is willing to offer a higher resale price to first-period consumers. In addition, the entrant's decision of whether to enter the market or not is directly related to the relicensing fee h, since the latter affects the profitability of refurbished products. Therefore, the OEM acts as a Stackelberg leader who decides between allowing the existence of a secondary market or not by her choice of h. To characterize the optimal OEM strategy, we need to examine the total profit across both periods. Thus, we now move to the OEM's first-period decisions.

Analysis of the OEM's First-Period Strategy. In the first period, the OEM's decisions include the quantity of new units to sell as well as the relicensing fee. More specifically, the OEM's problem is

$$Max_{q_1,h}\ \Pi(q_1,h) = \Pi_1(q_1,h) + \Pi_2^*(q_1,h) \quad s.t.\ q_1 \geq 0,\ h \geq 0, \tag{4}$$

where $\Pi_1(q_1,h)$ denotes the profit from the sales of new products in the first period. Thus,

$$\Pi_1(q_1,h) = [p_1(q_1,h) - c]\, q_1 = [(1-\gamma)(1-q_1) + s^*(q_1,h) - c]\, q_1,$$

where $s^*(q_1,h)$ is characterized in Lemma 2. Although we ignore discounting in our formulation, the addition of a discount factor to the second-period profit does not fundamentally change our results, but reinforces the resale value effect, as the OEM cares more about first-period profits.

We are now ready to state our main result for the baseline model. The following proposition states that as long as the refurbishing cost is below a threshold value, the OEM is always better off by maintaining a secondary market for her products.

Proposition 1. *For $c_r < c\frac{(\delta-\alpha\gamma)}{\alpha}$, it is not optimal for the OEM to eliminate the secondary market ($q_r^* > 0$). The OEM charges a positive relicensing fee $h^* > 0$, which is decreasing in c and c_r but increasing in α. For $c\frac{(\delta-\alpha\gamma)}{\alpha} \leq c_r < \frac{1}{2}[\delta(1+\frac{c}{\alpha}) - \gamma(1+c)]$, the OEM charges a positive relicensing* *fee so as to eliminate the secondary market ($q_r^* = 0$). For $c_r \geq \frac{1}{2}[\delta(1+\frac{c}{\alpha}) - \gamma(1+c)]$, $h^* = 0$ and $q_r^* = 0$.*

Proposition 1 may appear counter-intuitive at first glance: As the entrant becomes more competitive in relation to the OEM (c_r decreases in relation to c), the OEM chooses not to eliminate the secondary market. The result is driven by the double benefit that the OEM obtains from the secondary market: the resale value effect and relicensing fee revenues. At low values of refurbishing cost, these benefits outweigh the negative impact of cannibalization even though this is where the entrant poses the most competition to the OEM. But it is precisely because entry is more desirable for the third-party refurbisher that he offers a high resale value to first-period customers, which benefits the OEM. When consumers have a higher willingness-to-pay for the refurbished product or when their transactional disutility is lower, this makes entering the secondary market more attractive, captured in an increasing threshold value below which the OEM allows the secondary market to exist. These results warn against the common perception of many OEMs that competition from an outside firm through the secondary market is always detrimental to their profits. It is possible for the OEM to co-opt the third party into her business strategy by using the relicensing fee strategically.

As the technology improvement parameter α increases, the threshold value $c\frac{(\delta-\alpha\gamma)}{\alpha}$ decreases. For radical technology improvements ($\alpha \geq \frac{\delta}{\gamma}$), the OEM shuts down the secondary market regardless of the refurbishing cost. Intuitively, a higher technology improvement leads to a higher profit margin from the new product in the second period, and thus, the OEM adopts a more aggressive strategy against the secondary market. For this reason, we also observe that the optimal relicensing fee increases in α. On the other hand, when the refurbishing cost c_r increases, the OEM lowers the relicensing fee. Note that both higher α and higher c_r make the new product more competitive against a refurbished product, yet they have the opposite effect on the relicensing fee. A higher α gives the OEM an incentive to change the balance between the primary and secondary market to exploit the additional profit margins from the new products. In contrast, a higher c_r limits the ability of the entrant to maintain a secondary market and distorts the balance the OEM considers optimal. As a result, the OEM attempts to strengthen the secondary market by lowering the relicensing fee. Finally, when the production cost c increases, the OEM lowers the relicensing fee and the quantity of refurbished units increases. In this case, the OEM prefers to produce fewer new units in the second period and exploit the resulting increase in the resale value by charging a higher price for the new product in the first period.

In the range $c\frac{(\delta-\alpha\gamma)}{\alpha} \leq c_r \leq \frac{1}{2}[\delta(1+\frac{c}{\alpha})-\gamma(1+c)]$, the OEM sets $h^*>0$ so as to eliminate the secondary market ($q_r^*=0$) since the high refurbishing cost prevents the entrant from offering a high enough resale price. Hence, the resale value benefit from maintaining an active secondary market does not outweigh the detrimental effect of cannibalization. For even higher values of the refurbishing cost, $c_r > \frac{1}{2}[\delta(1+\frac{c}{\alpha})-\gamma(1+c)]$, the secondary market is not viable: $q_r^*=0$ even if the relicensing fee were set to zero. Thus, $h^*=0$ and $q_r^*=0$.

The Role of the Resale Value Effect

We attributed the OEM's choice to "live and let live" for low enough refurbishing cost to the resale value effect and the relicensing fee. To separate out the impact of these two factors, we can analyze the same problem, but with non-strategic consumers who do not take the resale value into account when they purchase a new product. In this case, there is no resale value effect by definition. It can be shown that Proposition 1 holds in this setting, with the first threshold changing to $\frac{c\delta-\frac{1}{2}\alpha\gamma(1+c)}{\alpha} < c\frac{(\delta-\alpha\gamma)}{\alpha}$ (see Oraiopoulos et al. 2007 for the derivation of this result when $\alpha=1$). Thus, when consumers are non-strategic, and the OEM only benefits from the relicensing fee revenue, it is optimal for the OEM to eliminate the secondary market under a much wider range of conditions. For example, the OEM may prefer to eliminate the secondary market even when the refurbishing cost is zero and there is no technology improvement (this happens when the threshold $c\delta-\frac{1}{2}\gamma(1+c)$ is negative).

This finding demonstrates that a forward-looking consumer base can influence the OEM's secondary market strategy. The common perception in the IT industry is that historically, consumers of IT products did not take into account the future resale value in their initial purchases. This could explain why some IT OEMs have historically deployed policies to deter the secondary market for their products. As mentioned in the introduction however, there are indications that consumers of IT equipment are becoming increasingly concerned about resale values during their initial purchase decisions. Our results suggest that this is not necessarily a bad trend for the OEM, but her secondary market strategies need to evolve with the market.

The Role of Competition

As discussed above, Proposition 1 reveals a somewhat counterintuitive finding about the role of third-party competition. To explore the impact of competition on the OEM's strategy further, we take a two-pronged approach: i) We analyze the effect of the competitive intensity of the secondary market on the OEM strategy and profit, and ii) We allow the OEM to interfere with the secondary market directly by refurbishing herself.

Competitive Intensity of the Secondary Market. The significant profit opportunity in the secondary market has given rise to a number of firms founded with the sole purpose of buying and refurbishing used IT equipment (CBRonline.com 2005). According to the United Network Equipment Dealer Association (uneda.com), there are over 300 certified refurbishers today and many more who are not yet certified. To capture this phenomenon, we increase the competitive intensity within the secondary market by allowing N symmetric third-party entrants to compete in acquiring, refurbishing and reselling the used products (this model is similar to Debo et al. 2005).

One may expect that as the number of entrants increases, the OEM employs a more aggressive strategy vis-à-vis the secondary market and her profit decreases. Interestingly, however, we show the OEM's relicensing fee is decreasing and her profit is concave increasing in the number of entrants. (The analysis for the case $\alpha = 1$ can be found in Oraiopoulos et al. 2007.) Consistent with standard economic theory, as the number of entrants increases, internal competition drives the prices of the refurbished units down and the secondary market attracts more consumers (the overall quantity of refurbished products increases). This leads to higher cannibalization of new units in the second period, but also to a higher resale value. In fact, adding an additional entrant increases the marginal impact of the relicensing fee on the resale value more than it increases the detrimental cannibalization effect. As a result, the OEM charges a lower relicensing fee, providing greater support to the secondary market. This result differs from Debo et al. (2005) who find that an increase in the competitive intensity of the secondary market reduces both the OEM's incentive to invest in remanufacturability and her profit. This difference can be explained through the strategic as well as the economic role of the relicensing fee: The OEM not only has a more powerful mechanism of controlling the demand for refurbished products, she also derives revenues from the relicensed equipment.

The OEM Participates in the Secondary Market. At first sight, our conclusion that the OEM welcomes competition in the secondary market seems counter to the previous results in the remanufacturing literature. For example, Ferrer and Swaminathan (2006) show a higher remanufacturing cost savings means higher participation by the OEM in the secondary market. Ferguson and Toktay (2006) find that as the entrant becomes more competitive (c_r becomes lower) and the cannibalization threat increases, the OEM should increase her efforts to deter the secondary market.

The difference in these findings is driven by how the OEM interferes with the secondary market. Remanufacturing is a direct approach, while imposing a relicensing fee is an indirect approach. In practice, some OEMs adopt a strategy of not participating in the secondary market, while others enter the refurbishing business. To investigate the impact of the latter approach, we extend our baseline model to allow refurbishing by the OEM. Our analysis yields the following results:

At low levels of the refurbishing cost, the OEM charges a high relicensing fee and places a much larger volume of refurbished product on the market compared to the entrant. This is because the OEM's margin on the refurbished product is $h + p_r - c_r - s$, while the entrant's margin is only $p_r - c_r - s$. In addition, the OEM benefits from the resale value effect. As the refurbishing cost increases, the margins from refurbished products drop, and the capacity to charge a high relicensing fee decreases, so the quantity refurbished by the OEM drops significantly. This allows the entrant to increase his quantity, but not enough to compensate the decrease in the OEM's quantity. Thus, similar to our baseline model, the overall size of the secondary market decreases in the refurbishing cost. As the refurbishing cost increases further, the OEM completely exits the secondary market, and in this range, the results are qualitatively the same as in the model where the OEM is not allowed to refurbish.

In summary, the OEM exploits the market for refurbished products herself when the profit margin is high, but leaves the entrant to do so when the margin is low, capturing value only via the relicensing fee and the resale value effect.

This analysis enriches our understanding of the role of competition: At low levels of refurbishing cost, it is optimal for the OEM to remanufacture in conjunction with imposing relicensing fees, a result consistent with previous models (Debo et al. 2005, Ferrer and Swaminathan 2006, Ferguson and Toktay 2006, etc.). This strategy limits the participation of third-party entrants in the market. If the OEM makes a strategic determination not to participate in the refurbished product market (e.g. Sun) for other reasons (brand equity worries, resistance from sales department, etc.), however, then she should pursue the diametrically opposed strategy of supporting the secondary market at low refurbishing cost to exploit the strong resale value effect in this cost range.

The Role of Durability

A key assumption in our baseline model is the one-period product lifetime assumption ($\delta_o = 0$). That is, a product bought in the first period provides no utility in the second period, unless it is refurbished by the entrant. This assumption reflects the fact that for IT equipment where relicensing fees are common such as servers and networking equipment, most users upgrade to the newest generation when it is introduced because of performance requirements and software compatibility issues. There is however, a portion of the IT market where these issues are of lower concern, such as mainframes and workstations. For these products, consumers may decide to "hold on to" their used products despite the reduced functionality they provide, and abstain from the market in the second period. We explore the implications of such a consumer segment by letting $\delta_o > 0$; the higher the δ_o, the more "durable" the product. To maintain tractability, we focus on the special case of $\alpha = 1$ (i.e., no technological improvement) and $\gamma = 0$ (no transactional disutility). With the assumption $\gamma = 0$, the consumer's decision about whether to return or keep a product boils down to a comparison of the utility the used product affords versus the sum of the resale value and the net utility from buying a new product. Since the utility of keeping the product is $\delta_o\theta$, consumers are heterogeneous in their utility from replacing the product, and the volume returned increases in s as in the baseline model even though $\gamma = 0$. The derivation of the demand functions based on two-period consumer strategies, and the supporting analysis leading up to the main result in Proposition 2 below are presented in Appendix B.

Proposition 2. *There exists $\widetilde{c_r}$ such that for $c_r < \widetilde{c_r}$, it is not optimal for the OEM to eliminate the secondary market: $q_r^* > 0$. Moreover, for $c_r < \widetilde{c_r'} < \widetilde{c_r}$, the OEM charges a positive relicensing fee h^* which decreases in c_r, but increases in c. For $\widetilde{c_r'} < c_r < \widetilde{c_r}$, the OEM sets the relicensing fee to zero ($h^* = 0$).*

Proposition 2 states that the OEM allows for a secondary market to exist when the refurbishing cost in low enough. In addition, the optimal relicensing fee decreases in the refurbishing cost c_r. These results are structurally the same as our findings in Proposition 1. Thus, the fundamental conclusions about when the OEM should allow the secondary market to exist and how she should deploy the relicensing fee do not depend on the level of durability of the product. A set of numerical experiments (available from the authors) show that the impact of α and γ in this model is also consistent with their impact described in the baseline model.

There is one difference however, in the role the production cost c plays: The relicensing fee h^* increases in the production cost c, whereas it decreases in the production cost when $\delta_o = 0$. This difference stems from how production cost impacts the resale value effect. When $\delta_o > 0$, as the production cost increases, fewer new products are sold in the second period, and thus, fewer first-period consumers decide to replace their used product with a new one. In other words, fewer first-period consumers benefit from the resale value effect. Consequently, the resale value effect is weakened as the production cost increases, and the OEM increases the relicensing fee. In contrast, when $\delta_o = 0$, the number of customers who decide to return their products is independent of the production cost. In fact, a higher production cost has only the direct effect of reducing the OEM's margin. As a result, the entrant is more competitive, and willing to pay a higher resale value to a larger number of customers. Hence, the resale value effect is strengthened as the production cost increases and the OEM lowers the relicensing fee.

COROLLARY 1. *The relicensing fee h^* decreases in δ_o, but increases in δ.*

The fact that h^* decreases in δ_o is particularly interesting if we contrast it with the impact of the production cost c. Higher durability expands the market segment that chooses to keep using the product, and shrinks the segment of consumers who decide to sell their used products and buy a new one in the second-period. This is similar to the effect of a higher production cost. However, higher durability generates higher consumer utility, and therefore, higher demand for new products in the first period. The increased volume amplifies the value captured from the resale value effect, since more consumers can be charged the price premium stemming from it. Consequently, the OEM finds it profitable to drop the relicensing fee as durability increases.

Corollary 1 allows us to disentangle the effect of inherent product durability from the effect of the remanufacturing operation. Prior work on durable goods theory assumes that consumers trade among each other, selling the (depreciated) used product, which offers relative utility δ_0, as is. In contrast, prior work on remanufacturing assumes that a product is of no value ($\delta_0 = 0$) unless it is refurbished, in which case it offers relative utility $\delta (> \delta_0)$. One might expect δ and δ_o to have the same impact on h^*, since as they increase, they both reduce the demand for the new product in the second period. Interestingly, Corollary 1 shows that they have opposite effects on the OEM's relicensing fee. A higher δ_o means that consumers obtain more utility from the product over its life-cycle and the size of the new product market increases. As discussed above, this results in the OEM decreasing h^* as the durability δ_o increases. In contrast, a higher δ generates a higher willingness-to-pay for a refurbished product that the entrant exploits and increases the threat of cannibalization. Consequently, as δ increases, the OEM increases the relicensing fee, both to exploit the additional value that consumers place on the refurbished product and to keep cannibalization in check. This is similar to the effect of decreasing c_r on the relicensing fee.

5. Analysis: Differentiated Duopoly in the Primary Market

Thus far, we have assumed a monopolist setting in the primary market with the competition being restricted to the secondary market. In practice, the IT primary market is characterized by competition. Industry experts stress performance, efficiency, flexibility, longevity, reliability, and maintenance as factors of primary importance (ServerWatch 2008, SearchServerVirtualization 2008). According to a recent market research report regarding the selection criteria for IT servers, quality and reliability were found to be the most important ones (IDC 2006). These are dimensions of vertical differentiation: For the same price, higher reliability, efficiency etc. are preferred to lower reliability, efficiency, etc. To capture this characteristic of the IT market, we relax the monopolistic primary market assumption and develop a vertically differentiated duopoly model where consumers place a higher value on firm A's product than on firm B's product. This assumption allows us to address two critical questions: What are the pricing and relicensing strategies of each OEM and how do they differ? What is the impact of the quality (performance, reliability, etc.) differential on those strategies?

We capture the difference in the perceived quality between firms as follows: A consumer who derives utility θ from a new product by firm A derives utility $(1-\beta)\theta$ from a new product by firm B. Without loss of generality, we assume that $\beta > 0$ so that firm B represents the low-end firm. The relative difference in consumers' valuations, β, is called the brand differential or the brand premium of the high-end OEM. We also assume an equal rate of perceived utility depreciation for both firms. That is, a consumer derives utility $\delta\theta$ from firm A's refurbished product, while he derives utility $(1-\beta)\delta\theta$ from firm B's. This assumption allows us to maintain the same relative brand differential between OEMs on the secondary market. We assume that $\delta < 1-\beta$ so that a given consumer values the low-end firm's new product strictly more than the high-end firm's refurbished product. This is a reasonable assumption based on observations of the current state of the IT industry and eliminates the trivial case where one firm dominates both the primary and secondary markets. In addition, we normalize the cost of refurbishing to zero for both products. This rules out refurbishing cost disparity from explaining the differences in the OEMs' strategies and corresponds to the more interesting cases in Proposition 1 where the existence of a secondary market is beneficial for the OEM. Finally, we assume a perfectly competitive secondary markets for each type of refurbished product. This implies that for any given used product purchase prices, s^A and s^B, $p^A_{2,r} = s^A$ and $p^B_{2,r} = s^B$. While we do this for tractability, the analysis of the competitive secondary market case suggests that the structure of the optimal policy is essentially the same for any level of competitive intensity on the secondary market.

Similar to our baseline model, we solve the problem by backward induction, starting with the second period (Appendix C). Unlike our previous analysis, however, deriving the Nash equilibrium $(q^*_{1A}, h^*_A, q^*_{1B}, h^*_B)$ for any arbitrary set of parameters is much more complex because the profit expressions are long and do not allow easy algebraic handling. Rather, our approach is to solve the unconstrained game and subsequently identify the range of parameter values in which the results are meaningful (e.g. Desai 2001). Therefore, hereafter, we focus on those parameter values for which all non-negativity constraints are satisfied, namely, all market segments have positive quantities in equilibrium. For those parameters, we conduct an extensive numerical investigation and explore how the optimal OEM strategies (relicensing fee and quantity decisions) change as a function of the brand premium. In the numerical study, we calculate the equilibrium quantity and relicensing fee decisions for every combination of the parameter values $\delta \in [0.3, 0.8]$, $\gamma \in [0.01, 0.15]$, and $c \in [0.01, 0.5]$ (discretized in increments of 0.1, 0.03, and 0.05, respectively). We find that as long as all non-negativity constraints are satisfied, the insights remain the same across all the parameter combinations. These insights are described in Observations 1-3 below. Figure 2 provides an illustrative example while Table 1 summarizes the impact of δ, γ, c on the equilibrium decisions.

	h^*_A	h^*_B	q^*_{2A}	q^*_{2B}	q^*_{UA}	q^*_{UB}
$\delta \nearrow$	$\nearrow$	$\nearrow$	$\searrow$	$\searrow$	$\nearrow$	$\nearrow$
$\gamma \nearrow$	$\searrow$	$\searrow$	$\nearrow$	$\nearrow$	$\searrow$	$\searrow$
$c \nearrow$	$\searrow$	$\searrow$	$\searrow$	$\searrow$	$\nearrow$	$\nearrow$

Table 1: Comparative Statics when all Market Segments Exist.

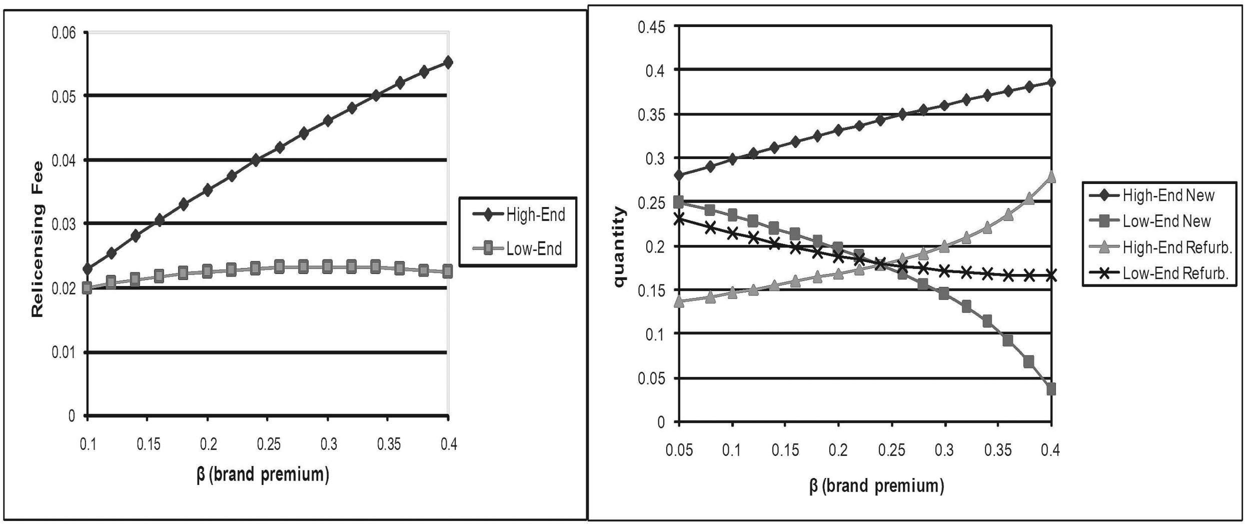

Figure 2 **Relicensing Fees (left) and Equilibrium Quantities in Second Period (right) as a function of β for δ=0.5, γ=0.05, and c=0.15,**

Observation 1: *The high-end OEM always charges a higher relicensing fee than the low-end OEM and the difference between the relicensing fees can be large.*

This is because the high-end OEM's relative brand premium exists in the secondary market as well, which she capitalizes on by charging a higher relicensing fee. Note that despite the higher relicensing fee h_A^*, the high-end OEM maintains an active secondary market. Thus, a high relicensing fee need not be indicative of an attempt to shut down the secondary market, but rather reflect the brand premium a particular OEM commands. As reported in Table 1, our comparative statics analysis suggests that for a fixed brand premium between the two OEMs, both relicensing fees increase in δ, and decrease in γ and c.

Observation 2: *The high-end OEM's relicensing fee increases in the brand premium (β). For the low-end OEM, there is a non-monotonic relationship between the relicensing fee and the brand premium: h_B^* first increases and then decreases in β.*

To understand this relationship, we must look at how a marginal change in the brand premium affects the equilibrium decisions of each OEM. A marginal increase in β increases both the primary and the secondary markets for the high-end OEM's products. An increase in the brand premium β is translated to a higher relicensing fee at any β value since consumers have higher willingness-to-pay for her refurbished products. In contrast, the low-end OEM increases h_B^* only at low values of β. For low values of β, the low-end OEM has a considerable presence in both the primary and secondary markets. An increase in the brand premium hurts both the primary and secondary markets, the former to a larger extent. The low-end OEM attempts to maintain her primary market presence by increasing her relicensing fee and limiting the cannibalization effect. On the contrary, for high values of β where the high-end OEM dominates, the low-end OEM's primary market has significantly shrunk, and the impact of a marginal increase in β on cannibalization is much less significant. As a result, we observe a decrease in the relicensing fee as an attempt to strengthen the resale value effect.

The effect of δ, γ and c on the equilibrium quantities can be observed in Table 1. A higher δ makes the secondary market more profitable, so the secondary market grows at the expense of the primary. A higher γ makes the secondary market less profitable, so the opposite effect is seen. Finally, a higher c lowers the profitability of new products, so the primary market shrinks and the secondary market grows.

Observation 3: *There is a threshold value for the brand premium β below which the low-end OEM's product makes up a larger share of the secondary market. This threshold increases as δ decreases, γ* increases, or *c decreases.*

Observation 3 suggests that although a positive brand premium always translates to a larger market share in the primary market (under symmetric production costs), the same is not true for the corresponding secondary markets. This result could explain the strategy of some high-end OEMs who choose not to have large secondary markets for their refurbished products despite the brand premium they command. Note also that a lower c makes the primary market more profitable, while a lower δ or a higher γ reduces the margins of the secondary market. Thus, the above conditions make the primary market more attractive to the high-end OEM, who has a leadership advantage, leaving the low-end OEM to focus on the secondary market (via relicensing fees).

In our analysis, we assume an equal unit production cost for both the high-end and low-end OEM; thus the differentiation is along the brand premium dimension. This is a reasonable assumption for many IT products since they can be characterized as development-intensive-products, i.e. products whose fixed costs of development far outweigh the unit variable costs (Krishnan and Zhu 2006). Because our focus is on a firm's decisions for a given product line, we do not consider these initial fixed costs. If the assumption of equal production costs is relaxed and the high-end OEM has a higher production cost, we expect her to decrease her relicensing fee to increase the resale value of her primary product.

6. Conclusions

Secondary markets in the IT industry have grown steadily, forcing OEMs to form strategies to respond to them. For products such as servers and storage devices, OEMs have a powerful mechanism at their disposal: instituting a software relicensing fee charged to secondary users. A high relicensing fee can virtually shut down the secondary market, while a low relicensing fee can allow it to thrive. The optimal strategy is not obvious: An active secondary market not only generates relicensing revenues for the OEM but also has an indirect positive benefit by increasing the OEM's new product's resale value, which in turn, increases the price that can be charged for the new product (resale value effect). At the same time, it also has a direct detrimental effect as the refurbished product competes with the OEM's new product (cannibalization effect) in future periods. In practice, comparable OEMs have surprisingly different relicensing fee strategies. The existing literature on secondary markets does not provide guidance concerning this widespread mechanism. Our paper fills this gap by contributing to the theory of secondary markets and by providing managerial guidelines on the use of relicensing fees.

Our research makes several theoretical contributions to the literature on how OEMs should balance their primary and secondary markets. First, we explicitly model the role of the relicensing fee. Though widespread, the relicensing fee mechanism has not been studied in the literature to date. Our paper is the first to examine both the economic (i.e., direct revenues) and the strategic (i.e., interference mechanism) implications of this mechanism. Second, unlike prior research that assumes that used products are traded among consumers in a perfectly competitive market, we model the incentive of independent entrants to purchase, refurbish, and resell those used products. By doing so, we account for the operational realities of maintaining a secondary market, that is, the refurbishing process. In practice, reselling an IT product worth several thousand dollars requires a number of procedures (e.g., replacing hardware components, testing performance, etc.) that are not costless. As our analysis reveals, the effect of such procedures, proxied by the magnitude of the refurbishing cost, is a key determinant of the OEM's strategy vis-à-vis the secondary market. In addition, by explicitly modeling the independent entrants, we are able to examine how an increase in the competitive intensity in the secondary market (i.e., higher number of entrants) affects the OEM's strategy. Third, current theoretical frameworks that consider a monopolist OEM have limited power in explaining the adoption of different secondary market strategies by competing OEMs. In our duopoly model, we capture the equilibrium relicensing fee strategies of competing OEMs and compare how they evolve as the brand premium between them increases. To our knowledge, our paper is the first to study differentiated new and refurbished products competing in both the primary and secondary markets.

In parallel, we complement the rapidly growing literature on remanufacturing by linking the consumers' willingness-to-pay for a new product to the potential resale value of the product at the end of use. By doing so, we show that a market for refurbished products can benefit the OEM even if it is operated by independent entrants. Finally, our comprehensive model allows us to disentangle the effect of inherent product durability from the effect of the remanufacturing process. Prior work on remanufacturing assumes that after one period of use, the product has zero utility for the consumer unless it is refurbished, in which case it offers a fraction of the utility offered by a new product. In contrast, the literature on durable goods assumes that a product can be used in subsequent periods as is, offering the consumer a fraction of its original utility. Our model is the first to integrate these two effects, namely, the inherent durability of the product and the value added by the refurbishing process. We show that although they both imply that the used or refurbished product is a closer substitute to the new product, their effect on the OEM's relicensing fee strategy is diametrically opposite.

Our results help IT OEMs to identify critical tradeoffs involving the relicensing fee along the dimensions of technology improvement, refurbishing cost, and competitive dynamics. We find that in the presence of radical technology improvements, the OEM should increase the relicensing fee to make the refurbished product less affordable and to increase the market share of her second-generation new product. A second critical factor in the OEM's decision is the refurbishing cost. If the OEM chooses to enter the refurbishing business herself, then she should do so aggressively at low refurbishing cost. Interestingly, if the OEM chooses not to undertake refurbishing, a low refurbishing cost should make the OEM willing to support a secondary market, even though this market is operated by third-party entrants who become more competitive as the refurbishing cost decreases. This happens because the OEM can then exploit the secondary market through the resale value effect and the relicensing fee revenues. This is especially important for an OEM with high production costs: The right combination of price and relicensing fee allows the OEM to mitigate the low margin of her new product by producing fewer units but charging a price premium for them due to the resale value effect. Our experience is that OEMs are very concerned with cannibalization and tend to overlook the resale value effect. When using the relicensing fee mechanism only, it is precisely in cases where cannibalization is a strong threat that the OEMs should embrace the secondary market. This requires a strategic shift in the OEM's approach relative to the case where she refurbishes her own products. The above results hold even when the OEM faces competition from multiple third-party entrants. In fact, the strategic and economic value of an active secondary market for the OEM are amplified as the number of entrants increases. Therefore, the OEM should actually lower the relicensing fee to strengthen the resale value effect as the competitive intensity increases, despite the stronger threat of cannibalization.

Finally, our differentiated duopoly model offers insights regarding the different relicensing fee strategies observed in practice. As we would expect, the high-end OEM always charges a higher relicensing fee since her brand premium is maintained in the secondary market. In fact, the high-end OEM should monotonically increase her relicensing fee as her brand premium is strengthened. Interestingly, however, although a brand premium always translates to a larger market share in the primary market, the same is not true for the corresponding secondary market. This result could explain the strategy of some high-end OEMs who choose not to have large secondary markets for their refurbished units despite the brand premium they command. Thus, it is possible that certain conditions make the primary market more attractive to the high-end OEM, who has a leadership advantage, leaving the low-end OEM to focus on the secondary market (via her relicensing fees).

To conclude, our paper highlights the strategic importance of supporting an active secondary market under a wide range of circumstances, particularly in the presence of strategic consumers and a low refurbishing cost. These conditions are valid in the IT industry today: There exist a large number of industry analyst firms who specialize in forecasting the resale value of IT equipment and who offer comprehensive cost/benefit analysis over the life-cycle of the IT equipment while the modularity of IT solutions makes refurbishment a cost-effective proposition for many products. Thus, charging very high relicensing fees with the purpose of shutting down the secondary market, a strategy attributed to some IT OEMs, appears to be myopic and suboptimal in the presence of strategic consumers. At the same time, we demonstrate that charging higher relicensing fees than lower end competitors need not mean an OEM is doing so with the sole purpose of eliminating the secondary market, but rather that she is capitalizing on her brand premium.

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Appendices

Appendix A: Proofs

Proof of Lemma 1. The entrant's optimization problem given the OEM's choice of q_2 is

$$Max_{q_r,s}\Pi_e(q_r,s|q_2) = [\delta(1-q_r-q_2)-h-c_r]\,q_r - s(\frac{s}{\gamma}-\frac{p_1-s}{1-\gamma})$$

$$\text{s.t.}\quad 0 \le q_r \le \frac{s}{\gamma}-\frac{p_1-s}{1-\gamma}. \tag{EC.1}$$

The Lagrangian for the entrant's problem is $L(q_r,s,\lambda_1,\lambda_2) = [\delta(1-q_r-q_2)-h-c_r]\,q_r - s(\frac{s}{\gamma}-\frac{p_1-s}{1-\gamma}) + \lambda_1(\frac{s}{\gamma}-\frac{p_1-s}{1-\gamma}-q_r)+\mu_1 q_r$.

The Kuhn-Tucker conditions for optimality are $\frac{\partial L}{\partial q_r}=0$, $\frac{\partial L}{\partial s}=0$, $\lambda_1(\frac{s}{\gamma}-\frac{p_1-s}{1-\gamma}-q_r)=0$ and $\mu_1 q_r=0$, with $0\le q_r \le \frac{s}{\gamma}-\frac{p_1-s}{1-\gamma}$, $\lambda_1\ge 0$, $\mu_1\ge 0$.

Assume $\frac{s}{\gamma}-\frac{p_1-s}{1-\gamma}-q_r>0$. Then, at optimality, $\lambda_1=0$. Solving $\frac{\partial L}{\partial s}=0$, we get $s^*=\frac{\gamma p_1}{2}$, which gives $\frac{s^*}{\gamma}-\frac{p_1-s^*}{1-\gamma}=-\frac{p_1}{2(1-\gamma)}<0$, which violates the original condition $\frac{s}{\gamma}-\frac{p_1-s}{1-\gamma}-q_r>0$.

Since this case cannot meet the KT conditions, we hereafter assume that the right constraint in (EC.1) is binding. Intuitively, the entrant would not be willing to acquire more used units than the quantity she would sell in the secondary market. Rewriting this equality, we obtain $s^*(q_r)=\gamma(1-\gamma)q_r+\gamma p_1$, where we suppress dependence on p_1 determined in period 1.

Proof of Lemma 2. Based on Lemma 1 we can reduce the entrant's problem to a single decision variable optimization problem in q_r:

$$Max_{q_r}\Pi_e = [p_r - s^*(q_r)-c_r]\,q_r = [p_r-\gamma(1-\gamma)q_r-\gamma p_1-c_r]\,q_r \quad s.t.\;\; q_r\ge 0. \tag{EC.2}$$

We also know the profit function of the OEM

$$Max_{q_2}\Pi_2(q_2|q_r) = (p_2-c)q_2+hq_r = (\alpha-\alpha q_2-\delta q_r-c)\,q_2+hq_r \quad s.t.\; q_2\ge 0. \tag{EC.3}$$

Here, Π_e and Π_2 are concave in q_r and q_2, respectively. By solving the first-order conditions simultaneously, we can obtain the following Nash equilibrium:

$$q_2^*(p_1,h) = \frac{2(\delta+\gamma-\gamma^2)(\alpha-c)-\delta^2+\delta h+\delta\gamma p_1+\delta c_r}{4\gamma\alpha(1-\gamma)+\delta(4\alpha-\delta)} \tag{EC.4}$$

$$q_r^*(p_1,h)=\frac{\alpha(\delta-2c_r-2h-2\gamma p_1)+\delta c}{4\gamma\alpha(1-\gamma)+\delta(4\alpha-\delta)}. \tag{EC.5}$$

Substituting q_r^* from (EC.5) into the expression derived in Lemma 1 gives

$$s^*(p_1,h)=\frac{\gamma[(2\alpha\gamma(1-\gamma)p_1+\delta(4\alpha-\delta)p_1-2\alpha(1-\gamma)(h-c_r)+\delta(1-\gamma)c]}{4\gamma\alpha(1-\gamma)+\delta(4\alpha-\delta)}. \tag{EC.6}$$

Recall that the quantity of new units sold in the first period by the OEM can be expressed as

$$q_1=1-\frac{p_1-s}{1-\gamma},\ \text{or, } p_1=(1-\gamma)(1-q_1)+s. \tag{EC.7}$$

Substituting p_1 from (EC.7) into (EC.6), we obtain the equilibrium price s^* that the entrant pays the first-period consumers to collect used products as a function of q_1 and h:

$$s^*(q_1,h)=\gamma\frac{[2\gamma\alpha(\gamma-1)+\delta(\delta-4\alpha)]q_1+[5\delta+2\gamma(1-\gamma)-2(h+c_r)]\alpha+\delta c-\delta^2}{2\gamma\alpha(2-\gamma)+\delta(4\alpha-\delta)}. \tag{EC.8}$$

Moreover, from (EC.6) and (EC.7) we can rewrite (EC.4) and (EC.5) in terms of q_1 and h:

$$q_2^*(q_1,h)=\frac{\delta h-\gamma\delta q_1-\delta(\delta-\gamma)+\delta c_r-(\alpha-c)[\gamma(\gamma-2)-2\delta]}{2\gamma\alpha(2-\gamma)+\delta(4\alpha-\delta)} \tag{EC.9}$$

$$q_r^*(q_1,h)=\frac{2\alpha(\gamma q_1-h-\gamma-c_r)+\delta(\alpha+c)}{2\gamma\alpha(2-\gamma)+\delta(4\alpha-\delta)}. \tag{EC.10}$$

This Nash equilibrium is valid as long as the right-hand sides of (EC.9) and (EC.10) are non-negative, respectively, which can be written as $h-\gamma q_1\geq A$ and $h-\gamma q_1\leq B$, where $A\doteq(\delta-\gamma)-c_r+\frac{(\alpha-c)\gamma(\gamma-2)}{\delta}-2(\alpha-c)$ and $B\doteq\frac{1}{2\alpha}\delta(\alpha+c)-(\gamma+c_r)$.

Proof of Proposition 1. In period 1, the OEM chooses $q_1\geq 0$ and $h\geq 0$ so as to maximize the sum of first- and second-period profits. The OEM's second-period profit can be obtained using (EC.9 - EC.10) as long as q_1 and h satisfy $h-\gamma q_1\geq A$ and $h-\gamma q_1\leq B$. For completeness, we need to characterize the OEM's second-period profit outside this range, or argue that the optimal solution will satisfy the two conditions. For a given q_1, it is in fact sufficient to restrict the domain of h to values yielding a non-negative quantity in (EC.10), $h-\gamma q_1\leq B$, since once the secondary market has been eliminated, increasing h does not improve the OEM's profits. The same need not be true however for (EC.9); even when the OEM abstains from the primary market in the second period, he can improve his profits by decreasing h and increasing first-period resale value, and we cannot use the expressions in Lemma 2 to calculate second-period profits in this range ($h-\gamma q_1 < A$). We proceed by enforcing $h-\gamma q_1 \leq B$, but determining the optimal OEM strategy for those values of q_1 and h yielding $h-\gamma q_1 \geq A$ (Case A) and $h-\gamma q_1 \leq A$ (Case B), separately, and then combining the results.

Case A ($h-\gamma q_1 \geq A$). The OEM's optimization problem is

$$Max_{q_1,h}\ \Pi(q_1,h) = \Pi_1(q_1,h) + \Pi_2^*(q_1,h)$$

$$\text{s.t.}\quad A \leq h-\gamma q_1 \leq B$$

$$q_1 \geq 0, \quad h \geq 0,$$

where $\Pi_1(q_1,h) = (p_1(q_1,h)-c)q_1$ denotes the profit from the sales of new products in the first period and $\Pi_2^*(q_1,h)$ is calculated using (EC.9) and (EC.10). The determinant of the Hessian of the objective function $\Pi(q_1,h)$ is $\frac{4\alpha(8\delta\alpha-3\delta^2+8\gamma\alpha(1-\gamma)}{[2\gamma\alpha(\gamma-2)+\delta(\delta-4\alpha)]^2} > 0$ with $\frac{\partial^2\Pi(q_1,h)}{\partial q_1^2} < 0$. Thus, the Hessian is negative definite and the profit function is concave in (q_1,h).

Define the Lagrangian $L(q_1,h,\lambda_1,\lambda_2) = \Pi(q_1,h) + \lambda_1(h-\gamma q_1 - A) + \lambda_2(B-h+\gamma q_1) + \mu_1 h$. The Kuhn-Tucker conditions for optimality are:

$$\frac{\partial L}{\partial q_1} = 0 \tag{EC.11}$$

$$\frac{\partial L}{\partial h} = 0 \tag{EC.12}$$

$$\lambda_1(h-\gamma q_1 - A) = 0 \tag{EC.13}$$

$$\lambda_2(B-h+\gamma q_1) = 0 \tag{EC.14}$$

$$\mu_1 h = 0 \tag{EC.15}$$

and $\lambda_1 \geq 0$, $\lambda_2 \geq 0$, $\mu_1 \geq 0$. The constraint $q_1 \geq 0$ will be checked separately. Note that $\lambda_1\lambda_2 = 0$, since otherwise both constraints (EC.13) and (EC.14) would be binding, which is not possible.

Case A.I : $\lambda_1 = 0$, $\lambda_2 \neq 0$, $\mu_1 = 0$.

$\lambda_2 \neq 0$ implies $B - h^* + \gamma q_1^* = 0$. Solving the KT conditions, we obtain $h^* = \frac{1}{2}[\delta(1+\frac{c}{\alpha}) - \gamma(1+c)] - c_r$, $q_1^* = \frac{1}{2}(1-c) > 0$, $q_2^* = \frac{1}{2}(1-\frac{c}{\alpha}) > 0$ and $\lambda_2 = 2\,\frac{c(\delta-\alpha\gamma)-\alpha c_r}{2\gamma\alpha(\gamma-2)+\delta(\delta-4\alpha)}$ with corresponding profit $\frac{(1-c)^2}{2}$. Case I is valid for $\lambda_2 > 0$ and $h^* \geq 0$, or, $\frac{c(\delta-\alpha\gamma)}{\alpha} < c_r \leq \frac{1}{2}[\delta(1+\frac{c}{\alpha}) - \gamma(1+c)]$ and represents the case of having no refurbished products in the second period due to the high remanufacturing cost and the positive relicensing fee.

Case A.II : $\lambda_1 = 0$, $\lambda_2 \neq 0$, $\mu_1 \neq 0$.

$\lambda_2 \neq 0$ implies $B - h^* + \gamma q_1^* = 0$. Moreover, $\mu_1 \neq 0$ implies $h^* = 0$. Solving the KT conditions, we obtain $q_1^* = \frac{1}{2}\,\frac{2(\alpha\gamma+c_r)-\delta(\alpha+c)}{\alpha\gamma}$ and $\mu_1 = \frac{(1+c)\alpha\gamma-\delta(\alpha+c)+2\alpha c_r}{\alpha\gamma^2}$.

We need $\mu_1 > 0$, which is true for $c_r > c_{r,\mu_1} \doteq \frac{1}{2}[\delta(1+\frac{c}{\alpha}) - \gamma(1+c)]$. We also need $\lambda_2 > 0$. From the expression for λ_2 (omitted for brevity), we have $\frac{\partial\lambda_2}{\partial c_r} = \frac{2(\delta^2-4\alpha\delta+3\alpha\gamma^2-4\alpha\gamma)}{(2\alpha\gamma^2-4\alpha\gamma-4\alpha\delta+\delta^2)\gamma^2} > 0$, so λ_2 is increasing in c_r. Therefore it is sufficient to show that $\lambda_2(c_r = c_{r,\mu_1}) > 0$. But $\lambda_2(c_r = c_{r,\mu_1}) = -\frac{(\alpha\gamma-\delta)c+(\delta-\gamma)\alpha}{(2\alpha\gamma^2-4\alpha\gamma-4\alpha\delta+\delta^2)} > 0$, so $\lambda_2 > 0$.

Therefore, this case is valid for $c_r > \frac{1}{2}[\delta(1+\frac{c}{\alpha}) - \gamma(1+c)]$ and represents the case of having no refurbished products in the second period due to the high remanufacturing cost even if the OEM sets the relicensing fee to zero. This condition also ensures that $q_1^* > 0$.

Case A.III : $\lambda_1 \neq 0, \lambda_2 = 0$, $\mu_1 = 0$.

$\lambda_1 \neq 0$ implies $h^* - \gamma q_1^* = A$. Solving the KT conditions, we obtain $q_1^* = \frac{1}{2}\,\frac{(1-c)(\delta+2\alpha\gamma)}{\delta} > 0$, $h^* = \frac{1}{2}\,\frac{[4\gamma(1-\gamma)+\delta(4-\gamma]c+4\gamma\alpha(\gamma-1)+2\delta(\delta-c_r)-\delta(4\alpha+\gamma)}{\delta}$, and $\lambda_1 = \frac{[\delta(\delta-8\alpha+2\alpha\gamma)+8\gamma\alpha(\gamma-1)]c+\delta(8\alpha^2-3\delta\alpha+2\alpha c_r)+8\gamma(1-\gamma)\alpha^2}{\delta\left(2\alpha\gamma^2-4\alpha\gamma-4\alpha\delta+\delta^2\right)}$. Case III is valid for $\lambda_1 > 0$ and $h^* \geq 0$ or, $c \geq \max\{c_{\lambda_1}, c_{h^*}\}$, where $c_{\lambda_1} = \frac{\alpha[\delta(8\alpha-3\delta+2c_r)+8\gamma\alpha(1-\gamma)]}{\delta(8\alpha-\delta-2\gamma\alpha)+8\alpha\gamma(1-\gamma)}$ and $c_{h^*} = \frac{4\alpha\gamma(\gamma-1)+2\delta(\delta-c_r)-\delta(4\alpha+\gamma)}{4\gamma(\gamma-1)+\delta(\gamma-4]}$ are the values of c that satisfy $\lambda_1(c) = 0$ and $h^*(c) = 0$, respectively. Let $\bar{c} \doteq c_{\lambda_1} - c_{h^*}$. Note that $\frac{d\bar{c}}{d\alpha} = \frac{\delta^3[(8\gamma^2-8\gamma-8\delta+2\delta\gamma)c_r-8\gamma^2\delta+8\gamma\delta+8\delta^2-3\delta^2\gamma}{\left(8\alpha\gamma^2-8\alpha\gamma-8\alpha\delta+2\delta\gamma\alpha+\delta^2\right)^2\left(-2\gamma^2+4\gamma+4\delta-\delta^2\right)} > 0$ because the denominator is always positive, while the numerator is decreasing in c_r and is positive for $c_r = \delta-\gamma > \frac{(\delta-\alpha\gamma)}{\alpha} > \frac{c(\delta-\alpha\gamma)}{\alpha}$. Thus $\frac{d\bar{c}}{d\alpha} > 0$ for $c_r < \delta-\gamma$. Also $\bar{c}(\alpha=1) = -\frac{2\delta(4\gamma^2-4\gamma+\delta\gamma-4\delta+\delta^2)(\delta-\gamma-c_r)}{\left(8\gamma^2-8\gamma+2\delta\gamma-8\delta+\delta^2\right)\left(4\gamma^2-4\gamma-4\delta+\delta\gamma\right)} > 0$ because $c(\delta-\gamma) > c_r$ (for if we assume that $c(\delta-\gamma) \leq c_r$, $\lambda_1 < 0$ and this case becomes impossible) and $c < 1$. Therefore, $\max\{c_{\lambda_1}, c_{h^*}\} = c_{\lambda_1}$ and $h^* > 0$.

Case III represents the case of having no new products in the second period due to the high unit production cost, but charging a positive relicensing fee, and is valid for $c > \frac{\alpha[\delta(8\alpha-3\delta+2c_r)+8\gamma\alpha(1-\gamma)]}{\delta(8\alpha-\delta-2\gamma\alpha)+8\alpha\gamma(1-\gamma)}$.

Case A.IV : $\lambda_1 \neq 0, \lambda_2 = 0,\ \mu_1 \neq 0$.

$\lambda_1 \neq 0$ implies $h^* - \gamma q_1^* = A$. Case IV is valid for $\lambda_1 > 0$, $\mu_1 > 0$ and $q_r^* > 0$. The latter is positive when $c_r < \delta - \frac{1}{2}\gamma(1+\alpha)$. However, μ_1 is linearly decreasing in c, λ_1 is linearly increasing in c, and $c_{\mu_1} < c_{\lambda_1}$because $\lambda_1(c_{\mu_1}) < 0$. To prove the latter note that $\dfrac{\partial \lambda_1(c_{\mu_1})}{\partial c_r} = \frac{\delta\,(-8\alpha+2\delta+2\gamma\alpha)-8\alpha\gamma(1-\gamma)}{\delta\left(4\,\gamma^2-4\,\gamma-4\,\delta+\delta\gamma\right)} > 0$ and also that for $c_r = \delta - \frac{1}{2}\gamma(1+\alpha)$, $\lambda_1(c_{\mu_1}) = \frac{\alpha\gamma(1-\alpha)}{\delta} \leq 0$ since $\alpha \geq 1$. Therefore, λ_1 and μ_1 can never be positive at the same time, and this case is impossible.

Case A.V : $\lambda_1 = 0, \lambda_2 = 0, \mu_1 = 0$. Solving the KT conditions we obtain $h^* = \frac{1}{2}\frac{(-8\delta\gamma^2+8\delta^2+8\gamma^3-8\gamma^2-8\gamma c_r+8\gamma^2 c_r-8\delta c_r)\alpha^2+(3\gamma\delta^2-3\delta^3+\gamma\delta^2 c+4c_r\delta^2)\alpha-\delta^3 c}{\alpha[8\,\gamma(1-\gamma)\alpha+8\delta\alpha-3\delta^2]}$, $q_1^* = \frac{1}{2}\frac{(8\gamma+4c\gamma^2-8\gamma^2-8\delta c-4\gamma c_r-8c\gamma+8\delta^2)\alpha-3\delta^2(1+c)+4\gamma\delta c}{8\,\gamma(1-\gamma)\alpha+8\delta\alpha-3\delta^2}$, $q_2^* = \frac{1}{2}\frac{(8\gamma^2-8\gamma-8\delta)\alpha^2+(8c\gamma+3\delta^2-8c\gamma^2-2\delta c_r-2\gamma\delta c+8\delta c)\alpha-\delta^2 c}{\alpha[8\,\gamma(\gamma-1)\alpha+3\,\delta^2-8\delta\alpha]}$, and $q_r^* = \frac{2(\alpha c_r-c(\delta-\alpha\gamma))}{8\,\gamma(\gamma-1)\alpha+3\,\delta^2-8\delta\alpha}$.

We can see that $q_2^* \geq 0$ for $c \leq c_{q_2^*} = \frac{\alpha[\delta(8\alpha-3\delta+2c_r)+8\gamma\alpha(1-\gamma)]}{\delta\,(8\alpha-\delta-2\gamma\alpha)+8\alpha\gamma(1-\gamma)}$, while $q_r^* \geq 0$ for $c_r \leq \frac{c(\delta-\alpha\gamma)}{\alpha}$.

Moreover, $h^* \geq 0$ for $c \leq c_{h^*} \doteq -\frac{(3\gamma\delta^2-8\delta\alpha\gamma^2+8\delta^2\alpha+8\gamma^3\alpha-8\gamma^2\alpha-8c_r\delta\alpha-3\delta^3-8c_r\gamma\alpha+8c_r\gamma^2\alpha+4c_r\delta^2)\alpha}{\delta^2(-\delta+\gamma\alpha)}$. But $c_{h^*} - c_{q_2^*} > 0$ and therefore this case is valid for $c \leq \frac{\alpha[\delta(8\alpha-3\delta+2c_r)+8\gamma\alpha(1-\gamma)]}{\delta\,(8\alpha-\delta-2\gamma\alpha)+8\alpha\gamma(1-\gamma)}$.

Case V represents the case where both new and refurbished products exist in the second period with a positive relicensing fee.

Case A.VI : $\lambda_1 = 0, \lambda_2 = 0, \mu_1 \neq 0$.

Here $q_2^* > 0$ and $h^* = 0$. This case was also found to be impossible because $q_2^* \mu_1 < 0$. Another of way of seeing this is to note that both q_2^* and h^* decrease in c, but as c increases, it is always q_2^* that becomes zero first ($c_{h^*} > c_{q_2^*}$). Therefore the case of $q_2^* > 0$ and $h^* = 0$ is not possible.

Case B ($h - \gamma q_1 \leq A$). Solving for the Nash equilibrium in the second period under this condition, we obtain $q_2^*(q_1, h) = 0$ and $q_r^*(q_1, h) = \frac{\gamma q_1 - h + \delta - \gamma - c_r}{2(\delta+\gamma)-\gamma^2}$. The OEM's optimization problem is:

$$Max_{q_1,h}\ \Pi(q_1,h) = \Pi_1(q_1,h) + h q_r^*(q_1,h) = (p_1(q_1,h) - c)q_1 + h\frac{\gamma q_1 - h + \delta - \gamma - c_r}{2(\delta+\gamma)-\gamma^2} \qquad \text{(EC.16)}$$

$$\text{s.t.} \quad h - \gamma q_1 \leq A \qquad \text{(EC.17)}$$

$$h - \gamma q_1 \leq B \qquad \text{(EC.18)}$$

$$q_1 \geq 0, \quad h \geq 0.$$

Note that since $A < B$, constraint (EC.18) will never be binding at the optimal solution, and therefore can be eliminated. Solving the constrained maximization problem, we have the following cases:

Case B.I : For $c \geq \frac{\alpha[\delta(8\alpha-3\delta+2c_r)+8\gamma\alpha(1-\gamma)]}{\delta(8\alpha-\delta-2\gamma\alpha)+8\alpha\gamma(1-\gamma)}$, constraint (EC.17) is non-binding and the optimal values are $q_1^* = \frac{1}{4}\frac{\delta(2+\gamma)+2\gamma(1-\gamma)-\gamma c_r-(2\gamma+2\delta-\gamma^2)c}{\delta+\gamma-\gamma^2}$ and $h^* = \frac{1}{2}(\delta-\gamma-c_r)$, yielding $q_r^* = \frac{1}{4}\frac{\delta-\gamma c-c_r}{\delta+\gamma-\gamma^2}$. In this parameter range, $c_r < c(\delta-\gamma)$, which is in turn less than $\delta-\gamma$, so $h^* > 0$, $q_r^* > 0$ and $q_1^* > 0$.

Case B.II : For $c \leq \frac{\alpha[\delta(8\alpha-3\delta+2c_r)+8\gamma\alpha(1-\gamma)]}{\delta(8\alpha-\delta-2\gamma\alpha)+8\alpha\gamma(1-\gamma)}$, constraint (EC.17) is binding and the optimal values are $q_1^* = \frac{1}{2}\frac{(1-c)(\delta+2\alpha\gamma)}{\delta} > 0$, $h^* = \frac{1}{2}\frac{[4\gamma(1-\gamma)+\delta(4-\gamma]c+4\gamma\alpha(\gamma-1)+2\delta(\delta-c_r)-\delta(4\alpha+\gamma)}{\delta}$, yielding $q_r^* = \frac{\alpha-c}{\delta}$. Note that this case yields the same optimal solution and objective function value with Case A.III.

We illustrate the structure of the optimal solution subject to the conditions of Cases A and B in Figure EC.1, where we use the observation that $c \geq \tilde{c}(\delta,\gamma,c_r)$ implies $c \geq \frac{\alpha c_r}{\delta-\alpha\gamma}$, or, $c_r \leq \frac{c(\delta-\alpha\gamma)}{\alpha}$.

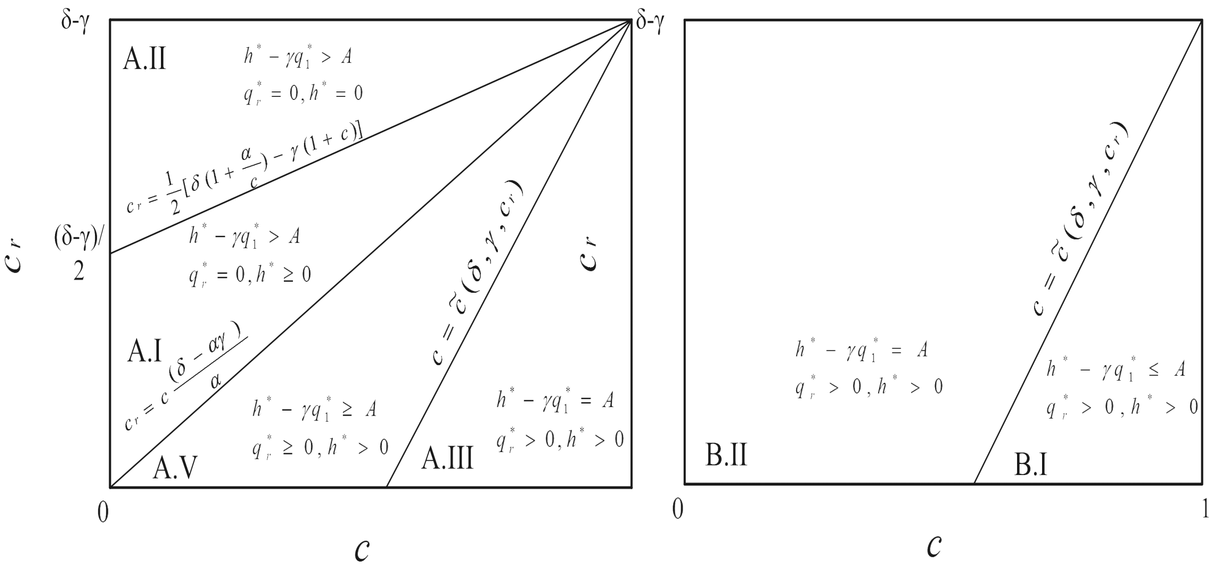

Figure EC.1 **Structure of Optimal Solution subject to constraints $h-\gamma q_1 \geq A$ (left panel) and $h-\gamma q_1 \leq A$ (right panel).**

We now compare the optimal constrained solutions of cases A and B to find the global optimal solution structure.

For $c \geq \tilde{c}(\delta,\gamma,c_r) \doteq \frac{\alpha[\delta(8\alpha-3\delta+2c_r)+8\gamma\alpha(1-\gamma)]}{\delta(8\alpha-\delta-2\gamma\alpha)+8\alpha\gamma(1-\gamma)}$, Cases A.III and Case B.I need to be compared to find q_1^* and h^* in this parameter range. Since both cases A and B include the boundary $h-\gamma q_1 = A$, but the optimal solution in case B satisfies $h^* - \gamma q_1^* < A$, while that in case A.III satisfies $h^* - \gamma q_1^* = A$, we conclude that case B.I gives the global optimum in this range.

For $c < \widetilde{c}(\delta, \gamma, c_r)$, Case B.II needs to be compared with Cases A.I, A.II and A.V to find q_1^* and h^* in their respective parameter ranges. Since both cases A and B include the boundary $h - \gamma q_1 = A$, but the optimal solutions in case A satisfy $h^* - \gamma q_1^* > A$, while that in case B.II satisfies $h^* - \gamma q_1^* = A$, we conclude that cases A.I, A.II and A.V give the global optimum in their respective parameter ranges. The structure of the optimal solution is summarized in the following table.

Condition	Equilibrium Outcome in the Second Period
$c > \widetilde{c}(\delta, \gamma, c_r) \doteq \frac{\alpha[\delta(8\alpha - 3\delta + 2c_r) + 8\gamma\alpha(1-\gamma)]}{\delta(8\alpha - \delta - 2\gamma\alpha) + 8\alpha\gamma(1-\gamma)}$	Only refurbished products
$c \leq \widetilde{c}(\delta, \gamma, c_r)$ and $c_r \leq \frac{c(\delta - \alpha\gamma)}{\alpha}$	Both new and refurbished products
$c \leq \widetilde{c}(\delta, \gamma, c_r)$ and $\frac{c(\delta - \alpha\gamma)}{\alpha} < c_r \leq \frac{1}{2}[\delta(1 + \frac{c}{\alpha}) - \gamma(1 + c)]$	Only new products. ($q_r^* = 0$ due to $h^* > 0$)
$c \leq \widetilde{c}(\delta, \gamma, c_r)$ and $c_r > \frac{1}{2}[\delta(1 + \frac{c}{\alpha}) - \gamma(1 + c)]$	Only new products. ($q_r^* = 0$ even if $h^* = 0$)

We now examine the impact of c, c_r, and α on h^* for the more interesting case where both new and refurbished products exist in the second period (Case V). The expression for h^* is given by $h^* = \frac{1}{2} \frac{(-8\gamma^2 - 8\gamma c_r - 8\delta c_r + 8\gamma^3 - 8\delta\gamma^2 + 8\delta^2 + 8\gamma^2 c_r)\alpha^2 + (4\delta^2 c_r - 3\delta^3 + 3\delta^2\gamma + \delta^2\gamma c)\alpha - \delta^3 c}{\alpha(8\alpha\delta - 3\delta^2 + 8\alpha(1-\gamma))}$. First note that $\frac{\partial h^*}{\partial c} = -\frac{1}{2} \frac{\delta^2(\delta - \alpha\gamma)}{\alpha(8\alpha\delta - 3\delta^2 + 8\alpha(1-\gamma))} < 0$ and also that $\frac{\partial h^*}{\partial c_r} = -2 \frac{(2\alpha\gamma + 2\alpha\delta - 2\alpha\gamma^2 - \delta^2)}{(8\alpha\delta - 3\delta^2 + 8\alpha(1-\gamma))} < 0$. We will now show that $\frac{\partial h^*}{\partial \alpha} > 0$. $\frac{\partial h^*}{\partial \alpha} = \frac{1}{2} \frac{\Pi(\alpha)}{\alpha^2(8\alpha\delta - 3\delta^2 + 8\alpha(1-\gamma))^2}$ where $\Pi(\alpha) = (-8\gamma\delta c - 8c\gamma^2 + 8\gamma^2 c_r - 8c_r\gamma + 8c\gamma^3 - 8\delta c_r)\alpha^2 + (16\delta^2 c - 16\delta^2\gamma^2 c + 16\gamma\delta c)\alpha^2 - 3\delta^2 c$ but $\frac{\partial \Pi(\alpha)}{\partial c_r} = 8(\gamma^2 - \gamma - \delta)\alpha^2 < 0$ and $\Pi(\alpha, c_r = \frac{c(\delta - \alpha\gamma)}{\alpha}) = \delta c(8\alpha\delta - 3\delta^2 + 8\alpha(1-\gamma)) > 0$, thus $\Pi(\alpha) > 0$ and $\frac{\partial h^*}{\partial \alpha} > 0$.

Appendix B: Two-period useful lifetime model.

We assume that a consumer who bought a new product in the first period will either return the product to get a new one or hold onto it. In other words, a consumer will not return a used product to get a refurbished one. This assumption is valid in situations where the willingness-to-pay for a refurbished product is not significantly higher from the utility offered by a used product, and therefore consumers are not willing to engage into the reselling process and pay the additional relicensing fee associated with it. To maintain tractability, we focus on the special case of $\alpha = 1$ (i.e., no technological improvement) and $\gamma = 0$ (no transactional disutility).

Under the above assumptions, the consumer state space is divided into the following segments illustrated in Fig. EC.2. Consumers who buy a new product in the first period, resell it, and again buy a new one in the second period, with total utility $U_{NSN}(\theta) = \theta - p_1 + s + \theta - p_2$. Consumers who buy a new product in the first period and continue using it in the second period, with total utility $U_{NK}(\theta) = \theta - p_1 + \delta_o \theta$. Consumers who do not buy in the first period, but buy a new product in the second period, with total utility $U_{ON}(\theta) = \theta - p_2$. And finally, consumers who do not buy in the first period, but buy a refurbished product in the second one, with total utility $U_{OR}(\theta) = \delta\theta - p_r - h$. We focus our analysis on those sets of parameters for which all four segments exist in equilibrium. Although this analysis does not address the optimal strategy for the entire range of parameter values, it does capture the effect of product durability on the OEM's relicensing policy and it identifies the region where a secondary market exists.

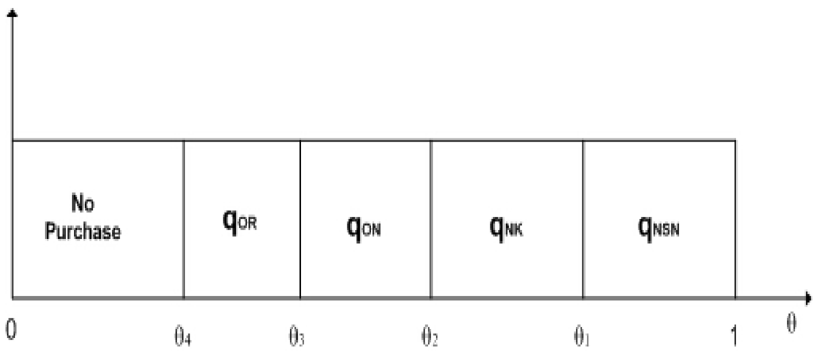

Figure EC.2 Consumer state space over the two-period horizon.

Solving for the indifferent consumers we get $\theta_1 = \frac{p_2 - s}{1-\delta_o}$, $\theta_2 = \frac{p_1 - p_2}{\delta_o}$, $\theta_3 = \frac{p_2 - p_r - h}{1-\delta}$, $\theta_4 = \frac{p_r + h}{\delta}$, and the corresponding demand for each segment, $q_{nsn} = 1 - \theta_1$, $q_{nk} = \theta_1 - \theta_2$, $q_{on} = \theta_2 - \theta_3$, $q_r = \theta_3 - \theta_4$. Moreover, $q_1 = q_{nsn} + q_{nk}$ and $q_2 = q_{nsn} + q_{on}$, while the number of units returned to the entrant will be $q_u = 1 - \theta_1$. To find the prices that correspond to the market sizes q_2 and q_r we solve the following system:

$$q_2 = q_{nsn} + q_{on} = 1 - \theta_1 + \theta_2 - \theta_3$$

$$q_r = \theta_3 - \theta_4,$$

from which we get

$$p_2 = \frac{(1 - q_r\delta - q_2)\delta_o{}^2 + (q_r\,\delta - s - 1 + q_2 + p_1)\delta_o - p_1}{-1 - \delta_o + \delta_o^2}$$

$$p_r = -\frac{(-\delta + q_2\delta + q_r\delta + h)\delta_o^2 + [\delta(1 + s - p_1 - q_2 - q_r) - h]\delta_o + \delta(\delta q_r - q_r + p_1) - h}{-1 - \delta + \delta^2}.$$

As in the baseline model, in the second-period the OEM sets the quantity q_2, while the entrant sets the quantity q_r and the resale price s offered to first-period consumers. The OEM's second-period objective given the entrant's choice of q_r is

$$Max_{q_2}\ \Pi_2(q_2|q_r) = (p_2 - c)q_2 + hq_r \quad \text{s.t.} \quad q_2 \geq 0$$

while the entrant's objective function is given by

$$Max_{q_r,s}\ \Pi_e(q_r, s|q_2) = (p_r - c_r)q_r - sq_u$$

$$\text{s.t. } q_r \leq q_u$$

$$q_r \geq 0, s \geq 0.$$

Let $q_2^*(q_1,h), q_r^*(q_1,h)$, and $s^*(q_1,h)$ denote the equilibrium of the above game. Then, the first-period OEM's problem is:

$$Max_{q_1,h}\ \Pi_1(q_1,h) + \Pi_2(q_2^*(q_1,h)) \quad \text{s.t. } q_1 \geq 0,\ h \geq 0.$$

Lemma EC.1. *At optimality, the entrant has no incentive to collect more units than the ones he intends to sell in the market. That is, the constraint $q_r \leq q_u$ is binding and the optimal resale price offered by the entrant satisfies $s^*(q_r) = (2 - \delta - \delta_o)q_r + \delta - q_1 - q_2$. Moreover, the equilibrium resale value is decreasing in q_1 and h.*

Proof of Lemma EC.1 We will show that for a given q_2, the entrant will always set q_r and s such that $q_r^* = q_u(s^*)$. Assume that there exist q_r^* and s^* such that $q_r^* < q_u(s^*)$. The FOC with respect to q_r and s give $\frac{\partial \Pi_e}{\partial q_r} = 0$ and $\frac{\partial \Pi_e}{\partial s} = 0$, or equivalently, $s^* = \frac{1}{2}(\delta_o - q_1 - q_2)$ and $q_r^* = \frac{1}{2}\frac{(q_1+q_2-2)(\delta_o-1)\delta+(h+c_r)(\delta_o-2)}{\delta(\delta-2+\delta_o)}$. After substituting s^*, we get $q_u(s^*) = \frac{1}{2}\frac{(q_1+q_2-1)\delta+(h+c_r)+\delta_o-q_1-q_2}{\delta-2+\delta_o}$ and the inequality $q_r^* < q_u(s^*)$ can be rewritten as $\frac{1}{2}\frac{(q_1+q_2-1)\delta+(h+c_r)}{\delta} > 0$. However, if $q_u(s^*) > 0$, then $(q_1+q_2-1)\delta + (h+c_r) + \delta_o - q_1 - q_2 < 0$, and since $\frac{1}{2}\frac{(q_1+q_2-1)\delta+(h+c_r)}{\delta} > 0$, we need $\delta_o - q_1 - q_2 < 0$. Recall that $s^* = \frac{1}{2}(\delta_o - q_1 - q_2)$, and therefore, that would lead to $s^* < 0$ which cannot be true. Therefore, we cannot have non-binding solutions, and therefore, $q_r^* = q_u(s^*)$.

Proof of Proposition 2.

The entrant's first-period problem is

$$Max_{q_1,h}\ \Pi_1(q_1,h) + \Pi_2^*(q_1,h)$$

$$\text{s.t. } q_1 \geq 0$$

$$h \geq 0.$$

Define the Lagrangian $L(q_1, h, \lambda_1, \lambda_2) = \Pi(q_1, h) + \mu_1 h$. The Kuhn-Tucker conditions for optimality are:

$$\frac{\partial L}{\partial q_1} = 0 \tag{EC.19}$$

$$\frac{\partial L}{\partial h} = 0 \tag{EC.20}$$

$$\mu_1 h = 0 \tag{EC.21}$$

with $\mu_1 \geq 0$.

Case I : $\mu_1 = 0$. Solving the KT conditions, we obtain $h^* = \frac{1}{2}\frac{(-8\delta_o^3+(-4\delta^2-8c_r+12+6\delta)\delta_o^2+(-3\delta^2c-4\delta^2c_r+\delta^3c+3\delta c+3\delta^2-c-10\delta+10c_r+2\delta^3+1)\delta_o-\delta^2c_r+\delta^3+3c_r-3\delta}{8\delta_o^2+(2\delta+3\delta^2-11)\delta_o+\delta^2-3}$ and $q_{or}^* = -\frac{1}{2}\frac{-4\delta_o^2+(4+4\delta c-4c-4c_r-\delta)\delta_o+1-c-c_r+\delta c}{8\delta_o^2+(2\delta+3\delta^2-11)\delta_o+\delta^2-3}$. Case I is valid for $q_{nsn}^* = q_{or}^* \geq 0$, $q_{nk}^* \geq 0$, $q_{on}^* \geq 0$ and $h^* \geq 0$. The above conditions are satisfied in the area $\underline{c_r^I} \leq c_r \leq \widetilde{c_r'}$ where $\underline{c_r^I} = \frac{(2-8c-2\delta)\delta_o^2+(-\delta^2c-2\delta c+2\delta^2+9c-3+3\delta)\delta_o+2(1+c)\delta-\delta^2(c-1)-2}{1+(2\delta+2)\delta_o}$ and $\widetilde{c_r'} = \frac{(-8\delta_o^3+(6\delta+12-4\delta^2)\delta_o^2+(\delta^3c+3\delta c+3\delta^2-10\delta+2\delta^3-3\delta^2c+1-c)\delta_o+\delta^3-3\delta)}{(4\delta_o+1)(2\delta_o+\delta^2-3)}$. This case represents the setting of having all market segments positive as well as a positive relicensing fee.

To see that h^* is decreasing in c_r and increasing in c, note that $\frac{\partial h^*}{\partial c_r} = -\frac{1}{2}\frac{(4\delta_o+1)(2\delta_o+\delta^2-3)}{8\delta_o^2+(2\delta+3\delta^2-11)\delta_o+\delta^2-3} < 0$ and $\frac{\partial h^*}{\partial c} = \frac{1}{2}\frac{\delta_o(\delta-1)^3}{8\delta_o^2+(2\delta+3\delta^2-11)\delta_o+\delta^2-3} > 0$ since $8\delta_o^2 + (2\delta + 3\delta^2 - 11)\delta_o + \delta^2 - 3 < 0$.

Note that the lower bound $\underline{c_r^I}$ corresponds to the c_r value such that $q_{on}^*(c_r) = 0$. For lower values of c_r, there will exist an even larger secondary market. To see that this secondary market exists, note that when $q_{on} = 0$, $q_2 = q_{nsn} = q_{or}$ and therefore, assuming that $q_{or} = 0$ would mean that neither new nor refurbished products are sold in the second period. Since q_{on} and q_{or} cannot be simultaneously zero, $q_{or}^* > 0$ for $c_r < \underline{c_r^I}$.

Case II : $\mu_1 \neq 0$. Case II is valid for $q_{nsn}^* = q_{or}^* \geq 0$, $q_{nk}^* \geq 0$, $q_{on}^* \geq 0$ and $h^* = 0$. The above conditions are satisfied in the area $\widetilde{c_r'} \leq c_r \leq \widetilde{c_r}$, where $\widetilde{c_r'}$ is defined in Case I and $\widetilde{c_r} = \frac{(-16\delta_o^3+(8\delta c+36-4\delta(1+\delta)-8c)\delta_o^2+(-\delta+12c+4\delta^2+2\delta^2c+\delta^3-16\delta c-12+2\delta^3c)\delta_o+\delta^3-\delta+4(c-1)-6\delta c+2\delta^2c}{(4\delta_o+1)(4\delta_o-7+\delta^2+2\delta)}$. This case represents the setting of having all market segments positive but a relicensing fee equal to zero.

To summarize, when $0 \leq c_r < \widetilde{c}_r'$ $q_r^* > 0$ and $h^* > 0$, while for $\widetilde{c}_r' \leq c_r < \widetilde{c}_r$, $q_r^* > 0$ and $h^* = 0$.

Proof of Corollary 1.

To show that $\frac{\partial h^*}{\partial \delta_o} < 0$, note that $\frac{\partial h^*}{\partial \delta_o}$ can be written as $\frac{\partial h^*}{\partial \delta_o} = -\frac{1}{2}\frac{\Phi_1(\delta,\delta_o,c_r,c)}{[\Phi_2(\delta,\delta_o)]^2}$ where Φ_1 and Φ_2 are defined as follows: $\Phi_1 \doteq 3 + 72\delta_o + 3\delta + 68\delta_o^2 - 4\delta^3 + 2\delta^2 - 176\delta_o^3 + 64\delta_o^4 + \delta^5 - \delta^4 - 3c_r - 3c + 8\delta^3 c\delta_o^2 - 8c_r\delta_o^2\delta^2 + 16c_r\delta_o^2\delta - 12\delta_o\delta - c\delta^5 - 48\delta_o\delta^2 - 8c\delta_o^2 - 8c_r\delta_o^2 + 32\delta_o^3\delta + c_r\delta^4 - 38\delta_o^2\delta + 6c_r\delta + 6\delta_o^2\delta^3 + 9c\delta - 8c\delta^2 + 12\delta_o^2\delta^4 - 44\delta_o^2\delta^2 - 2\delta^2 c_r + 4\delta^3\delta_o + 3c\delta^4 - 2\delta^3 c_r - 24c\delta^2\delta_o^2 + 24\delta_o^2 c\delta + 8\delta_o\delta^4 + 48\delta_o^3\delta^2$ and $\Phi_2 \doteq 8\delta_o^2 + 2\delta_o\delta + 3\delta_o\delta^2 - 11\delta_o - 3 + \delta^2$. Therefore, it is sufficient to show that $\Phi_1(\delta,\delta_o,c_r,c) > 0$. But $\frac{\partial \Phi_1}{\partial c_r} = -(\delta-1)^2(8\delta_o^2 + 3 - \delta^2) < 0$ and $\frac{\partial \Phi_1}{\partial c} = (\delta-1)^3(8\delta_o^2 + 3 - \delta^2) < 0$ and thus, it is sufficient to show that $\Phi_1(\delta,\delta_o,c_r = 1, c = 1) > 0$. The latter is a function of only δ and δ_o, and by plotting the function for all possible values $0 < \delta_o < \delta < 1$, it can be readily seen that it is always positive. Thus, $\frac{\partial h^*}{\partial \delta_o} < 0$.

Similarly, to show that $\frac{\partial h^*}{\partial \delta} > 0$, we can rewrite $\frac{\partial h^*}{\partial \delta}$ as $\frac{\partial h^*}{\partial \delta} = \frac{1}{2}\frac{\Phi_3(\delta,\delta_o,c_r,c)}{[\Phi_2(\delta,\delta_o)]^2}$ where $\Phi_3 \doteq 9 + \delta_o\delta^4 c + 24\delta_o^3\delta^2 c - 16\delta_o^3 c_r\delta + 20c\delta_o\delta + 8c_r\delta_o\delta - 48c\delta_o^3\delta + 63\delta_o + 66\delta_o^2 - 6\delta^2 - 170\delta_o^3 + 64\delta_o^4 + \delta^4 + 4\delta^3 c\delta_o^2 - 8c_r\delta_o^2\delta^2 + 28c_r\delta_o^2\delta - 2\delta^2 c_r\delta_o - 20\delta_o\delta - 32\delta_o\delta^2 - 31c\delta_o^2 - 20c_r\delta_o^2 + 80\delta_o^3\delta - 72\delta_o^2\delta + 8\delta_o^2\delta^3 + 6\delta_o^2\delta^4 - 12\delta_o^2\delta^2 + 4\delta^3\delta_o - 48c\delta^2\delta_o^2 + 72c\delta_o^2\delta + 5\delta_o\delta^4 + 22\delta_o^3\delta^2 - 12\delta_o\delta^2 c + 3\delta_o^2\delta^4 c + 24c\delta_o^3 - 16\delta_o^4\delta - 6c_r\delta_o - 9c\delta_o + 16c_r\delta_o^3$ and Φ_2 is defined above. Therefore, it is sufficient to show that $\Phi_3(\delta,\delta_o,c_r,c) > 0$. But $\frac{\partial \Phi_3}{\partial c_r} = -2\delta_o(\delta-1)(1+4\delta_o)(\delta-3+2\delta_o) < 0$ and $\frac{\partial \Phi_3}{\partial c} = \delta_o(\delta-1)^2(3\delta_o\delta^2 + \delta^2 + 10\delta_o\delta + 2\delta - 9 - 31\delta_o + 24\delta_o^2) < 0$ (for all $0 < \delta_o < \delta < 1$), and thus, it is sufficient to show that $\Phi_1(\delta,\delta_o,c_r = 1, c = 1) > 0$. The latter is a function of only δ and δ_o, and by plotting the function for all possible values $0 < \delta_o < \delta < 1$, it can be readily seen that it is always positive. Thus, $\frac{\partial h^*}{\partial \delta} < 0$.

Appendix C: Competition in both the primary and secondary markets with brand differentiation.

Second-Period Analysis

The net utility consumer θ derives from purchasing firm A's new product is $U_2^A(\theta) = \theta - p_2^A$, firm B's new product $U_2^B(\theta) = (1-\beta)\theta - p_2^B$, firm A's refurbished product $U_{2,r}^A(\theta) = \delta\theta - p_{2,r}^A - h^A$, and firm B's refurbished product $U_{2,r}^B(\theta) = (1-\beta)\delta\theta - p_{2,r}^B - h^B$. Solving for the marginal consumers, we get

$$\theta_1 = \frac{p_2^A - p_2^B}{\beta}, \theta_2 = \frac{p_2^B - p_{2,r}^A - h^A}{1-\beta-\delta}, \theta_3 = \frac{p_{2,r}^A - p_{2,r}^B + h^A - h^B}{\beta\delta}, \theta_4 = \frac{p_{2,r}^B + h^B}{(1-\beta)\delta}$$

with respective demand for each product of $q_2^A = 1-\theta_1$, $q_2^B = \theta_1-\theta_2$, $q_{2,r}^A = \theta_2-\theta_3$, and $q_{2,r}^A = \theta_3-\theta_4$. Figure EC.3 illustrates the four market segments.

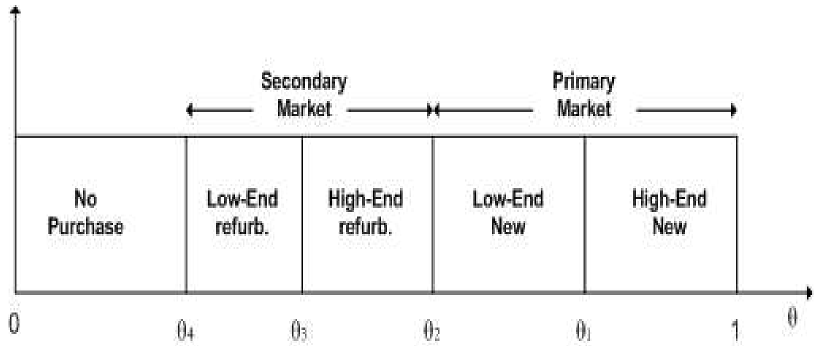

Figure EC.3 **Consumer State Space in the Second Period**

Under perfect competition in the secondary markets and no refurbishing cost, the refurbished products are available at a price equal to the resale value of used products ($p_{2,r}^A = s^A$ and $p_{2,r}^B = s^B$) with corresponding inverse demand functions

$$p_2^A = (\delta-1+\beta)q_2^B + h^A - (1-\delta)q_2^A + 1-\delta+s^A$$
$$p_2^B = (\delta-1+\beta)q_2^A + h^A - (1-\beta-\delta)q_2^B + 1-\beta-\delta+s^A.$$

Finally, the second-stage optimization problems for firms A and B are

$$Max_{q_2^A}\Pi_2^A(q_2^A|q_2^B) = (p_2^A - c)q_2^A + h^A q_{2,r}^A$$
$$Max_{q_2^B}\Pi_2^B(q_2^B|q_2^A) = (p_2^B - c)q_2^B + h^B q_{2,r}^B.$$

By solving the first-order conditions simultaneously, we derive the N.E. of this game, $q_2^{A*}(h^A,h^B,s^A,s^B)$ and $q_2^{B*}(h^A,h^B,s^A,s^B)$, and subsequently the quantities $q_{2,r}^{A*}(h^A,h^B,s^A,s^B)$ and $q_{2,r}^{B*}(h^A,h^B,s^A,s^B)$, from the demand equations corresponding to the market segmentation presented in Figure EC.3.

First-period analysis

Similar to our analysis for the monopolistic OEM, if s^j denotes the resale value of firm j's new product ($j = A,B$) at the end of period 1, then consumers of firms A and B will derive the corresponding utilities in period 1:

$$U_1^A(\theta) = \theta - p_1^A + (s^A - \gamma\theta)I_{(s^A \geq \gamma\theta)}$$
$$U_1^B(\theta) = (1-\beta)\theta - p_1^B + (s^B - (1-\beta)\gamma\theta)I_{(s^B \geq (1-\beta)\gamma\theta)}.$$

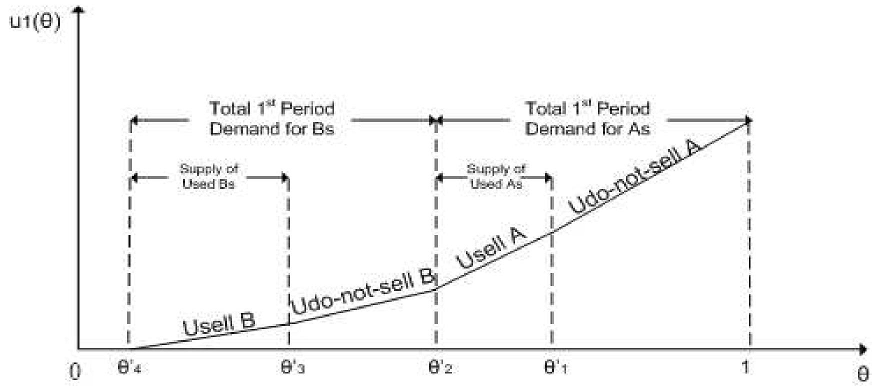

Figure EC.4 Consumer State Space in the First Period

Figure EC.4 illustrates the total demand in the first period as well as the segment of consumers who decide to sell their used products.The marginal consumers are $\theta_1' = \frac{s^A}{\gamma}$, $\theta'_2 = \frac{p_1^A - p_1^B - s^A}{\beta - \gamma}$, $\theta_3' = \frac{s^B}{(1-\beta)\gamma}$ and $\theta'_4 = \frac{p_1^B - s^B}{(1-\beta)(1-\gamma)}$, with respective demand for new products of $q_1^A = 1 - \theta_2'$, and $q_1^B = \theta_2' - \theta'_4$, and respective supply of used products of $q_{1,r}^A = \theta_1' - \theta'_2$ and $q_{1,r}^B = \theta_3' - \theta'_4$. By setting these quantities equal to the equilibrium secondary market sizes of the second period $q_{2,r}^{A*}(h^A, h^B, s^A, s^B)$ and $q_{2,r}^{B*}(h^A, h^B, s^A, s^B)$, we can express the resale values in terms of the prices of new products and the relicensing fees: $s^A(h^A, h^B, p_1^A, p_1^B)$ and $s^B(h^A, h^B, p_1^A, p_1^B)$. The first-period profits are given by $\Pi_1^A(q_1^A|q_1^B) = (p_1^A - c)q_1^A$ and $\Pi_1^B(q_1^B|q_1^A) = (p_1^B - c)q_1^B$, while the total optimal profits over the two-period horizon are:

$$Max_{q_1^A, h^A} \Pi_A(q_1^A, h^A|q_1^B, h^B) = (p_{1A} - c)q_1^A + \Pi_{2A}^*(q_1^A, h^A|q_1^B, h^B)$$
$$Max_{q_1^B, h^B} \Pi_B(q_1^B, h^B|q_1^A, h^A) = (p_{1B} - c)q_1^B + \Pi_{2B}^*(q_1^B, h^B|q_1^A, h^A)$$

We verify that the conditions for a unique unconstrained Nash Equilibrium are met (convex strategy set, Hessian negative definite) and solve the first-order conditions simultaneously for all the decision variables to derive the values $q_1^{A*}, h^{A*}, q_1^{B*}, h^{B*}$. The equilibrium is valid only for parameters yielding positive quantities, thus, the analysis in the paper is reflective of this set. For example, Figure 2 in the paper is plotted for $\beta \in [0.1, 0.4]$. The upper threshold $\overline{\beta}$ is the highest value of $\beta \in (0, 1 - \delta)$ for which the low-end OEM produces new products in the second period. That is, for values of β above that point, the low-end OEM is priced out of the primary market in the second period (this constraint is always the first to be violated). On the other hand, the lower threshold $\underline{\beta} = \gamma$ denotes the lowest value of β for which the ordering of the consumer state space in Figure EC.4 is valid (low-end OEM's new product above high-end OEM's refurbished product).