Essays on Sustainable Operations and Corporate Social Responsibility

Adem Orsdemir

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Approved by:

Vinayak Deshpande

Ali K. Parlakturk

Bin Hu

Ann Marucheck

Robert Swinney

ABSTRACT

Adem Orsdemir: Essays on Sustainable Operations and Corporate Social Responsibility.
(Under the direction of Vinayak Deshpande and Ali K. Parlakturk.)

Environmental and social issues have gained significant attention recently as stakeholders have become more aware of the impact of unsustainable practices on the quality of life and profitability. Governments have been developing environmental and social regulations, and constantly tightening the limits of these regulations in order to incentivize adoption of environmentally sustainable and socially desirable practices. This push drove many firms around the world to consider business practices that have been touted as environmentally sustainable, socially responsible and profitable. These practices can be incorporated into a firms' business strategy at different phases of product lifecycle: production, use, and end-of-use. We examine three business practices that are implemented at these phases of the product lifecycle. At the end-of-use phase, the products can be collected after consumer use, and remanufactured and sold back to consumers to save material and energy (Product Remanufacturing). At the use phase, manufacturers, instead of selling the product, can sell the functionality of the product and bear the operating cost (Product Servicization). At the production phase, manufacturers can choose to source from suppliers who follow socially responsible practices (Responsible Sourcing). This thesis aims to identify the key trade-offs in these business strategies that drive the environmental and social benefits for the society, and profitability for firms. More specifically, in my dissertation, I intend to understand when these strategies improve firms' profit, and environmental and social footprint.

To my wife, my parents and my sister

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CHAPTER 1

INTRODUCTION

In a globalized world, environmental and social impacts of business operations cannot be swept under the rug. Consumers are becoming more and more environmentally and socially conscious and demanding companies to follow environmentally and socially sustainable practices. In this dissertation, we study the impact of several business operations on the environment and corporate social responsibility, and suggest sensible practices to reduce environmental impact and increase compliance levels with the environmental and labor standards.

1.1 Dissertation Overview

1.1.1 Competitive Quality Choice and Remanufacturing

In this chapter, we consider an original equipment manufacturer (OEM) who faces competition from an independent remanufacturer (IR). The OEM decides the quality of the new product, which also determines the quality of the competing remanufactured product. The OEM and the IR then competitively determine their production quantities. We explicitly characterize how the OEM competes with the IR in equilibrium. Specifically, we show that the OEM relies more on quality as a strategic lever when it has a stronger competitive position (determined by the relative cost and value of new and remanufactured products), and in contrast it relies more heavily on limiting quantity of cores when it has a weaker competitive position. The IR's entry threat as well as its successful entry can decrease the consumer surplus. Furthermore, our results illustrate that ignoring the competition or the OEM's quality choice leads to overestimating benefits of remanufacturing for consumer and social welfare. In addition, we show an IR with either a sufficiently weak competitive position (so the OEM deters entry) or a sufficiently strong one (so the OEM is forced to limit quantity of cores) is desirable for reducing the environmental impact. Comparing our results with the benchmark in which the OEM remanufactures suggests that encouraging IRs to remanufacture in lieu of the OEMs may not benefit the environment. Furthermore, the benchmark illustrates that making remanufacturing more attractive improves the environmental impact when the remanufacturer is the OEM, while worsening it when remanufacturing is done by the IR.

1.1.2 Is Servicization a Win-Win Strategy? Profitability and Environmental Implications of Servicization

Servicization, a business strategy to sell the functionality of a product rather than the product itself, has been touted as a profitable and an environmentally friendly business practice. Profitability can increase because a firm can tailor the service to the needs of a customer. Environmental impact may be reduced because, under servicization, the firm retains the ownership and is responsible for the maintenance of the product. As a result, the firm has stronger incentives to invest in product durability. Motivated by these dynamics, we analytically characterize when servicization can simultaneously increase a firm's profits and decrease its environmental impact compared to selling products. We endogenize the firm's product durability and pricing decisions, as well as the customer's level of use of a product. We allow for heterogeneous customer segments with differing product valuations, and capture the difference in product operating cost incurred by the firm and by the customer.

We find that whether servicization is greener and more profitable depends on the firm's relative operating efficiency and the relative environmental impact of a product in its use phase as compared to the production and disposal phase. When the relative operating efficiency of the firm is high (low) and the product's relative use impact is low (high), servicization can be both environmentally friendly and more profitable. In addition, we show that servicization does not necessarily increase the product durability. It may decrease the product durability when servicization leads to market expansion. We also show that servicization can be more profitable for the firm even when its relative operating efficiency is low. However, we also show that servicization may lead to lower social surplus even when a firm's relative operating efficiency is high. Thus, while servicization as a business strategy holds promise, it should be implemented with care.

1.1.3 Responsible sourcing via vertical integration: the impacts of scrutiny, demand externality, and cross sourcing

As outsourcing to emerging economies have increased, many unfortunate events about the practices in those countries hit the news channels. These includes but not limited to collapse of the Rana Plaza factory in Bangladesh (New York Times, 2013), allegations of sweatshop and child labor at factories of Nike suppliers (Daily Mail, 2011). Companies outsource from emerging economies mainly because the lower operating and labor costs. However, many times this cost advantage comes at the expense of social responsibility compliance. Suppliers may engage in unethical practices to lower costs and squeeze more profits. Insufficient regulations in these countries also fuel noncompliance.

In this chapter, we investigate vertical integration as a way to ensure compliance in a competitive setting. One of the firms is capable of vertical integration and chooses to comply/not comply with the environmental and labor standards, whichever is more profitable. If at least one of the firms does not comply with the law, with positive probability it will get caught and lose a portion of its demand. This may have positive or negative impact on the other firm. The impact may be positive because a portion of the consumers exited the firm caught with a violation may purchase from the other firm. On the other hand, it may be negative because the violation publicity may tarnish the image of entire industry.

Motivated from these dynamics we research how violation externality impact the firms decision to become socially responsible. We find that the answer depends on whether it is viable for a firm to sell to its competitor (cross sourcing), or not. When cross sourcing is not viable, higher positive externality always increases the compliance. On the other hand, when cross sourcing is viable, higher positive externality may reduce the compliance.

CHAPTER 2

COMPETITIVE QUALITY CHOICE AND REMANUFACTURING

2.1 Introduction

Remanufacturing operations involve taking used products, bringing them back to as-new condition, and selling them again (Atasu et al., 2010). These activities in an industry can be carried out either by third-party independent remanufacturers (IR) or by original equipment manufacturers (OEM). Especially in the US, majority of remanufacturing is done by IRs (Hauser and Lund, 2008). The same study finds that the remanufacturing industry in the U.S. is worth $53 billion, which means that IRs are not an insignificant competitive threat to OEMs. OEMs try to fend off competition from IRs through limiting quantity, specifically by creating scarcity of cores available for remanufacturing (e.g., by offering free take-back of cores from consumers (HP 2010a) or making cores ineligible for remanufacturing (Lexmark 2010)) and rarely through litigation (e.g., HP 2010b).

There is also evidence that OEMs change their product designs with remanufacturing concerns in mind. For example, Subramanian et al. (2011) argue that HP refrains from using common print heads in its business inkjet printers because doing so makes the IRs a bigger competitive threat in the market. Atasu and Souza (2012) describe how Xerox and Kodak take remanufacturing into consideration when they design their products. An important product design decision that is the focus of this paper is quality. Following Moorthy (1988) and Desai (2001), we define quality as an attribute which exhibit the “more is better” property, so given the same price, all customers prefer the higher quality product. It is well known that firms can use quality as a competitive lever; however, in the remanufacturing context the dynamics around the quality decision are intricate because when an OEM increases its product quality, it also increases the quality of the remanufactured product to a certain extent. Therefore, the results on product quality from papers that consider competition between *independent* products (e.g., Moorthy 1988; Desai 2001) do not immediately extend to the remanufacturing context. Thus, in this paper we study *how an OEM can use product quality along with quantity as a competitive lever against an IR.*

Remanufacturing is generally perceived as an environmentally-friendly end-of-use management option for many products. Commonly-cited benefits include diversion of discarded products from landfills, reduced virgin raw material usage and reduced energy usage when compared to manufacturing (U.S.EPA, 1997). At the same time, Gutowski et al. (2011) find that while remanufacturing itself uses less energy than manufacturing, remanufactured products may be less energy efficient. Thus, the relative environmental impacts of new and remanufactured products should be carefully considered and the *total* environmental impact of remanufacturing in a given market is not clear.

Recently, we have seen a surge of activities that promote remanufacturing. For example, the Automobile Parts Remanufacturers Association introduced the Recycling/Remanufacturing Tax Credit Bill, HR 5695 (The Remanufacturing Institute, 2008) and campaigns such as Manufactured Again (Motor and Equipment Remanufacturers Association 2011) work to increase remanufacturing levels by increasing consumer awareness. An underlying tenet of these activities is that remanufacturing is good for the consumer. However, just like total environmental impact, the social welfare implications of remanufacturing, especially when it is conducted by a third-party are not well understood. To this end, we research *how the competition between the IR and the OEM affects total environmental impact and social welfare*, specifically when the OEM can adjust product quality in response to competition.

We consider an OEM who faces competition from an IR. The OEM decides the quality of the new product which also determines the quality of competing remanufactured product. The OEM and the IR competitively determine their production outputs which determine the prices of the new and remanufactured products. Remanufactured product can be perceived inferior in quality but cheaper to manufacture. We study the relation between the competitive positioning of the OEM and the IR and how the OEM chooses to compete with the IR as well as the environmental and social welfare implications of this choice. In our base model, the OEM sells the new product and remanufacturing is done solely by the IR. In addition to our base model, we consider several benchmarks: a monopolist OEM without remanufacturing capability (NR benchmark), a monopolist OEM with remanufacturing capability, and competition with exogenous quality decision. These benchmarks help tease out the effects of competition, the OEM's quality choice and the type of the remanufacturing firm on our results.

Even though most remanufacturing in the US is done by IRs, OEMs like Xerox, Kodak and Caterpillar have remanufacturing operations, too. In an extension to our base model, we study how the answers to our research questions change when the OEM remanufactures instead of the IR. Comparing our findings with the results of this extension, we are able to provide insights on how the environmental and social welfare benefits of remanufacturing depend on the *type* of company (IR vs. OEM) offering the remanufactured product. When faced with competition from an IR, some OEMs like Lexmark choose to collect cores and dispose of them rather than remanufacture in-house. We analyze this scenario as an extension to our base model as well and provide insights regarding when the OEM prefers to collect cores to compete with the IR. We now summarize our key findings:

- We explicitly characterize how the OEM competes with the IR in equilibrium. When the OEM has a significant competitive advantage (which is determined by the relative cost and the perceived quality of the remanufactured product vis-a-vis the new product and is explained in detail in Section 2.3), it deters the IR's entry by choosing a quality level that is higher than it would if the IR was not in the market. In contrast, when the IR has a significant competitive advantage, the OEM reduces production and, hence, decreases the number of cores the IR can remanufacture. In between, the IR enters the market and does not encounter core shortage. In this region, when the OEM has the competitive advantage, it chooses a higher quality level compared to the NR benchmark to emphasize its advantage. When the IR has the competitive advantage, the OEM chooses a lower quality level to de-emphasize its competitor's advantage. Our results show that when the OEM has a stronger competitive position, it is more likely rely on quality as a strategic lever whereas when the IR's competitive position gets stronger, the OEM is more likely to rely on limiting core availability.

- The IR's entry threat as well as its successful entry can decrease the consumer surplus compared to the NR benchmark; that is, remanufacturing may harm consumer welfare. This is because the OEM chooses an inefficiently high quality level to deter or weaken the IR. In contrast, when the product quality is exogenously fixed, the consumer surplus always increases with remanufacturing. We show a similar result for the social surplus. These results are in contrast with our monopoly remanufacturing benchmark which shows remanufacturing by an OEM always benefits the consumer and social surplus. There are two factors in play here: (i) An IR chooses to remanufacture even when the perceived value to cost ratio of the remanufactured product is unfavorable relative to the new product. In other words, the OEM's remanufacturing incentives are better aligned with consumer and social surplus than that of the IR. (ii) When the OEM remanufactures itself, it chooses product quality more efficiently as far as consumer and social surplus are concerned. Overall, our results illustrate that ignoring competition or OEM's quality choice lead to overestimating benefits of remanufacturing for consumer and social welfare.

- We also study the environmental impact of remanufacturing. When the OEM deters the IR's entry through increasing quality, the environmental impact always decreases. Basically, a higher quality product implies a smaller sales volume reducing the environmental impact. When the IR enters the market and remanufactures, the environmental impact decreases if and only if the remanufactured product has a sufficiently smaller per unit relative impact compared to the new product and we explicitly characterize this critical threshold. As far as environmental impact is concerned, an IR with either a sufficiently weak competitive position (so the OEM deters entry) or a sufficiently strong one (so the OEM is forced to limiting quantity of cores) is desirable. When neither the OEM nor the IR has a strong advantage, the bitter competition between the two increases the total sales quantity aggravating the environmental impact. Comparisons with our NR benchmark show that when remanufacturing has a competitive advantage determined by its relative cost and perceived quality, remanufacturing by the OEM is more likely to reduce environmental impact than remanufacturing by an IR. This is due to two factors. (i) Competition increases the sales quantity worsening the environmental impact. (ii) The OEM can choose a lower quality level when competing with the IR, which also increases the sales quantity. Our results can have important policy implications: Encouraging OEMs to remanufacture their own products may be more beneficial for the environment than encouraging IRs to remanufacture.

• For the two alternative models we consider, in which the OEM can also remanufacture or it can preemptively collect cores, we show through numerical studies that the way the OEM chooses to compete with the IR is similar to our base model. Consistent with our insights from the base model, the OEM follows a deterrent quality strategy when remanufacturing does not have a strong value proposition; in contrast, it uses a deterrent quantity strategy (remanufacturing itself or collecting cores and disposing of them) when the IR's remanufacturing becomes a bigger threat. Furthermore, we find making remanufacturing more attractive, by either lower cost or higher quality perception, can worsen the environmental impact when remanufacturing is done by the IR; in contrast it lessens the environmental impact when the OEM is remanufacturing. Thus, the consequences of these incentives on environmental impact critically depend on the type of the remanufacturing firm.

• We demonstrate the robustness of the equilibrium structure, which shows how the OEM chooses to compete with the IR, under three different extensions: the IR incurs an additional cost independent of the quality level; perceptual quality gap between new and remanufactured products is independent of product quality; the OEM and the IR compete in prices. Comparison of our results from the base model and the extensions, however, shows that the effect of IR's competitive threat on the OEM's quality choice may critically depend on how the cost and perceived quality of the remanufactured product are modeled. Furthermore, the implication of remanufacturing on the social and consumer surplus and environmental impact can be sensitive to the type of competition (price vs. quantity).

2.2 Literature Review

The closed-loop supply chain literature has studied a number of questions that arise when a remanufactured product is introduced into the product mix. The literature makes different assumptions regarding who produces the remanufactured product: a monopolist OEM who also sells the new product (e.g., Ferrer and Swaminathan 2010; Esenduran et al. 2010), an IR competing with an OEM (e.g., Majumder and Groenevelt 2001; Ferrer and Swaminathan 2006; Esenduran et al. 2012) or an OEM who faces competition from another firm (e.g., Heese et al. 2005; Atasu et al. 2008). Ferguson and Toktay (2006) compare, from the point of view of an OEM, the profitability of introducing a remanufactured product versus collecting and disposing of used products to deter the entry of an IR. This stream of literature studies how the competition between new and remanufactured products affects the pricing and quantity decisions of the OEM (a feature that also exists in our model) but does not capture the OEM's *endogenous quality decision*. We extend this literature by allowing the OEM to explicitly set product quality. We characterize how the OEM uses two modes of competition–quality and quantity–as its competitive position vis-a-vis the IR changes. We also research how the competition between an OEM and an IR and the OEM's ability to choose the quality level affect consumer surplus and the product's total environmental impact.

How competition affects a firm's quality choice has been studied extensively in marketing literature. One fundamental difference of our model is that the OEM makes the quality decision and its decision locks in the quality of the remanufactured product whereas in the extant literature, competing firms are allowed to choose their own quality levels independently. This difference leads to significantly different insights. For example, Moorthy (1988) shows that in a duopoly when firms choose their quality levels first and then compete in prices, consumer surplus is higher than the monopoly case. In our model, consumer surplus may be lower than the monopoly case because the OEM takes advantage of the interdependency between the products and may inefficiently increase or decrease quality in order to weaken the IR's competitive position. Desai (2001) also models a duopoly but with symmetric firms. In contrast, the asymmetry between the OEM and the IR determine their relative competitive positioning which plays a key role in our results.

In the operations management literature, a number of papers study how competition impacts firms' quality decisions or related variables such as service levels and waiting times. Banker et al. (1998) model the quality and price competition between two manufacturers. They find that product quality increases when a low-cost entrant enters the market where an incumbent has the intrinsic demand advantage. We reach the exact opposite conclusion and this is because, in their model, both firms are allowed to choose their own quality levels independently. In other work in operations management (e.g., Tsay and Agrawal 2000; Bernstein and Federgruen 2004) there is an interdependency between quality and demand/supply parameters, and imbalance between supply and demand deteriorates quality. In contrast, in our model quality is an intrinsic product attribute independent of the magnitude of demand.

We study competitive quality choice for a remanufacturable product. Quality is an important product design decision and has been of great interest in the new product development literature (e.g., Souza et al. 2004; Plambeck and Wang 2009; Fishman and Rob 2000). However, these papers are mainly concerned with sequential quality improvements whereas quality choice is made only once in our model. Furthermore, the remanufacturing context has some unique aspects: the remanufactured product's cost and quality level depend on the new product's quality level and the OEM can limit the cores that the IR can access for remanufacturing, which adds another layer of interdependence. Here, we contribute by studying quality choice for a product that competes with an interrelated product.

In the context of product recovery, few papers consider product quality explicitly. In Debo et al. (2005) and Robotis et al. (2009), quality refers to the remanufacturability level of the returned product, which reduces the remanufacturing cost; this is different from our definition. Debo et al. (2005) model a monopolist OEM and research whether the OEM should sell a remanufacturable product and if so, what the level of remanufacturability should be. In an extension that allows competition with IRs, they find that as remanufacturing competition intensifies, the remanufacturability level of the product goes down. However, we find that as the IR becomes more competitive up to a threshold level, product quality goes up. Robotis et al. (2009) consider a monopolist and show uncertainty in remanufacturing cost may lead to higher reusability investment. Subramanian et al. (2011) study how remanufacturing threat of an IR affects component commonality decision for an OEM selling two vertically differentiated products with exogenous qualities.

Atasu and Souza (2012) is the closest to our work. They consider a monopolist who remanufactures in-house and study the effect of three product recovery forms, i.e., quality recovery (remanufacturing is an example), profitable material recovery and costly recovery, on quality levels. They find that quality recovery and costly recovery lead to increased quality and decreased environmental impact while profitable material recovery leads to decreased quality and increased environmental impact. Furthermore, quality recovery benefits the consumers, but costly recovery reduces the consumer surplus. Atasu and Souza's work clearly demonstrates that not all forms of recovery are equally beneficial for the environment and the consumers. In this work, we confine ourselves to a single recovery form, i.e., remanufacturing, but consider the competition between the OEM and the IR. We also study how the product quality level and benefits of remanufacturing depend on the party (OEM or IR) doing the remanufacturing. We find that when an OEM and an independent remanufacturer are in competition, remanufacturing may indeed result in decreased quality and increased environmental impact.

2.3 Model

We consider an original equipment manufacturer (OEM) selling a new product and an independent remanufacturer (IR) selling the remanufactured product. We begin by introducing the demand model, discuss the cost structure and finally describe the firms' decisions.

Each customer considers new product, remanufactured product and no purchase options and chooses the one that maximizes her utility. We model consumer preferences as in Moorthy (1988). Consumers are heterogeneous in their willingness to pay for quality and are uniformly distributed over a bounded support with unit density, which we normalize to $[0, 1]$. A consumer of type $\theta \in [0, 1]$ is willing to pay θs for a product of quality level s. This implies that everything else being equal all consumers prefer higher quality over lower quality. Given that p_n is the new product's price, the utility a type θ customer receives from the new product is $\theta s - p_n$. Consumers often perceive the remanufactured product as being of inferior quality. We capture this by modeling consumers' willingness to pay for the remanufactured product as a δ fraction of the new product where $\delta \in (0, 1)$. Consumption of the remanufactured product provides a utility of $\delta\theta s - p_r$ where p_r is the remanufactured product's price. This implies that the quality gap between the new and remanufactured products is proportional to product quality s. Among others, Ferguson and Toktay (2006) and Atasu et al. (2008) model demand and the relative valuation of the remanufactured product similarly. In Section 2.8.3, we consider an alternative model where the quality gap is independent of product quality.

The unit variable cost of producing a new product with quality level s is βs^2 where β is a scaling parameter and does not alter our insights (e.g., Moorthy 1988, Desai 2001, Atasu and Souza 2012). The quality level of the new product impacts the remanufacturing cost, too. Since remanufacturing brings a product to like-new condition by replacing older and worn-out parts, it is costlier to repair and replace the higher quality parts of a higher quality product. At the same time, remanufacturing a product costs less than manufacturing a product because some parts are reused. The remanufacturing cost is proportional to the cost of new product, specifically, it is equal to $\beta\alpha s^2$. As such, our base model does not consider a quality-independent cost term. An extension in section 2.8.2 allows for such an additional cost term as in Atasu and Souza (2012). Here, $\alpha \in (0, 1)$ is an indicator of the remanufacturing cost advantage and it decreases as the cost savings from remanufacturing increases. Like Debo et al. (2005) and Ferrer and Swaminathan (2006), we assume that the remanufacturing cost subsumes the cost of all remanufacturing related activities.

The order of decisions is as follows. First, the OEM decides the quality of the product s. Then the OEM and the IR competitively choose new product and remanufactured product quantities, q_n and q_r that are sold in a single period. The IR's remanufacturing quantity is constrained by the available cores, which is determined by the new product quantity. The IR can also choose to stay out of the competition by choosing to remanufacture zero units. Finally, consumers make their choices.

We consider a product that has a single (long) life and the quality decision is made at the beginning of this long life cycle. Single period models have previously been used in Atasu and Souza (2012); Agrawal et al. (2011a); Subramanian et al. (2011) in the sustainable operations management literature. This approach, which focuses on steady state profits, facilitates analytical tractability in our model and allows us to focus on our research questions. Furthermore, the OEM and IR engage in Cournot type quantity competition in our model as in Ferguson and Toktay (2006); Debo et al. (2005); Atasu et al. (2009a). Both quantity and price competition models are extensively used in the OM literature. While our base model adopts quantity competition, we also study price competition showing that our equilibrium results propagate.

Following Johnson and Myatt (2006), the OEM's and the IR's chosen quantities and customer choices lead to following prices for the new and remanufactured products:

$$p_n = s(1 - q_n - \delta q_r),\ p_r = \delta s(1 - q_n - q_r).$$

The above equations assume that the product's useful lifetime is one period, it can be remanufactured only once and all recovered cores are in good enough shape for remanufacturing (e.g., Atasu and Souza 2012; Debo et al. 2005; Ferguson and Toktay 2006). Our model can be extended such that only a fraction of the cores is available for remanufacturing, but for tractability and to keep the focus on our research question, we only consider the case where all cores can be remanufactured.

We derive the equilibrium by backward induction. For a given quality level s, the OEM and the IR play the quantity game. Formally, the OEM solves

$$\max_{q_n} \ \pi_{OEM}(q_n|s) = [s(1 - q_n - \delta q_r) - \beta s^2]q_n$$
$$s.t \ \ q_n \geq 0$$

and the IR simultaneously solves

$$\max_{q_r} \ \pi_{IR}(q_r|s) = [\delta s(1 - q_n - q_r) - \alpha\beta s^2]q_r$$
$$s.t \ \ q_r \geq 0, \ q_r \leq q_n.$$

This solution approach is the same as in Agrawal et al. (2011a). The IR's problem has an additional constraint reflecting the fact that the remanufactured product quantity cannot exceed the new product quantity, i.e., $q_r \leq q_n$, core availability constraint. Finally, the OEM chooses the optimal quality level s^* by solving $\max_s \pi_{OEM}\left(s|q_n^*(s), q_r^*(s)\right)$. The resulting equilibrium is described in the next section. Note that we use the superscript (*) to denote equilibrium values throughout the paper.

In addition to our base model, we consider the monopoly no-remanufacturing, monopoly remanufacturing and exogenous quality benchmarks. The monopoly no-remanufacturing (NR) benchmark considers a monopolist OEM who sells only the new product, deciding the quality and quantity of its product. In the monopoly remanufacturing benchmark, a monopolist can sell both new and remanufactured products. In the exogenous quality benchmark, the quality of new product is fixed at level s_f and the OEM competes with the IR using only quantity. Thus, in this benchmark, when the IR enters the market, the OEM adjusts its product quantity but cannot change exogenous product quality. These benchmarks help us characterize the effects of competition, remanufacturing and OEM's quality choice on our results. The equilibria for the benchmarks and all the proofs are provided in Appendix A.

2.4 Equilibrium

In this section, we discuss the decisions of the OEM and the IR in equilibrium. As it will be evident, remanufactured product's relative cost-to-value ratio, α/δ, simply referred to as the cost-to-value ratio plays an important role in our result. When α/δ ratio decreases, the IR's competitiveness increases and vice versa for the OEM. This is because increasing α/δ ratio indicates either the cost of remanufacturing goes up or the consumer perception of the remanufactured product goes down. Specifically, when α/δ is greater than 1, the OEM has the cost-to-value advantage against the IR. In contrast, when the cost-to-value ratio is smaller than 1, the IR has the advantage. Consider medical imaging equipments and printer cartridges for two examples that fall on two opposite ends of the spectrum. Remanufacturing medical imaging equipments (e.g., computer tomography and magnetic resonance imaging) have a high marginal cost due to high technology components used in these products. In addition, hospitals are skeptical about buying remanufactured imaging devices (Elsberry, 2002) since they can have a direct impact on patients' health. Thus, medical imaging equipments can be characterized by a large α/δ ratio. In contrast, printer cartridges possess a small α/δ ratio due to low cost and high consumer acceptance of remanufactured cartridges. In fact, cartridge industry is one of the prominent examples where the competition between the IRs and the OEMs (e.g., Lexmark, HP) is very severe. The next proposition describes the equilibrium.

Proposition 1. *The following characterizes the equilibrium regions. The equilibrium quality, new and remanufactured product quantities are provided in Table 2.1.*

R1. If $\frac{\alpha}{\delta} \geq 2$*, the IR cannot enter the market and the OEM acts like a monopoly.*

R2. If $\frac{8-\delta}{4+\delta} \leq \frac{\alpha}{\delta} < 2$*, the IR is a threat and its entry is deterred by the OEM.*

R3. If $\frac{\delta(18-8\delta-2\delta^2+\delta^3)}{(4-\delta)^2} < \frac{\alpha}{\delta} < \frac{8-\delta}{4+\delta}$*, the IR enters the market but does not remanufacture all available cores.*

R4. If $0 < \frac{\alpha}{\delta} \leq \frac{\delta(18-8\delta-2\delta^2+\delta^3)}{(4-\delta)^2}$*, the IR enters and remanufactures all available cores.*

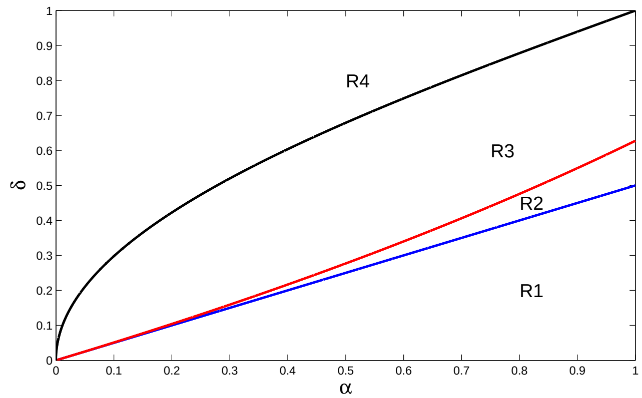


Figure 2.1: Characterization of Equilibrium Regions

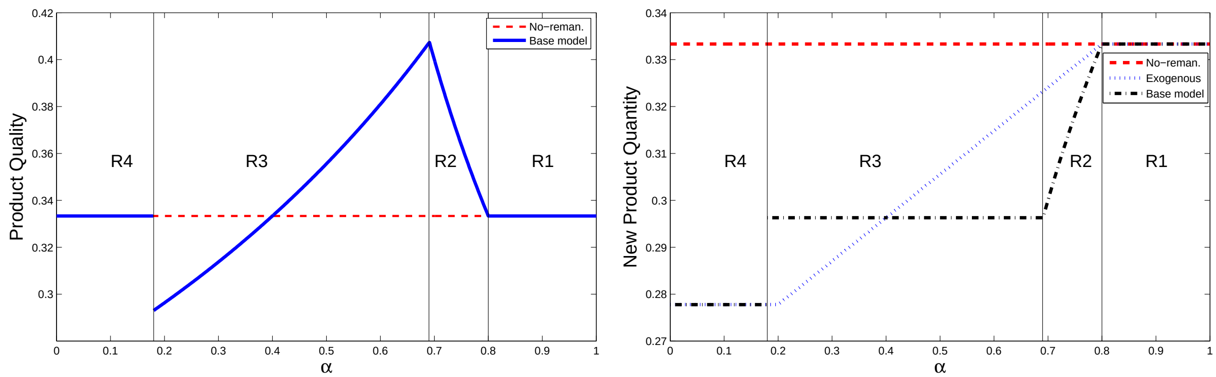
Region	s^*	q_n^*	q_r^*
R1	$\frac{1}{3\beta}$	$\frac{1}{3}$	0
R2	$\frac{\delta}{\beta(2\alpha-\delta)}$	$\frac{\alpha-\delta}{2\alpha-\delta}$	0
R3	$\frac{2-\delta}{3\beta(2-\alpha)}$	$\frac{2(2-\delta)}{3(4-\delta)}$	$\frac{(8-\delta)\delta-\alpha(4+\delta)}{3(2-\alpha)(4-\delta)\delta}$
R4	$\frac{1}{3\beta}$	$\frac{2}{3(2+\delta)}$	$\frac{2}{3(2+\delta)}$

Table 2.1: Equilibrium product quality, and new and remanufactured product quantities

Figure 2.1 graphically depicts the equilibrium regions in the Proposition. Note that the cost-to-value advantage shifts from the OEM to the IR as we move from region R1 to R4. In region R1, the IR does not pose a threat due to its severe cost-to-value disadvantage and the OEM acts as a monopolist leading to the same outcome as the NR benchmark.

In region $R2$, the IR is a competitive threat. However, the OEM is able to deter entry by choosing a higher level of quality compared to the NR benchmark. Because the quality of the new product directly impacts its remanufacturing cost, by increasing quality the OEM also increases the cost of remanufacturing. Thus, the IR cannot recover its cost due to its significant cost-to-value disadvantage and stays out of the market. Table 2.1 shows that the OEM needs to increase quality to deter entry when the IR becomes a bigger threat as a result of more favorable cost-to-value ratio. Figure 2.2a graphically demonstrates how the OEM's chosen quality level depends on the IR's cost of remanufacturing. We refer to the OEM's behavior in region R2 as entry deterrence because the OEM prevents the IR's entry by deviating from the NR benchmark. Note that entry deterrence does not exist in the exogenous quality benchmark (see Section A.1). In other words, quantity alone is not sufficient to deter entry.

In region $R3$, the OEM can no longer deter the IR's entry. In this region, the OEM can



(a) Quality (b) New Product Quantity

Figure 2.2: Equilibrium new product quality and quantity ($\delta = 0.4$, $\beta = 1$, Exogenous quality $s_f = \frac{1}{3\beta}$)

choose a higher or lower quality level when compared to the NR benchmark depending on who has the cost-to-value advantage. When the OEM has the cost-to-value advantage, i.e., $\frac{\alpha}{\delta} > 1$, it chooses a higher quality level. In this case, increasing product quality increases the remanufacturing cost but customer perception of remanufactured product does not increase proportionally, which in turn weakens the IR's competitive position. In contrast, when IR has the cost-to-value advantage, i.e., $\frac{\alpha}{\delta} < 1$, the OEM chooses a lower quality level to de-emphasize its competitor's advantage.

Finally, in region $R4$, the IR is very powerful and remanufactures all available cores. In this region, there is little perceived quality difference between the new and remanufactured products due to high δ, and the OEM cannot compete with the IR using the quality lever. Thus, the OEM keeps the quality at the NR benchmark level, instead competes with the IR by limiting the new product quantity, thereby the available cores for remanufacturing. We call this the quantity limiting strategy. Figure 2.2b shows the OEM's quantity in the base model as well as in the NR and exogenous quality benchmarks. The figure illustrates that the OEM reduces the new product quantity compared to the NR benchmark to restrain the IR. Because the OEM stops using the quality lever and instead focuses on the quantity lever in region $R4$, there is discontinuity in the quantity and the quality levels in Figure 2.2 when moving from region $R3$ to $R4$ due to this strategy switch. We do not observe the same phenomenon in the order quantity of the exogenous quality benchmark shown in Figure 2.2b. This is because quantity is the only lever in the exogenous quality benchmark, therefore there is no switching between strategies.

Proposition 1 demonstrates when the IR has a significant cost-to-value advantage, the OEM focuses primarily on a quantity limiting strategy. Indeed, this is consistent what we see in the printer cartridge industry where IRs have a significant cost-to-value advantage and OEMs mostly try to compete with IRs by creating quantity scarcity.

Proposition 1 illustrates that when the OEM has the cost-to-value advantage it relies more on the quality lever whereas when the advantage shifts to the IR, it increasingly relies on the quantity lever. Regions $R2$ and $R4$ demonstrate two extremes. In $R2$, the OEM has a significant cost-to-value advantage, and it relies solely on quality to deter the IR's entry (the OEM's quantity is the monopoly quantity given its chosen quality). In contrast in $R4$, the IR has a significant cost-to-value advantage, and the OEM uses only the quantity lever in this case keeping its quality at the NR benchmark level.

It is worthwhile to contrast our findings with the monopoly remanufacturing benchmark. A monopolist always increases its chosen product quality after engaging in remanufacturing (Details of the analysis are provided in section A.1.2). In contrast, when remanufacturing is performed by the IR, the OEM can decrease product quality compared to the NR benchmark. This happens because the OEM's quality decision directly affects the IR's competitive position while a monopolist OEM who remanufactures in-house does not need to worry about a competitor. When faced with competition from an IR, the OEM needs to take into account who has the cost-to-value advantage when making its quality decision. Under different modeling assumptions, Atasu and Souza (2012) also find that a monopolist OEM engaging in quality recovery (of which remanufacturing is an example) chooses a quality level that is weakly higher than the no-recovery scenario.

2.5 Consumer and Social Welfare

In this section we investigate the impact of remanufacturing and quality choice on consumer surplus (CS) and social surplus (SS). The consumer surplus is given by

$$CS = \int_{1-q_n-q_r}^{1-q_n} (\delta\theta s - p_r)d\theta + \int_{1-q_n}^{1} (\theta s - p_n)d\theta, \tag{2.1}$$

where the first term is the surplus from remanufactured products, and the second term is the surplus from new products sold. The social surplus is the sum of the consumer surplus and the firm profits.

Intuition suggests remanufacturing should improve consumer welfare. Indeed, the next proposition confirms this conjecture for the exogenous quality benchmark, that is, when the OEM responds to the IR's entry only with its quantity keeping its quality constant.

Proposition 2. *IR's entry always increases CS in the exogenous quality benchmark.*

However, the OEM does not keep its product quality constant when faced with the IR threat. Proposition 1 shows how the OEM adjusts its product quality to strengthen its competitive position. Basically, it may choose lower or higher quality levels depending on its cost-to-value position relative to the IR. The next proposition demonstrates remanufacturing can hurt CS due to the OEM's quality choice.

Proposition 3. *There exists α_c satisfying $1 < \frac{\alpha_c}{\delta} < \frac{8-\delta}{4+\delta}$ such that CS is higher than that of the NR benchmark if and only if $\alpha < \alpha_c$. Furthermore, CS is strictly smaller than that of the NR benchmark when $\frac{\alpha_c}{\delta} < \frac{\alpha}{\delta} < 2$.*

Propositions 1 and 3 show $\frac{\alpha_c}{\delta}$ falls in region $R3$. Thus, CS is lower than or equal to the NR benchmark in regions $R1$ and $R2$. In region $R1$, the IR is not a threat and the outcome is identical to the NR benchmark. In region R2, however, CS is strictly smaller than that of the NR benchmark as shown in the second half of the proposition. Specifically, in region $R2$, the OEM inefficiently chooses higher quality to deter the IR's entry, therefore focuses on the higher valuation consumers which in turn reduces CS. Interestingly, CS can also suffer in region $R3$ even when the IR enters the market. This is again due to the OEM's choice of high quality to play to its cost-to-value advantage.

Proposition 3 indicates that an IR with a weak competitive position is not preferable for CS. In order for CS to benefit from remanufacturing, the IR must have a sufficiently strong cost-to-value advantage, otherwise OEM's quality response hurts CS. This dynamic does not exist and CS always increases with remanufacturing in the exogenous quality benchmark. Thus, Propositions 2 and 3 imply that disregarding the OEM's quality decision can lead to overestimating the benefit of remanufacturing for consumers. Now let us consider the impact of remanufacturing on social surplus.

Proposition 4. *There exists α_s satisfying $1 < \frac{\alpha_s}{\delta} < \frac{8-\delta}{4+\delta}$ such that SS is higher than that of the NR benchmark if and only if $\alpha < \alpha_s$. Furthermore, SS is strictly smaller than that of the NR benchmark when $\frac{\alpha_s}{\delta} < \frac{\alpha}{\delta} < 2$.*

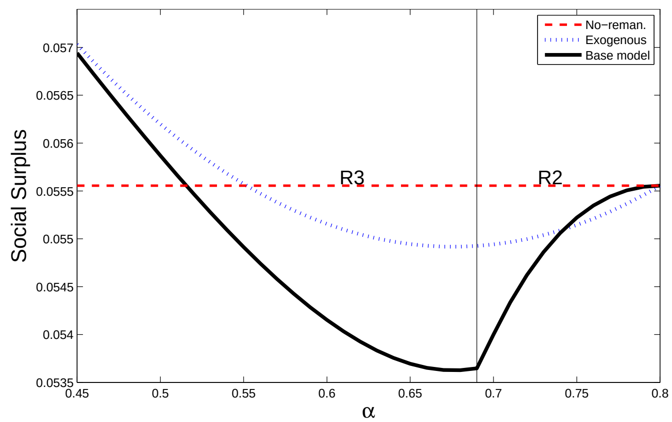


Figure 2.3: Comparison of Social Surplus with NR and Exogenous Quality Benchmarks ($\delta = 0.4$, $\beta = 1$ and Exogenous quality $s_f = \frac{1}{3\beta}$)

The proposition indicates that the IR's entry threat as well as its successful entry can decrease not only CS but also SS when the IR's cost-to-value position is not sufficiently favorable. Figure 2.3 compares SS against the NR and exogenous quality benchmarks. In the exogenous quality benchmark, the new product quality is kept at the NR benchmark quality disregarding the OEM's quality response to the IR threat. When the IR remanufactures, SS is always lower than the exogenous quality benchmark. Furthermore, note that when $0.516 < \alpha < 0.55$, remanufacturing worsens SS in our base model while improving it in the exogenous quality benchmark. In this case, ignoring the OEM's quality decision leads to incorrectly concluding that remanufacturing would benefit social welfare.

Propositions 3 and 4 show an IR's remanufacturing can decrease CS and SS. In contrast, our monopoly remanufacturing benchmark demonstrates both CS and SS increase when a monopolistic OEM engages in remanufacturing. Likewise, our extension in Section 2.7.1 (when only the OEM remanufactures) show a similar result. This contrast is due to two factors. First, an IR chooses to remanufacture products even when remanufacturing does not have a very attractive cost-to-value position. The OEM would not choose to remanufacture in regions in which the IR's remanufacturing decreases CS and SS.[1] In other words, the OEM's remanufacturing incentives are better aligned with consumer and social welfare compared to the IR's. Second, when the OEM utilizes the benefits of remanufacturing, it chooses product quality more efficiently as far as CS and SS are concerned. In contrast, when an IR does the remanufacturing, the OEM can inefficiently increase quality to deter entry or decrease quality to undermine the cost-to-value advantage of its competitor.

Our findings have important policy implications. There is an ongoing policy debate whether and when to promote remanufacturing. For example, the Recycling/Remanufacturing Tax Credit Bill, HR 5695 (The Remanufacturing Institute, 2008) introduced by the Automobile Parts Remanufacturers Association (APRA) calls for tax credits for investments in remanufacturing equipment. Although the bill did not pass the first time round, efforts to pass it continue. Similarly, the Waste Electrical and Electronic Equipment (WEEE) Directive legislation in the European Union holds manufacturers financially responsible for taking back and disposing of end-of-life electric and electronic equipment. In a recent vote on changes to the directive, a 5% reuse target was introduced to promote higher levels of reuse/remanufacturing (Jowitt, 2011). In addition, environmental awareness campaigns, companies promoting sustainable business practices, etc. may work to improve customers' perception of remanufactured products. Such incentives and campaigns can alter competitive positioning of IRs and OEMs and change their behavior. Our findings illustrate policy makers should be careful when designing such incentives especially when IRs (rather than OEMs themselves) engage in remanufacturing. Making remanufacturing attractive for IRs does not necessarily improve social welfare. Propositions 3 and 4 show that the IR's threat and entry can decrease both CS and SS. Furthermore, ignoring competition or the OEM's quality decision can lead to overestimating benefits of remanufacturing for consumer and social surplus.

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[1] The monopoly remanufacturing benchmark in Appendix A illustrates that the OEM never remanufactures when the remanufactured product has an inferior cost-to-value position compared to the new product.

Region	α	δ
R1	Constant	Constant
R2	$\uparrow$	$\downarrow$
R3	$\downarrow$	Concave(if $\frac{e}{E} < 1$), $\uparrow$ (if $\frac{e}{E} > 1$)
R4	Constant	$\downarrow$

Table 2.2: Environmental impact comparative statics

2.6 Environmental Impact

We follow the convention in the literature (Atasu and Souza, 2012; Agrawal et al., 2011b; White et al., 1999), and assume that one unit of new product and remanufactured product entail E and e environmental impact respectively considering all stages of product life cycle which includes production, use by customers, end of life and remanufacturing. Therefore, when the OEM produces q_n units and the IR remanufactures q_r units, the total environmental impact is $q_nE + q_re$.

Next proposition shows the effect of remanufacturing on the environment comparing it the NR benchmark and describes how environmental impact depends on relative cost α and perception δ of the remanufactured product.

Proposition 5. *Table 2.2 shows how the environmental impact changes with α and δ.*

- *When the IR is not a threat (region $R1$), the environmental impact is the same as the NR benchmark level.*

- *When the IR's entry is deterred by the OEM (region $R2$), the environmental impact is always lower than the NR benchmark level.*

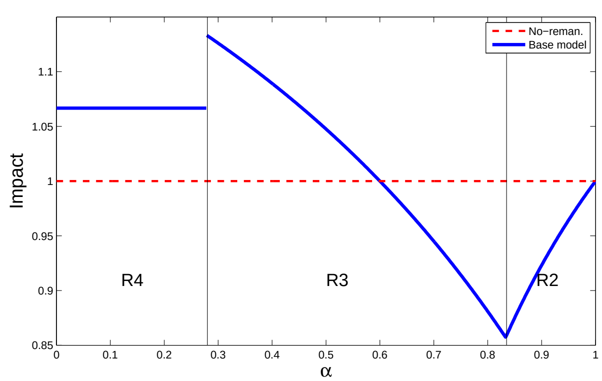
- *When the IR enters the market but does not remanufacture all available cores (region $R3$), the environmental impact is lower than the NR benchmark level if and only if $\frac{e}{E} < \frac{(-2+\alpha)\delta^2}{(-8+\delta)\delta+\alpha(4+\delta)}$.*

- *When the IR enters the market and remanufactures all available cores (region $R4$), the environmental impact is lower than the NR benchmark level if and only if $\frac{e}{E} < \frac{\delta}{2}$.*

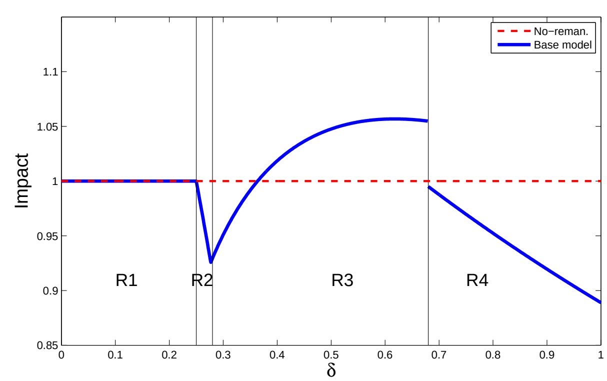
The proposition demonstrates that the IR's entry threat in region $R2$ reduces environmental impact. To deter entry, the OEM increases product quality and focuses on higher valuation customers, which in turn decreases the quantity sold. Furthermore, Table 2.2 shows that as the IR becomes a bigger threat, the environmental impact decreases further in this region since the OEM needs to keep increasing quality to deter entry as the IR's cost-to-value position improves.

The IR remanufactures in regions $R3$ and $R4$ and the relative impact of new and remanufactured products $\frac{e}{E}$ determines the environmental impact of remanufacturing in these regions. Specifically, when remanufactured product has a sufficiently smaller relative environmental impact indicating small $\frac{e}{E}$, the overall environmental impact decreases with the IR's entry. Otherwise, remanufacturing increases the environmental impact.

Figure 2.4 illustrates how the environmental impact depends on the IR's relative competitive position showing that environmental impact attains its worst level in region $R3$. This is because competition between the IR and the OEM is more intense yielding more quantity sold (new + remanufactured) when neither has a significant cost-to-value advantage. The environmental impact gets smaller near region $R2$, as the OEM's cost-to-value advantage improves. Similarly at the other end, the environmental impact is also smaller in region $R4$, where the IR has a significant cost-to-value advantage.[2]



(a) Effect of α



(b) Effect of δ

Figure 2.4: Environmental Impact ($e = 1$, $E = 3$, $\delta = 0.5$ in (a), $\alpha = 0.5$ in (b))

In region $R4$, the OEM follows the quantity scarcity policy to limit the IR's remanufacturing. Table 2.2 shows that when the IR's cost-to-value position gets even better due to a higher δ in this region, the OEM further decreases its quantity, benefiting the environmental impact.

[2]Although $e < E$ in Figure 2.4, the insights discussed here hold for $e \geq E$ as well.

Both in regions $R2$ and $R4$, quantity hence the environmental impact decreases when the IR becomes more powerful. But there are different dynamics in place. In $R2$, quantity decreases because the OEM increases quality to deter the IR, whereas in region $R4$, the OEM creates scarcity to limit the IR's remanufacturing.

Comparisons with the monopoly remanufacturing benchmark (see section A.1.2 for details) show that how remanufacturing changes the environmental impact level depends on *who*—OEM or IR—does the remanufacturing. We find that if remanufacturing has the cost-to-value advantage ($\frac{\alpha}{\delta} < 1$), and hence, is socially desirable[3], whenever the environmental impact in the base model is smaller than the NR benchmark, environmental impact in the monopoly remanufacturing benchmark is also smaller than the NR benchmark but not vice versa. Hence, remanufacturing by an OEM is more likely to decrease environmental impact than remanufacturing by an IR (Our extension in Section 2.7.1 finds a similar result). This is mainly due to two factors: (i) Competition increases the total quantity sold; a monopoly always sells fewer units. (ii) The OEM can reduce the quality level when the competing IR has the cost-to-value advantage and a lower quality level implies a bigger quantity in the market. Under somewhat different modeling assumptions, Atasu and Souza (2012) find that quality recovery (of which remanufacturing is an example) carried out by a monopolistic OEM always decreases the environmental impact, which is also in contrast with our base model. Our findings together with Atasu and Souza (2012) suggest that as far as the environmental impact is concerned, it may not be beneficial to encourage IRs rather than OEMs to remanufacture. Furthermore, when an IR does the remanufacturing, increased competition can aggravate environmental impact. In this case, it is desirable to have an IR with either a sufficiently unfavorable cost-to-value ratio so the OEM increases the quality level or a sufficiently favorable cost-to-value ratio so the OEM competes by creating quantity scarcity.

[3]We know from section 2.5 and section A.1.2 that in both the base model and the monopoly remanufacturing benchmark, CS and SS levels are higher than the NR benchmark when $\frac{\alpha}{\delta} < 1$. In addition, in the monopoly remanufacturing benchmark, the OEM remanufactures only when it is socially advantageous to do so.

δ	s^*	q_n^*	q_{mr}^*	q_{ir}^*	CS	SS	$\overline{e/E}$	δ	s^*	q_n^*	q_{mr}^*	q_{ir}^*	CS	SS	$\overline{e/E}$
0.40	0.333	0.333	0	0	0.0185	0.0556	–	0.70	0.315	0.183	0.183	0	0.0163	0.0489	0.824
0.43	0.368	0.316	0	0	0.0184	0.0551	∞	0.73	0.320	0.181	0.181	0	0.0167	0.0501	0.844
0.46	0.403	0.298	0	0	0.0179	0.0538	∞	0.76	0.326	0.179	0.179	0	0.0171	0.0513	0.863
0.49	0.419	0.287	0	0.014	0.0181	0.0516	3.278	0.79	0.331	0.177	0.177	0	0.0175	0.0525	0.883
0.52	0.411	0.284	0	0.042	0.0193	0.0527	1.186	0.82	0.333	0.175	0.175	0	0.0179	0.0538	0.901
0.55	0.403	0.280	0	0.067	0.0205	0.0531	0.793	0.85	0.345	0.174	0.174	0	0.0183	0.0550	0.919
0.58	0.394	0.277	0	0.090	0.0217	0.0538	0.631	0.88	0.348	0.172	0.172	0	0.0188	0.0563	0.936
0.61	0.298	0.190	0.190	0	0.0152	0.0455	0.758	0.91	0.354	0.171	0.171	0	0.0192	0.0577	0.953
0.64	0.304	0.187	0.187	0	0.0155	0.0466	0.780	0.94	0.359	0.169	0.169	0	0.0197	0.0590	0.969
0.67	0.309	0.185	0.185	0	0.0159	0.0478	0.802	0.97	0.365	0.168	0.168	0	0.0201	0.0603	0.974

Table 2.3: Equilibrium and the resulting consumer/social surplus and environmental impact when the OEM can also remanufacture ($\beta = 1, \alpha = 0.8$)

2.7 Additional Competitive Levers

In this section we study two additional levers an OEM can use to compete with an IR. Specifically, the OEM can also remanufacture its own product or it can collect cores to make them unavailable for the IR.

2.7.1 Remanufacturing by both OEM and IR

Remanufacturing can be done by IRs as well as by the OEM itself. There are examples of both in practice. For example, Xerox leases its copiers and remanufactures end-of-lease copiers by itself; in contrast in the cartridge industry mainly IRs do the remanufacturing. Here, we extend our base model and allow the OEM to remanufacture its own product in addition to the IR. We conduct a numerical study to analyze the resulting equilibrium.

The OEM and the IR have the same remanufacturing cost ($\beta\alpha s^2$ in our model) and they choose their desired remanufacturing quantities simultaneously. However, the OEM has the priority in quantity allocation when their total demand exceeds the number of available cores. In other words, the IR can remanufacture only the cores that the OEM chooses not to remanufacture. Admittedly, this approach favors OEM's remanufacturing, but even with this bias, we show the OEM may prefer letting the IR remanufacture and instead continue to compete through manipulating quality. Note the other extreme where the IR gets priority in the allocation of available cores results in the same equilibrium outcome as our base model.[4]

[4]Essentially, in this scenario, any core that is not profitable for the IR to remanufacture is not profitable for the OEM either. Therefore, in equilibrium remanufacturing is done only by the IR, which is the same as our base model. However, when the OEM has the priority, a core that is not profitable for the OEM can be profitable

Table 2.3 reports results of our numerical study as δ varies for one α value, $\alpha = 0.8$. In our study, we repeat the same analysis for $\alpha \in \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9\}$ values and find that Table 2.3 is representative of their outcomes as well. Quality cost coefficient β is a scale factor in our model and it is kept at $\beta = 1$. In the table, q_{mr} and q_{ir} show the number of remanufactured units by the OEM and the IR, respectively. Furthermore, $\overline{e/E}$ shows the maximum e/E ratio–environmental impact of remanufactured product relative the new product–below which remanufacturing (or the possibility of it) reduces environmental impact compared to the NR benchmark. In the Table $\overline{e/E}$ is not reported for $\delta = 0.4$ since when $\delta \leq 0.4$, remanufacturing is not viable, and the NR benchmark and our extended model yields the same outcome.

To better understand the effect of competition, consider the OEM's optimal policy in the absence of an IR. A monopolist OEM does not remanufacture when the cost-to-value ratio favors the new product, i.e., $\alpha/\delta > 1$. It remanufactures some but not all available cores when the remanufactured product has the cost-to-value advantage, i.e., $\alpha/\delta < 1$ but the advantage is not sufficiently big ($0.8 < \delta < 0.9$ in Table 2.3). Finally, when the remanufactured product has a significant cost-to-value advantage, a monopolist OEM remanufactures all available cores. Table 2.3 shows when remanufacturing has a sufficiently big advantage or disadvantage, the OEM does not need to deviate from the monopoly optimal policy to compete with the IR. Specifically, when remanufacturing has a severe disadvantage ($\delta \leq 0.4$), the IR is not a threat, the OEM sells only the new product. In contrast, when remanufacturing has a significant advantage ($\delta \geq 0.91$), the OEM remanufactures all available cores leaving no cores to the IR.

When cost-to-value ratio of remanufacturing α/δ is moderate ($0.4 < \delta \leq 0.88$ in Table 2.3), the OEM needs to actively compete with the IR. The OEM uses different policies depending on the cost-to-value position of remanufacturing. Note remanufacturing becomes increasingly attractive as δ increases. When $0.40 < \delta < 0.49$, similar to our base model, the OEM increases quality to deter the IR from remanufacturing. When $0.49 \leq \delta < 0.61$, the OEM lets the IR remanufacture but it increases quality to weaken the IR's competitive position. It is interesting that the OEM is using only quality as a strategic lever in $0.40 < \delta < 0.61$ although our core

to remanufacture for the IR since unlike the OEM, the IR does not need to worry about cannibalization of the new product.

allocation gives absolute priority to the OEM. Finally, the OEM inefficiently remanufactures *all* available cores itself in order to leave no cores available to the IR when $0.61 \leq \delta \leq 0.81$. This discussion demonstrates that similar to our base model, the OEM relies on quality as a competitive lever when remanufacturing does not have a strong cost-to-value position, in contrast, it uses a quantity limiting strategy when the IR's remanufacturing becomes a bigger threat.

The OEM increases quality when the remanufactured product has the cost-to-value advantage, i.e, $\alpha/\delta < 1$. This is in direct contrast to the base model. Essentially, when the OEM itself rather than a competitor IR does the remanufacturing, the OEM is better off underscoring the remanufactured product's advantage by increasing quality. However, when the remanufactured product has the disadvantage, i.e., $\alpha/\delta > 1$ and the OEM remanufactures solely to eliminate available cores for the IR, the OEM decreases quality.

Similar to the base model, CS and SS decrease when the OEM uses quality to deter the IR's entry ($0.40 < \delta < 0.49$).[5] Likewise, the IR's remanufacturing can also decrease CS and SS ($\delta = 0.49$). In these examples, the OEM inefficiently chooses a high quality level to strengthen its competitive position. Similarly, CS and SS suffer when $0.61 \leq \delta \leq 0.85$ and the OEM inefficiently remanufactures all available cores itself to starve the IR in this range. When cost-to-value position of remanufacturing improves ($\delta \geq 0.88$), the OEM's remanufacturing increases both CS and SS compared to the NR benchmark.

When the OEM does not remanufacture, the environmental impact is the same as our base model and our insights carry over. However, contrasting the environmental impact of OEM's and IR's remanufacturing generates an additional insight. Remanufacturing decreases the environmental impact when e/E is smaller than $\overline{e/E}$ in Table 2.3. Thus a larger $\overline{e/E}$ indicates that remanufacturing is more likely to reduce the environmental impact. Improving cost-to-value ratio of remanufacturing (higher δ in the Table) decreases $\overline{e/E}$ when the IR is remanufacturing and increases $\overline{e/E}$ when the OEM is remanufacturing. This suggests that making remanufacturing more attractive can worsen the environmental impact when remanufacturing is done by the IR whereas it lessens the environmental impact when remanufacturing

[5]The NR benchmark is equivalent to the $\delta = 0.4$ outcome.

is done by the OEM itself.

2.7.2 Preemptive Collection

In our base model, the OEM competes with the IR using quality and quantity as strategic levers. Here, in addition to using quality and quantity, we allow the OEM to collect and dispose of cores to compete with the IR. As before, the OEM first chooses the quality level. Then simultaneously, the OEM decides the number of cores to collect for disposal and the new product quantity and the IR decides the remanufactured product quantity. The OEM has priority in core collection (i.e., it has first access to cores) if the total demand for cores exceeds the available cores. Even then, we show that the OEM may still rely on quality to compete with the IR rather than collecting and disposing of cores. Similar to Ferguson and Toktay (2006), we assume that the total collection and disposal cost the OEM incurs is hq_d^2 where q_d is the quantity collected and h is a measure of how difficult and expensive it is to collect cores. Due to the analytical complexity of this model, we conduct a numerical study.

Figure 2.5 illustrates the OEM's quality choice and equilibrium regions for $\delta = 0.4$ and $h = 0.04$ when α varies from 0 to 1. In region Rd the OEM collects all available cores and the regions $R1 - R3$, in which the OEM does not utilize preemptive collection, are the same as those of our base model. We repeat the numerical study for all combinations of $\delta = \{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9\}$ and $h = \{0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, 0.11\}$ and observe that the figure is a representative outcome.

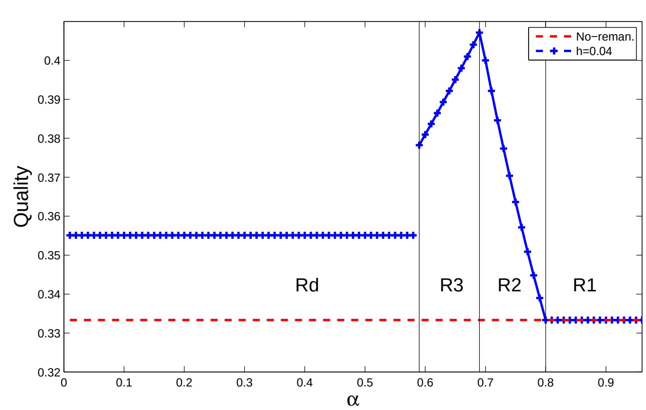


Figure 2.5: Equilibrium quality when the OEM can collect and dispose the used cores ($\delta = 0.4, \beta = 1, h = 0.04$)

The Figure shows that when the cost-to-value ratio $\frac{\alpha}{\delta}$ is sufficiently high ($0.59 \leq \alpha < 0.8$), the OEM uses quality to compete with the IR instead of preemptive collection (The IR does not pose a threat when $\alpha \geq 0.8$). When $0.69 \leq \alpha < 0.8$, the OEM deters the IR's entry by increasing quality. When $0.59 \leq \alpha < 0.69$ the OEM lets the IR remanufacture but still chooses a high quality level to weaken the IR. Drivers of these results are same as those in the base model. When the cost-to-value ratio $\frac{\alpha}{\delta}$ is sufficiently small ($0 < \alpha < 0.59$), the IR's competitive position is strong. In this case, the OEM collects and disposes of all available cores to deter the IR's entry. While doing so, the OEM also increases quality relative to the NR benchmark to decrease the number of cores to be collected. Hence, the OEM utilizes the preemptive collection and quality levers together to deter IR's entry.

When the OEM uses quality to deter or compete with the IR (i.e., $0.59 \leq \alpha < 0.8$), the threat or actual entry can decrease the CS and SS compared to the NR benchmark. This behavior is similar to our base model. For $0 < \alpha < 0.59$, the OEM uses preemptive collection to deter the IR's entry, and CS and SS are lower than the NR benchmark levels. This behavior is also consistent with our base model where entry deterrence reduces CS and SS levels. In Section A.2, we provide further details on our social welfare results.

In the numerical study we observe that when h is high ($h \geq 0.09$), collecting all available cores may not be viable. In this case, the OEM collects and disposes of a fraction of the available cores and the IR remanufactures the remaining cores. On the other hand, when h is very low, as intuition would suggest, the OEM collects and disposes of all cores.

2.7.3 Comparison of Competitive Levers

Through a numerical study, we now discuss how the OEM chooses to compete with the IR when all three competitive levers, i.e., quality choice, remanufacturing in-house and preemptive collection, are available. In our study, we considered all combinations of $\alpha \in \{0.1, 0.2, \ldots, 0.8, 0.9\}$ and $h \in \{0.04, 0.05, 0.06\}$. Table 2.4 is representative of our results.

Similar to our earlier results, the OEM's choice depends on the remanufactured product's relative cost-to-value ratio $\frac{\alpha}{\delta}$. Consistent with our insights from the base model, when the cost-to-value ratio is high but the remanufactured product is still a competitive threat, the OEM relies only on the quality lever to compete with the IR. Specifically, when $\delta = 0.5$, the OEM

δ	s^*	q_n^*	q_{mr}^*	q_d^*	q_{ir}^*
0.4	0.333	0.333	0	0	0
0.45	0.392	0.304	0	0	0
0.5	0.417	0.286	0	0	0.024
0.6	0.338	0.277	0.043	0.234	0
0.7	0.332	0.254	0.085	0.169	0
0.8	0.336	0.220	0.126	0.094	0
0.9	0.352	0.171	0.171	0	0

Table 2.4: Equilibrium when the OEM can remanufacture and preemptively collect ($\beta = 1, \alpha = 0.8, h = 0.04$)

allows the IR to remanufacture but increases product quality relative to the NR benchmark to undermine the IR's competitive position. Likewise, when $\delta = 0.45$, the OEM increases quality relative to the NR benchmark to deter the IR's entry. The IR is not a competitive threat when $\delta \leq 0.4$.

When the remanufactured products's relative cost-to-value ratio is low, that is, the IR becomes a bigger competitive threat, the OEM uses in-house remanufacturing and preemptive collection jointly to cause scarcity of cores. In particular, when $\delta \geq 0.6$, the OEM remanufactures a fraction of the available cores and preemptively collects any remaining cores, deterring the IR's entry. Furthermore, the OEM remanufactures a larger proportion of collected cores when δ increases indicating a higher perceived value for the remanufactured product. This result is in agreement with our insight from the base model, in which the OEM decreases the production of new product to limit the available cores when the IR becomes a bigger threat.

2.8 Extensions

2.8.1 Price Competition

Here, we study what happens when the OEM and the IR compete in prices. The following proposition describes the equilibrium for the price competition game showing that the structure of the equilibrium is the same as the quantity game.

Proposition 6. *The following characterizes the equilibrium regions when the OEM and the IR compete in prices.*

$R1^p$. If $\frac{\alpha}{\delta} \geq 2$, the IR cannot enter the market and the OEM acts like a monopoly.

$R2^p$. If $\frac{4-\delta}{2+\delta} \leq \frac{\alpha}{\delta} < 2$, the IR is a threat and its entry is deterred by the OEM.

$R3^p$. If $\frac{\delta(10-\delta)}{(4-\delta)^2} < \frac{\alpha}{\delta} < \frac{4-\delta}{2+\delta}$, the IR enters but does not remanufacture all available cores.

$R4^p$. If $0 < \frac{\alpha}{\delta} \leq \frac{\delta(10-\delta)}{(4-\delta)^2}$, the IR enters the market and remanufactures all available cores.

The equilibrium quality, new and remanufactured product prices and quantities are provided in the proof of the proposition.

Regions $R1^p$-$R4^p$ are the same as regions $R1$-$R4$ of our base model. Specifically, in region $R1^p$, the IR is not a threat due to its poor cost-to-value position. In region $R2^p$, the OEM chooses a higher quality level compared to the NR benchmark to deter the IR's entry. In region $R3^p$, the OEM chooses a higher or lower quality level depending on whether it has the cost-to-value advantage or disadvantage. Finally, in region $R4^p$, the OEM follows a quantity limiting strategy. Drivers of these results are the same as those in our base model. In region $R2^p$, the OEM's price is smaller than the monopoly price for its chosen product quality. Different from our base model, the OEM uses price in addition to quality to deter entry in region $R2^p$.

It is well known that price competition is more intense than quantity competition and leads to higher CS and SS (Singh and Vives, 1994). Consistent with this fact, we find that CS and SS are higher than the NR benchmark when the OEM and the IR compete in prices (More detailed analysis of the CS and SS under price competition is relegated to Section A.3). Another artifact of the intense competition is that the new product quantity is always higher than or equal to the NR benchmark. Therefore, remanufacturing by an IR *always* increases environmental impact under price competition.

2.8.2 Alternative Remanufacturing Cost

Up to this point, we assumed that all remanufacturing related costs are subsumed in $\beta\alpha s^2$. In this section we consider an additional cost term n that is independent of the quality level. Specifically, the IR's total unit remanufacturing cost becomes $\beta\alpha s^2 + n$.

We are able to characterize the equilibrium when the OEM has the cost-to-value advantage, i.e, $\frac{\alpha}{\delta} \geq 1$, and we state our result in Proposition 7. However, when the IR has the cost-to-value advantage, i.e, $\frac{\alpha}{\delta} < 1$, the model is not analytically tractable; therefore we resort to a numerical study. Figure 2.6 demonstrates the results for $\frac{\alpha}{\delta} < 1$ as well as for $\frac{\alpha}{\delta} \geq 1$. While the Figure reports the result for one δ and $n = \{0, 0.01, 0.02, 0.05, 0.06\}$, we have run the numerical study for all combinations of $\delta \in \{0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.9\}$ and $n \in \{0.005, 0.010, 0.020, 0.025, 0.030, 0.035, 0.040, 0.045, 0.050\}$ and found that they are all consistent. We also study the impact of the quality independent remanufacturing cost on the CS and SS in Appendix A (see Section A.4) and observe numerically that the insights from Propositions 3 and 4 continue to hold.

Proposition 7. *The following characterizes the equilibrium regions for $\frac{\alpha}{\delta} \geq 1$ when the IR incurs an additional cost n per unit.*

$R1^i$. If $\frac{\alpha}{\delta} \geq 2$, or $2 > \frac{\alpha}{\delta} > 1$ and $n \geq \frac{2\delta-\alpha}{9\beta}$, the IR cannot enter and the OEM acts like a monopoly.

$R2a^i$. If $2 > \frac{\alpha}{\delta} \geq \frac{8-\delta}{4+\delta}$ and $\frac{2\delta-\alpha}{9\beta} > n$, or $\frac{8-\delta}{4+\delta} > \frac{\alpha}{\delta} \geq \frac{5}{4}$ and $\frac{2\delta-\alpha}{9\beta} > n \geq n_0$, the IR's entry is deterred by the OEM who chooses a quality level higher than the NR benchmark.

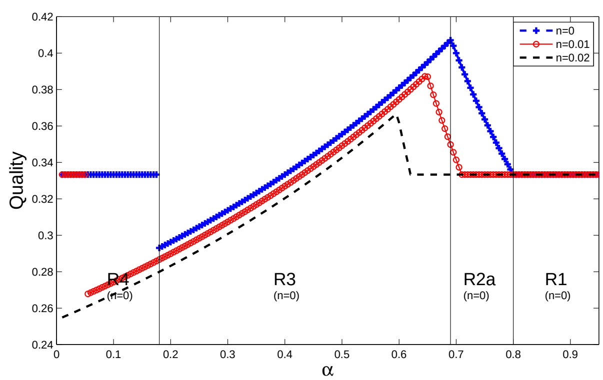
$R2b^i$. If $\frac{5}{4} > \frac{\alpha}{\delta} \geq 1$ and $\frac{2\delta-\alpha}{9\beta} > n \geq n_0$, the IR's entry is deterred by the OEM who chooses a quality level lower than the NR benchmark.

$R3^i$. If $\frac{8-\delta}{4+\delta} > \frac{\alpha}{\delta} \geq 1$ and $n_0 > n$, the IR enters the market but does not remanufacture all available cores.

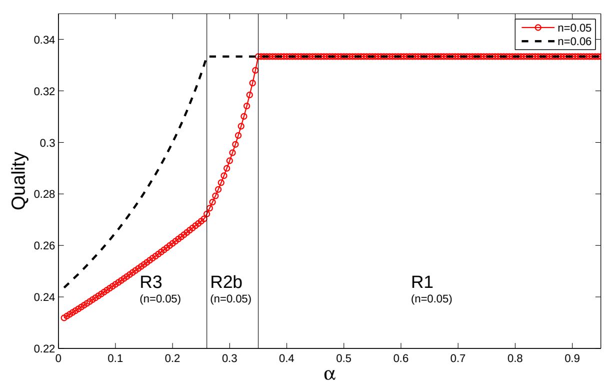
The equilibrium quality, new and remanufactured product quantities, and n_0 are stated in the proof of the Proposition.

Regions $R1^i - R3^i$ are same as the regions $R1 - R3$ in the base model. The Proposition demonstrates all three regions that exist in our base model for $\frac{\alpha}{\delta} \geq 1$, namely $R1 - R3$, continue to exist. In addition to these regions an additional region (region $R2b^i$) where the OEM deters the IR's entry by choosing a quality level *lower* than the NR benchmark is also possible when the cost-to-value ratio and the quality independent remanufacturing cost are at moderate levels, i.e, $\frac{-\alpha+2\delta}{9\beta} > n \geq n_0$. The OEM's choice of low quality decreases the demand for the remanufactured product but also decreases the remanufacturing cost. The key point is that the quality independent component (n) of the remanufacturing cost does not change when the OEM chooses a low quality level and therefore, the positive effect of cost reduction on the IR's profit is smaller when compared to the negative effect of demand reduction. This allows the OEM to deter the IR's entry through decreasing quality in the presence of the quality independent cost component. The Proposition also demonstrates that when the quality independent remanufacturing cost is too high, i.e, $\frac{2\delta-\alpha}{9\beta} \leq n$, the IR cannot enter at all, as expected.

Figures 2.6a and 2.6b illustrate the equilibrium structure for $n \in 0, 0.01, 0.02$ and $n \in 0.05, 0.06$ respectively. Figure 2.6a shows that when the IR has a strong cost-to-value position, the OEM may continue to rely on reducing production and limiting core availability (region $R4^i$). However, as intuition suggests, region $R4^i$ gets smaller as n increases. In fact, when $n \geq 0.02$, $R4^i$ disappears. Figure 2.6 also shows that as n increases, the OEM relies more on the quality lever to compete with the IR. However as n increases, the regions where the OEM chooses a quality level higher than the NR benchmark shrink. In fact, for $n \geq 0.05$, the OEM always chooses a lower level of quality (if different from the NR benchmark level).



(a) $n \in \{0, 0.01, 0.02\}$ (Partitions R1-R4 are shown for $n = 0$)



(b) $n \in \{0.05, 0.06\}$ (Partitions R1-R3 are shown for $n = 0.05$)

Figure 2.6: Equilibrium quality level when the IR incurs quality-independent cost($\delta = 0.4, \beta = 1$)

2.8.3 Independent Quality Gap

In our base model the quality gap between the new and remanufactured product is proportional to the product quality s. Here, we consider an alternative model in which the quality gap is independent of product quality, specifically the value of remanufactured product is $\theta(s - \phi)$ for type-θ consumer, where ϕ shows the quality gap for the remanufactured product.

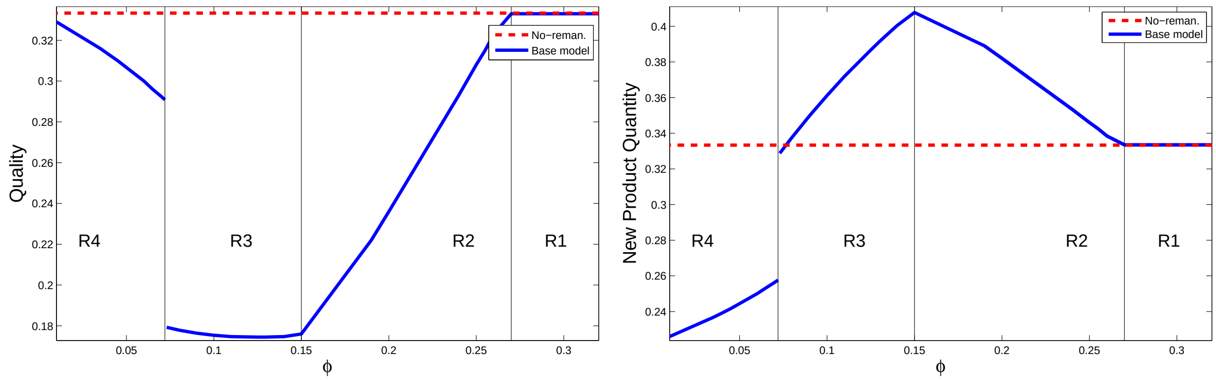
Due to the analytical complexity of this alternative model, we resort to numerical studies.

Figure 2.7 shows the equilibrium quality and quantity as quality gap ϕ varies for $\alpha = 0.4$. We find the behavior in this figure to be robust by also checking other $\alpha \in \{0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9\}$ values. The Figure identifies four regions similar to our base model (see Proposition 1). In particular, in region $R1$, quality gap is sufficiently high and the IR is not a threat. In region $R2$, the OEM deters the IR's entry through its quality choice. In region $R3$, the quality gap is sufficiently small and the IR remanufactures a portion of available cores. In region $R4$, the quality gap is very small, and the OEM follows a quantity limiting strategy. This strategy shift is evident in Figure 2.7b as the quantity drops discontinuously between regions $R3$ and $R4$. Note that similar to our base model, when the IR is weak (large ϕ in this extension), the OEM competes using the quality lever; in contrast when the IR is strong (small ϕ), the OEM relies on limiting quantity.

Figure 2.7a demonstrates that the OEM always chooses a lower quality level compared to the NR benchmark. This is the main difference between this extension and our base model. Because the quality gap is independent of the quality level, increasing the quality of the new product also increases the quality of the remanufactured product by the same amount. Therefore, the OEM does not want to increase quality too much which would undermine the relative significance of the quality gap. A lower quality level ensures that the OEM's quality advantage is sufficiently large relative to the remanufactured product's perceived quality. When the OEM chooses a much lower quality level than the NR benchmark, this negatively affects social welfare and results in CS and SS levels lower than the NR benchmark (a more detailed analysis is provided in Section A.5).

2.9 Concluding Remarks

We study how an OEM can use product quality as a competitive strategic lever along with quantity against an IR. Even though there is evidence that OEMs take competition and remanufacturing into consideration in their product design decisions, this problem has not been studied before. The relationship between quality and competition has been studied in the economics and marketing literatures, but their results do not directly apply because the remanufacturing context is fundamentally different. By characterizing how the OEM competes with the IR in equilibrium, we find that the OEM relies more on quality as a strategic lever



(a) Quality (b) New Product Quantity

Figure 2.7: Equilibrium quality and new product quantity when the perceptual quality gap is independent of new product quality. ($\alpha = 0.4, \beta = 1$)

when it has a stronger competitive position , and in contrast, it relies more heavily on limiting quantity of cores when it has a weaker competitive position.

A commonly-held belief is that remanufacturing is good for the environment and consumers even though these relationships are not well understood, especially in industries where predominantly IRs remanufacture. We study the effect of remanufacturing by an IR on total environmental impact and consumer surplus. We find that unless the IR has a sufficiently weak competitive position (so the OEM can deter entry) or a sufficiently strong one (so the OEM switches its competitive strategy and limits product quantity), environmental impact can increase when compared to the NR benchmark. Because when neither the OEM nor the IR has a sufficiently strong competitive advantage, the competition between the two becomes more intense yielding more quantity sold (new+remanufactured). On the consumer surplus side, not only the IR's entry threat but also its successful entry can cause a decrease in the consumer surplus level. This is also in contrast with our monopoly remanufacturing benchmark which shows remanufacturing by an OEM always benefits the consumers (Atasu and Souza (2012) have a similar finding). Taken together, our findings regarding environmental impact and social welfare suggest that policy makers should be careful about promoting IR-remanufacturing over OEM-remanufacturing.

Some limitations of our work are worth mentioning. We study a single period model due to its tractability and to keep our focus on our research questions. This approach is plausible when a product's pay-off during its mature stage makes up a bulk of its total pay-offs. Indeed, most papers looking at firms' quality choice consider stationary demand as we do (e.g., Atasu and Souza 2012; Plambeck and Wang 2009; Netessine and Taylor 2006; Johnson and Myatt 2006). The relation between the shape of a product's life-cycle and its remanufacturing decisions can be an interesting research question, which we do not study in this paper and leave for future work. Furthermore, comparison of our results from the base model with results from extensions where we consider alternative cost and consumer valuation functions for the remanufactured product, indicate that whether the OEM chooses to increase or decrease the quality level vis-a-vis the NR benchmark can be sensitive to the functional form assumed. Similarly, the implication of remanufacturing on the social and consumer surplus, and environmental impact can be sensitive to the form of competition (price vs. quantity). Future research on this issue should be careful about these relations.

CHAPTER 3

IS SERVICIZATION A WIN-WIN STRATEGY? PROFITABILITY AND ENVIRONMENTAL IMPLICATIONS OF SERVICIZATION

3.1 Introduction

There has been a significant structural economic shift to services from manufacturing in the US and other advanced industrial countries over the last century. While the contribution of manufacturing to the US economy has shrunk, the contribution of the service sector has increased by over 200% in the post-1950 era (White et al. 1999). A recent report of the US Department of Commerce (April 2013) shows that the service sector comprises 80.3% of the US GDP (US Department of Commerce, 2013). Services also now constitute more than 80% of the US employment (Bureau of Labor Statistics, 2013).

The service economy itself has also been changing and adding new concepts in its structure. Traditional services, which generally rest upon the provision of labor and expertise, not physical goods, are not the only kinds of services anymore. Some manufacturers have started using their products as means for service delivery; not the end. These business models are called product-service systems. Some of these product-service systems are of the more familiar kind where the manufacturers sell services *along* with the products, such as warranties and maintenance services for autos and other durable goods. In others, manufacturers sell services *instead* of products. The latter type of product-service system is referred to as 'servicization'. While various notions of 'servicization' have been conceptualized (Toffel, 2002), we adopt the commonly used definition of servicization where, in a servicization strategy, the manufacturer sells the functionality of the product rather than the product itself, i.e., the manufacturer owns and incurs the cost to operate the product while the customer pays for the use and the value derived from the use of the product. Thus, the two distinctive features of servicization, as compared to selling or leasing products, are: payments based on the amount of use of a product and the inclusion of the operating cost including maintenance and supplies in the service agreement. For example, Rolls Royce offers its customers power-by-hour contracts where Rolls Royce retains the ownership of the engines, maintains them regularly, and the customers only pay based on number of hours they use the engines. AB Electrolux installs washing machines in a customer's home, maintains and repairs them regularly, and charges customers by the laundry load. Other examples of servicization include Interface Inc. (Modular Carpet), Caterpillar (Earth Moving), Bombardier (Transportation Services), Better Place (Electric Cars). Hawken (2010) nicely summarizes the idea behind the servicization: 'What we want from these products is not ownership per se, but the service the products provide; transportation from our car, cold beer from the refrigerator, news or entertainment from our television.'

The arguments supporting servicization draws on two themes: profitability and environmental benefits. From a profitability perspective, servicization can increase customer retention and also provide higher margins. In an increasingly commoditized world, customers can easily defect to a competitor with a similar product because manufacturers' core products are increasingly being imitated and produced at a lower cost. Because services are harder to imitate, servicization can offer a way out of the commoditization problem and grant competitive advantage to product manufacturers by locking out potential competitors. Servicization also offers firms unique opportunities in terms of allowing for service differentiation. This can be done through identifying the use needs of the different consumer segments and offering contracts with different use levels. In some sense, servicization allows the firm to control the level of product use by consumers. This lever allows the firm to segment the market more efficiently and potentially increases the firm's profit. Hence, customer segmentation of distinct market segments is an important attribute of servicization that we capture in our model by allowing the firm to offer different use-based contracts to different consumer segments.

From the environmental perspective, servicization encourages the manufacturer to take more responsibility for their products because the firm retains the ownership of the product under servicization. This potentially decreases the environmental impact of a product by incentivizing the firms to design more durable products (Toffel, 2002), and hence decreasing the material use intensity. Thus, adoption of a servicization strategy can lead a firm to change its product attributes, and, in particular, the durability of its products. A key feature of our model is that product durability is an endogenous firm decision.

Despite these compelling arguments for servicization, many manufacturers are reluctant to adopt servicization, and some have failed to implement it profitably. Ray Anderson, an entrepreneur with an environmental focus, embraced the servicization idea at Interfaces, Inc. However, Interfaces faced significant obstacles in implementing the servicization idea. The challenges of selling this idea to a customer (University of Texas) have been documented in a well-known case (Olivia and Quinn, 2003). Thus from a practical perspective, a firm is unlikely to embrace servicization if it is not a profitable strategy, even though it might lead to environmental benefits. In addition, it has also been argued that servicization does not necessarily incentivize the profit maximizing manufacturers' to design products with lower environmental impact (White et al., 1999). Thus it is important to understand when servicization *simultaneously* leads to an increase in profits and reduce environmental impact. The primary goal of this paper is to analytically investigate the arguments *for/against* servicization and characterize when servicization creates a win-win situation by increasing a firm's profit and decreasing environmental impact. In what follows, we outline some of the key features of servicization that we capture in our analysis.

First, operating cost of a product impacts the profitability of servicization. Consumers' operating cost might be higher or lower than the firm's operating cost because consumers and the firm may have different levels of effectiveness in operating the product. For example, in its proposed contract with the University of Texas, Interface carpet stated a higher maintenance cost per square feet than UT's own established janitorial service (Olivia and Quinn 2003). On the other hand, the firm may benefit from economies of scale and expertise and may have lower operating cost. In addition, a lack of sense of ownership may lead to abuse of equipment, and eventually increase the maintenance cost of the product under servicization. If the firm has a very high relative operating cost (compared to the customer), then servicization may not be as profitable as the traditional selling strategy. Thus, the relative difference in a firm and consumer's operating cost (relative operating efficiency) is an important factor that can affect the profitability of servicization, which we capture in our model.

Second, although, product durability has been seen as a sustainable product feature, higher durability might have adverse effects on the environment. More durable products potentially stays in the economy for a longer time with decreasing use efficiency. The environmental impact may increase due to this drop in use efficiency and the longer use horizon. On the other hand, more durable products can spread the environmental impact incurred during the production and disposal of the product over a longer horizon which may decrease the overall environmental impact. Therefore, the environmental impact depends on the trade-off between the environmental impact incurred during the product use, production, and disposal. Hence, we capture the environmental impact of a product in our model through the three life stages of the product: production, use, and disposal.

Next, on the demand side, we allow heterogeneity by assuming that the consumers belong to one of two segments with different product valuations. This heterogeneity allows us to evaluate the impact of market segmentation on the profitability of servicization. In addition, consumers' product use level is endogenously determined in the equilibrium and depends on the product characteristics and the consumer type.

Finally, on the supply side, we endogenize both the price and the product durability decisions. Essentially, this provides the manufacturer two levers to control consumer purchase and use behavior. Under selling, the manufacturer decides on the price for a single product whereas it can offer different use based contracts tailored for two segments under servicization. In contrast to selling, the firm incurs the operating cost under servicization.

A summary of our analysis and key findings are as follows: First, we analytically characterize the equilibrium product durability and consumer product-use decisions under both a selling and a servicization strategy adopted by the firm. We then analytically compare the profits and environmental impact under these strategies. We show that a servicization strategy can be more profitable for a firm even when it is operationally inefficient. This is because the servicizing firm can utilize product use information in pricing to differentiate the consumer segments. A commonly held belief is that servicization increases the product durability because it increases the firm's responsibility toward its product. We show that this intuition is true when the firm serves same consumer segments under selling and servicization strategies. However, when the firm targets more consumer segments under servicization, product durability may be lower than that of the selling strategy.

We find that whether servicization is greener and more profitable depends on the firm's relative operating efficiency and the relative environmental impact of a product in its use phase as compared to the production and disposal phase. We find that, when the firm's relative operating efficiency is high, servicization can be more environmentally friendly for products with low use impact relative to their production and disposal impacts. On the other hand, when the firm's relative operating efficiency is low, servicization can be more environmentally friendly for products with high use impact relative to their production and disposal impacts. We also show that servicization can be more profitable for the firm even when its relative operating efficiency is low. However, we also show that servicization may lead to lower social surplus even when a firm's relative operating efficiency is high. Thus, while servicization as a business strategy holds promise, it should be implemented with care.

The remainder of the paper is structured as follows: In Section 3.2, we highlight our contribution to the current literature. In Section 3.3, we develop our model, and discuss the assumptions. In Section 3.4, we analyze our model, and characterize the impact of servicization on profitability and product durability. In Section 3.5, we discuss the impact of servicization on the consumer and social surplus, and the environment. Finally, we extend our model to two vertically differentiated products in Section 3.6, and discuss our concluding remarks in Section 3.7.

3.2 Literature Review

Our work is primarily related to three streams of research: sustainability, contract theory and durable goods.

A stream of research in sustainable operations literature studies the impact of various business strategies and regulations on the profitability of firms and the environment: some of these are related to e-waste regulations (Plambeck and Wang 2009), product architecture choice (Agrawal and Ulku 2011), original equipment manufacturer-versus-independent remanufacturer product recovery (Örsdemir et al. 2013; Ferrer and Swaminathan 2006), product take back legislations (Atasu et al. 2009b; Atasu and Subramanian 2012), carbon emissions (Drake et al., 2012). We contribute to this literature by explicitly comparing the profitability and the environmental impact of servicization with those of selling. Agrawal et al. (2011b) identify the conditions when leasing is a win-win strategy for the firm and the environment. They show that leasing may be environmentally undesirable despite remarketing of all used products, and may be environmentally superior despite premature removal of used products. However, in this paper operating cost is not a part of the model because it is implicitly assumed that consumers are primarily responsible for the operating cost under both leasing and selling. In servicization context, contrary to leasing, it is important to model the operating cost because under selling consumers incur the operating cost whereas under servicization the firm incurs the operating cost. We characterize the impact of relative operating cost on the profitability, the product durability, social surplus and environmental impact when the firm uses servicization strategy.

There have been many conceptual and case studies on servicization (Toffel, 2002; White et al., 1999; Stoughton et al., 2009). These studies have been very useful in defining the value of servicization for both the firms and the environment conceptually. In our work, we research some of these anecdotal evidences and conceptual ideals provided in these works for servicization by approaching the problem in an analytical way.

An emerging stream of papers has studied the different aspects of servicization. Avci et al. (2012) studies how the adoption and environmental impact of electric vehicles change when the consumers are charged based on how much they drive rather than paying for the battery upfront. They find that servicizing the battery may increase the electric car adoption but also increase the total environmental impact. Agrawal and Bellos (2013) studies impact of pay-per-use contracts on the environmental impact. They find that servicization without pooling increases the environmental impact due to production but results in less consumer use. On the other hand, servicization with pooling decreases the production impact but increases the consumer use. We contribute to this literature in various ways. First, we endogenize the business model choice by explicitly comparing the profitability of servicization and selling strategies which allow us to characterize when servicization creates a win-win situation for both the firm and the environment. Second, we allow the servicizing firm to differentiate consumer segments based on their product use needs through a menu contract. We find that this ability may have detrimental implications on product durability and the social surplus.

Finally, these papers focus on the products and product features where business model choice may change the consumer's product use intensity (consumer product use per unit of time). They assume that product lifecycle length is fixed but product use intensity may change based on the business model and product characteristic. In other words, consumers may use the product more or less frequently over a *fixed* length of use phase depending on whether they purchased the equipment itself (selling) or service of the equipment (servicization). On the contrary, we mainly focus on the products with low discretionary use and product feature (i.e., product durability) that is less likely to change the consumer use intensity but the product lifecycle length is endogenously determined by the consumers' chosen use level. We explain this distinction in more detail when we introduce our environmental impact metric in Section 2.6.

In contracting literature a number of papers research the impact of performance based contracts (PBC), a variant of servicization, on the product design and supply chain alignment. Kim et al. (2007) determine the optimal contract when the customer can offer contracts contingent on the performance of the equipment. They find that in a supplier-customer environment as product matures, optimal contracts assume less cost sharing but more performance incentives. Kim et al. (2010) show that infrequent system disruptions may create inefficiencies for PBC. Guajardo et al. (2012) empirically find that PBC increases the product reliability. We contribute to this literature by explicitly considering the environmental impact of servicization. Yadav et al. (2003) and Corbett and DeCroix (2001) study the impact of shared saving contract for indirect materials on aligning the incentives in the supply chain. Corbett and DeCroix (2001) find that the goal of maximizing profits and minimizing consumption is not generally aligned. In these papers, the focus is on the indirect materials which are at best indirectly related to the quantity of final products. However, in our case, the focus of servicization is the final product itself, and we consider the impact of servicization business model on the product design by endogenizing the product durability.

In durable goods literature, several problems on the profitability of employing leasing versus selling have been explored. Some of those are effect of product depreciation rate (Desai and Purohit 1998), competition (Desai and Purohit 1999), channel structure (Bhaskaran and Gilbert 2009), and presence of a complementary product (Bhaskaran and Gilbert 2005). However, these works are neither concerned with the environmental impact of different strategies nor with the operating cost. Our contribution to this literature is two folds. Firstly, we endogenize the product durability and research the impact of operating cost and market segmentation on the product durability under different strategies. Secondly, we explicitly compare the environmental impact of servicization with selling strategy.

3.3 Model Overview

We consider a monopolist which produces a single product and it either sells or servicizes its product to the consumers. In the following, we introduce the consumer and product characteristics, and then discuss consumers' and firm's decisions. Table B.1 in online appendix B.3 summarizes the parameters and decision variables of our model.

3.3.1 Consumer and Product Characteristics

Consumers differ in their valuation of the product. There are two consumer segments, θ_i, $i = H, L$, where θ_H and θ_L show the valuations of high and low end segments, respectively. We assume $\alpha\theta_H = \theta_L$ where $\alpha \in (0, 1)$ and $\theta_L = \theta$. The mass of potential customers is M and $\beta \in (0, 1)$ shows the fraction of θ_H consumers.

Here, θ_i represents consumer segment i's utility from the first use, then the product's utility deteriorates with each use. The deterioration rate depends on the product durability, δ, that is, it will be slower for products with higher levels of durability. Specifically, the consumer *marginal utility per unit use* is $\theta_i - \frac{t}{\delta}$, $i = H, L$, where $\frac{t}{\delta}$ shows the drop in marginal utility after t units of use.

There is a cost of operating the product. This cost includes the maintenance and all other costs incurred to keep the product operational. When the consumers own the product (which is the case under selling), the consumers incur the operating cost; otherwise, when the firm owns the product (which is the case under servicization), the firm incurs the operating cost.[1] For copiers the operating cost includes maintenance, toners, papers etc. For instance, University of California Davis and Oregon State University have adopted servicization contracts for their copier needs (U.C.D, 2014; O.S.U, 2014). The consumers and the firm may differ in their

[1] If we relax this assumption and assume that consumers bear a part of the operating cost under servicization, our results remain unaltered.

operational efficiency to operate the product, that is, for the same amount of use the firm can incur higher or lower total operating cost than the consumers. For example, in its failed deal attempt with University of Texas at Houston, Interface carpet stated a higher maintenance cost per square feet than UT's own established janitorial service, (Olivia and Quinn 2003). Furthermore, as Bardhi and Eckhardt (2012) points out, when a consumer does not own the product, her use behavior toward the product changes. When a consumer owns the product she has incentive to use the product properly because misuse of the product will increase her product maintenance cost. This incentive disappears in servicization model as the firm bears the operating cost, as a result the firm may incur a higher operating cost for the same use level. On the other hand, the economies of scale may lower operating cost for the firm.

Since more durable products require less maintenance and are expected to lose their energy efficiency slower, we assume that the operating cost is decreasing in product durability δ. In addition, we assume that total operating cost is increasing in use τ in a convex manner. Because as the product is used more it may require more frequent repairs and may lose material and energy efficiency. In order to capture all these features, we use the following operating cost functions: when the consumer or the firm owns the product, they incur an operating cost $\frac{m_c\tau^2}{2\delta}$, $i = c, f$, where m_c and m_f denote the operating cost parameters, respectively. m_c can be lower or higher than m_f as explained above. We study an alternative cost model through a numerical study in the Appendix B, where the operating cost is not correlated with product durability. We show that our key results continue to hold.

3.3.2 Consumer and Firm Decisions

In this section, we introduce the consumers' and firm's problems first for selling strategy, then for servicization strategy.

In selling strategy, on the demand side, each consumer first decides whether to purchase the product. If type θ_i consumer buys the product, she then determines her level of use τ, to maximize her utility:

$$U_r(\theta_i) = \max_{\tau} \int_0^{\tau} (\theta_i - \frac{t}{\delta})dt - \frac{m_c\tau^2}{2\delta} - p. \tag{3.1}$$

Marginal utility per unit use is integrated over use to obtain consumer's utility in equation (3.1), then total operating cost $\frac{m_c \tau^2}{2\delta}$ and the product price p are deducted. Once the marginal utility per unit use, the product provides, drops below the marginal operating cost per unit use, the consumer stops using the product, and the product is disposed. There is no disposal cost or salvage value.

On the supply side, the firm determines the product durability δ. We assume that production cost is convex in product durability and is equal to $c\delta^2$, where c is a positive scaling parameter. The firm then sets the selling price p. Because the high valuation segment has a higher willingness-to-pay serving only the low valuation segment is never optimal. Let $\pi^*_{r,B}$ and $\pi^*_{r,H}$ denote the manufacturer's optimum profit when it sells to both segments and only to θ_H segment, respectively. If $\pi^*_{r,B} \geq \pi^*_{r,H}$, the manufacturer sells to both segments; otherwise it sells only to high valuation segment. $\pi^*_{r,B}$ and $\pi^*_{r,H}$ are given by:

$$\begin{aligned} \pi^*_{r,B} &= \max_{p,\delta}(p - c\delta^2)M, \qquad (3.2)\\ s.t \quad & U_r(\theta_L) \geq 0. \\ \pi^*_{r,H} &= \max_{p,\delta}(p - c\delta^2)M\beta, \qquad (3.3)\\ s.t \quad & U_r(\theta_H) \geq 0. \end{aligned}$$

We normalize the reservation utility of both segments to zero. If the firm sells to both segments, low valuation segment θ_L must receive at least its reservation utility, i.e., $U_r(\theta_L) \geq 0$. Similarly, if the firm sells only to the high valuation segment θ_H, high valuation segment must capture at least its reservation utility, $U_r(\theta_H) \geq 0$.

In servicization strategy, on the demand side, the consumers choose one of the contract options offered by the firm, including not receiving any service. Each contract option specifies a use-price pair, i.e., (τ_i, F_i), $i = H, L$. Consumers choosing the contract (τ_i, F_i) use the product for τ_i units and pays the firm F_i.

On the supply side, the firm determines the product durability δ and the parameters of the menu contract (τ_i, F_i), $i = H, L$. Similar to selling strategy, because the high valuation segment has a higher willingness-to-pay, inducing only the low valuation segment to purchase the service is never optimal. If the firm induces both segments to purchase the service, the menu must satisfy the following individual rationality and incentive compatibility constraints.

$$IR_i \quad : \quad \int_0^{\tau_i} (\theta_i - \frac{t}{\delta})dt - F_i \geq 0, \qquad i : H, L \tag{3.4}$$

$$IC_i \quad : \quad \int_0^{\tau_i} (\theta_i - \frac{t}{\delta})dt - F_i \geq \int_0^{\tau_j} (\theta_i - \frac{t}{\delta})dt - F_j, \qquad i \neq j, \text{and } \ i, j : H, L. \tag{3.5}$$

Otherwise, if the firm induces only high valuation segment to accept the offer, then the contract only needs to satisfy individual rationality constraint of the high valuation segment, i.e., $U_v(\theta_H) \geq 0$. Let $\pi^*_{v,B}$ and $\pi^*_{v,N}$ denote the manufacturer's optimum profit when it serves both segments and only the θ_H segment, respectively. Then,

$$\begin{aligned}
\pi^*_{v,B} \quad &= \quad \max_{\delta, F_i, \tau_i, i=H,L} \sum_{i=H,L} (F_i - \frac{m_f \tau_H^2}{2\delta} - c\delta^2) Q_i, &(3.6)\\
s.t, \quad &IR_i, \quad IC_i \quad i = H, L. \\
\pi^*_{v,H} \quad &= \quad \max_{\delta, F_H, \tau_H} (F_H - \frac{m_f \tau_H^2}{2\delta} - c\delta^2) Q_H, &(3.7)\\
s.t, \quad &IR_H.
\end{aligned}$$

where $Q_L = (1-\beta)M$ and $Q_H = \beta M$. The firm serves both segments if $\pi^*_{v,B} \geq \pi^*_{v,H}$; otherwise, it serves only θ_H segment.

3.4 Analysis

In this section, we first characterize the equilibrium choices of consumers and the firm. Then, we compare the equilibrium decisions under selling and servicization strategy to tease out the implications of servicization on profitability, and product durability.

3.4.1 Equilibrium

The next proposition describes the equilibrium decisions of the firm and the consumer for both selling and servicization strategies. As it will be evident $\frac{\alpha}{\beta}$ plays a critical role in the characterization of equilibria. It shows the relative profitability of serving low-end segment. Increasing $\frac{\alpha}{\beta}$ indicates either the valuation or the mass of the low end segment increases. Therefore, when this ratio increases, the profitability of serving low-end segment increases,

Strategy	Regions	δ^*	τ^*	π^*
Selling	$R1$	$\frac{\alpha^2\theta^2}{4c(1+m_c)}$	$\tau_H^* = \frac{\theta\delta^*}{1+m_c},\ \ \tau_L^* = \frac{\alpha\theta\delta^*}{1+m_c}$	$\frac{a^4\theta^4 M}{16c(1+m_c)^2}$
	$R2,\ R3$	$\frac{\theta^2}{4c(1+m_c)}$	$\tau_H^* = \frac{\theta\delta^*}{1+m_c},\ \ \tau_L^* = 0$	$\frac{\theta^4 M}{16c(1+m_c)^2}$
Servicization	$R1,\ R2$	$\frac{(\alpha^2+\beta-2\alpha\beta)\theta^2}{4c(1-\beta)(1+m_f)}$	$\tau_H^* = \frac{\theta\delta^*}{1+m_f},\ \ \tau_L^* = \frac{(\alpha-\beta)\theta\delta^*}{(1-\beta)(1+m_f)}$	$\frac{(\alpha^2+\beta-2\alpha\beta)^2\theta^4 M}{16c(1-\beta)^2(1+m_f)^2}$
	$R3$	$\frac{\theta^2}{4c(1+m_f)}$	$\tau_H^* = \frac{\theta\delta^*}{1+m_f},\ \ \tau_L^* = 0$	$\frac{\theta^4 M}{16c(1+m_f)^2}$

Table 3.1: Equilibrium product durability, product use and firm profits under selling and servicization strategy.

and vice versa.

Proposition 8. *The following characterizes the equilibrium regions. The optimum product durability, product use and firm profits are provided in Table 3.1.*

($R1$) *When* $\frac{1}{\beta^{3/4}} \leq \frac{\alpha}{\beta}$, *the firm serves both segments under both selling and servicization strategies.* ($R2$) *When* $\gamma(\alpha,\beta) \leq \frac{\alpha}{\beta} < \frac{1}{\beta^{3/4}}$, *the firm serves high valuation segment under selling strategy and both segments under servicization strategy.*

($R3$) *When* $0 < \frac{\alpha}{\beta} < \gamma(\alpha,\beta)$, *the firm serves only the high valuation segment under both selling and servicization strategies.* $\gamma(\alpha,\beta)$ *is characterized in the proof of the proposition.*

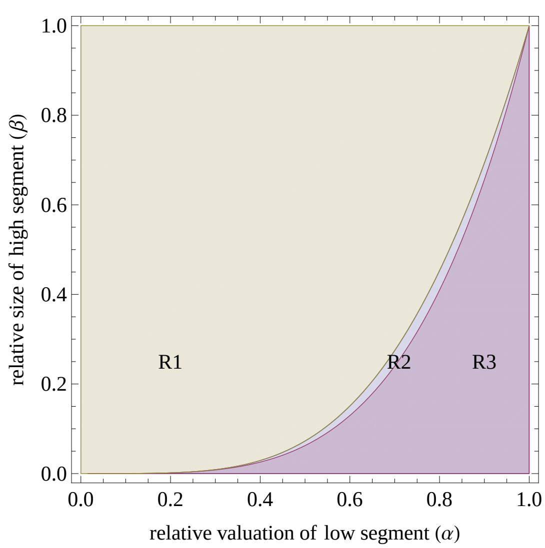


Figure 3.1: Equilibrium regions under selling and servicization strategies.

Figure 3.1 graphically depicts the equilibrium regions in Proposition 8. Note that the equilibrium regions depend on only $\frac{\alpha}{\beta}$ ratio. As we move from $R1$ to $R3$, $\frac{\alpha}{\beta}$ ratio decreases, and serving the low end segment becomes relatively less profitable. In fact, the firm abandons low end consumer segment when $\frac{\alpha}{\beta}$ ratio is smaller than a certain threshold. This happens because when the firm serves both segments, the low end segment only receives its reservation utility, but the high end segment receives an additional informational rent, which increases as $\frac{\alpha}{\beta}$ ratio decreases. In this case, either β increases, and hence the relative market size of consumers receiving informational rent increases, or α decreases, and hence the firm needs to decrease its price to appeal to the low-end segment. When the informational rent becomes too high, it is more profitable for the firm to serve only the high-end consumers.

Note that the firm is more likely to abandon low-end segment under selling strategy compared to servicization. When $\frac{\alpha}{\beta}$ ratio is moderate as in $R2$, the firm serves both segments when it owns the product, but serves only the high-end segment when it sells the product. This result follows from the fact that servicization strategy enables the firm to control consumers' use levels. Thus, the servicizing firm can induce the consumer segments use the product at a more efficient level from a profitability perspective, and extract a higher portion of the consumer surplus. Therefore, the firm can continue to serve the low-end consumer segment. Note that the result is independent of the consumer and the firm's operating costs and continues to hold even when firm has a high operating cost.

Table 3.1 shows that regardless of the targeted segments product durability decreases when its operating cost increases: consumers' and firm's operating costs respectively in selling and servicization strategies. Essentially, the benefit of extending the product's useful lifetime by improving its durability is lower when the operating cost is higher.

Table 3.1 shows that when the firm sells its product, the optimal durability choice does not depend on relative size of the segments, which is determined by β. In contrast, when the firm servicizes the product the optimal durability may depend on the size of each segment. Essentially, when the firm sells the product, it cannot differentiate among customers based on their use levels. In this case, optimal product configuration is determined by the lowest segment that the product needs to attract. In contrast, the firm can offer differentiated offerings based on use levels in the case of servicization. When β increases, high segment becomes relatively more important, and the firm wants to create a bigger separation between the two segments by increasing the use level of high segment and decreasing it for low segment. Thus, the firm improves product durability to extend the use level of high segment.

Variable	α	β
f_1	$\uparrow$	$\downarrow$
f_2	$\downarrow$	$\uparrow$

Table 3.2: Comparative statics in Proposition 3 for f_1 and f_2. f_1 and f_2 are explicitly stated in the proposition

3.4.2 Profitability

In this section, we study how servicization affects the profitability. As it will be evident, $r \triangleq \frac{1+m_c}{1+m_f}$ ratio, simply referred to as the *relative efficiency of servicization* plays an important role in our result. When r decreases, relative profitability of servicization decreases and vice versa for selling. This is because decreasing r indicates either the firm's operating cost goes up or the consumer operating cost goes down. The next proposition compares profitability of selling and servicization strategies.

Proposition 9. *(Profitability) Servicization is more profitable than selling strategy if and only if*

(i) $r > \frac{\alpha^2(1-\beta)}{\alpha^2+\beta-2\alpha\beta} \triangleq f_1$ *in* $R1$.

(ii) $r > \frac{(1-\beta)\sqrt{\beta}}{\alpha^2+\beta-2\alpha\beta} \triangleq f_2$ *in* $R2$.

(iii) $r > 1$ *in* $R3$.

In addition, $f_1, f_2 < 1$. *Table 3.2 shows how* f_1 *and* f_2 *change with* α *and* β.

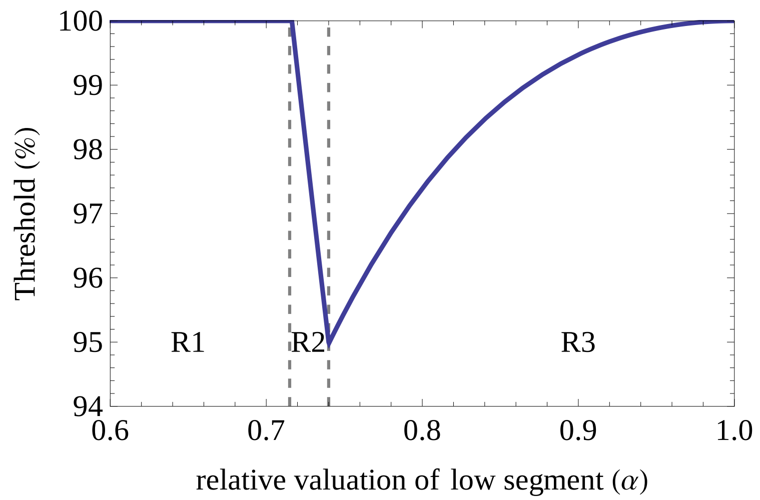
Recall that regions $R1$-$R3$ are characterized in Proposition 8, and they depend only on the $\frac{\alpha}{\beta}$ ratio. Because $f_1, f_2 < 1$, the proposition indicates that the firm may find it attractive to keep the ownership and servicize its product even when consumers are more efficient in maintaining the product, that is, when they have a lower operating cost. This happens when the low end segment is sufficiently profitable ($\frac{\alpha}{\beta}$ is sufficiently high) so that the firm chooses to serve both segments under servicization.

Servicization can be more profitable even when it is operationally inefficient, because it allows the firm to track and control consumer use levels and utilize this information in pricing to extract more surplus from consumers. Therefore, ability to utilize use levels can give servicization a pricing advantage.

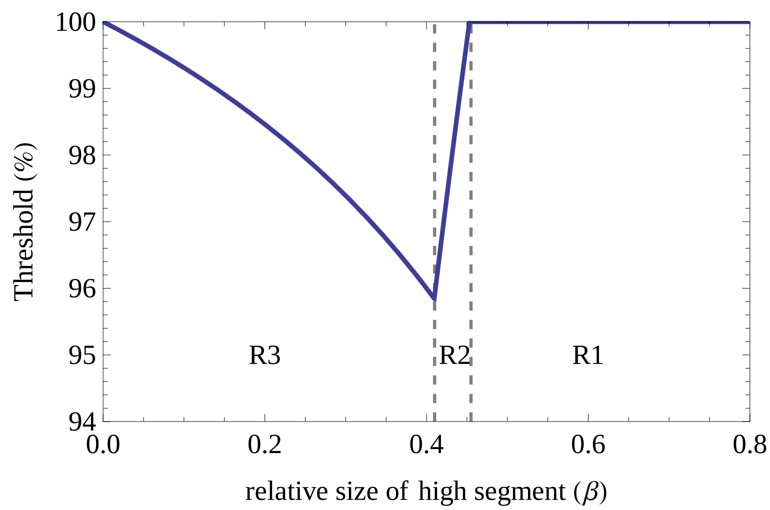
Figure 3.2 shows the relative operating efficiency threshold above which servicization becomes more attractive. The figure shows that servicization is more likely to be attractive when $\frac{\alpha}{\beta}$ ratio is moderate and the threshold has its minimum at $R1$-$R2$ boundary. Essentially pricing advantage of servicization as a result of utilizing use levels becomes more valuable when the gap between valuations of low and high end segments (i.e., $1 - \alpha$) and relative mass of high end segment (i.e., β) increase. Therefore, in $R1$, where both segments are served under both strategies, decreasing $\frac{\alpha}{\beta}$ ratio makes servicization relatively more attractive. However, in $R2$, when low end segment is served only under servicization strategy, a smaller $\frac{\alpha}{\beta}$ makes low end segment to be relatively less profitable, which in turn makes selling more attractive. When $\frac{\alpha}{\beta}$ ratio is too small, only high end segment is served under both strategies. In this case, servicization does not have a pricing advantage, and relative operating efficiencies determine the optimal choice: When the firm has a lower operating cost, $r > 1$, servicization is more profitable. When $\alpha = 0.8$ or $\beta = 0.3$ (these are the parameters used in Figure 3.2), even when the firm and consumers have the same operating efficiencies, we found that servicization may increase the firm's profit up to 10%.

Our results show that servicization can be preferable even when it is operationally less efficient. Indeed servicization can have a higher cost as in Interface carpet example. Firms who are new to servicization may not be as operationally efficient as their consumers since building expertise and improving the processes of servicized offerings require time (Heal, 2008).

Our results may also offer one possible explanation as to why Interface's servicization experiment did not succeed. In addition to its high operating cost, its contract design may have prevented servicization to be more profitable for Interface. Interface offered only one type of contract that fixed the product use length to 7 years in their Evergreen Lease program. This was required due to accounting restrictions on operating leases in some cases. However, even when UT Dallas, a tax exempt institution, requested a 10-year contract. Interface declined this offer (Heal, 2008). Electrolux, in its failed servicization attempt with its washing machines, followed a similar strategy and instead of segmenting the market, charged a single pay-per-use price from its customer. Our results show that utilizing use levels to segment the market can greatly increase profitability of servicization, and Interface and Electrolux could have benefited significantly by offering a menu of use length durations.



(a)



(b)

Figure 3.2: The minimum operating efficiency above which servicization is more profitable than selling strategy. ($\beta = 0.3$ in (a) and $\alpha = 0.8$ in (b))

3.4.3 Product Durability

It has been widely argued that because the firm is responsible for the maintenance of the product, servicization would encourage firms to invest in product durability so that the product would need less frequent repairs (White et al. 1999; Stoughton et al. 2009; Toffel 2002). While these papers provide only qualitative arguments, here, we consider a quantitative model. We find that servicization indeed increases product durability in many cases. However, we show this conjecture need not be always true: Servicization can decrease product durability.

Our model captures how servicization affects the firm's pricing policy. Ability to utilize use levels in pricing enables the firm target more consumer segments which may result in choosing a lower durability level. In a non-regulatory setting, the firm will adopt servicization only if it leads to higher profits than selling strategy. Therefore, we study the impact of servicization on product durability when servicization is more profitable. Next proposition summarizes our results.

Proposition 10. *(Durability) When servicization is preferred over selling strategy, servicization increases product durability except when $r < \frac{1-\beta}{\alpha^2+\beta-2\alpha\beta}$ in $R2$. In addition, $\frac{1-\beta}{\alpha^2+\beta-2\alpha\beta} > 1$.*

The Proposition demonstrates that when servicization is attractive in regions $R1$ and $R3$, it always increases product durability. However, there are different dynamics in place in these regions. In $R3$, only high segment is served under both strategies, and servicization is chosen only when $r > 1$, i.e., when consumers have a higher operating cost. Therefore, servicization results in a lower operating cost and makes it attractive to extend the useful lifetime of the product by increasing its durability. In contrast, in $R1$, servicization can be preferred even when the firm has a higher operating cost, $r < 1$. Here, both segments are served under both strategies. Because servicization enables segmentation based on use levels, the firm can extract a significantly higher surplus from high end segment, therefore, benefits more from extending the use level by increasing product durability.

In $R2$, different from $R1$ and $R3$, the firm does not serve the same consumer segments under servicization, and it can result in a lower product durability. In particular, low segment is served only under servicization, which may make it optimal to choose a less durable product.

However, a sufficiently strong operating efficiency (i.e., $r > \frac{1-\beta}{\alpha^2+\beta-2\alpha\beta}$) may overcome this effect, and the servicization can still result in a more durable product despite targeting more consumer segments.

Increased product durability has been considered as a key goal to decrease environmental burden of products Toffel (2002). However, our results in section 3.5.2 show that higher product durability as a result of servicization may not necessarily improve environmental impact. The relative significance of use, production and disposal related components of environmental impact, and relative operating efficiency of servicization are critical.

3.4.4 Use Decisions

We next focus on the use decisions. The following proposition compares the use levels under selling and servicization.

Proposition 11. *(Use Decisions) When servicization is preferred over selling,*
(i) in $R1$, servicization increases the use levels of both segments when $r > \sqrt{\frac{\alpha^3(1-\beta)^2}{(\alpha-\beta)(\alpha^2-2\alpha\beta+\beta)}}$. It decreases the use levels of both segments when $\sqrt{\frac{\alpha^2(1-\beta)}{\alpha^2-2\alpha\beta+\beta}} > r$. Otherwise, when $\sqrt{\frac{\alpha^3(1-\beta)^2}{(\alpha-\beta)(\alpha^2-2\alpha\beta+\beta)}} > r > \sqrt{\frac{\alpha^2(1-\beta)}{\alpha^2-2\alpha\beta+\beta}}$, it increases the use level of the high segment but decreases the use level of low end segment.
(ii) in $R2$, servicization always increases the use level of low end segment. It increases the use level of high end segment when $r > \sqrt{\frac{1-\beta}{\alpha^2-2\alpha\beta+\beta}}$. Otherwise, when $\sqrt{\frac{1-\beta}{\alpha^2-2\alpha\beta+\beta}} > r$, it decreases the use level of high segment.
(iii) in $R3$, servicization always increases the use level of the high end segment, and does not alter the use level of low end segment.

Region $R1$ can be broken down into three regions with respect to the relative operating efficiency of firm. When the relative operating efficiency is low, the servicizing firm reduces the use levels for both segments compared to selling. On the other hand, when the relative operating efficiency of firm is high, servicizing firm offers higher use levels for both segments. Essentially, lower operating cost per unit of use allows servicizing firm to increase the use levels but higher operating cost per unit of use discourages higher use level offerings. When the firm has a medium relative operating efficiency, servicization affects the use levels of different segments in the opposite direction. Use level of high end segment increases but use level of low end segment decreases. This is because the firm distorts the low end segments use level downward in order to achieve segmentation, and the relative operating efficiency is not high enough to overcome this negative effect on use level in this region. However, high segment always receives its preferred use level which is higher under servicization for this range of relative operating efficiencies.

In $R2$, low-end segment is served only under servicization, and hence, servicization increases the use level for this segment. In this region, use level of high end segment increases under servicization only if relative operating efficiency is high enough. The intuition is similar to the one given for $R1$. Finally, in $R3$, segmentation does not play a role in use levels because the firm only serves high end segment under both selling and servicization. The relative operating efficiency of firm becomes the only factor that affects the use level of high end segment relative to selling strategy. Therefore, servicization increases the use level of high end segment when the relative operating efficiency of firm is higher than 1, and this condition is always satisfied when servicization is more profitable than selling in $R3$.

3.5 Environmental and Social Implications of Servicization

In this section, we study the impact of servicization on the consumer and social surplus, and the environment.

3.5.1 Consumer and Social Surplus

The consumer surplus (CS) is given by

$$CS_r = \sum_{i=L,H} \int_0^{\tau^*_{i,r}} (\theta_i - \frac{t}{\delta})dt - \frac{m_c}{2\delta}\tau^{*2}_{i,r} - p, \tag{3.8}$$

$$CS_v = \sum_{i=L,H} \int_0^{\tau^*_{i,v}} (\theta_i - \frac{t}{\delta})dt - F_i, \tag{3.9}$$

for selling in equation (3.8) and for servicization in equation (3.9), where $\tau^*_{i,r}$ and $\tau^*_{i,v}$ show type-θ_i equilibrium use levels in these strategies, respectively. The social surplus (SS) is the sum of the consumer surplus and the firm's profit. Next proposition compares the CS generated by selling and servicization strategies. Note that regions $R1$-$R3$ are defined in Proposition 8.

Proposition 12. *(Consumer Surplus)*
(i) In $R1$, servicization increases the CS if and only if $r > \sqrt{\frac{\alpha^2(1+\alpha)(1-\beta)^2}{2(\alpha-\beta)(\alpha^2+\beta-2\alpha\beta)}} \triangleq h(\alpha, \beta)$*. In addition, $h > 1$.*
(ii) In $R2$, servicization always increases the CS.
(iii) In $R3$, servicization does not alter the CS.

The proposition demonstrates that in $R1$, servicization increases the CS only if servicizing firm has high enough operating efficiency. In fact, the firm's operating cost has to be strictly lower than the consumer operating cost ($h > 1$). This result indicates that consumers may prefer to own the product and incur a higher per unit use operating cost rather than purchasing the service from a more efficient firm when $h > r > 1$. Essentially, when the firm can manipulate the use levels of the product, it can extract a higher portion of the consumer utility. This effect can only be overcome if relative operating efficiency of servicization is sufficiently high, i.e., $r > h$. The proposition shows that, servicization can have a detrimental impact on the CS, when the relative profitability of low-end segment is high enough so that the firm always serves both segments (region $R1$).

In $R2$, servicization always increases the CS. Note that the firm serves only the high end segment under selling strategy in this region. Hence, it extracts the entire consumer surplus. On the other hand, the firm serves both segments under servicization strategy, and the high end segment can still achieve a positive surplus. Recall that this region emerges because the servicizing firm can control the use levels, which enables it to continue to serve the low end segment. Therefore, as opposed to $R1$, where increased control over product use levels has a detrimental effect on consumer surplus, in R2, utilizing use levels in pricing increases the CS. Finally, in $R3$, since the firm serves only the high end segment under both strategies, the CS is always zero. Overall, when servicization and selling have the same operating efficiency, servicization improves the CS, only if it extends the market coverage. Now, let us consider the impact of servicization on the social surplus.

Proposition 13. *(Social Surplus) When servicization is preferred over selling strategy, servicization increases the SS except when $r < k_1(\alpha, \beta)$ in R1. Furthermore, $k_1(\alpha, \beta) < 1$ if and only if $\sigma(\beta) > \alpha$. The expressions for k_1 and σ are explicitly characterized in the proof of the proposition.*

Intuition suggests that whenever the firm's operating cost is smaller than those of consumers ($r > 1$), the servicization should improve the SS because shifting the operating cost burden to the firm should improve overall efficiency in the system. However, contrary to this intuition, Proposition 13 shows that servicization may decrease the SS even it has a better operating efficiency than selling. This case happens when the firm serves both segments under both selling and servicization, and $\sigma(\beta) < \alpha$. This result indicates that social planner may prefer selling over servicization even when the consumers have inferior operating efficiency. The outcome deviates from the social optimum due to two factors: product durability choice and consumers' use levels. On one hand, when servicization is chosen, the firm's product durability choice is closer to socially optimum compared to firm's choice under selling in $R1$. [2] On the other hand, the servicizing firm distorts the use level offered to the low-end segment away from the socially optimum level to make this option less attractive for high segment, so it can charge a higher price to the high-end segment. In contrast, when the firm sells the product, consumers always use the product at socially optimal level given the chosen product durability.

Because the firm determines its product durability choice based on low-end segment in the case of selling, it moves further away from the social optimum as the gap between customer valuations widens, i.e., α gets smaller. When the gap between the segments is low, i.e., $\alpha > \sigma(\beta)$, product durability is not too far from the social optimum, and inefficient use level of servicization dominates. Therefore, servicization may decrease the SS even when the firm has a better operating efficiency than the consumers.

In region $R2$, a servicizing firm serves more consumer segments than a selling firm, that is, the low-end segment is served only by the servicizing firm. The high end segment can capture positive CS. Thus, servicization always result in a higher SS in $R2$ as long as it is more

[2] This can be shown by comparing the product durability choices in Proposition 8 and Proposition 23 in the online appendix

profitable. In region $R3$, only the high end segment is served in both cases. Therefore, the CS is always zero, and the SS is equal to firm's profit. In this region, servicization increases the SS, when it is more profitable.

3.5.2 Environmental Impact

Here, we first describe our environmental impact metric. We then study how servicization affects the environment using this metric. We follow the convention in the literature to quantify total environmental impact (Atasu and Souza, 2012; Agrawal et al., 2011b). One unit of product entails environmental impact over three life cycle phases: production, use and disposal. Environmental impact during the production and disposal phases are denoted by e_p and e_d, respectively. Environmental impact during the use phase is convex increasing in product use level τ, and it is given by $e_u\tau_i^2$. Convexity is assumed because the product's resource efficiency may decrease with use, which may increase per unit use environmental impact (Intlekofer, 2009; White et al., 1999). Adding up these three components, the total environmental impact due to segment i's consumption is given by $Q_i(e_p + e_d + e_u\tau_i^2)$.

We focus on the products with low discretionary use. Furthermore, we assume that product features, e.g., product durability and price, do not change the consumer use intensity, i.e., product use per unit of time. For example, if a consumer uses a Xerox copier to copy a certain number of pages per month, that rate does not change regardless of price and durability of the product. In contrast, product lifecycle length is endogenously determined by the consumers' chosen use level of the product. For example, when the consumers' chosen use level is high, the consumer will keep the product for a longer time. Therefore, products may have different use durations. We need an environmental impact metric which can provide a fair comparison of products possibly with different use durations. Hence, we compare how much environmental impact products cause per-unit of the time they stay in the economy, and we call this metric environmental impact per-unit-time metric, defined as the total environmental impact divided by the use duration and summed over all segments. It is given by,

$$E_k = \sum_{i=H,L} \frac{(e_u\tau_i^2 + e_p + e_d)Q_i}{\tau_i}, \qquad k = r, v. \tag{3.10}$$

In equation (3.10), use duration is assumed to be proportional to the use level τ_i following our assumption that consumer use intensity is constant.

Total environmental impact metric, i.e., $\sum_{i=H,L}(e_u\tau_i^2+e_p+e_d)Q_i$ has been used in Agrawal and Bellos (2013); Avci et al. (2012) to assess the environmental performance. These papers fix product use duration, instead consumers choose product use intensity based on product characteristics. This assumption is appropriate when a product has high discretionary use, and hence, consumers are likely to alter their consumption intensity based on price or other product characteristics. However, products such as Interface carpet, Xerox copiers and Electrolux washing machines, have low discretionary use and consumers' use intensity does not significantly depend on the product characteristics. Instead, product characteristic may alter the product use duration. For example, consumers may not use a more durable product more intensely, but they may use it for a longer time (Koenigsberg et al., 2011). This argument is also supported in White et al. (1999).

Environmental impact per-unit time metric, E_k, consists of two main components: $e_u\tau_i$ per unit time use impact and $\frac{e_p+e_d}{\tau_i}$ per unit time production and disposal impacts. Products can be classified based on the phase in which they entail most of their environmental impact: Environmental impact during the use phase dominates (i.e., high $\frac{e_u}{e_p+e_d}$) for some products, such as automobiles, refrigerators, washing machines. In contrast, environmental impact during production and disposal phase dominates (i.e. low $\frac{e_u}{e_p+e_d}$) for some other products, such as carpets, computers. In order to facilitate the discussion, we refer to $\frac{e_u}{e_p+e_d}$ ratio as the relative use impact of a product in the remainder of this section.

The next proposition compares the environmental impact of servicization and selling strategies. Our goal is to identify the conditions that make servicization a win-win strategy. Hence, the proposition focuses on the region in which servicization is more profitable than selling strategy.

Proposition 14. *(Environmental Impact) When servicization is preferred over selling,*

(i.) in $R1$, servicization is more environmentally friendly than selling if and only if

(i.a) $g_1 \triangleq \sqrt{\frac{\alpha(1-\beta)(\alpha+\beta-\alpha\beta)}{\alpha^2+\beta-2\alpha\beta}} > r$ *and* $\frac{e_u}{e_d+e_p} > \Delta_1$, *or*

(i.b) $r > \sqrt{\frac{\alpha^3(1-\beta)(1+(-2+\alpha)\beta)}{(\alpha-\beta)(1+(-1+\alpha)\beta)(\alpha^2+\beta-2\alpha\beta)}} \triangleq g_2$ *and* $\frac{e_u}{e_d+e_p} < \Delta_1$.

In addition, $g_2 > g_1 > f_1$.

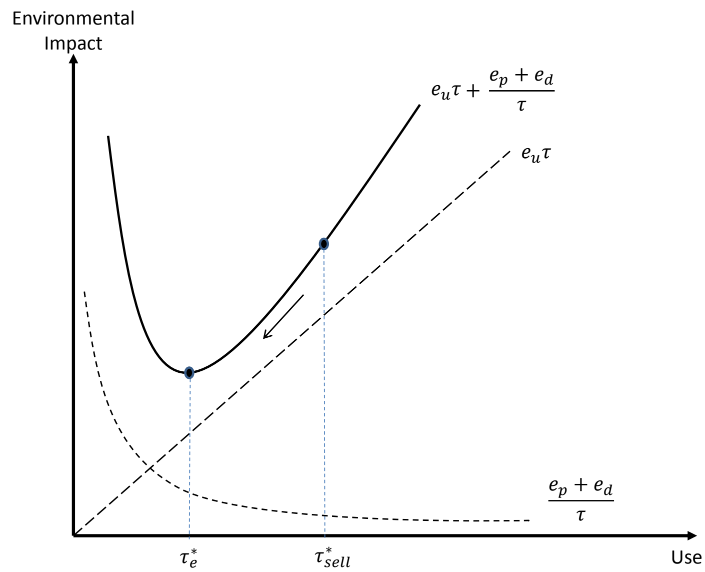


Figure 3.3: How servicization can improve environmental impact?

(ii) in R2, servicization is more environmentally friendly than selling if and only if $r > \sqrt{\frac{(1-\beta)(1+(-2+\alpha)\beta)}{(\alpha-\beta)\beta(\alpha^2+\beta-2\alpha\beta)}} \triangleq g_3$ *and* $\frac{e_u}{e_d+e_p} < \Delta_2$.

(iii) in R3, servicization is more environmentally friendly than selling if and only if $\frac{e_u}{e_d+e_p} < \Delta_3$.

The expressions for Δ_1*,* Δ_2*, and* Δ_3 *are stated in the proof of the proposition.*

Before explaining the details of the proposition, we first how servicization can decrease environmental impact of a single segment pictorially by Figure 3.3. The figure shows that selling strategy leads to overuse of the product from an environmental perspective. Servicization can decrease the environmental impact of this product only if it decreases the use level. However, $\tau_e^*(=\sqrt{\frac{e_p+e_d}{e_u}})$ must be low enough such that decreased use level under servicization cannot go further away from τ_e^*. This means that product must have high enough relative use impact. Same logic applies if selling leads to underuse of the product. In that case, servicization decreases the environmental impact only if it increases the use level, and τ_e^* is high enough (low enough relative use impact). Note that although the figure illustrates the change in environmental impact for a single segment, overall change would depend on the changes in both segments.

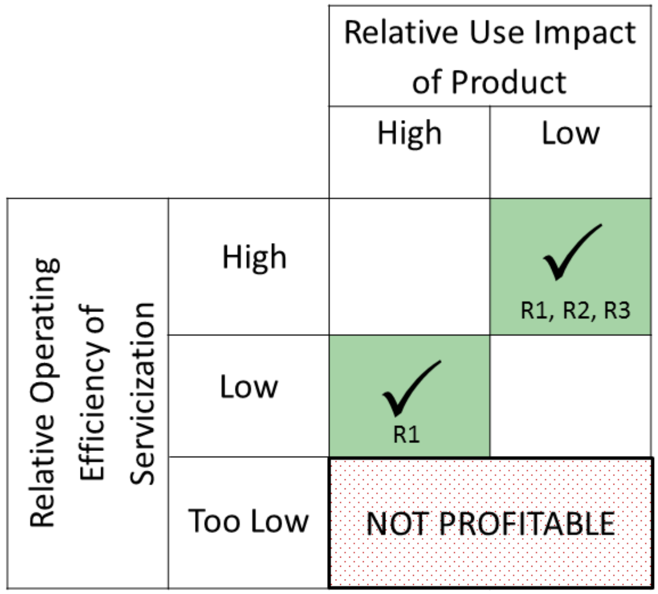


Figure 3.4: When servicization can improve both profitability and environmental impact?

In order to asses when servicization jointly improves profitability and environmental impact, we need to consider two factors: relative operating efficiency of servicization and relative use impact of the product. Figure 3.4 illustrates when servicization becomes a win-win strategy based on these two factors. In $R1$, when the relative operating efficiency of servicization is low enough (Proposition 14.$i.a$), servicization is environmentally preferable for products with sufficiently high values of relative use impact, i.e., $\frac{e_u}{e_p+e_d} > \Delta_1$. The rationale behind this result is as follows: When the relative operating efficiency of servicization satisfies $g_1 > r$, the firm tends to shorten product use duration offered to both segments compared to selling strategy because it is costlier for the firm to operate the product for longer durations. This change in turn decreases the use impact, which is a weighted average of use durations, i.e., $\beta\tau^*_{H,v} + (1-\beta)\tau^*_{L,v}$, in contrast, increases the production and disposal impacts, which are proportional to $\frac{\beta}{\tau^*_{H,v}} + \frac{1-\beta}{\tau^*_{L,v}}$. As a result, the use impact decreases but production and disposal impacts increase. Thus, servicization is greener only if the product has sufficiently high use impact relative to production and disposal impacts. For example, washing machines, cars and printers fall into this category.

On the other hand, when the relative operating efficiency of servicization is high, i.e., $r > g_2$ as in Proposition 14.$i.b$, servicization is greener for products with sufficiently low relative use impact, i.e., $\frac{e_u}{e_p+e_d} < \Delta_1$. When servicization has high enough relative operating efficiency, the firm tends to increase the product use levels offered to both segment compared to selling strategy because it is cheaper for the firm to operate the product. In this case, servicization increases the use impact, which is proportional to $\beta\tau^*_{H,v} + (1-\beta)\tau^*_{L,v}$, while decreasing the production and disposal impacts, which are proportional to $\frac{\beta}{\tau^*_{H,v}} + \frac{1-\beta}{\tau^*_{L,v}}$. Hence, servicization is greener for products with sufficiently low use impact relative to production and disposal impacts (e.g., carpets and laptops). It is interesting to note that although, servicization increases the product durability in $R1$ as shown in Proposition 10, it may still reduce product use levels for low-end segment. Therefore, more durable products are not necessarily used for a longer duration. This result is a consequence of downward distortion of low-end segment's product use level.

The proposition also implies that when the relative operating efficiency of servicization is at a medium range as in $g_2 > r > g_1$, servicization always increases both use, and production and disposal related impacts, and hence servicization increases the overall environmental impact for all product types. For this range of r values, while servicization increases the product use level of the high-end segment, it decreases the product use level of the low-end segment compared to selling strategy in a way that the use impact increases due to the high-end segment, and the production and disposal impacts increase due to the low-end segment. The increase in high-end segment's use level is due to higher product durability. The reduction in low-end segment's use level is mainly due to firm's desire to segment the market by distorting the low-end segment's use level away from the socially optimal level. This result shows that the firm's increased control over the product may adversely affect the environment regardless of the product type when the relative operating efficiency is moderate.

In R2, servicization can be a win-win strategy for products with sufficiently low relative use impact, i.e., low $\frac{e_u}{e_p+e_d}$, when servicization has high enough relative operating efficiency. The intuition for this results is similar to that of part $i.b$. In this region, however, when servicization is more profitable, it always increases the environmental impact for high relative use impact products. Environmental impact for high relative use impact products decreases only if the firm reduces the use durations offered to both segments sufficiently such that use impact under servicization is lower than the use impact under selling, i.e., $\beta\tau_{H,v} + (1-\beta)\tau_{L,v} < \beta\tau_{H,r}$. This requires that the firm must have low enough relative operating efficiency. However, in this case, operating efficiency must be too low, because more consumers use the product under servicization, and at these operating efficiency values servicization is not profitable anymore. Therefore, servicization cannot be both environmentally friendly and profitable for high relative use impact products in $R2$. This result shows that when servicization increase market coverage, it adversely impacts the environmental performance for high relative use impact products in this region.

In $R3$, the firm always serves only the high-end segment, and servicization is more profitable than selling strategy, when $r > 1$. In this case, Table 3.1 indicates that high-end segment uses the product for a longer duration under servicization. As a result, servicization is more environmentally friendly when the product has sufficiently low relative use impact.

Our results also contrast with the popular argument that higher product durability decreases the environmental impact. We found that product durability, by itself, does not determine the environmental impact: Product type (relative use impact of the product) should be taken into account as well. One might also argue that a more durable product should reduce the environmental impact for high production and disposal impact products since it would extend the product use duration. However, in $R1$, we show that environmental impact may increase for high production and disposal impact products even when servicization results in higher product durability. Therefore, product durability cannot be a good proxy for the environmental impact. One needs to look at the product type and relative operating efficiency of servicization jointly to assess the environmental benefits of servicization.

3.6 Product Line

We have shown that ability to price based on use volume may provide servicization an edge over selling when the firm produces a single product. However, in practice, firms can sell a product line to segment the market. For example, Interface sells carpets made of type 6 and type $6,6$ fiber, and type $6,6$ is known to be more durable. In order to study the impact of different segmentation practices on the profits, here, we allow the firm to sell two products with different product durabilities, and compare the profitability of selling *two products* and servicizing *single* product. We denote high and low product durability δ_H and δ_L in selling

Strategy	Regions	δ^*	τ^*	π^*
Selling	$R1$, $R2$	$\delta_H^* = \frac{\theta^2}{4c(1+m_c)}$, $\delta_L^* = \frac{\left(-\alpha^2+\beta\right)\theta^2}{4c(-1+\beta)(1+m_c)}$	$\tau_H^* = \frac{\theta^3}{4c(1+m_c)^2}$, $\tau_L^* = \frac{\alpha\left(\alpha^2-\beta\right)\theta^3}{4c(1-\beta)(1+m_c)^2}$	$\frac{M\left(\alpha^4+\beta-2\alpha^2\beta\right)\theta^4}{16c(1-\beta)(1+m_c)^2}$
	$R3$	$\delta^* = \frac{\theta^2}{4c(1+m_c)}$	$\tau_H^* = \frac{\theta\delta^*}{1+m_c}$, $\tau_L^* = 0$	$\frac{\theta^4 M}{16c(1+m_c)^2}$

Table 3.3: Equilibrium product durability, product use and firm profits under selling strategy when the firm can sell two vertically differentiated products.

strategy, respectively. Next proposition describes the equilibrium for selling and servicization strategies.

Proposition 15. *Suppose the firm can sell two vertically differentiated products with different durabilities. The following characterizes the equilibrium. The optimum product durability, product use and firm profits for selling strategy are provided in Table 3.3 and for servicization strategy in Table 3.1.*

$R1^{pl}$ *When $\gamma(\alpha,\beta) \leq \frac{\alpha}{\beta}$, the firm serves both segments under both selling and servicization strategies. $\gamma(\alpha,\beta)$ is characterized in the proof of the Proposition 8.*

$R2^{pl}$ *When $\sqrt{\beta} \leq \frac{\alpha}{\beta} < \gamma(\alpha,\beta)$, the firm serves high valuation segment under servicization strategy and both segments under selling strategy.*

$R3^{pl}$ *When $\frac{\alpha}{\beta} < \sqrt{\beta}$, the firm serves high valuation segment under both selling and servicization strategies.*

The equilibrium structure is similar to that of single product scenario. That is, it depends on the relative profitability of low-end segment, i.e., $\frac{\alpha}{\beta}$. As we move from $R1^{pl}$ to $R3^{pl}$, serving the low-end segment becomes less attractive and the firm stops serving low-end segment when the $\frac{\alpha}{\beta}$ is small enough. Furthermore, as expected, when the firm sells two products, it is more likely to serve low-end segment compared to single product case. More interesting insight emerges when we compare segmentation strategies under selling and servicization. When the firm sells two vertically differentiated products, the firm is more likely to serve both segments compared to servicization, i.e., $\sqrt{\beta} < \gamma(\alpha,\beta)$. This suggests that customizing the product design is more effective in segmentation than customizing the product use levels. To see the impact of this dynamic on profitability, we next compare the profitability of selling and servicization.

Proposition 16. *Suppose the firm can sell two vertically differentiated products. Servicization* *is more profitable than selling strategy if and only if*

(*i*) $r > \sqrt{\frac{(1-\beta)(\alpha^4+\beta-2\alpha^2\beta)}{(\alpha^2+\beta-2\alpha\beta)^2}} \triangleq h_1(\alpha, \beta)$ *in* $R1$.

(*ii*) $r > \sqrt{\frac{\alpha^4+\beta-2\alpha^2\beta}{(1-\beta)\beta}} \triangleq h_2(\alpha, \beta)$ *in* $R2$.

(*iii*) $r > 1$ *in* $R3$.

In addition h_1, $h_2 > 1$.

The proposition shows that when the firm can sell a product line, servicization is more profitable only when the firm has a higher operating efficiency than the consumers. Otherwise, selling strategy is more profitable. Although, servicizing firm can customize the use levels for each individual consumer segments, the level of customization is limited because same product is offered to both consumer segments. On the other hand, selling firm can control the consumer use levels more freely by designing two products.

Although selling a product line is more profitable for the same operating efficiencies, in practice, the firm may have a higher operating efficiency. In that case, servicization may, in fact, be more profitable. Figure 3.5 illustrates how the profit gap between two strategies change with respect to the mass of the high-end segment (which is a proxy for the relative profitability of low-end segment, i.e., $\frac{\alpha}{\beta}$.):

$$\%\Delta = 100 \times \frac{\pi_r^{pl} - \pi_v}{\pi_r^{pl}},$$

where π_r^{pl} and π_v represents the profits of selling a product line and servicization, respectively. In Figure 3.5a, selling strategy is more attractive than servicization since selling and servicization strategies have same operational efficiencies as indicated in Proposition 16. However, the advantage of selling strategy over servicization is small, unless the relative profitability of low-end segment is moderate, that is, $\frac{\alpha}{\beta}$ ratio is close to the boundary between $R1^{pl}$ and $R2^{pl}$ regions. In fact, higher operating efficiency of the firm may overcome the additional segmentation benefit of selling and servicization may yield a higher profit when $\frac{\alpha}{\beta}$ ratio is sufficiently high or low. This is demonstrated in Figure 3.5b: servicization is more profitable when $\beta > 0.28$ or $\beta < 0.02$; otherwise, selling is more profitable. Essentially, selling a product line is more effective when the low-end segment has a low profitability potential (low α and high β). Therefore, in $R1^{pl}$, the profit gap between selling and servicization increases as $\frac{\alpha}{\beta}$ decreases.

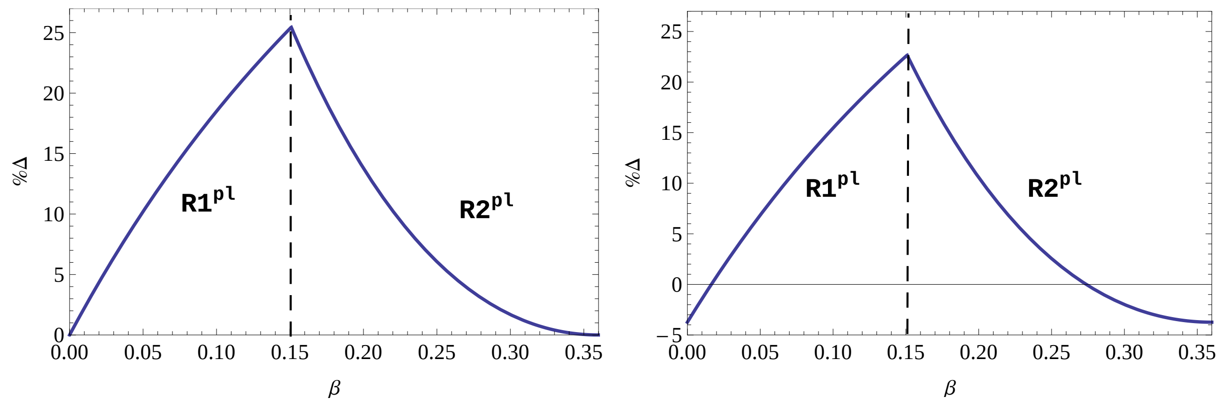


Figure 3.5: Relative profititability of servicizing a single product to selling two differentiated products. ($\alpha = 0.6$)

However, in $R2^{pl}$, servicizing firm serves only the high-end segment and lower profitability of low-end segment only hurts the selling firm.

Firms can achieve segmentation by designing and selling differentiated products. Our results in this section shows that servicization can be an alternative to this strategy. Segmenting the market through servicization can be more valuable when the fixed cost of designing an additional product variant is very high. Furthermore, many manufacturing firms already have an established aftermarket services infrastructure to provide variety of services to their customers. For these firms, segmentation by servicization can be a more attractive and cheaper business practice compared to designing and selling additional product variants.

3.7 Conclusion

We study when servicization increases profitability and product durability, and decreases the environmental impact. Even though there are anecdotal evidences that servicization has potential to achieve these outcomes, this problem has not been studied before. By characterizing the equilibrium decisions of a monopolist serving a heterogeneous consumer base with endogenous product use and product durability, we show that servicization can be more profitable even when it is operationally inefficient. This is because servicizing firm can utilize product use information in pricing to differentiate the consumer segments.

A commonly held belief is that servicization increases the product durability because it increases the firm's responsibility toward its product. We show that this intuition is true when the firm serves same consumer segments under selling and servicization strategies. However, when the firm targets additional consumer segments under servicization, product durability may be lower than that of selling strategy.

In order to asses the environmental impact of servicization, we need to consider two factors: relative operating efficiency of servicization and relative use impact of the product. When the relative operating efficiency of servicization is high, servicization can be more environmentally friendly for products with low use impact relative to their production and disposal impacts. On the other hand, when the relative operating efficiency of servicization is low, servicization can be more environmentally friendly for products with high use impact relative to their production and disposal impacts.

We also study the impact of servicization on the consumer and the social surplus. We show that servicization may decrease both the consumer and the social surplus even when the firm is more efficient in maintaining the product than consumers.

It is worth mentioning some of the limitations of our work. Although in some examples of the servicization pooling the resources may be an option (such as ZipCar), we do not consider resource pooling. With resource pooling, the firm can serve more consumers with fewer products. However, resource pooling is not feasible in many other examples of servicization such as in carpets (Interface Inc.). Finally, we do not consider the product recovery options such as remanufacturing and recycling. In reality, the firm can undertake these activities to decrease its production cost or reach out secondary markets.

CHAPTER 4

RESPONSIBLE SOURCING VIA VERTICAL INTEGRATION: THE IMPACTS OF SCRUTINY, DEMAND EXTERNALITY, AND CROSS SOURCING

4.1 Introduction

Deadly collapse of the Rana Plaza factory in Bangladesh (New York Times, 2013), allegations of sweatshop and child labor at factories of Nike suppliers (Daily Mail, 2011) are all examples of news that brought much media attention to firms' sourcing practices in emerging economies. A major advantage, if not the most important one, of sourcing from emerging economies, is the lower operating and labor costs. It is not uncommon that such cost advantages come at the expense of social responsibility compliance. Suppliers may engage in unethical practices to lower costs and squeeze more profits. Ineffective regulatory enforcements in these countries also fuel noncompliance.

In recent years, rising awareness among the general public about corporate social responsibilities makes it inevitable for firms to take into account consequences of practices of their suppliers. The publicity of social responsibility violations may impact not only a firm's image, but also that of other firms in the industry, partly due to the general opinion that firms in one industry tend to procure from the same set of suppliers, which are often concentrated in a few countries. In fact, in some cases a critical input to the production process is only available from a specific geographic region. For example, ebony wood is widely used in the fingerboards of high-end guitars. Unfortunately, ebony is an endangered species, and can only be harvested in bulk in one country—the small eastern African country of Cameroon. Therefore, a responsibility violation at one firm may tarnish the images of other firms in the industry, and driving down demand for all, even in the absence of any concrete evidence. We refer to this phenomenon as the negative externality of a violation. On the other hand, when one firm's violation is exposed, disappointed consumers may potentially switch to other competing firms, leading to increased demand for competitors. We refer to this phenomenon as the poise externality of a violation. Interestingly, when governments and NGOs publish audit reports, they may influence the nature of the violation externality by either emphasizing the practice of the entire industry, or targeting a specific firm's practices. It is unclear whether governments and NGOs should create positive or negative externalities.

A common way to mitigate supplier responsibility risks is to increase auditing efforts (Distelhorst et al., 2014). However, using data from Nike's audits of its suppliers, Locke et al. (2007) found that auditing is ineffective in improving suppliers' labor standards. In this chapter, we propose another strategy—vertical integration. For example, Taylor Guitars, a major guitar manufacturer, purchased an ebony mill in Cameroon to ensure that ebony is harvested in an environmentally sustainable way (Los Angeles Times, 2012). In addition to ensuring compliance in the sourcing process, vertical integration also offers the possibility of supplying component to competitors. a firm may benefit from doing so in two ways: first, it is an additional revenue source. Second, in the case of negative violation externality, the firm can protect its own brand from being tarnished due to a competitor's malpractice. Modeling the above aspects, in this chapter, we aim to answer the following questions:

1. How do probabilities of detection and violation externalities influence manufacturers' responsibility decisions?
2. What is the impact of cross sourcing on firms' operational and compliance decisions?

This chapter contributes to the growing body of literature on socially responsible sourcing. Guo et al. (2014) study the sourcing decision of a buyer choosing between responsible and risky suppliers. They find that efforts to improve responsibility that focus on consumers may actually encourage risky sourcing. Plambeck and Taylor (2012) and Chen and Lee (2014) investigate the mechanisms that may incentivize suppliers to comply with responsibility standards. We contribute to this stream of research by exploring vertical integration as a strategy to promote socially responsible sourcing, and by considering the impacts of both negative and positive externalities.

4.2 Model

We study the vertical integration and CSR decisions of manufacturers in two competing supply chains selling a product to a consumer market. Each supply chain consists of a manufacturer ($i = A, B$) and a supplier ($i = A, B$). Each manufacturer may source a critical component/product from an outside supplier. We assume that firm A has vertical integration capabilities. Firm B cannot vertically integrate and has to procure from an outside supplier. The terms manufacturer (she) and supplier (he) are used to describe the flow of the material through the supply chain. The manufacturer may not have any production capability and supplier may fully carry out the entire production process. We analyze the impact of industry structure, driven by the manufacturers' vertical integration/disintegration decisions, and the impact of CSR externality on the manufacturers' choice of social responsibility. Next, we describe our demand model, CSR externality, and firms' characteristics and decisions.

The available outside suppliers are not reliable and they may not follow the social responsibility standards. A violation may be detected with an exogenous probability $\sigma \in (0, 1)$. The probability of detection σ depends on how aggressive the NGOs or governments in their auditing efforts to identify the violations. Firm A can avoid responsibility violations, i.e., $\sigma = 0$, by vertical integrating and investing in CSR. It still faces the same probability of detection $\sigma \in (0, 1)$ as in the disintegrated supply chain case, if it vertically integrates but does not invest in CSR. The wholesale price of the procured component from outside suppliers is w. If firm A vertically integrates, it incurs a fixed cost f. Firm A, once vertically integrated, can continue to cut corners to increase its profit margin or choose to comply with environmental and labor standards. In the former case, it incurs a marginal cost of production, for the critical component, normalized to 0. In the latter case, the cost is $c_r > w$.

Firms sell the product to a market of fixed total size $2Q$ at an exogenous price p. Firms have equal market share Q if no violation is detected in the industry. If a firm sources from a supplier that experiences a violation, there are two potential consequences on the consumer demand: i) a decrease in the firm's demand, ii) a decrease/increase in the competitor's demand. The former results from a fraction of consumers abandoning the firm after the violation detection at its supplier. Examples include but not limited to: Apple, Nike and Mango. Specifically, we assume that the consumer demand for the firm becomes $(1+\beta)Q$ where $\beta \in (-1,0)$. The latter derives from indirect impact of a violation on the competitor's demand. This indirect impact can be positive or negative. It will be positive if some of the consumers exited the firm's market switch to the competitor. It can be negative if the violation hurts the industries reputation. For example, after a mercury spill in Peru by a transportation contractor for Newmont Mining Corporation. BHP Billiton is affected by increased hostility toward mining companies although it does not have any connections to Newmont (Puffer and Wesley, 2012). More specifically, we assume that the demand of the competitor becomes $(1+\alpha)Q$, where $\alpha \in (\beta, -\beta)$. $\alpha > \beta$ because the indirect impact cannot be stronger than the direct impact. $\alpha < -\beta$ because number of customers switching to the competitor cannot be larger than the number of customers abandoning the firm. However, if a violation is detected at the both supply chains, then the demands of both firms become $(1+\beta)Q$.

The sequence of events is as follows: First, firm A decides whether to vertically integrate or stay disintegrated. If firm A vertically integrates, it decides whether to become responsible or stay normal. After these strategic decisions, a violation may be detected at each of the suppliers with probability σ. Finally, the manufacturers produces, and consumers arrive and purchase the product.

In Section 4.4, we allow vertically integrated firm to sell the component to its competitor. More specifically, if firm A vertically integrates, then it has the option to sell to firm B at a wholesale price of w_c which is a decision variable. This stage takes place after firm A decides on its responsibility choice. Then, the firm B decides whether to source from the integrated manufacturer or from outside supplier. Selling a critical component to your competitor may be viable strategy in some industries. For example, Taylor guitar has been selling ebony to Gibson guitar after purchasing the Cameroon's largest ebony mill. Similarly, Samsung, which is a major competitor of Apple, is the main supplier of microprocessor chips for Iphone and Ipad. We compare the cases where cross sourcing is viable and not viable to determine how different industry dynamics may impact CSR.

Let (D,N), (V,N), (V,R) denote the three possible strategies available to a firm where first index refers to supply chain structure and second index refers whether the supplier is responsible or normal. We use V if a firm is vertically integrated, and D if it stays disintegrated.

We use N if the supplier is prone to responsibility violations, and R if the supplier is fully compliant with the environmental and labor standards. Note that if a firm is disintegrated, the available suppliers are only the normal ones. Let $\pi^i_{\cdot|\cdot}$ denote firm i's profit given the competitor's strategy. Then, we can write the profit functions for these three strategies as follows:

$$\pi^i_{dn|dn} = \pi^i_{dn|vn} = (p-w)Q(\sigma^2(1+\beta) + \sigma(1-\sigma)(1+\beta) + (1-\sigma)\sigma(1+\alpha) + (1-\sigma)^2) \quad (4.1)$$

$$\pi^i_{dn|vr} = (p-w)Q(\sigma(1+\beta) + (1-\sigma)) \quad (4.2)$$

$$\pi^i_{vn|dn} = pQ(\sigma^2(1+\beta) + \sigma(1-\sigma)(1+\beta) + (1-\sigma)\sigma(1+\alpha) + (1-\sigma)^2) - f \quad (4.3)$$

$$\pi^i_{vr|dn} = (p-c_r)Q(\sigma(1+\alpha) + (1-\sigma)) - f \quad (4.4)$$

4.3 Optimal Strategy In the Absence of Cross Sourcing

This section presents the optimal strategy of firm A when cross sourcing is not an option. We solve the model using backward induction. In order to eliminate the trivial cases, we assume that fixed cost f is small enough such that staying disintegrated does not dominate (V,N) and (V,R). Specific threshold values on the fixed cost are stated in Appendix C. We also assume cost of responsible sourcing is small enough, i.e., $c_r < -\frac{\beta p}{2(\beta+2)}$. This condition is slightly stronger than the condition that ensures that staying normal after vertical integration does not dominate responsible sourcing. These two assumptions essentially eliminates the uninteresting cases. Finally, we make the technical assumption that $\beta > \frac{-1}{2}$ which means that a firm does not lose more than half of its consumer base. Although, this is mainly for tractability purposes, it is also practically meaningful because it is not very likely that a firm would lose more than the half of its market after publicity of a responsibility violation.

Next proposition establishes the optimum strategy of firm A when externality is strongly negative, i.e., $\beta < \alpha < \frac{\beta p + c_r}{p - c_r},$. Proposition 18 gives the optimum strategy for weakly negative and positive externality, i.e., $\min\{\frac{c_r+\beta(p-w)}{p-c_r}, \frac{\beta(p-w)}{-c_r+2p+w}\} < \alpha < -\beta$. Note that $\frac{\beta p+c_r}{p-c_r} < \min\{\frac{c_r+\beta(p-w)}{p-c_r}, \frac{\beta(p-w)}{-c_r+2p+w}\}$ and they are both negative values. These two extreme cases are sufficient to highlight the fundamental differences on optimal strategy for different

α values. As α increases from $\frac{\beta p+c_r}{p-c_r}$ to $\min\{\frac{c_r+\beta(p-w)}{p-c_r}, \frac{\beta(p-w)}{-c_r+2p+w}\}$ (when α is moderately negative), the optimal strategy slowly changes from one extreme case to another, and does not provide any additional insights. Nevertheless for completeness, the optimal strategy for this α range is stated in the Appendix C.

Proposition 17. *Suppose* $\beta < \alpha < \frac{\beta p+c_r}{p-c_r}$,

(1.) *When* $f \leq Qw(1+\beta)$, *for* $\sigma^1_{vr,vn} \leq \sigma \leq \sigma^2_{vr,vn}$, *firm A chooses (V,R), and for* $0 < \sigma < \sigma^1_{vr,vn}$ *and* $\sigma^2_{vr,vn} < \sigma < 1$ *chooses VN.*

(2.) *When* $Qw(1+\beta) < f < f_1$, *for* $\sigma^1_{vr,vn} \leq \sigma \leq \sigma^2_{vr,vn}$, *firm A chooses (V,R), for* $0 < \sigma < \sigma^1_{vr,vn}$ *and* $\sigma^2_{vr,vn} < \sigma \leq \sigma^2_{vn,dn}$ *chooses (V,N), and for* $\sigma_{vn,dn} < \sigma < 1$ *firm chooses (D,N).*

(3.) *When* $f_1 \leq f < f_2$, *for* $\sigma^1_{vr,vn} \leq \sigma \leq \sigma_{vr,dn}$, *firm A chooses (V,R), and for* $0 < \sigma < \sigma^1_{vr,vn}$, *firm chooses (V,N), and for* $\sigma^2_{vr,dn} < \sigma < 1$ *chooses (D,N).*

(4.) *When* $f_2 \leq f < \min\{Qw, f_m\}$, *for* $\sigma^1_{vr,dn} \leq \sigma \leq \sigma^2_{vr,dn}$, *firm A chooses (V,R), and for* $0 < \sigma \leq \sigma_{vn,dn}$ *chooses (V,N), for* $\sigma_{vn,dn} < \sigma < \sigma^1_{vr,dn}$ *and* $\sigma^2_{vr,dn} < \sigma < 1$ *chooses (D,N).*

Figure 4.1 depicts the proposition graphically. The proposition reveals several interesting insights. Neither responsibility decision nor supply chain strategy are necessarily monotone in probability of detection σ. When fixed cost is small, it is more profitable to vertically integrate for firm A. However, whether it will choose responsible sourcing depends on the probability of detection. Lower probability of detection leads to normal sourcing because the firm has less incentive for responsible sourcing. As probability of detection σ increases, responsible sourcing becomes the optimal strategy because the possibility that a violation would be public and potential consumer would exit firm A's market increases. However, when probability of detection is very high, firm A revert to normal sourcing. This is counter intuitive because one would expect that higher probability of detection should discourage firms from noncompliance with the environmental and labor standards. In fact, this is true when externality α is weakly negative or positive that we show in Proposition 18. The intuition for this is that high probability of detection makes compliance with the labor and environmental standards less effective in protecting the brand image. This is because even firm A chooses to meet the compliance standards, the competitor is very likely to be caught, and this would in turn hurt firm A because of strong negative externality. As a result, firm A benefits from compliance when probability of detection is at a medium range. Otherwise, firm A is better off not meeting the compliance standards.

As fixed cost of vertical integration increases, staying disintegrated may be an optimal strategy. Interestingly, when $f < f_2$, firm A chooses (D,N) only if probability of detection is very high, as parts (2.) and (3.) of the proposition state. Essentially, (D,N) replaces (V,N) at high probability of detection values for this region as fixed cost f increases. The advantage of (V,N) over (D,N) is that the firm can produce at a cheaper rate . This advantage decreases as probability of detection increases. As a result, (D,N) becomes more profitable at high probability of detection values.

Part (4.) of the proposition shows that not only responsibility choice but also the supply chain structure may not be monotone in the probability of detection when fixed cost f is high. Staying disintegrated is optimal for medium-low and high probability of detection values, but vertical integration is optimal for low and medium-high probability of detection values.

The relative weight of impact of a violation and production cost leads to this optimal structure. When probability of detection is not high, impact of a violation, either at the firm's own supply chain or its competitor's supply chain, has less impact on the firm's expected profit than the production cost. Therefore, the firm does not source responsibly. When it comes to choosing between (V,N) and (D,N), as explained above, increasing probability of detection decreases the cost advantage of vertical integration. Because of this, staying disintegrated is more profitable for medium-low probability of detection values but vertical integration is more profitable for low probability of detection values.

When probability of detection is high, the impact of a violation becomes the prominent concern for firm A's profit. Hence, firm A can benefit from choosing responsible sourcing when probability of detection is not too high. When probability of detection is very high strong negative externality undermines the benefit of being responsible, as a result firm chooses (D,N).

Overall, the proposition suggests that higher probability of detection may decrease the incentives for compliance when externality is strongly negative. Therefore, increasing NGO or government efforts to detect the violations of labor and environmental standards may lead to unintended consequences if violations at one firm result in shrinks the other firm's market significantly. Next, we research the optimal strategy when externality is weakly negative or positive.

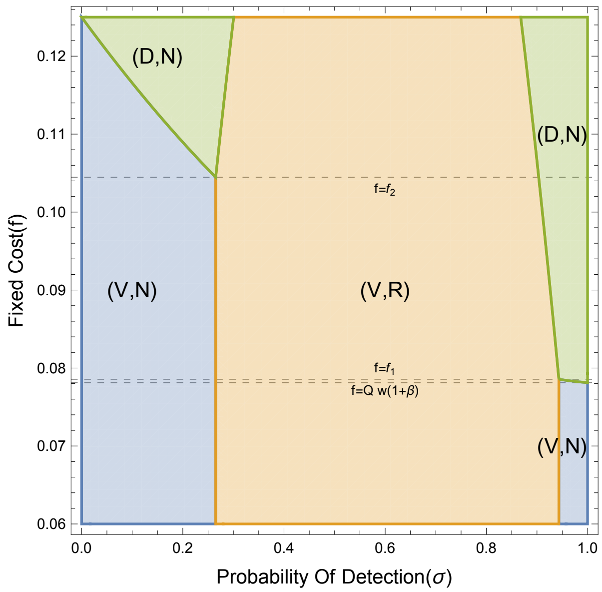


Figure 4.1: Firm A's optimal supply chain structure and its responsibility decision when externality is strongly negative. Dashed lines show the thresholds on fixed cost. ($p = 3,\ w = \frac{1}{8},\ c_r = \frac{1}{4},\ Q = 1,\ \alpha = -\frac{1}{3},\ \beta = -\frac{3}{8}$)

Proposition 18. *Suppose* $\min\{\frac{c_r+\beta(p-w)}{p-c_r}, \frac{\beta(p-w)}{-c_r+2p+w}\} < \alpha < \beta$,

(1.) *When* $f \leq f_2$, *for* $\sigma^1_{vr,vn} \leq \sigma < 1$, *firm A chooses (V,R), and for* $0 < \sigma < \sigma^1_{vr,vn}$ *chooses (V,N).*

(2.) *When* $f_2 < f < Qw$, *for* $\sigma^2_{vr,dn} \leq \sigma < 1$, *firm A chooses (V,R), for* $0 < \sigma \leq \sigma_{vn,dn}$ *chooses (V,N), for* $\sigma_{vn,dn} < \sigma < \sigma^2_{vr,dn}$, *chooses (D,N).*

Figure 4.2 illustrates the proposition. When fixed cost is low, vertical integration is always the optimal strategy. The firm chooses between (V,R) and (V,N). When probability of detection is low, the firm prefers normal sourcing because low probability of detection does not provide strong incentives to invest in responsibility. In fact, as probability of detection increases, the incentive becomes stronger and the firm chooses responsible sourcing.

When we compare Proposition 17 and 18, we see that when externality is weakly negative or positive, unlike strongly negative externality, high probability of detection always incentivizes

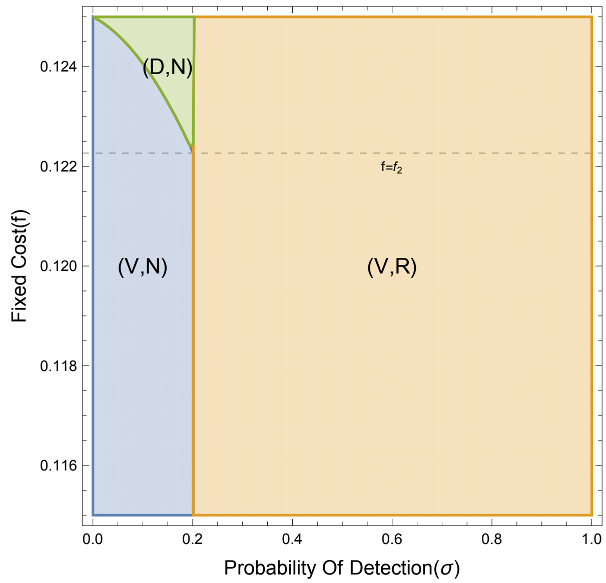


Figure 4.2: Firm A's optimal supply chain structure and its responsibility decision when externality is weakly negative or positive. ($p = 3,\ w = \frac{1}{8},\ c_r = \frac{1}{4},\ Q = 1,\ \alpha = \frac{1}{3},\ \beta = -\frac{3}{8}$)

compliance. To understand this difference we need to look how the direction and strength of externality impacts firm A's decisions. Positive externality always encourages compliance because if firm B gets caught, firm A benefits from influx of consumers to its market. Even the externality is negative, if it is weak, the firm prefers compliance at high probability of detection values because the negative impact due to a violation at the competitor' supply chain is much smaller than the negative impact due to a violations at its own supply chain.

Our results in this section establishes how CSR externality plays a role in firm's choice of vertical integration vs. disintegration, and compliance vs. non-compliance. In the next section, we research how these results change when firm A can sell the critical component to firm B if it vertically integrates.

4.4 Equilibrium With Cross Sourcing

In this section, we extend our model and assume that firm A can sell the critical component to its competitor firm B when it vertically integrates with its supplier. We refer to this strategy as *cross sourcing.* In this case there are 5 different possible equilibrium outcomes. For brevity, Proposition 19 presents the result for $f = 0$. Then, we use Figure 4.4 to show how increasing fixed cost f impacts the equilibrium structure. We refer readers to Appendix C

Equilibrium	$(V,N)_c$	$(V,R)_c$
w_c	$\frac{\alpha p(\sigma-1)\sigma+\sigma w(\alpha+\beta)+\alpha\sigma^2(-w)+w}{\beta\sigma+1}$	$w-\beta\sigma(p-w)$

Table 4.1: Equilibrium wholesale price

for the complete analytical characterization with a nonnegative fixed cost. If cross sourcing arises in the equilibrium, we attach subscript c to the descriptions of the equilibrium. For example, $(V,R)_c$ means firm A vertically integrates, complies with the environmental and labor standards, and sells to firm B. This notation is also sufficient to describe firm B's equilibrium structure, which is $(D,R)_c$ in this case, hence we will use only firm A's equilibrium outcome to describe a particular equilibrium.

Proposition 19. *Suppose that vertically integrated firm A can sell the critical component to firm B. The equilibrium wholesale prices are provided in Table 4.1. The following characterizes the equilibrium regions.*

(1.) *When $\beta < \alpha \leq \alpha_1$, for $\sigma_{vrc,vn} \leq \sigma < 1$, firm A chooses $(V,R)_c$, and for $0 < \sigma < \sigma_{vrc,vn}$ chooses $(V,N)_c$.*

(2.) *When $\alpha_1 < \alpha \leq \alpha_2$, for $\sigma_{vrc,vn} \leq \sigma < 1$, firm A chooses $(V,R)_c$, for $0 < \sigma \leq \sigma_{vnc,vn}$ chooses $(V,N)_c$, and for $\sigma_{vnc,vn} < \sigma < \sigma_{vrc,vn}$ chooses (V,N).*

(3.) *When $-\alpha_2 < \alpha \leq \frac{-c_r+(-\beta)(p-w)+w}{p-c_r}$, for $\sigma_{vrc,vr} \leq \sigma < 1$, firm A chooses $(V,R)_c$, for $\sigma_{vr,vn} \leq \sigma < \sigma_{vrc,vr}$ chooses (V,R), for $0 < \sigma \leq \sigma_{vnc,vn}$ chooses $(V,N)_c$, and for $\sigma_{vnc,vn} < \sigma < \sigma_{vr,vn}$ chooses (V,N).*

(4.) *When $\frac{-c_r+(-\beta)(p-w)+w}{p-c_r} < \alpha < -\beta$, for $\sigma_{vr,vn} \leq \sigma < 1$ chooses (V,R), for $0 < \sigma \leq \sigma_{vnc,vn}$ chooses $(V,N)_c$, and for $\sigma_{vnc,vn} < \sigma < \sigma_{vr,vn}$ chooses (V,N).*

Furthermore, $\alpha_1, \alpha_2 > 0$.

Figure 4.3 depicts the proposition graphically. The proposition indicates that when externality is negative or weakly positive firm A always finds it profitable to sell to its competitor. To understand this we need to look how risk and expected sales associated with it change by cross sourcing. If firm A vertically integrates but does not become responsible, and does not sell to firm B, in this case expected sales of both firm A and firm B are $E[S^i_{(V,N)}] = Q(-\alpha\sigma^2 + (\alpha+\beta)\sigma + 1)$ where $E[S^i_j]$ denotes the firm i's expected sales to the market for equilibrium structure j. Instead if firm A is to sell to firm B, their expected sales

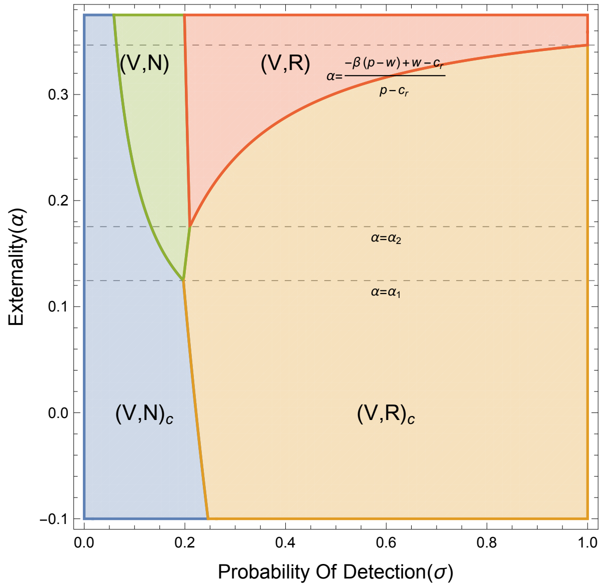


Figure 4.3: Equilibrium when firm A can sell to firm B and $f = 0$. ($p = 3$, $w = \frac{1}{8}$, $c_r = \frac{1}{4}$, $Q = 1$, $\beta = -\frac{3}{8}$)

would be $E[S^i_{(V,N)_c}] = Q(1+\sigma\beta)$. Firstly, suppose that externality is negative. It is straightforward to see that $E[S^i_{(V,N)_c}] > E[S^i_{(V,N)}]$. This shows that by selling to firm B, firm A increases the expected sales, by decreasing the violation risk, of both itself and firm B. Therefore, firm B prefers to procure from firm A by paying a premium ($w_c > w$ if and only if externality is negative), and firm A prefers to sell to firm B because it can both decrease the violation risk and benefit from extra revenue stream due to component sales.

Similar insights holds when firm A decides to comply with the environmental and labor standards. In this case $E[S^A_{(V,R)_c}] = Q > Q(1+\alpha\sigma) = E[S^A_{(V,R)}]$ and $E[S^B_{(V,R)_c}] = Q > Q(1+\beta\sigma) = E[S^B_{(V,R)}]$. Therefore, cross sourcing increases the expected sales for both firm A and B as long as externality is negative. Therefore, firm A finds selling to firm B, and firm B finds procuring from firm A more profitable.

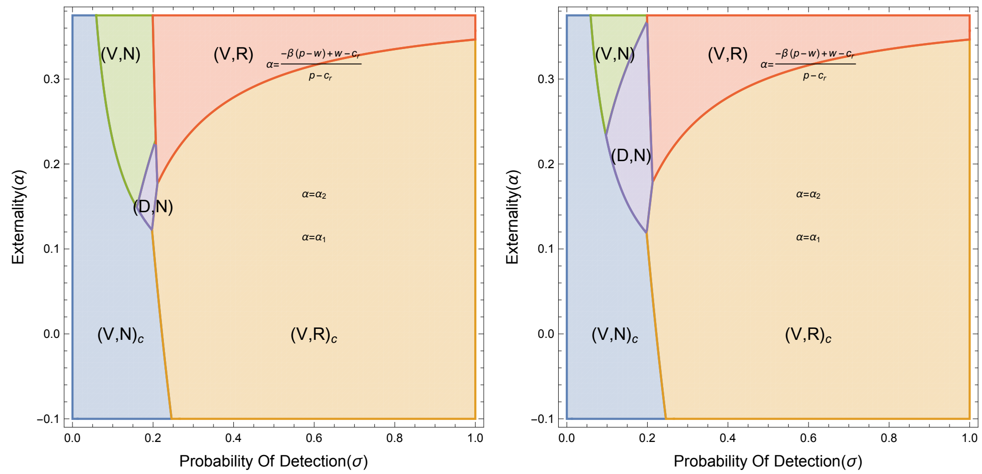
When we compare this region to the one in Proposition 17, we observe that when externality is negative, at high probability of detection values, non-compliance cannot be an equilibrium anymore. Furthermore, firm A does not only comply with the law but also helps the entire industry become responsible. Hence, whether it is beneficial to increase the pressure on firms depends on the industry dynamics. If cross sourcing is a viable option, then for NGOs and governments auditing the suppliers more frequently and increasing the chances to find the violation always increases the compliance. Otherwise, it decreases the compliance.

When externality is positive, it is easy to see from inequalities above, cross sourcing always decreases the expected sales of firm A. Then, the question is why cross sourcing always take place when α is weakly positive. Although, cross sourcing decreases the expected sales, it provides additional revenue opportunity to firm A. However, when externality exceeds a certain threshold, i.e., $\alpha > \alpha_1$, the reduction in expected sales may be too large to justify the additional revenue. In that case, firm A may be better off not selling to firm B, but instead capturing the consumers that defect firm B in the case of a violation.

When $\alpha_1 < \alpha \leq \frac{-c_r+(-\beta)(p-w)+w}{p-c_r}$, we observe that (V, N) and (V, R) may arise in the equilibrium at medium probability of detection values. Interestingly, too low and too high probability of detection σ lead to cross sourcing. When probability of detection is too high, it is more profitable for the compliant firm A to sell to firm B because firm B is willing to accept a higher wholesale price w_c to avoid the detection risk. Note that w_c is increasing in σ when the equilibrium is $(V, R)_c$. When probability of detection is too low, firm A prefers not to comply with the environmental and labor standards. In this case, cross sourcing decreases the expected sales of both firms, as explained before, because the externality is positive. However, firm A benefits from additional sales to firm B and firm B benefits from purchasing at a lower rate, i.e., $w < w_c$. Which of these two opposite forces has more value depends on the probability of detection. Note that $\lim_{\sigma \to 0} E[S^i_{(V,N)}] - E[S^i_{(V,N)_c}] = 0$ and this difference increases as σ increases when $\sigma < \sigma_{vr,vn}$. Therefore, when probability of detection is too low, the additional revenue due to cross sourcing is higher than the reduction in expected sales, and firm A sells to firm B.

Finally, when $\alpha > \frac{-c_r+(-\beta)(p-w)+w}{p-c_r}$, the proposition shows that cross sourcing does not arise when firm B is responsible. This is because the size of consumers who may defect from firm B's market to purchase from firm A is to high that firm A would not prevent this by selling to firm B.

Figure 4.4 illustrates how the equilibrium changes when fixed cost is nonnegative. When fixed cost is sufficiently high, for firm A staying disintegrated can be a viable strategy. The graphs show that when α is positive, and probability of detection is at a medium level (D,N) may arise in the equilibrium. This structure is somewhat similar to Proposition 18, and the



(a) (b)

Figure 4.4: Equilibrium when firm A can sell to firm B and $f > 0$. (a) $f = 0.120$, (b)$f = 0.123$ ($p = 3,\ w = \frac{1}{8},\ c_r = \frac{1}{4},\ Q = 1,\ \beta = -\frac{3}{8}$)

intuition is similar to the one given for this proposition. Contrary to the without cross sourcing model, in this case (D,N) cannot be in the equilibrium when externality is negative because benefits of cross sourcing outweighs the fixed cost. Note that we have assumed that fixed cost is low enough such that (D,N) does not dominate (V,N) or (D,N). Therefore, these insights holds as long as fixed cost is not too high. Otherwise, too high fixed cost would make any vertical integration strategy worse off.

4.5 Discussion

In this section we further discuss our results to see how different parameters affect CSR. One of the factors that governments and NGOs can influence is the probability of detection σ. Governments can increase the probability of detection by increasing their auditing effort while NGO can be more aggressive in their research to evaluate a firm or an industry. In the previous section, we commented on how these efforts can impact CSR. We showed that higher probability of detection may disincentivize compliance when cross sourcing cannot be employed and the externality α is strongly negative.

Another factor that governments and NGOs may influence is the externality. They can do so by structuring the violation announcements. For example, the following is a quote from a report on Amazon forests in Brazil released by Greenpeace:

“The cattle sector in the Brazilian Amazon is the largest driver of deforestation in the world, responsible for one in every eight hectares destroyed globally. Efforts to halt global deforestation emissions must tackle this sector.”

Greenpeace blames the entire cattle industry without making a distinction among any of the suppliers or their buyers. Such an announcement would be expected to create a negative externality. On the other hand, announcement could be made in a more distinguishing fashion to highlight the firms complying and not complying with the environmental and labor standards. This may potentially create a positive externality for presumably compliant firms. To see which way strategy incentivizes firms to comply we analyze how externality changes the firms actions. Next proposition presents the results when cross sourcing cannot be employed.

Proposition 20. *Suppose that cross sourcing is not a viable strategy, then increasing externality increases the likelihood of compliance.*

When it is not feasible for firm A to sell to firm B, decreasing externality reduces the size of the region where firm A complies with the environmental and labor standards. Negative externality discourages the compliance because firm A cannot reap the fruits of compliance. Therefore, in order to encourage compliance government agencies and NGO should highlight the firm that comply with the environmental and labor standards. However, this holds when vertically integrated firm cannot sell the components to its competitors. Now we turn our attention to the case where firm A may sell the component to its competitor.

Proposition 21. *Suppose that cross sourcing is a viable strategy, then increasing externality increases the likelihood that both firm would comply with the environmental and labor standards if and only if* $\beta < \alpha \leq \frac{4\beta^2 w(2p-w)(2c_r-p)}{(p-w)(4c_r-w)(4c_r+4\beta p-(2\beta+1)w)}$, *or* $\frac{4\beta^2 w(2p-w)(2c_r-p)}{(p-w)(4c_r-w)(4c_r+4\beta p-(2\beta+1)w)} < \alpha \leq \alpha_1$ *and* $f < f_1$.

Note that $\frac{4\beta^2 w(2p-w)(2c_r-p)}{(p-w)(4c_r-w)(4c_r+4\beta p-(2\beta+1)w)}$ is positive. Cross sourcing leads to more subtle results compared to Proposition 20. As long as externality is not strongly positive, increasing externality increases the chance that firm A would be compliant and would sell to firm B. This behavior would make the entire industry comply with the environmental and labor standards. However, when externality is strongly positive, increasing externality may in fact reduce firm A’s incentives to sell to firm B which in turn leaves firm B with the only option to procure from a supplier with questionable practices. This also contrast with our previous results where we show that increasing externality always increases the compliance when cross sourcing cannot be employed.

To understand the intuition, suppose that α is low enough and only $(V,N)_c$ and $(V,R)_c$ can arise in the equilibrium (This is true when $\beta < \alpha \leq \frac{4\beta^2 w(2p-w)(2c_r-p)}{(p-w)(4c_r-w)(4c_r+4\beta p-(2\beta+1)w)}$, or $\frac{4\beta^2 w(2p-w)(2c_r-p)}{(p-w)(4c_r-w)(4c_r+4\beta p-(2\beta+1)w)} < \alpha \leq \alpha_1$ and $f < f_1$). In this case, as externality α increases, the wholesale price that firm B is willing to accept decreases if firm A does not comply with the law, i.e., $\frac{dw_c}{d\alpha} < 0$. This is because firm B becomes less concerned about the spillover from firm A's irresponsible behavior. However, when firm A is responsible, firm B does not face any externality threat, and hence, increasing externality does not affect the wholesale price under $(V,R)_c$ equilibrium. This causes $(V,R)_c$ region expand, and $(V,N)_c$ region to shrink.

On the other hand, when externality is strongly positive, firms prefers to capture the defecting consumers from their competitors in the event of a violation detection. As a result, cross sourcing becomes less valuable for both firms, and $(V,R)_c$ region shrinks.

4.6 Conclusion

Globalization has led many firms to outsource their production to emerging economies. Sourcing from emerging economies may have direct cost benefits. However, this cost benefit may come in the expense of corporate social responsibility (CSR). CSR violation hurts the brand image of a company and may reduce its market size. CSR violation may also affect the companies that have nothing to do with the company where the violation is found. This effect can be positive or negative. If the consumers believes that the violation is prevalent in the industry, it would be negative. Otherwise, if they conclude that the violation is specific to a firm, the effect would be positive because more consumer would prefer to buy from trustworthy company. In some cases, the only way to prevent these CSR violations and their impact on demand is to vertically integrate with your supplier. We research these different dynamics to see when firms vertically integrate to prevent/benefit from industry-wide CSR violations.

Our results indicate that whether governments and NGOs should be more aggressive against the firms depends on the externality and viability of the cross sourcing. When cross sourcing is not a viable strategy, medium probability of detection leads firms with vertical integration capability to comply with the law. However, higher or lower probability of detection may lead to irresponsible behavior. On the other hand, when cross sourcing is a viable strategy higher probability of detection always incentivize behaviors that are more aligned with social responsibility.

We also shed a light on how governments and NGOs should design their announcements of violations to incentivize higher levels of compliance by the firms. We show that when cross sourcing cannot be employed, announcements should highlight the firms with presumably responsible practices. As the externality increases, capable firms are more likely to adopt responsible practices. On the other hand when cross sourcing may be used by the firm, strongly positive externality may lead to less responsible behaviors.

APPENDIX A

COMPETITIVE QUALITY CHOICE AND REMANUFACTURING

In this section, we present additional results and proofs for Chapter 2

A.1 Benchmarks

A.1.1 Monopoly No-Remanufacturing (NR) Benchmark

The *monopoly no-remanufacturing benchmark* considers a monopolist OEM who only sells the new product. The OEM decides on the quality and quantity of its product by solving the following problem

$$\max_{q_n, s} \ \pi_{OEM}(q_n, s) = [s(1-q_n) - \beta s^2]q_n$$
$$s.t \ \ q_n, s \geq 0$$

Firstly, notice that, for $s \geq \frac{1}{\beta}$, the profit function is negative. Hence, the optimum quality satisfies $s < \frac{1}{\beta}$. $\frac{\partial^2 \pi_{OEM}}{\partial q_n^2} = -2s < 0$. Hence, it is concave in q_n and the optimum is $q_n^*(s) = \frac{1}{2}(1 - s\beta)$. If we plug this into the profit function, we have $\pi_{OEM}(s) = \frac{1}{4}s(-1+s\beta)^2$. This function is unimodal for $s < \frac{1}{\beta}$ and has its maximum at $s^* = \frac{1}{3\beta}$. Hence, $q_n^* = \frac{1}{3}$ and $\pi_{OEM}^* = \frac{1}{27\beta}$. From the optimal quality and the new product quantity, it can be found that consumer surplus is $\frac{1}{54\beta}$ and the social surplus is $\frac{1}{18\beta}$ for the no-remanufacturing benchmark. $\square$

A.1.2 Monopoly Remanufacturing Benchmark

The *monopoly remanufacturing benchmark* considers a monopolist OEM who may sell both the new product and the remanufactured products. The OEM decides on the quality of the new products and the quantity of new and remanufactured products by solving the following problem

$$\max_{q_n,q_r,s} \quad \pi_{OEM}(q_n,q_r,s) = [s(1-q_n-\delta q_r)-\beta s^2]q_n + [\delta s(1-q_n-q_r)-\alpha\beta s^2]q_r$$

$$s.t \quad q_n, s \geq 0$$

$$q_n \geq q_r \geq 0$$

We first optimize for q_n and q_r. In this case, the Hessian of π_{OEM} is $\begin{pmatrix} -2s & -2s\delta \\ -2s\delta & -2s\delta \end{pmatrix}$. Hence, it is jointly concave in q_n and q_r. From the first order conditions, it is straightforward to show that the interior solution is $q_r = \frac{\beta s(\delta-\alpha)}{2(1-\delta)\delta}$ and $q_n = \frac{\beta s(\alpha-1)+1-\delta}{2(1-\delta)}$. It can be seen that, $q_r \leq 0$ if and only if $\alpha \geq \delta$; therefore, the OEM does not remanufacture for $\frac{\alpha}{\delta} \geq 1$ and remanufactures otherwise. If it does not remanufacture, all the decisions are same as in the no-remanufacturing benchmark. From $0 < q_r < q_n$, this case applies if $s < \frac{\delta(-1+\delta)}{\beta(\alpha-2\delta+\alpha\delta)} \triangleq s_0$. Similarly, if the core constraint binds, $q_n = q_r = \frac{1+\delta-\beta s(1+\alpha)}{2(1+3\delta)}$ and this case applies if $s \geq s_0$. It is easy to see that in equilibrium $s < \frac{1+\delta}{\beta(1+\alpha)}$. Now we can optimize for quality. For $\frac{\alpha}{\delta} < 1$, the profit, as a function of s ($\pi_{OEM}(s)$), is a piecewise function and changes characteristic at s_0. $\pi_{OEM}(s)$ is continuous at s_0. It can be shown that for $s \geq s_0$, π_{OEM} is a unimodal function and has only one maximizer at $s = \frac{1+\delta}{3(1+\alpha)\beta}$. Similarly, π_{OEM} is either unimodal or an increasing function for $s < s_0$. If it is unimodal, maximizer is $s = -\frac{-2\delta+2\delta^2+\sqrt{(-1+\delta)\delta(3\alpha^2-6\alpha\delta+\delta(-1+4\delta))}}{3\beta(\alpha^2+\delta-2\alpha\delta)} \triangleq s_1$. Using these, it can be shown that if $0 < \frac{\alpha}{\delta} \leq \frac{1-5\delta}{2\delta^2-5\delta-1}$, the core constraint binds and $s^* = \frac{1+\delta}{3(1+\alpha)\beta}$, $q_n^* = q_r^* = \frac{1+\delta}{3(1+3\delta)}$. Note that, in this case optimum quality is higher than the NR benchmark. On the other hand if $\frac{1-5\delta}{2\delta^2-5\delta-1} < \frac{\alpha}{\delta} < 1$, the core constraint does not bind and the optimum solution is $s^* = s_1$, $q_r^* = \frac{\beta s^*(\delta-\alpha)}{2(1-\delta)\delta}$ and $q_n^* = \frac{\beta s^*(\alpha-1)+1-\delta}{2(1-\delta)}$. Similar to the previous case, it can be shown that optimal quality is higher than the NR benchmark.

For this model, by some algebra it can be shown that $CS = \pi_{OEM}/2$. Hence, if the profit increases, CS and SS increase as well and vice-versa. Notice that, under remanufacturing, profit cannot be lower than the no-remanufacturing case. Hence, CS and SS is more than or equal to no-remanufacturing.

Following proposition states the effect of OEM remanufacturing on environment by comparing it to the NR benchmark.

Region	Condition	q_n^*	q_r^*
$R1^{exo}$	$\frac{\alpha}{\delta} \geq \frac{1+\beta s_f}{2\beta s_f}$	$\frac{1-\beta s_f}{2}$	0
$R3^{exo}$	$\frac{\left(3\beta s_f-1+\delta\right)}{(2+\delta)\beta s_f} < \frac{\alpha}{\delta} < \frac{1+\beta s_f}{2\beta s_f}$	$\frac{2-\delta+\beta s_f(\alpha-2)}{4-\delta}$	$\frac{\delta+\beta s_f(\delta-2\alpha)}{\delta(4-\delta)}$
$R4^{exo}$	$0 < \frac{\alpha}{\delta} \leq \frac{\left(3\beta s_f-1+\delta\right)}{(2+\delta)\beta s_f}$	$\frac{1-\beta s_f}{(2+\delta)}$	$\frac{1-\beta s_f}{(2+\delta)}$

Table A.1: Equilibrium when product quality is exogenously given

Proposition 22. *The following compares environmental impact of the monopoly remanufacturing benchmark to the NR benchmark.*

- *When the OEM does not remanufacture, the environmental impact is the same as the NR benchmark level.*
- *When the OEM remanufactures but does not remanufacture all available cores, the environmental impact is lower than the NR benchmark level if and only if* $\frac{e}{E} < \frac{(-1+3\alpha-2\delta)\delta}{3(\alpha-\delta)} + \frac{\sqrt{(-1+\delta)\delta(3\alpha^2-6\alpha\delta+\delta(-1+4\delta))}}{3(\alpha-\delta)} \triangleq r^m$.
- *When the OEM remanufactures all available cores, the environmental impact is lower than the NR benchmark level if and only if* $\frac{e}{E} < \frac{2\delta}{1+\delta}$.

When the OEM remanufactures maximum $\frac{e}{E}$ *ratios below which remanufacturing improves environmental impact stated in this Proposition is always higher than that of the base model stated in Proposition 5.*

A.1.3 Exogenous Quality Benchmark

In the *exogenous quality benchmark*, the OEM sells the new product and the IR sells the remanufactured product, but the quality level is fixed at s_f. In this case, the OEM's optimization problem is $\max_{q_n} \pi_{OEM}\left(q_n|s_f\right)$ and that of the IR is $\max_{q_r} \pi_{IR}(q_r|s_f)$ subject to the feasibility constraints. Table A.1 describes the equilibrium of this benchmark. In the proof of proposition 1, we first solve the quantity game for a given quality level. Hence, proof of the exogenous quality benchmark is included in there. □

A.2 Consumer and Social Welfare Results for Extensions to the Base Model

Preemptive Collection

In this section, we study CS and SS when the OEM can collect and dispose of the used cores to compete with the IR. Figure A.1 is a representative illustration of the resulting CS and SS levels from our numerical study.

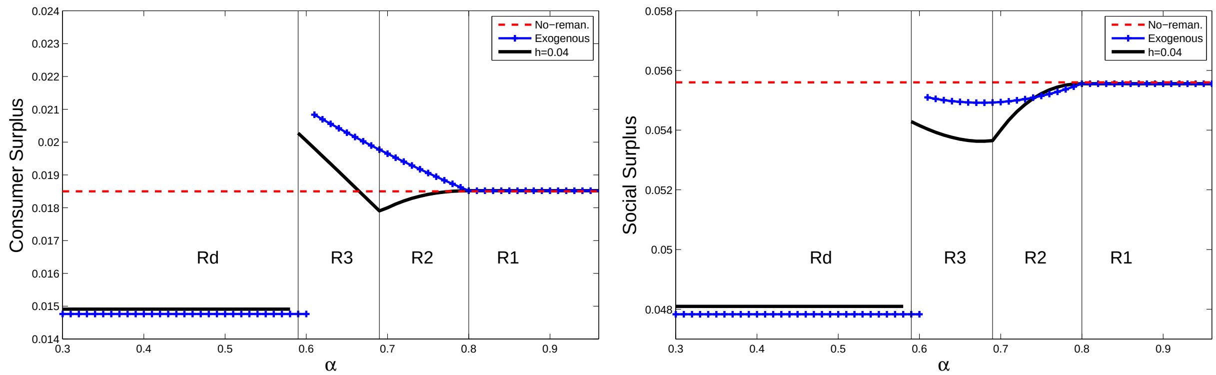
When the cost-to-value ratio $\frac{\alpha}{\delta}$ is high $(0.59 < \alpha < 1)$, the OEM does not preemptively collect cores and the equilibrium decisions are similar to those in the base model. Hence, same as in our base model, the IR's threat and actual entry can decrease the CS and the SS compared to NR benchmark.

When the cost-to-value ratio is low $(0 < \alpha \leq 0.59)$, the IR is a bigger threat and the OEM relies on preemptive collection as a competitive strategy. The OEM decreases its total new product quantity and collects all cores to deter the IR's entry. This strategy decreases the CS and SS significantly compared to NR benchmark. This result is also consistent with our base model where we show that entry deterrence reduces both CS and SS.

In the exogenous quality benchmark, new product quality is kept at the NR benchmark quality disregarding the OEM's quality response to the IR's threat as before. Figure A.1 shows that when the OEM does not use preemptive collection strategy and the IR remanufactures (i.e, cost-to-value ratio is high), the CS and SS are lower than the exogenous quality benchmark as in the base model. However, when the OEM collects and disposes all available cores to deter the IR's entry (i.e, cost-to-value ratio is low), the CS and SS are higher than the exogenous benchmark with a small margin. The reason is as follows: In this case, the OEM mainly relies on collection of used cores to deter the IR's entry. Having additional lever quality allows the OEM to use collection strategy more efficiently in terms of the consumer surplus and firm's profits. Hence the CS and SS are higher than the exogenous quality benchmark.

A.3 Price Competition

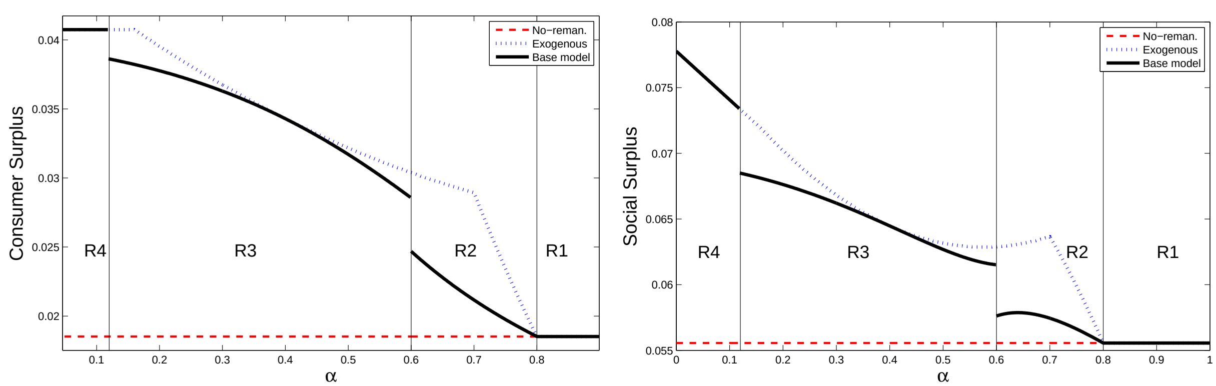
Figure A.2 demonstrates our findings. It is well known that price competition leads to a more intense competition and a higher CS and SS than quantity competition (Singh and Vives,



(a) Consumer Surplus (b) Social Surplus

Figure A.1: Comparison of Consumer and Social Surplus with NR and Exogenous Quality Benchmarks when the OEM can collect and dispose used cores ($\alpha = 0.4, \beta = 1$ and Exogenous quality $s_f = \frac{1}{3\beta}$)

1994). Consistent with this fact, Figure A.2 shows that CS and SS are higher than the NR benchmark when the OEM and the IR compete in prices. The Figure also illustrates that CS and SS are lower than the exogenous quality benchmark (with NR benchmark quality). Thus, similar to our base model, ignoring the OEM's quality decision leads to overestimating the benefits of remanufacturing for social welfare.



(a) Consumer Surplus (b) Social Surplus

Figure A.2: Comparison of Consumer and Social Surplus in Price competition with NR and Exogenous Quality Benchmarks ($\delta = 0.4, \beta = 1$ and Exogenous quality $s_f = \frac{1}{3\beta}$)

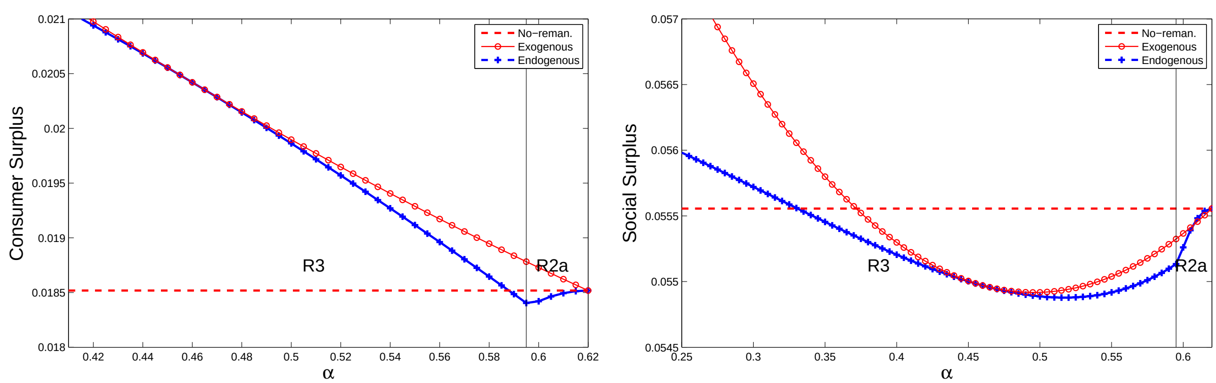
A.4 Alternative Remanufacturing Cost

In this section we study the CS and SS when the IR incurs an additional cost n independent of the product quality level.

Since the IR's total unit remanufacturing cost is now $\beta\alpha s^2 + n$, IR's competitive position depends not only on the ratio $\frac{\alpha}{\delta}$ (as in the base model) but also on the quality-independent cost component n. Specifically, the IR's competitive position is strong when $\frac{\alpha}{\delta}$ and n are simultaneously low.

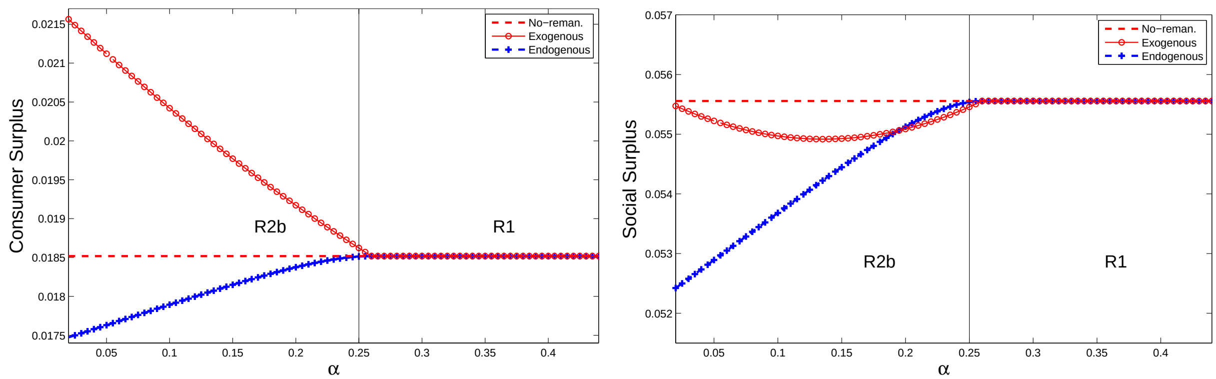
In the base model we showed that when the IR's competitive position is strong enough, the CS and SS are always higher than the NR benchmark levels. Otherwise, the CS and SS are lower than the NR benchmark levels (see Propositions 3 and 4). Figures A.3 and A.4 illustrate that these results continue to hold in the presence of an additional quality-independent cost component n. In Figure A.3, n is low ($n = 0.02$). On the same figure, when $\frac{\alpha}{\delta}$ is also low (Given $\delta = 0.4$, $0 < \alpha < 0.59$ for CS and $0 < \alpha < 0.34$ for SS), the IR is strong and the CS and the SS are above the NR benchmark levels. On the other hand when n is high ($n = 0.06$) as in Figure A.4 or $\frac{\alpha}{\delta}$ is high (Given $\delta = 0.4$, $\alpha \geq 0.59$ for CS and $\alpha \geq 0.34$ for SS) as in Figure A.3, the IR is weak and the CS and SS are always lower than the NR benchmark case.

The Figures also illustrate that ignoring the OEM's quality decision may result in overestimating remanufacturing benefits, since the CS and the SS in exogenous benchmark is always higher than that of endogenous quality model when the IR remanufactures.



(a) Consumer Surplus (b) Social Surplus

Figure A.3: Comparison of Consumer and Social Surplus with NR and Exogenous Quality Benchmarks in the presence of quality independent remanufacturing cost ($\delta = 0.4, \beta = 1, n = 0.02$ and Exogenous quality $s_f = \frac{1}{3\beta}$)



(a) Consumer Surplus

(b) Social Surplus

Figure A.4: Comparison of Consumer and Social Surplus with NR and Exogenous Quality Benchmarks in the presence of quality independent remanufacturing cost ($\delta = 0.4, \beta = 1, n = 0.06$ and Exogenous quality $s_f = \frac{1}{3\beta}$)

A.5 Independent Quality Gap

In this section we study CS and SS when the quality gap between the new and remanufactured product is independent of product quality.

Figure A.5 illustrates that all the insights we derived from the base model continue to hold for this extension. More specifically, the CS and SS can decrease compared to the NR benchmark when the OEM deters the IR's entry or when a weak IR (high ϕ) enters the market. To achieve a higher CS than the NR benchmark, the IR needs to be strong (small ϕ).

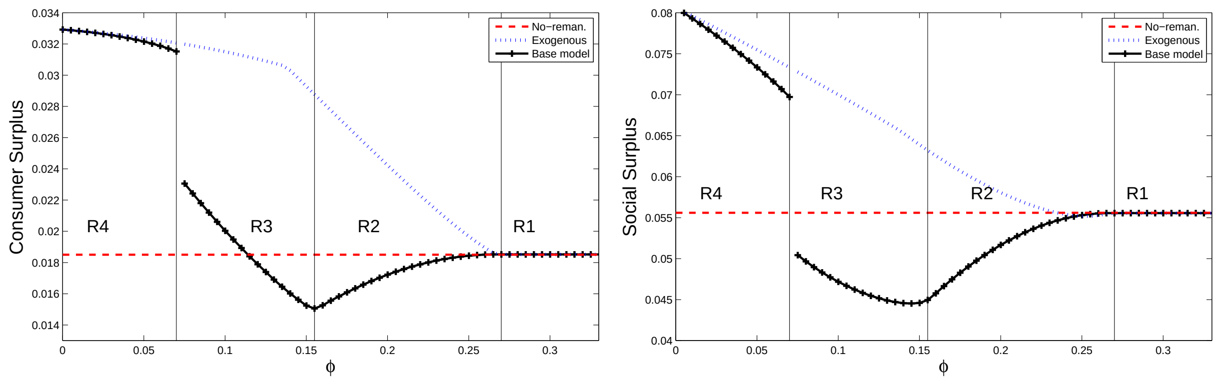
In the exogenous quality benchmark, the Figure shows that, as opposed to endogenous quality, independent of the IR's competitive position remanufacturing always increases CS. And SS in endogenous quality model is always lower than the exogenous quality benchmark when the IR remanufactures. These results are same as those derived in the base model.

A.6 Proofs

Proof of Proposition 1

Given s and q_r, $\frac{\partial^2 \pi_{OEM}}{\partial q_n^2} = -2s < 0$. Hence, it is concave in q_n and the optimum[1] is $q_n^*(s) = \frac{1}{2}(1 - \beta s - q_r\delta)$. This is positive if and only if $q_r < \frac{1-\beta s}{\delta}$ and $s < \frac{1}{\beta}$. Therefore,

[1]It is straightforward to show that $q_n = 0$ can never be an equilibrium; therefore, we do not consider this case.



(a) Consumer Surplus (b) Social Surplus

Figure A.5: Comparison of Consumer and Social Surplus with NR and Exogenous Quality Benchmarks when the perceptual quality gap is independent of new product quality ($\alpha = 0.4, \beta = 1$ and Exogenous quality $s_f = \frac{1}{3\beta}$)

equilibrium quality satisfies $s < \frac{1}{\beta}$. For the IR, $\frac{\partial^2 \pi_{IR}}{\partial q_r^2} = -2\delta s < 0$ and interior solution is $q_r^i \triangleq \frac{-\beta\alpha s+\delta-q_n\delta}{2\delta}$. Thus, there can be three cases:

1. If $q_r^i \leq 0$, then $q_r^* = 0$.

   In this case $q_n^* = \frac{1-\beta s}{2}$ and from $q_r^i = \frac{-\beta\alpha s+\delta-q_n^*\delta}{2\delta} \leq 0$ and $q_n^* > 0$, we have $\frac{\alpha}{\delta} \geq \frac{(1+\beta s)}{2\beta s}$ ($\equiv s \geq \frac{\delta}{\beta(2\alpha-\delta)}$) and $\alpha > \delta$.

2. If $0 < q_r^i < q_n$, then $q_r^* = q_r^i$.

   By solving $q_r = q_r^i$ and $q_n = \frac{1}{2}(1 - s\beta - q_r\delta)$, we obtain $q_n^* = \frac{2-\delta+\beta s(\alpha-2)}{4-\delta}$ and $q_r^* = \frac{\delta+s\beta(\delta-2\alpha)}{(4-\delta)\delta}$. From the condition $0 < q_r^* < q_n^*$, we have $\frac{\alpha}{\delta} > \frac{\delta(3\beta s-1+\delta)}{(2+\delta)\beta s}$ ($\equiv s < \frac{(-1+\delta)\delta}{\beta(2\alpha+\alpha\delta-3\delta)}$) for $\alpha < \delta$, and $\frac{\alpha}{\delta} < \frac{(1+\beta s)}{2\beta s}$ ($\equiv s < \frac{\delta}{\beta(2\alpha-\delta)}$) for $\alpha \geq \delta$.

3. If $q_n \leq q_r^i$, then $q_r^* = q_n$.

   In this case $q_r^* = q_n^* = \frac{1-\beta s}{2+\delta}$ and from $q_r^i \geq q_n^* > 0$, we have $\frac{\alpha}{\delta} \leq \frac{\delta(3\beta s-1+\delta)}{(2+\delta)\beta s}$($\equiv s \geq \frac{(-1+\delta)\delta}{\beta(2\alpha+\alpha\delta-3\delta)}$) and $\alpha < \delta$.

For the exogenous quality benchmark, by considering $\alpha \to \delta$, $\delta \to 0$ for $\alpha \geq \delta$ and $\delta \to 1$ for $\alpha < \delta$, it can be shown that all these three cases exist for any $s < \frac{1}{\beta}$.

Now, we proceed for the solution of the equilibrium quality. From the quantity game equilibrium, if $\alpha > \delta$ and $s < \frac{\delta}{\beta(2\alpha-\delta)}$, then $q_r^* = q_r^i$. On the other hand, if $\alpha > \delta$ and $s \geq \frac{\delta}{\beta(2\alpha-\delta)}$, then $q_r^* = 0$. This means that for $\alpha > \delta$, the profit function is a piecewise function and changes characteristic at $s_0 \triangleq \frac{\delta}{\beta(2\alpha-\delta)}$. We define $\pi_1 \triangleq \pi_{OEM}(s \geq s_0)$ and

$\pi_2 \triangleq \pi_{OEM}(s < s_0)$. $\pi_{OEM}(s)$ is continuous at s_0, i.e $\pi_1(s_0) = \pi_2(s_0)$. π_2 can be written as $sq_{n_2}^2$ where $q_{n_2} \triangleq \frac{2-\delta+\beta s(\alpha-2)}{4-\delta}$. π_2 has one root at $s = 0$ and two roots at $s = \frac{2-\delta}{(2-\alpha)\beta}$ and it is positive between these roots. Since $\alpha > \delta$, $\frac{2-\delta}{(2-\alpha)\beta} > \frac{1}{\beta}$. $\frac{\partial \pi_2}{\partial s}$ has roots at $s = \frac{2-\delta}{(2-\alpha)\beta}$ and at $s = \frac{2-\delta}{3(2-\alpha)\beta}$. One of these roots ($s = \frac{2-\delta}{(2-\alpha)\beta}$) is same as the roots of π_2 and the other one satisfies $\frac{1}{\beta} > \frac{2-\delta}{3(2-\alpha)\beta} > 0$. Thus, for $s < \frac{1}{\beta}$, π_2 is unimodal and the maximizer is $s = \frac{2-\delta}{3(2-\alpha)\beta}$. Similarly, we can write $\pi_1 = s\left(\frac{1-\beta s}{2}\right)^2$ and show that this is unimodal for $s < \frac{1}{\beta}$ with a unique maximizer at $s = \frac{1}{3\beta}$. By checking the derivatives of π_1 and π_2 at the boundary s_0, we can determine where s^*, the maximizer of the profit function, is. For $\frac{\partial \pi_1}{\partial s}|_{s=s_0} \geq 0$ and $\frac{\partial \pi_2}{\partial s}|_{s=s_0} \geq 0$, the optimum s^* is in the region $s \geq s_0$ and it is $s^* = \frac{1}{3\beta}$. We can show that these inequalities are satisfied if and only if $\frac{\alpha}{\delta} \geq 2$. Therefore, for $\frac{\alpha}{\delta} \geq 2$, we have $s^* = \frac{1}{3\beta}$, $q_n^* = \frac{1}{3}$ and $q_r^* = 0$. Recall that, these are the no-remanufacturing benchmark optimum quality and quantities. For $\frac{\partial \pi_1}{\partial s}|_{s=s_0} < 0$ and $\frac{\partial \pi_2}{\partial s}|_{s=s_0} \geq 0$, the optimum s^* is at the boundary s_0. Similar to the previous case, inequalities are satisfied if and only if $\frac{8-\delta}{4+\delta} \leq \frac{\alpha}{\delta} < 2$. For this case we have $s^* = \frac{\delta}{\beta(2\alpha-\delta)}$, $q_n^* = \frac{2(2-\delta)}{3(4-\delta)}$ and $q_r^* = 0$. Hence, the OEM deters the IR's entry in this region. For $\frac{\partial \pi_1}{\partial s}|_{s=s_0} \leq 0$ and $\frac{\partial \pi_2}{\partial s}|_{s=s_0} < 0$, the optimum s^* is in the region $s < s_0$ and it is $\frac{2-\delta}{3(2-\alpha)\beta}$. The inequalities are satisfied if and only if $\frac{8-\delta}{4+\delta} > \frac{\alpha}{\delta} > 1$. For this case we have $s^* = \frac{2-\delta}{3(2-\alpha)\beta}$, $q_n^* = \frac{2(2-\delta)}{3(4-\delta)}$ and $q_r^* = \frac{(8-\delta)\delta-\alpha(4+\delta)}{3(2-\alpha)(4-\delta)\delta}$. Hence, the IR enters and collects a portion of the available cores. It is straightforward to show that $\frac{\partial \pi_1}{\partial s} > 0$ and $\frac{\partial \pi_2}{\partial s} < 0$ is infeasible.

For $\alpha = \delta$, from the quantity game equilibrium, only $q_n > 0$ and $q_n > q_r > 0$ applies. Hence, the equilibrium quality and the quantities are the same as the equilibrium outcome in region $\frac{8-\delta}{4+\delta} > \frac{\alpha}{\delta} > 1$.

For $\alpha < \delta$, from the equilibrium of the quantity game, $q_r^* > 0$ is always true. The core availability constraint may or may not bind depending on s. If $s < \frac{\delta(-1+\delta)}{\beta(2\alpha-3\delta+\alpha\delta)} \triangleq s_1$, then $0 < q_r^* < q_n^*$ and if $s \geq s_1$, then $q_r^* = q_n^*$ (see the quantity game equilibrium.). We define $\pi_3 \triangleq \pi_{OEM}(s \geq s_1)$ and $\pi_2 \triangleq \pi_{OEM}(s < s_1)$ (essentially this is the same function as π_2 defined for $\alpha > \delta$). $\pi_{OEM}(s)$ is continuous at $s = s_1$, i.e $\pi_2(s_1) = \pi_3(s_1)$. Before we look at how π_2 and π_3 behave at the boundary $s = s_1$, we first show that π_3 has only one maximizer in the region of interest, $s \in (0, \frac{1}{\beta})$. π_3 can be written as $s\left(\frac{1-\beta s}{2+\delta}\right)^2$, which has one root at $s = 0$ and two roots at $s = \frac{1}{\beta}$. Similar to π_1, for $s < \frac{1}{\beta}$, π_3 is unimodal and has one maximizer at $s = \frac{1}{3\beta}$. If $\frac{\partial \pi_2}{\partial s}|_{s=s_1} < 0$ and $\frac{\partial \pi_3}{\partial s}|_{s=s_1} \leq 0$, the optimum quality is in $s < s_1$ and it is $s^* = \frac{2-\delta}{3(2-\alpha)\beta}$. The inequalities hold if and only if $\frac{3\delta^2}{2+\delta} \leq \alpha < \delta$. In this case, the equilibrium quality and quantities are $s^* = \frac{2-\delta}{3(2-\alpha)\beta}$, $q_n^* = \frac{2(2-\delta)}{3(4-\delta)}$ and $q_r^* = \frac{(8-\delta)\delta-\alpha(4+\delta)}{3(2-\alpha)(4-\delta)\delta}$. It is easy to show that $\frac{\partial \pi_2}{\partial s}|_{s=s_1} >= 0$ and $\frac{\partial \pi_3}{\partial s}|_{s=s_1} < 0$ is infeasible. Therefore, s_1 can never be an optimum. If $\frac{\partial \pi_2}{\partial s}|_{s=s_1} \geq 0$ and $\frac{\partial \pi_3}{\partial s}|_{s=s_1} \geq 0$, the optimum quality is in $s > s_1$ and it is $s^* = \frac{1}{3\beta}$. Inequalities are satisfied if and only if $\alpha \leq \frac{3\delta^2}{4-3\delta+2\delta^2}$. In this case, $q_n^* = \frac{2}{3(2+\delta)} = q_r^*$. If $\frac{\partial \pi_2}{\partial s}|_{s=s_1} < 0$ and $\frac{\partial \pi_3}{\partial s}|_{s=s_1} > 0$, we need to compare the profit function's values at $s = \frac{1}{3\beta}$ and $s = \frac{2-\delta}{3(2-\alpha)\beta}$. Inequalities are satisfied if and only if $\frac{3\delta^2}{4-3\delta+2\delta^2} < \alpha < \frac{3\delta^2}{2+\delta}$. $\pi_2(s = \frac{2-\delta}{3\beta(2-\alpha)}) - \pi_3(s = \frac{1}{3\beta}) = -\frac{4\left(\alpha(-4+\delta)^2-\delta^2\left(18-8\delta-2\delta^2+\delta^3\right)\right)}{27(-2+\alpha)\beta(-4+\delta)^2(2+\delta)^2}$ and it is positive for this region if and only if $\frac{\delta(18-8\delta-2\delta^2+\delta^3)}{(4-\delta)^2} < \frac{\alpha}{\delta} < \frac{3\delta}{2+\delta}$. If we combine this case with the previous cases we can conclude that if $0 < \frac{\alpha}{\delta} \leq \frac{\delta(18-8\delta^2-2\delta^3+\delta^4)}{(4-\delta)^2}$, then $s^* = \frac{1}{3\beta}$, $q_n^* = q_r^* = \frac{2}{3\beta(2+\delta)}$. If $\frac{\delta(18-8\delta^2-2\delta^3+\delta^4)}{(4-\delta)^2} < \frac{\alpha}{\delta} < \frac{8-\delta}{4+\delta}$, then $s^* = \frac{2-\delta}{3(2-\alpha)\beta}$, $q_n^* = \frac{2(2-\delta)}{3(4-\delta)}$, $q_r^* = \frac{(8-\delta)\delta-\alpha(4+\delta)}{3(2-\alpha)(4-\delta)\delta}$.□

Proof of Proposition 2

In $R3^{exo}$, where the IR enters and the core constraint does not bind, consumer surplus is $CS_3^{exo} \triangleq \frac{s_f\left(4+\delta-\delta^2\right)}{2(-4+\delta)^2} - \frac{s_f^2\beta\left(4-2\alpha(-2+\delta)-3\delta+\delta^2\right)}{(-4+\delta)^2} + \frac{s_f^3\beta^2\left(\alpha^2(4-3\delta)+(4-3\delta)\delta+2\alpha\delta^2\right)}{2(-4+\delta)^2\delta}$. If the OEM is monopoly without remanufacturing, consumer surplus is $CS_m^{exo} = \frac{s_f}{8} - \frac{s_f^2\beta}{4} + \frac{s_f^3\beta^2}{8}$. $\Delta = CS_3^{exo} - CS_m^{exo} = -\frac{s_f\delta(-12+5\delta)}{8(-4+\delta)^2} - \frac{s_f^3\beta^2\left(-8\alpha\delta^2+\delta^2(4+\delta)+4\alpha^2(-4+3\delta)\right)}{8(-4+\delta)^2\delta} - \frac{s_f^2\beta(-8\alpha(-2+\delta)+\delta(-4+3\delta))}{4(-4+\delta)^2}$. Δ has three roots for s_f: $\{0, \frac{\delta}{\beta(2\alpha-\delta)}, \frac{\delta(12-5\delta)}{\beta(8\alpha+4\delta-6\alpha\delta+\delta^2)}\}$. In Δ, coefficient of s_f^3 is positive for $\frac{\delta}{2} < \alpha < 1$, and $\frac{\delta(12-5\delta)}{\beta(8\alpha+4\delta-6\alpha\delta+\delta^2)} \geq \frac{\delta}{\beta(2\alpha-\delta)}$ for $\alpha \geq \delta$. Recall that for the exogenous quality model, the condition for $R3^{exo}$ (where the IR enters and the core constraint does not bind) is $s_f < \frac{\delta}{\beta(2\alpha-\delta)}$ if $\alpha \geq \delta$. Therefore if $\alpha \geq \delta$, $\Delta > 0$. If $\alpha < \delta$, the condition for $R3^{exo}$ is $s_f < \frac{(-1+\delta)\delta}{\beta(2\alpha-3\delta+\alpha\delta)}$. If $\frac{\delta}{2} < \alpha < \delta$, it is easy to show that $\frac{(-1+\delta)\delta}{\beta(2\alpha-3\delta+\alpha\delta)} < \frac{\delta(12-5\delta)}{\beta(8\alpha+4\delta-6\alpha\delta+\delta^2)} < \frac{\delta}{\beta(2\alpha-\delta)}$. Then if $\frac{\delta}{2} < \alpha < \delta$, $\Delta > 0$. If $0 < \alpha < \frac{\delta}{2}$, then $\frac{\delta(12-5\delta)}{\beta(8\alpha+4\delta-6\alpha\delta+\delta^2)} > \frac{(-1+\delta)\delta}{\beta(2\alpha-3\delta+\alpha\delta)} > 0 > \frac{\delta}{\beta(2\alpha-\delta)}$ and the coefficient of s_f^3 is negative, therefore $\Delta > 0$. Finally, for $\alpha = \frac{\delta}{2}$, Δ is a second order polynomial of s_f and roots are $\{0, \frac{12-5\delta}{2\beta(4-\delta)}\}$. For $\alpha = \frac{\delta}{2}$, $0 < \frac{(-1+\delta)\delta}{\beta(2\alpha-3\delta+\alpha\delta)} < \frac{12-5\delta}{2\beta(4-\delta)}$ and the coefficient of s_f^2 is negative; hence, $\Delta > 0$.

If the IR enters and the core constraint binds, $CS_4^{exo} \triangleq \frac{s_f(1+3\delta)}{2(2+\delta)^2} - \frac{s_f^2\beta(1+3\delta)}{(2+\delta)^2} + \frac{s_f^3\beta^2(1+3\delta)}{2(2+\delta)^2}$ and $CS_4^{exo} - CS_m^{exo} = \frac{s_f(-1+s_f\beta)^2(8-\delta)\delta}{8(2+\delta)^2}$ and this is always positive.□

Proof of Proposition 3

In $R2$, since the IR cannot enter, and the OEM acts like a monopoly without remanufacturing, consumer surplus is same as the NR benchmark.

Consumer surplus in $R2$ is $CS_2 \triangleq \frac{(\alpha-\delta)^2\delta}{2\beta(2\alpha-\delta)^3}$ and consumer surplus for the NR benchmark is $CS_m \triangleq \frac{1}{54\beta}$. $CS_2 - CS_m = -\frac{(8\alpha-7\delta)(\alpha-2\delta)^2}{54\beta(2\alpha-\delta)^3}$ and this is always negative for $\alpha > \delta$.

For $R3$, consumer surplus is $CS_3 \triangleq (-2+\delta)\left(-\frac{2(-2+\delta)\left(-4+6\alpha-6\delta+\delta^2\right)}{27(-2+\alpha)^2\beta(-4+\delta)^2} + \frac{((-8+\delta)\delta+\alpha(4+\delta))^2}{54(-2+\alpha)^3\beta(-4+\delta)^2\delta}\right)$. We show that CS_3 at $\alpha = \delta$ is greater than CS_m and CS_3 at $\alpha = \frac{(8-\delta)\delta}{4+\delta}$ is smaller than the CS_m. Then, we show that in $R3$, CS_3 is always decreasing in α which proves that there exists a critical α_c satisfying $\delta < \alpha_c < \frac{\delta(8-\delta)}{4+\delta}$ such that $CS_3 > CS_m$ if and only if $\alpha < \alpha_c$ in $R3$. $CS_3|_{\alpha=\delta} = \frac{(12-5\delta)\delta}{54\beta(-4+\delta)^2}$ and it is always positive. Similarly, $CS_3\big|_{\alpha=\frac{\delta(8-\delta)}{(4+\delta)}} = \frac{(12-5\delta)\delta^2}{54\beta(-4+\delta)^3}$ and it is always negative. $\frac{\partial CS_3}{\partial\alpha} = \frac{\alpha^2(-2+\delta)\left(-16-56\delta+23\delta^2\right)}{54(-2+\alpha)^4\beta(-4+\delta)^2\delta} + \frac{(-2+\delta)\left(192-400\delta+172\delta^2-19\delta^3\right)}{54(-2+\alpha)^4\beta(-4+\delta)^2} + \frac{2\alpha(-2+\delta)\left(-16+40\delta+19\delta^2-17\delta^3+2\delta^4\right)}{27(-2+\alpha)^4\beta(-4+\delta)^2\delta}$ and we want to show that this is negative. This expression is negative if and only if $q \triangleq \alpha^2\left(16+56\delta-23\delta^2\right) + \delta\left(-192+400\delta-172\delta^2+19\delta^3\right) - 4\alpha\left(-16+40\delta+19\delta^2-17\delta^3+2\delta^4\right) < 0$. q has two roots with respect α, i.e $\alpha_1 = \frac{x-\sqrt{y}}{z}$ and $\alpha_2 = \frac{x+\sqrt{y}}{z}$, where $x \triangleq -2\left(-16+40\delta+19\delta^2-17\delta^3+2\delta^4\right)$, $y \triangleq (-4+\delta)^2(-2+\delta)^2(16-8\delta+105\delta^2-80\delta^3+16\delta^4)$, $z \triangleq -16-56\delta+23\delta^2$. Since $z<0$, $\alpha_2 < \alpha_1$. In $R3$, if the boundaries of α lies within α_1 and α_2, then $\frac{\partial CS_3}{\partial\alpha} < 0$. More specifically, if $\alpha_2 < \frac{\delta^2(18-8\delta-2\delta^2+\delta^3)}{(4-\delta)^2} < \alpha_1$ and $\alpha_2 < \frac{\delta(8-\delta)}{4+\delta} < \alpha_1$, then consumer surplus is decreasing in α in $R3$. By some tedious algebra, similar to the one in the proof of Proposition 4 (skipped here), it can be shown that this is indeed the case. Therefore, CS_3 is decreasing in α. Therefore, $CS_3 = CS_m$ has a unique solution in $R3$ and it is defined as α_c. Once we show that in $R4$, consumer surplus is always higher than the NR benchmark, this proves the existence of α_c satisfying $1 < \frac{\alpha}{\delta} < \frac{8-\delta}{4+\delta}$, and consumer surplus is higher than the NR benchmark if and only if $\alpha < \alpha_c$.

For $R4$, $CS_4 \triangleq \frac{2(1+3\delta)}{27\beta(2+\delta)^2}$ and $CS_4 - CS_m = \frac{(8-\delta)\delta}{54\beta(2+\delta)^2}$ which is always positive.

α_c is only a function of δ and δ is in the bounded region $(0,1)$; therefore, we can numerically verify that the derivative of α_c with respect to δ is always positive in $R3$.

The CS in $R1$ is same as the NR benchmark. If we exclude this region, we find that CS is strictly lower than the NR benchmark for $\frac{\alpha_c}{\delta} < \frac{\alpha}{\delta} < 2$.□

Proof of Proposition 4

In $R1$, the IR cannot enter, and the OEM acts like a monopoly without remanufacturing. Hence, social surplus is same as NR benchmark.

In $R2$, social surplus is $SS_2 \triangleq \frac{3(\alpha-\delta)^2\delta}{2\beta(2\alpha-\delta)^3}$. The NR benchmark social surplus is $SS_m \triangleq \frac{1}{18\beta}$. $SS_2 - SS_m = \frac{(8\alpha-7\delta)(\alpha-2\delta)^2}{18\beta(2\alpha-\delta)^3}$ and it is easy to see that this is always positive for $\alpha > \delta$.

In $R3$, social surplus is $SS_3 \triangleq \frac{(-2+\delta)2\alpha\delta\left(-224+60\delta+3\delta^2-2\delta^3\right)}{54(-2+\alpha)^3\beta(-4+\delta)^2\delta} + \frac{(-2+\delta)\alpha^2\left(48+104\delta-53\delta^2+8\delta^3\right)}{54(-2+\alpha)^3\beta(-4+\delta)^2\delta} + \frac{(-2+\delta)\delta\left(192+128\delta-80\delta^2+11\delta^3\right)}{54(-2+\alpha)^3\beta(-4+\delta)^2\delta}$. We evaluate SS_3 at $\alpha = \delta$ and at $\alpha = \frac{\delta(8-\delta)}{4+\delta}$, and show that SS_3 is greater than SS_m at $\alpha = \delta$ and smaller than SS_m at $\alpha = \frac{\delta(8-\delta)}{4+\delta}$. Then, we show that SS_3 has a negative derivate in α, if $\delta > \frac{1}{2}$, and there exists a α' such that SS_m has a negative derivative if $\delta < \frac{1}{2}$ and $\alpha < \alpha'$ in $R3$, where $\frac{\delta(8-\delta)}{4+\delta} > \alpha' > \delta$. These imply that $SS_3 = SS_m$ has a unique solution for $\frac{\delta^2(18-8\delta-2\delta^2+\delta^3)}{(4-\delta)^2} < \alpha < \frac{\delta(8-\delta)}{4+\delta}$ (recall that these inequalities define $R3$) and are sufficient for the existence of an α_s value such that $SS_3 > SS_m$ if and only if $\alpha < \alpha_s$ in R3. $(SS_3 - SS_m)|_{\alpha=\frac{\delta(8-\delta)}{4+\delta}} = \frac{(12-5\delta)\delta^2}{18\beta(-4+\delta)^3}$ and this is negative. $(SS_3 - SS_m)|_{\alpha=\delta} = \frac{\delta(4+\delta)}{54\beta(-4+\delta)^2}$ and this is positive. $\frac{\partial SS_3}{\partial\alpha} = -\frac{(-2+\delta)\left(\alpha^2\left(48+104\delta-53\delta^2+8\delta^3\right)+\delta\left(-320+624\delta-228\delta^2+25\delta^3\right)\right.}{54(-2+\alpha)^4\beta(-4+\delta)^2\delta} + \frac{\alpha\left(192-480\delta+28\delta^2+44\delta^3-8\delta^4\right)}{54(-2+\alpha)^4\beta(-4+\delta)^2\delta}$ and denominator is always positive. Therefore we only need to consider the polynomial $p = \alpha^2\left(48+104\delta-53\delta^2+8\delta^3\right) + \delta\left(-320+624\delta-228\delta^2+25\delta^3\right) + \alpha\left(192-480\delta+28\delta^2+44\delta^3-8\delta^4\right)$. p is convex in α and has two roots α, i.e., $\alpha_1 = \frac{f-\sqrt{g}}{\eta}$ and $\alpha_2 = \frac{f+\sqrt{g}}{\eta}$ where $f = 2\left(-48+120\delta-7\delta^2-11\delta^3+2\delta^4\right)$, $g = (144-264\delta+481\delta^2-184\delta^3 +16\delta^4)(-4+\delta)^2(-2+\delta)^2$ and $\eta = (48+104\delta-53\delta^2+8\delta^3)$. Since $\eta > 0$ it can be seen that $\alpha_1 < \alpha_2$. We want to show that $\alpha_1 < \frac{\delta^2\left(18-8\delta-2\delta^2+\delta^3\right)}{(4-\delta)^2}$. This can be simplified to showing $-20480+53760\delta-50944\delta^2+9008\delta^3+13480\delta^4-5559\delta^5-1504\delta^6+1020\delta^7-32\delta^8-53\delta^9+8\delta^{10} < 0$. It can be further simplified to showing $20480-53760\delta+50944\delta^2-16929\delta^3 > 0$. It is straightforward to show that this is true for $0 < \delta < 1$. In a similar way, it can be shown that $\alpha_2 > \frac{\delta^2\left(18-8\delta-2\delta^2+\delta^3\right)}{(4-\delta)^2}$. Now, we compare α_2 with $\frac{\delta(8-\delta)}{4+\delta}$. $\alpha_2 = \frac{f+\sqrt{g}}{\eta} > \frac{\delta(8-\delta)}{4+\delta}$ if and only if $(4+\delta)\sqrt{g} > (8\delta-\delta^2)\eta - f(4+\delta)$. Both sides are positive and this inequality is equivalent to $(-2+\delta)\delta(1-2\delta)\left(48+104\delta-53\delta^2+8\delta^3\right) > 0$. It can be easily seen that this is true if and only if $\delta > \frac{1}{2}$. Then, $\alpha_2 > \frac{\delta(8-\delta)}{4+\delta}$ if and only if $\delta > \frac{1}{2}$. So far, we showed that SS_3 is always decreasing in α in $R3$ if and only if $\delta > \frac{1}{2}$, or $\delta < \frac{1}{2}$ and $\alpha < \alpha_2$. Since $(SS_3 - SS_m)|_{\alpha=\frac{\delta(8-\delta)}{4+\delta}} < 0$ and $(SS_3 - SS_m)|_{\alpha=\delta} > 0$, $\alpha_2 > \delta$. This proves that if α increases from $\frac{\delta^2\left(18-8\delta-2\delta^2+\delta^3\right)}{(4-\delta)^2}$ to $\frac{\delta(8-\delta)}{4+\delta}$, it crosses SS_m only once. The crossing point is defined as α_s and it is the unique solution to the equation $SS_3 = SS_m$ in $R3$.

In $R4$, $SS_4 \triangleq \frac{2\left(3-2\alpha+5\delta-\alpha\delta+3\delta^2\right)}{27\beta(2+\delta)^2}$. $SS_4 - SS_m = \frac{-4\alpha(2+\delta)+\delta(8+9\delta)}{54\beta(2+\delta)^2}$ and it is easy to see that this expression is always positive for $\alpha < \delta$. Taken together with the previous results for $R1$, $R2$ and $R3$, this proves that SS is higher than the NR benchmark if and only if $\alpha < \alpha_s$, where

α_s satisfies $1 < \frac{\alpha_s}{\delta} < \frac{8-\delta}{4+\delta}$.

Finally, α_s is only a function of δ and δ is confined to the region $(0,1)$. Hence, we numerically proved that α_s is increasing in δ.

In $R1$, SS is same as the NR benchmark. If we exclude this region, we find that SS is strictly smaller than the NR benchmark when $\frac{\alpha_s}{\delta} < \frac{\alpha}{\delta} < 2\square$

Proof of Proposition 5

In $R1$, the IR cannot enter and the OEM acts like a monopoly without remanufacturing. Hence, the environmental impact is same as the NR benchmark and it is constant in α and δ.

In $R2$, new product quantity is lower than the monopoly without remanufacturing new product quantity. In addition to that, the IR cannot enter the market and cannot remanufacture. Hence, the environmental impact is lower than the NR benchmark. In $R2$, new product quantity increases in α and decreases in δ; therefore, the environmental impact also increases in α and decreases in δ.

In $R3$, the environmental impact is lower than the NR benchmark if and only if $Eq_{n_3} + eq_{r_3} < Eq_m$, where q_{n_3}, q_{r_3} are new and remanufactured product quantities in $R3$ and q_m is the monopoly without remanufacturing new product quantity (which is $\frac{1}{3}$). This can be rewritten as $\frac{e}{E} < \frac{1/3-q_{n_3}}{q_{r_3}} = \frac{(-2+\alpha)\delta^2}{(-8+\delta)\delta+\alpha(4+\delta)}$. Without loss of generality we can assume that $E = 1$, then $\frac{\partial q_{n_3}}{\partial \alpha} + e\frac{\partial q_{r_3}}{\partial \alpha} = \frac{e(-2+\delta)}{3(-2+\alpha)^2\delta} < 0$. Hence the environmental impact is decreasing in α for $R3$. $\frac{\partial^2 q_{n_3}}{\partial \delta^2} + e\frac{\partial^2 q_{r_3}}{\partial \delta^2} = \frac{-2\left(-4(-2+\alpha)\delta^3+e\left(-4\delta^3+\alpha\left(64-48\delta+12\delta^2+\delta^3\right)\right)\right)}{3(-2+\alpha)(-4+\delta)^3\delta^3}$ and denominator of this is always positive. We only need to consider the numerator, $r \triangleq 4(-2+\alpha)\delta^3 - e\left(-4\delta^3+\alpha\left(64-48\delta+12\delta^2+\delta^3\right)\right)$. $\frac{\partial r}{\partial e} = 4\delta^3 - \alpha\left(64-48\delta+12\delta^2+\delta^3\right)$ and this is positive if and only if $\alpha < \frac{4\delta^3}{64-48\delta+12\delta^2+\delta^3}$. By some algebra, it can be shown that $\frac{4\delta^3}{64-48\delta+12\delta^2+\delta^3} < \frac{\delta^2\left(18-8\delta-2\delta^2+\delta^3\right)}{(4-\delta)^2}$; therefore, in $R3$, $\frac{\partial r}{\partial e}$ can never be positive. Hence r is decreasing in e. Since the minimum value of e is 0 and r is decreasing in e, maximum value of the r is $r_{e=0} = 8(-2+\alpha)\delta^3 < 0$. Since the maximum value of the r is negative, the environmental impact is a concave function of δ.

In $R4$, the environmental impact is lower than the NR benchmark if and only if $\frac{e}{E} < \frac{1/3-q_{n_4}}{q_{r_4}}$ where q_{n_4} and q_{r_4} are new and remanufactured product quantities in $R4$. This is equivalent to $\frac{e}{E} < \frac{\delta}{2}$. In $R4$, new and remanufactured product quantity is only a function of δ. Hence, the environmental impact is constant in α. In this region, if δ increases, new and remanufactured

Region	s^*	p_n^*	p_r^*	q_n^*	q_r^*
$R1^p$	$\frac{1}{3\beta}$	$\frac{2}{9\beta}$	$\frac{\alpha}{9\beta}$	$\frac{1}{3}$	0
$R2^p$	$\frac{2\delta}{3\alpha\beta}$	$\frac{4\delta}{9\alpha\beta}$	$\frac{4\delta^2}{9\alpha\beta}$	$\frac{1}{3}$	0
$R3^p$	$\frac{2(1-\delta)}{3\beta(2-\alpha-\delta)}$	$\frac{4(1-\delta)^2(8-2\alpha-3\delta)}{9\beta(4-\delta)(2-\alpha-\delta)^2}$	$\frac{2(1-\delta)^2(\delta(8-3\delta)+\alpha(4-3\delta))}{9\beta(4-\delta)(2-\alpha-\delta)^2}$	$\frac{4}{3(4-\delta)}$	$\frac{(8-3\delta)\delta-\alpha(4+\delta)}{3(4-\delta)\delta(2-\alpha-\delta)}$
$R4^p$	$\frac{1}{3\beta}$	$\frac{2-\delta}{9\beta}$	$\frac{\delta}{9\beta}$	$\frac{1}{3}$	$\frac{1}{3}$

Table A.2: Price Competition Equilibrium product quality, new and remanufactured product prices and quantities

quantities decreases. Therefore, the environmental impact is decreasing in δ. □

Proof of Proposition 6

The equilibrium quality, new and remanufactured product prices and quantities are provided in Table A.2.

In the price competition game, using the utility functions for the remanufactured and the new product, it is straightforward to show that if $q_n > 0$ and $q_r > 0$, $q_n = 1 - \frac{p_n - p_r}{s(1-\delta)}$ and $q_r = \frac{p_n - p_r}{s(1-\delta)} - \frac{p_r}{\delta s}$. Using these, profit functions can be written as $\pi_{OEM}(p_n, p_r) = (p_n - \beta s^2)(1 - \frac{p_n - p_r}{s(1-\delta)})$and $\pi_{IR}(p_n, p_r) = (p_r - \beta\alpha s^2)(\frac{p_n - p_r}{s(1-\delta)} - \frac{p_r}{\delta s})$ for the differentiated market. If $q_r = 0$, then $q_n = 1 - \frac{p_n}{s}$, and the OEM's profit function can be written as usual. Given s, it can be shown that OEM's profit function is piecewise concave in p_n and the IR's profit function is concave in p_r. Following the similar steps as in the proof of proposition 1, we plug in the optimal prices as a function of quality. For $\alpha/\delta \leq (>)1$, the OEM's profit function is a piecewise concave function of quality. This can be solved for the equilibrium quality as in the proof of proposition 1. □

Proof of Proposition 7

Similar to the base model, given s, profit functions of both the OEM and the IR are concave in production quantities and in the equilibrium $s < \frac{1}{\beta}$ is satisfied(see the proof of proposition 1). Using these we can show that for $\alpha \geq \delta$ there can be two cases and these are stated as follows:

C1. $q_r^* = 0$ and $q_n^* = \frac{1-\beta s}{2}$ if one of the followings is satisfied:

(a) $0 < n < -\frac{\delta^2}{-16\alpha\beta+8\beta\delta}$ and $0 < s \leq -\frac{\delta}{2\beta(-2\alpha+\delta)} - \frac{1}{2}\sqrt{\frac{-16n\alpha\beta+8n\beta\delta+\delta^2}{\beta^2(2\alpha-\delta)^2}} \triangleq s_0$

(b) $0 < n < -\frac{\delta^2}{-16\alpha\beta+8\beta\delta}$ and $s_1 \triangleq -\frac{\delta}{2\beta(-2\alpha+\delta)} + \frac{1}{2}\sqrt{\frac{-16n\alpha\beta+8n\beta\delta+\delta^2}{\beta^2(2\alpha-\delta)^2}} \leq s$

(c) $n \geq -\frac{\delta^2}{-16\alpha\beta+8\beta\delta}$

C2. The IR remanufactures but the core constraint does not bind and $q_r^* = \frac{2n+s(2s\alpha\beta-(1+s\beta)\delta)}{s(-4+\delta)\delta}$ and $q_n^* = \frac{-n+s(-2-s(-2+\alpha)\beta+\delta)}{s(-4+\delta)}$ if $n < -\frac{\delta^2}{-16\alpha\beta+8\beta\delta}$ and $s_0 < s < s_1$.

From above, the OEM's profit function is a piecewise function of s. For $C1$, define the profit function as π_1 and for $C2$ define the profit function as π_2. Unconstraint optimum for π_1 is $\frac{1}{3\beta}$ and for π_2 is $\frac{-2+\delta-\sqrt{4-24n\beta+12n\alpha\beta-4\delta+\delta^2}}{6(-2\beta+\alpha\beta)}$. Using a similar approach as in the proof of Proposition 1, one can show that only one of these unconditional optimums can exist at the same time and the profit function is unimodal in s. These lead us the following equlibrium regions and decisions:

1. If $\frac{\alpha}{\delta} \geq 2$, or $2 > \frac{\alpha}{\delta} > 1$ and $n \geq \frac{2\delta-\alpha}{9\beta}$, the IR cannot enter. Equilibrium decisions are as follows: $s^* = \frac{1}{3\beta}$, $q_n^* = \frac{1}{3}$, $q_r^* = 0$.

2. If $2 > \frac{\alpha}{\delta} \geq \frac{8-\delta}{4+\delta}$ and $\frac{2\delta-\alpha}{9\beta} > n$, or $\frac{8-\delta}{4+\delta} > \frac{\alpha}{\delta} \geq \frac{5}{4}$ and $\frac{2\delta-\alpha}{9\beta} > n \geq \frac{-16\alpha+32\delta+8\alpha\delta-28\delta^2+3\alpha\delta^2+3\delta^3}{144\beta-192\alpha\beta+64\alpha^2\beta+24\beta\delta-16\alpha\beta\delta+\beta\delta^2} \triangleq n_0$, the OEM deters IR's entry by increasing quality. The equilibrium decisions are $s^* = s_1$, $q_n^* = \frac{1-\beta s_1}{2}$, $q_r^* = 0$.

3. If $\frac{5}{4} > \frac{\alpha}{\delta} \geq 1$ and $\frac{2\delta-\alpha}{9\beta} > n \geq n_0$, the OEM deters the IR's by reducing quality. The equilibrium decisions are $s^* = s_0$, $q_n^* = \frac{1-\beta s_0}{2}$, $q_r^* = 0$.

4. If $\frac{8-\delta}{4+\delta} > \frac{\alpha}{\delta} \geq 1$ and $n_0 > n$, the IR enters the market but does not remanufacture all available cores. The equilibrium decisions are $s^* = \frac{-2+\delta-\sqrt{4-24n\beta+12n\alpha\beta-4\delta+\delta^2}}{6(-2\beta+\alpha\beta)}$, $q_n^* = \frac{-n+s^*(-2-s^*(-2+\alpha)\beta+\delta)}{s^*(-4+\delta)}$, $q_r^* = \frac{2n+s^*(2s^*\alpha\beta-(1+s^*\beta)\delta)}{s^*(-4+\delta)\delta}$.

□

Proof of Proposition 22

The monopoly remanufacturing benchmark achieves a lower environmental impact than the NR benchmark if and only if $eq_r + Eq_n < \frac{1}{3}E$. This leads to the $\frac{e}{E}$ thresholds stated in Proposition 22.

The binding region in the base model includes the binding region in the monopoly remanufacturing benchmark. Therefore, we need three types of comparison to show that maximum $\frac{e}{E}$ ratios in the monopoly remanufacturing benchmark are higher than that of the base model for $\frac{\alpha}{\delta} < 1$. These are as follows:

1. Compare thresholds when core constraint binds both in the monopoly remanufacturing benchmark and the base model.

2. Compare thresholds when core constraint does not bind in the monopoly remanufacturing benchmark and it binds in the base model.

3. Compare thresholds when core constraint does not bind both in the monopoly remanufacturing benchmark and the base model.

Then it can be easily shown that monopoly remanufacturing benchmark thresholds higher than the base model thresholds.□

APPENDIX B

IS SERVICIZATION A WIN-WIN STRATEGY? PROFITABILITY AND ENVIRONMENTAL IMPLICATIONS OF SERVICIZATION

B.1 Full Information

In this section, we study the full information case and assume that the firm can observe consumer types, and choose either selling or servicization, whichever is more profitable.[1] Note that the firm can charge different prices from each consumer segment even when it sells a single product. The equilibrium solution to this case is referred as *efficient* because it leads to maximum achievable firm's profit and the social surplus. Next proposition describes the equilibrium.

Proposition 23. *Suppose the firm can observe the consumer types, and can choose the business strategy.*

($R1^{FI}$) When $\gamma_f(\alpha,\beta) < \frac{\alpha}{\beta} < 1$, the firm serves both segments, and

$$\tau_H^* = \frac{\theta\delta^*}{1+m_i},\ \ \tau_L^* = \frac{\alpha\theta\delta^*}{1+m_i},\ \ \delta^* = \frac{\left(\alpha^2(1-\beta)+\beta\right)\theta^2}{4c\,(1+m_i)},\ \ \pi_r^* = \frac{\left(\alpha^2(1-\beta)+\beta\right)^2 M\theta^4}{16c\,(1+m_i)^{\,2}}.$$

($R2^{FI}$) When $0 < \frac{\alpha}{\beta} < \gamma_f(\alpha,\beta)$, the firm serves only high valuation segment, and

$$\tau_H^* = \frac{\theta\delta^*}{1+m_i},\ \ \delta^* = \frac{\theta^2}{4c(1+m_i)},\ \ \pi_f^* = \frac{\beta\theta^4 M}{16c(1+m_i)^2}.$$

If $r > 1$, the firm uses servicization, and $m_i = m_f$. Otherwise, the firm uses selling strategy, and $m_i = m_c$. Furthermore, $\gamma(\alpha,\beta) > \gamma_f(\alpha,\beta)$.

The proposition shows that the equilibrium outcome is similar to Proposition 8. When the valuation gap between the consumers segments is small, or the mass of high valuation segments is small, the firm serves both segments. Otherwise, the firm serves only the high

[1] Note that the equilibrium of full information model is socially optimal.

valuation segment. Furthermore, $\gamma_f < \gamma$. Therefore, under full information, it is optimal to serve both consumer segments for a larger region compared to selling and servicization. This is because, the firm can charge different prices from the consumers, and there is no cannibalization problem.

B.2 Alternative Operating Cost

In the main body of the paper, we assume that product durability is correlated with the operating cost. In this section, we consider an alternative operating cost where product durability does not impact the operating cost under selling and servicization. More specifically, we assume that the operating cost for τ units of use is $\frac{m_c\tau^2}{2}$ for selling, and $\frac{m_f\tau^2}{2}$ for servicization. This functional form does not allow an analytical characterization of the equilibrium. Therefore, we resort to numerical study. We have run the numerical study for all combinations of $\alpha \in \{0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9\}$, $\beta \in \{0.2, 0.3, 0.4, 0.5, 0.6, 0.7, .0.8, 0.9\}$, $\theta \in \{1, 2, 3..10\}$, $m_c \in \{0.4, 0.6, 0.8, 1, 1.2\}$, $c \in \{0.1, 0.2, 0.3\}$, and $e_{u,p,d} \in \{0.05, 0.10, 0.15, 0.20, 0.25\}$ and confirmed that the insights are consistent across these parameters. For brevity, we report the results for a representative parameter set and the regions.

Figure B.1 demonstrates the profits for selling and servicization strategies. Similar to the base model, servicization is more profitable than selling strategy even when the firm has lower operating efficiency than the consumers. This is because the firm can incorporate product use information in pricing under servicization.

Figure B.2 illustrates the equilibrium product durability decisions for selling and servicization for different regions. When the firm serves both segments under both selling and servicization (see Figure B.2a), servicization can lead to higher product durability even when servicization is operationally less efficient. However, when the firm serves larger consumer segment under servicization, product durability can be lower than product durability under selling strategy despite better operational efficiency. These results are consistent with our base model where operating cost is correlated with product durability.

Figure B.3 demonstrates the difference in equilibrium product durability under servicization when the operating cost is and is not correlated with product durability. When the product durability is correlated with operating cost, i.e., base case, the equilibrium product

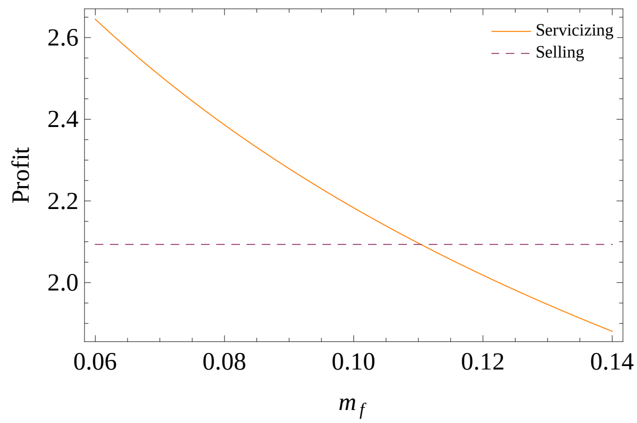
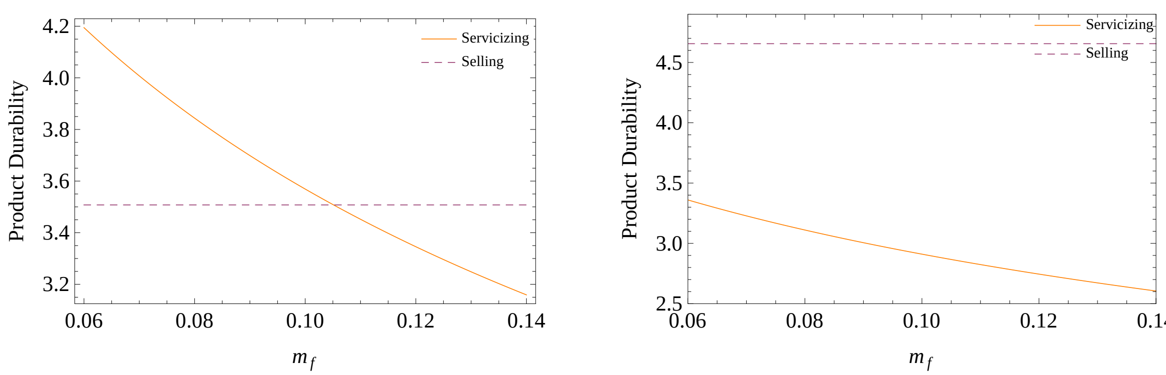


Figure B.1: Profit for the alternative operating cost. ($\theta = 2, c = 0.1, M = 1, \alpha = 0.8, \beta = 0.3, m_c = 0.1$)



(a) $\alpha = 0.8$

(b) $\alpha = 0.66$

Figure B.2: Product durability for the alternative operating cost. (a) firm serves both segments under both selling servicization, and (b) low end segment is served only under servicization. ($\theta = 2, c = 0.1, M = 1, \beta = 0.3, m_c = 0.10$)

durability is higher compared to product durability in alternative operating cost model. This is because, when the product durability lowers the operating cost, the firm takes advantage of this by investing more in product durability.

Figure B.4 illustrates environmental impact under selling and servicization strategy. In Figure B.4a, the product has low relative use impact, and environmental impact increases when the firm's relative operating efficiency decreases (high m_f). The intuition behind this result is similar to the base model, when the relative use impact is low, it is better to use the product for a longer time from an environmental perspective, and it is achieved when the relative efficiency of servicization is high. Therefore, servicization is environmentally preferable

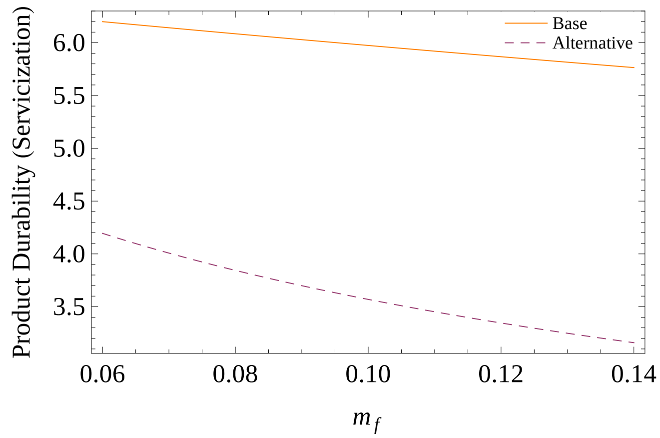
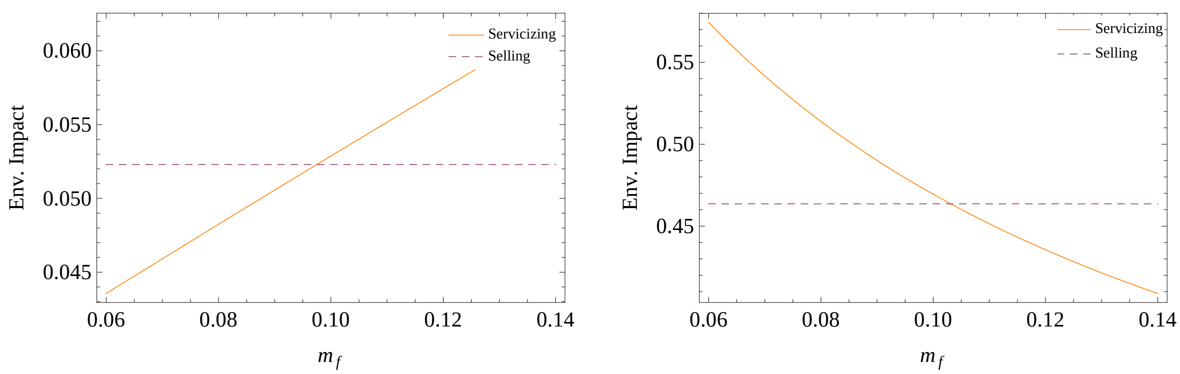


Figure B.3: Comparison of product durability for the alternative operating cost and the base case. $(\theta = 2, c = 0.1, M = 1, \alpha = 0.8, \beta = 0.3, m_c = 0.1)$



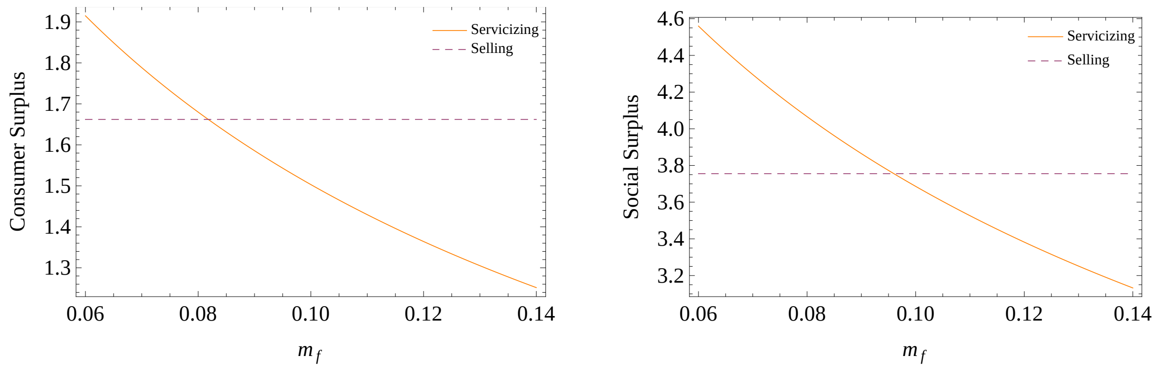
(a) $e_u = 0.001$

(b) $e_u = 0.1$

Figure B.4: Environmental impact for the alternative operating cost. $(\theta = 2, c = 0.1, M = 1, \alpha = 0.8, \beta = 0.3, m_c = 0.10, e_p = 0.1, e_d = 0.1)$

when the relative operating efficiency is high enough ($m_f < 0.097$). Otherwise, selling is more environmentally preferable. In Figure B.4b, the product has high relative use impact, and environmental impact decreases when the firm's relative operating efficiency decreases (high m_f). As explained in the base case, when the relative use impact is high, it is better to use the product for a shorter time from an environmental perspective. This is precisely the case when the relative operating efficiency of servicization is low enough ($m_f > 0.103$).

Finally, Figure B.5 compares the CS and SS for the alternative operating cost when the firm serves both segments under both selling and servicization strategies. As expected both the CS and SS decrease under servicization as the firm's relative operating efficiency decreases (high m_f). It is important to note that the CS and the SS under servicization can be lower



(a) Consumer Surplus (b) Social Surplus

Figure B.5: Consumer and Social Surplus for the alternative operating cost. ($\theta = 2, c = 0.1, M = 1, \alpha = 0.8, \beta = 0.3, m_c = 0.1$)

even when the firm has a better operating efficiency. From the Figure, this can be observed for m_f values smaller than but closer to 0.1. Therefore, similar to the base model, servicization can have a detrimental effect on both the CS and SS.

B.3 Parameters and Decision Variables

Table B.1 summarizes the parameters and decision variables of our model.

B.4 Proofs

Proof of Proposition 8: We first solve the equilibrium for selling strategy, then we solve it for servicization strategy. In selling strategy, if type-θ_i purchases the product, it uses the product for $\tau_i = \frac{\delta\theta}{1+m_c}$. Then, $U_r(\theta_i) = \frac{\delta\theta_i^2}{2(1+m_c)} - p$. If the firm sells to both segments, $p = \frac{\delta\theta_L^2}{2(1+m_c)}$; otherwise, $p = \frac{\delta\theta_H^2}{2(1+m_c)}$. It is easy to see that when these prices are plugged into firm's profit function, the function becomes concave in product durability δ. If the firm serves both segments, product durability is $\delta^* = \frac{\alpha^2\theta^2}{4c(1+m_c)}$; otherwise, $\delta^* = \frac{\theta^2}{4c(1+m_c)}$. The firm profits are $\pi_{r,B} = \frac{\alpha^4 M\theta^4}{16c(1+m_c)^2}$, $\pi_{r,H} = \frac{\beta^4 M\theta^4}{16c(1+m_c)^2}$, respectively. Therefore, the firm serves both segments if and only if $\alpha > \sqrt[4]{\beta}$.

In servicization, if the firm serves both segments, one can show that at the equilibrium, IR_H and IC_L constraints do not bind, but IR_L and IC_H bind. Hence, $F_L = \tau_L\left(\theta_L - \frac{\tau_L}{2\delta}\right)$ and $F_H = \tau_H\left(\theta_H - \frac{\tau_H}{2\delta}\right) - \tau_L\left(\theta_H - \frac{\tau_L}{2\delta}\right) + F_L$. When we plugged in these to the profit function,

Symbol	Definition
θ_i	Segment i's valuation
α	The ratio of θ_H to θ_L
M	Size of the market
Q_i	Size of segment i
β	Fraction of θ_H consumers
δ	Durability of the product
m_c	Consumers' operating cost coefficient
m_f	Firm's operating cost coefficient
τ_i	Segment i's total product use
p	Selling price
F	Service price
c	Cost coefficient for durability investment
e_u	Environmental impact cost coefficient for use phase
e_p	Environmental impact cost coefficient for production phase
e_d	Environmental impact cost coefficient for disposal phase

Table B.1: Parameters and Decision Variables

we have $\pi_{v,B}(.|F_H,F_L) = M\left(-c\delta^2 + b\theta_H(\tau_H-\tau_L)+\theta_L\tau_L\right) - \frac{(1+m)M\left(b\tau_H^2-(-1+b)\tau_L^2\right)}{2\delta}$. This function is concave in τ_H, then from FOC, $\tau_H = \frac{\delta\theta_H}{1+m_f}$. After incorporating this expression to the profit function, we obtain $\pi_{v,B}(.|F_L,F_H,\tau_H) = -M\left(c\delta^2+\beta\theta_H\tau_L-\theta_L\tau_L\right) + \frac{M\beta\delta\theta_H^2}{2+2m_f} + \frac{M(-1+\beta)\left(1+m_f\right)\tau_L^2}{2\delta}$. This is concave in τ_L; hence, τ_L can be found as $\frac{\delta(\beta\theta_H-\theta_L)}{(-1+\beta)\left(1+m_f\right)}$. Note that $\tau_L>0$ if and only if $\alpha>\beta$. After plugging this in, δ can be found as $\frac{\left(\alpha^2+\beta-2\alpha\beta\right)\theta^2}{4c\alpha^2(-1+\beta)\left(1+m_f\right)}$, similarly. When the firm serves only the high-end segment, only IR_H binds and the equilibrium can be obtained similar to the selling model.

Under servicization, the firm serves both segments if and only if $\pi_{v,B}\geq\pi_{v,H}$. One can show that $\lim_{\alpha\to 1}\frac{\pi_{v,B}}{\pi_{v,H}}>1$, $\lim_{\alpha\to\beta}\frac{\pi_{v,B}}{\pi_{v,H}}<1$, and $\frac{\pi_{v,B}}{\pi_{v,H}}$ is increasing in α when $\alpha\in(\beta,1)$. Therefore, there is only one threshold α_t where $\frac{\pi_{v,B}(\alpha_t(\beta))}{\pi_{v,H}(\alpha_t(\beta))}=1$. Define $\gamma(\alpha,\beta)=\frac{\alpha_t(\beta)}{\beta}=\gamma(\alpha,\beta)$. It can be shown that at $\alpha=\sqrt[4]{\beta}$, serving to both segment is more profitable. Hence, $\gamma(\alpha,\beta)<\sqrt[4]{\beta}$. $\square$

Proof of Proposition 9: In R1, $\frac{\pi_{v,B}}{\pi_{r,B}}>1$ if and only if $\frac{M\left(\alpha^2+\beta-2\alpha\beta\right)^2\theta^4}{16c(-1+\beta)^2\left(1+m_f\right)^2} > \frac{M\alpha^4\theta^4}{16c(1+m_c)^2}$. This can be rearranged to show that $\frac{\pi_{v,B}}{\pi_{r,B}}>1$ if and only if $r>\frac{\alpha^2(1-\beta)}{\alpha^2+\beta-2\alpha\beta}\triangleq f_1$. Simple algebra shows that $f_1<1$. The the other parts can be shown similarly. $\square$

Proof of Proposition 10: We only show the proof for region $R2$. The rest can be shown similarly. In R2, $\delta_v^* = \frac{(\alpha^2+\beta-2\alpha\beta)\theta^2}{4c(1-\beta)(1+m_f)}$ and $\delta_r^* = \frac{\theta^2}{4c(1+m_c)}$. We can rearrange the terms and find that product durability is higher under servicization if and only if $r > \frac{1-\beta}{\alpha^2+\beta-2\alpha\beta} \triangleq r_\delta$. We compare this with the minimum operating efficiency threshold above which servicization is more profitable than selling, i.e., $f_1 = \frac{\alpha^2(1-\beta)}{\alpha^2+\beta-2\alpha\beta}$. $r_\delta > f_1$ if and only if $1 > \alpha^2$ which is true by assumption. $\frac{\partial r_\delta}{\partial \alpha} < 0$ for $\alpha \in (\beta, 1)$ and $\lim_{\alpha \to 1} r_\delta > 1$. Hence $r_\delta > 1$.□

Proof of Proposition 11: In $R1$, $\tau_{H,v} > \tau_{H,r}$ if and only if $r > \sqrt{\frac{\alpha^2(1-\beta)}{\alpha^2-2\alpha\beta+\beta}}$. Similarly, $\tau_{L,v} > \tau_{L,r}$ if and only if $r > \sqrt{\frac{\alpha^3(\beta-1)^2}{(\alpha-\beta)(\alpha^2-2\alpha\beta+\beta)}}$. One can show that $\sqrt{\frac{\alpha^3(\beta-1)^2}{(\alpha-\beta)(\alpha^2-2\alpha\beta+\beta)}} > \sqrt{\frac{\alpha^2(1-\beta)}{\alpha^2-2\alpha\beta+\beta}} > f_1$, where f_1 is the thresholds above which servicization is more profitable and it is defined in the proof of Proposition 9. This proves the first part of the proposition. The other parts can be proved similarly. □

Proof of Proposition 12: $CS_v^{R1} = \sum_{i=L,H} \int_0^{\tau_{i,v}^*} (\theta_i - \frac{t}{\delta})dt - F_i, = \frac{M(-1+\alpha)\beta\theta^4}{8c}(\frac{\alpha^2(1+\alpha)}{(1+m_c)^2} - \frac{2(\alpha-\beta)\left(\alpha^2+\beta-2\alpha\beta\right)}{(-1+\beta)^2\left(1+m_f\right)^2})$ and $CS_r^{R1} = \sum_{i=L,H} \int_0^{\tau_{i,r}^*} (\theta_i - \frac{t}{\delta})dt - \frac{m_c}{2\delta}\tau_{i,r}^{*2} - p = -\frac{M\alpha^2\left(-1+\alpha^2\right)\beta\theta^4}{8c(1+m_c)^2}$. $CS_v^{R1} > CS_r^{R1}$ if and only if $-\left(\frac{\alpha^2(1+\alpha)}{(1+m_c)^2} - \frac{2(\alpha-\beta)\left(\alpha^2+\beta-2\alpha\beta\right)}{(-1+\beta)^2\left(1+m_f\right)^2}\right) > 0$. Then, $CS_v^{R1} > CS_r^{R1}$ if and only if $r^2 > \frac{(1-\beta)^2\alpha^2(1+\alpha)}{2(\alpha-\beta)(\alpha^2+\beta-2\alpha\beta)} = h^2$, and the result follows. $h > 1$ if and only if $(-1+\alpha)\left(-\alpha^2+2\alpha\beta-2\alpha^2\beta-2\beta^2+2\alpha\beta^2+\alpha^2\beta^2\right) > 0$. $\alpha < 1$ by assumption; hence, if we show that second expression is negative, the result follows. Second derivative of the expression is $2(-1+(-2+\beta)\beta) < 0$; hence, it is concave in α. At $\alpha = 1$, it is $-1+\beta^2 < 0$, and at $\alpha = \beta$, it is $\beta^2\left(-1+\beta^2\right) < 0$. Therefore, the expression is negative in $R1$.

In R2, the firm has to leave positive informational rent to high end segment under servicization. However, the firm extracts the entire surplus under selling. Hence, the CS under servicization is always higher. In R3, since the firm only serves high-end segment, the CS is zero for both selling and servicization strategies.□

Proof of Proposition 13: In R1, $SS_{v,B} = -\frac{M\left(-\alpha^2-\beta+2\alpha\beta\right)\left(\alpha^2+\beta+2(1-2\alpha)\alpha\beta+4(-1+\alpha)\beta^2\right)\theta^4}{16c(-1+\beta)^2\left(1+m_f\right)^2}$ and $SS_{r,B} = \frac{M\alpha^2\left(\alpha^2(1-2\beta)+2\beta\right)\theta^4}{16c(1+m_c)^2}$. By rearranging the terms, $SS_{v,B} > SS_{r,B}$ if and only if $r^2 > \frac{\alpha^2(-1+\beta)^2\left(-2\beta+\alpha^2(-1+2\beta)\right)}{(\alpha^2+\beta-2\alpha\beta)(-2\alpha\beta(1+2\beta)+\alpha^2(-1+4\beta)+\beta(-1+4\beta))} \triangleq k_1^2$. We need to show that $k_1 > f_1$. This is true if and only if $\frac{\alpha^2(-1+\beta)^2\left(-2\beta+\alpha^2(-1+2\beta)\right)}{(\alpha^2+\beta-2\alpha\beta)(-2\alpha\beta(1+2\beta)+\alpha^2(-1+4\beta)+\beta(-1+4\beta))} > \frac{\alpha^4(-1+\beta)^2}{(\alpha^2+\beta-2\alpha\beta)^2}$. This inequality can be written as $-\frac{2(-1+\alpha)^2\alpha^2(-1+\beta)^2\beta\left(\alpha^2+\beta\right)}{(\alpha^2+\beta-2\alpha\beta)^2(-2\alpha\beta(1+2\beta)+\alpha^2(-1+4\beta)+\beta(-1+4\beta))} > 0$. Note that numerator is always positive and $\left(\alpha^2+\beta-2\alpha\beta\right)^2 > 0$. Hence, we need to show that $e_1 \triangleq -\left(-2\alpha\beta(1+2\beta)+\alpha^2(-1+4\beta)+\beta(-1+4\beta)\right) > 0$. $\frac{\partial^2 e_1}{\partial\beta^2} = 8(-1+\alpha) < 0$, and hence, e_1 is concave in β. Then it is sufficient to show that e_1 is positive at $\beta = 0$ and $\beta = \alpha$. $e_1(\beta = 0) = \alpha^2$ and $e_1(\beta = \alpha) = \alpha(1-\alpha)$. This proves that when servicization is more profitable than selling strategy in R1, $SS_{v,B} > SS_{r,B}$ if and only if $r > k_1$. To complete the proof for region $R1$, we need to find when $k_1 > 1$ is true. Observe that this is true if and only if $l = -1-2\alpha+5\alpha^2+(4-2\alpha(2+\alpha))\beta > 0$. When $\beta < \frac{1}{2}$, l has two roots $\alpha_1^l = \frac{-1-2\beta-\sqrt{6}\sqrt{1-3\beta+2\beta^2}}{-5+2\beta}$ and $\alpha_2^l = \frac{-1-2\beta+\sqrt{6}\sqrt{1-3\beta+2\beta^2}}{-5+2\beta}$. Furthermore, $\alpha_1^l > \alpha_2^l$ and $\alpha_2^l < \beta$. Since, l is convex in this region, $l > 0$ if and only if $\alpha > \min\{\alpha_1^l, \sqrt[4]{\beta}\}$. $\frac{\partial\alpha_l^1}{\partial\beta} < 0$ for $\beta \in (0, 0.5)$. $\alpha_l^1(\beta = 0) \approx 0.69$ and $\alpha_l^1(\beta = 1) = 0.5$. Therefore, there exist a $\beta_c \in (0, 0.5)$ such that $\alpha_1^l > \sqrt[4]{\beta}$ if and if $0 < \beta < \beta_c$. When $\beta \geq \frac{1}{2}$, l does not have any roots. Hence it is either always positive or always negative. It is easy to see that it is always positive. Then, define

$$\sigma(\beta) = \begin{cases} \sqrt[4]{\beta} & : \beta \geq \beta_c \\ \alpha_1^l & : \beta < \beta_c \end{cases}$$

In R2, $SS_{r,H} = \frac{M\beta\theta^4}{16c\left(1+m_f\right)^2}$. By rearranging the terms we can show that $SS_{v,B} > SS_{r,H}$ if and only if $r > \sqrt{-\frac{(-1+\beta)^2\beta}{(-\alpha^2-\beta+2\alpha\beta)(\alpha^2+\beta+2\alpha\beta-4\alpha^2\beta-4\beta^2+4\alpha\beta^2)}} \triangleq k_2$. $f_2 > k_2$ if and only if $\frac{(1-\beta)^2\beta}{(\alpha^2+\beta-2\alpha\beta)^2} > -\frac{(-1+\beta)^2\beta}{(-\alpha^2-\beta+2\alpha\beta)(\alpha^2+\beta+2\alpha\beta-4\alpha^2\beta-4\beta^2+4\alpha\beta^2)}$. The inequality can be written as $\left(\alpha^2+\beta-2\alpha\beta\right)(-1-\alpha^2-\beta-2\alpha\beta+4\alpha^2\beta+4\beta^2-4\alpha\beta^2) < 0$. First expression in the equality is convex in α and takes its minimum value at $\alpha = \beta$ which is $\beta(1-\beta) > 0$. Second expression is convex in β, and hence, it is sufficient to show that it is negative at $\beta = 0$ and $\beta = \alpha$. These can be shown by simple algebra.

In R3, since the SS is equivalent to firm's profit under both selling and servicization. The proof is same as the comparison of the profits in the proof of Proposition 9.

Proof of Proposition 14: In $R1$, product use impact under servicization is $e_u\frac{M\alpha\left(\alpha^2+\beta-2\alpha\beta\right)\theta^3}{4c(1-\beta)\left(1+m_f\right)^2} = e_u U_v^B$ and under selling is $e_u\frac{M\alpha^2(\alpha+\beta-\alpha\beta)\theta^3}{4c(1+m_c)^2} = e_u U_r^B$. Then, use impact under servicization is smaller than under selling strategy if and only if $r < \sqrt{\frac{\alpha(1-\beta)(\alpha+\beta-\alpha\beta)}{\alpha^2+\beta-2\alpha\beta}}$. Product disposal and production impact under servicization is $(e_d+e_p)\frac{4cM(1-\beta)(1+(-2+\alpha)\beta)\left(1+m_f\right)^2}{(\alpha-\beta)(\alpha^2+\beta-2\alpha\beta)\theta^3} = (e_p+e_d)D_v^B$ and under selling is $(e_d+e_p)\frac{4cM(1+(-1+\alpha)\beta)(1+m_c)^2}{\alpha^3\theta^3}(e_p+e_d)D_r^B$. Hence, production and disposal impact is lower under servicization if and only if $r > \sqrt{\frac{\alpha^3(1-\beta)(1+(-2+\alpha)\beta)}{(\alpha-\beta)(1+(-1+\alpha)\beta)(\alpha^2+\beta-2\alpha\beta)}}$.

We now show that $g_2 > g_1 > f_1$ to complete the proof. $\frac{g_2}{g_1} > 1$ if and only if $\frac{\alpha^2(1+(-2+\alpha)\beta)}{(\alpha-\beta)(1+(-1+\alpha)\beta)(\alpha+\beta-\alpha\beta)} > 1$. This can be rewritten as $(-1+\alpha)^2(1+\alpha-\beta)\beta^2$. Because in this region $\alpha > \beta$, the result follows. In order to facilitate the discussion we define $j_1 = \left(\alpha-2\alpha^2-5\alpha^3+11\alpha^4-\alpha^5-\alpha^6\right)\beta^2 + \left(1-6\alpha+12\alpha^2-8\alpha^3\right)\beta^3$ and $j_2 = 3\alpha^5-2\alpha^6+\left(3\alpha^3-6\alpha^4-3\alpha^5+3\alpha^6\right)\beta$. $\frac{g_1}{f_1} > 1$ if and only if $j \triangleq j_1+j_2 > 0$. $\frac{\partial^3 j}{\partial\beta^3} = -6(-1+2\alpha)^3$ and it is greater than 0 if and only if $\alpha < 1/2$. Hence, $\frac{\partial^2 j}{\partial\beta^2}$ has its minimum at $\alpha = \frac{1}{2}$, and it is $\frac{1}{32} > 0$. This proves that $\frac{\partial^2(j)}{\partial\beta^2}$ is always positive. Furthermore, $j(\beta=\alpha) = -(-1+\alpha)^3\alpha^3\left(2+\alpha+\alpha^2\right) > 0$ and $j(\beta=0) = (3-2\alpha)\alpha^5 > 0$, which proves that $j > 0$. Since $g_2 > g_1 > f_1$ holds, when $g_1 > r > f_1$ servicization decreases use impact but increases production and disposal impact and profit. Therefore, it is more environmentally friendly and profitable for products with high relative use impact. When $r > g_2$, servicization increases use impact and profit but decreases production and disposal impact. Therefore, it is more environmentally friendly and profitable for products with low relative use impact. We define $\Delta_1 = \frac{D_r^B-D_v^B}{U_v^B-U_r^B}$.

In R2, product use impact, and production and disposal impact are same as in $R1$ under servicization. Under selling, product use impact is $e_u\frac{M\beta\theta^3}{4c(1+m_c)^2} = e_uU_r^H$. Use impact under servicization is lower if and only if $e_u\frac{M\beta\theta^3}{4c(1+m_c)^2} > e_u\frac{M\alpha\left(\alpha^2+\beta-2\alpha\beta\right)\theta^3}{4c(1-\beta)\left(1+m_f\right)^2}$. This can be reorganized as $r < \sqrt{\frac{(1-\beta)\beta}{\alpha(\alpha^2+\beta-2\alpha\beta)}} \triangleq g_p$. Under selling, product production and disposal impact is given by $(e_d+e_p)\frac{4cM\beta(1+m_c)^2}{\theta^3}$. Then, production and disposal impact under servicization is lower than under selling if and only if $r > \sqrt{\frac{(1-\beta)(1+(-2+\alpha)\beta)}{(\alpha-\beta)\beta(\alpha^2+\beta-2\alpha\beta)}} \triangleq g_3$.

We now show that $g_3 > f_2 > g_u$. $g_3 > f_2$ if and only if $\frac{(1-\beta)(1+(-2+\alpha)\beta)}{(\alpha-\beta)\beta(\alpha^2+\beta-2\alpha\beta)} > \sqrt{\frac{(1-\beta)^2\beta}{(\alpha^2+\beta-2\alpha\beta)^2}}$. By taking the square of both sides, the expression can be rewritten as $\triangleq \alpha^2(1-\beta)^3\beta^2 - 2\alpha(1-\beta)^3\beta\left(-1+\beta+\beta^2\right) + (1-\beta)^3\left(1-3\beta+\beta^2+\beta^3+\beta^4\right) > 0$. The expression is strictly convex in α and has its minimum at $\alpha = 1-\frac{1}{\beta}+\beta < \beta$. Therefore, if the expression is positive at $\alpha=\beta$, it is always positive in $R2$. The value of the expression at $\alpha=\beta$ is $(-1+\beta)^6 > 0$. $f_2 > g_u$ if and only if $f_2^2 - g_u^2 = \frac{\left(\alpha^2-\beta\right)(-1+\beta)^2\beta}{\alpha^2(\alpha^2+\beta-2\alpha\beta)^2} > 0$. Hence, it is enough to show that in $R2$, $\alpha > \sqrt{\beta}$.

In order to show this, we will prove that at $\frac{\pi_{v,B}}{\pi_{v,H}}|_{\beta=\alpha^2} < 1$. $\frac{\pi_{v,B}}{\pi_{v,H}}|_{\beta=\alpha^2} = \frac{\left(2\alpha^2-2\alpha^3\right)^2}{\alpha^2(-1+\alpha^2)^2} < 1$ if and only if $(-1+\alpha)^3\alpha^2(1+3\alpha) < 0$, which is indeed correct. Hence, $\gamma > \sqrt{\beta}$, and hence, in $R2$, $\alpha > \sqrt{\beta}$. Since $g_3 > f_2 > g_u$ holds, when $r > g_3$ servicization increases use impact and profit but decreases production and disposal impact. Therefore, it is more environmentally friendly and profitable for products with low relative use impact. We define $\Delta_2 = \frac{D_r^H - D_v^B}{U_v^B - U_r^H}$.

In R2, product use impact, and production and disposal impact are same as in $R1$ under selling. Under servicization product use impact is $e_u \frac{M\beta\theta^3}{4c\left(1+m_f\right)^2} = e_u U_v^H$. Use impact under servicization is lower if and only if $r < 1$. Under servicization, product production and disposal impact is given by $(e_d + e_p)\,\frac{4cM\beta\left(1+m_f\right)^2}{\theta^3}$. Then, production and disposal impact under servicization is lower than under selling if and only if $r > 1$. Furthermore, we know that servicization is more profitable if and only if $r > 1$. Hence, servicization is more environmentally friendly and profitable for products with low use impact. We define $\Delta_2 = \frac{D_r^H - D_v^H}{U_v^H - U_r^H}$.$\square$

Proof of Proposition 15: When a consumer segment buys the product, it uses the product at $\tau_i = \frac{\delta\theta_i}{1+m_c}$. Hence, maximized utility for type-θ_i consumers is $U_r^{pl}(\theta_i, \delta_i) = \frac{\delta_i\theta_i^2}{2(1+m_c)} - p_i$ where p_i is the price of the product. The firm solves the following:

$$\begin{aligned} \pi_r^{pl*} \quad &= \quad \max_{F_i,\tau_i,i=H,L} \sum_{i=H,L} (p_i - c\delta_i^2)Q_i, \qquad \text{(B.4.1)} \\ s.t, \quad & IR_i^{pl}, \quad IC_i^{pl} \quad i = H, L. \end{aligned}$$

where IR_i^{pl} : $U_r^{pl}(\theta_i, \delta_i) \geq 0$ and IC_i^{pl} : $U_r^{pl}(\theta_i, \delta_i) \geq U_r^{pl}(\theta_i, \delta_j)$, $i = H, L$ and $i \neq j$. We can easily show that IR_H and IC_L constraints do not bind. Therefore, $p_L = \frac{\delta_L\theta_L^2}{2(1+m_c)}$ and $p_H = \frac{\delta_H\theta_H^2}{2(1+m_c)} - \frac{\delta_L\theta_H^2}{2(1+m_c)} + p_L$. After plugging in these to the profit function, we can show that the profit function is jointly concave in δ_H and δ_L. Hence, from FOC, we can obtain the optimum values in Table 3.3. Note that $\delta_L > 0$ if and only if $\alpha > \sqrt{\beta}$. Combining these with the equilibrium for servicization with single product, the equilibrium structure in the proposition follows. $\square$

Proof of Proposition 16: In $R1^{pl}$, $\pi_r^{pl} > \pi_v$ if and only if $\frac{M\left(\alpha^2+\beta-2\alpha\beta\right)^2\theta^4}{16c(-1+\beta)^2\left(1+m_f\right)^2} > \frac{M\left(\alpha^4+\beta-2\alpha^2\beta\right)\theta^4}{16c(1-\beta)(1+m_c)^2}$. This can be rewritten to obtain $r > \sqrt{\frac{(1-\beta)(\alpha^4+\beta-2\alpha^2\beta)}{\left(\alpha^2+\beta-2\alpha\beta\right)^2}} \triangleq h_1(\alpha, \beta)$. $h_1 > 1$ if and only if

$-(-1+\alpha)^2\beta(-1+(-2+\alpha)\alpha+2\beta) > 0$. It can be shown that this expression is indeed positive. The other regions can be shown similarly. $\square$

Proof of Proposition 23:

If the firm uses selling strategy, the consumers use level will be $\tau_i = \frac{\delta\theta_i}{1+m_c}$. Given this, the maximized consumer utility is $\frac{\delta\theta_i^2}{2(1+m_c)}$. When the firm sells both segments, it can extract the entire consumer surplus by charging the consumers $p_i = \frac{\delta\theta_i^2}{2(1+m_c)}$. Then, $\pi_{r,B} = M\beta\left(-c\delta^2+\frac{\delta\theta_H^2}{2+2m_c}\right)+M(1-\beta)\left(-c\delta^2+\frac{\delta\theta_L^2}{2+2m_c}\right)$. $\frac{\partial^2\pi_{v,B}}{\partial\delta^2} = -2cM < 0$; hence, it is strictly concave in δ. From FOC, $\delta^* = \frac{\left(-\alpha^2(-1+\beta)+\beta\right)\theta^2}{4c(1+m_c)}$ and $\pi_{r,B} = \frac{M\left(-\alpha^2(-1+\beta)+\beta\right)^2\theta^4}{16c(1+m_c)^2}$. $\pi_{r,B} > \pi_{r,H}$ if and only if $\frac{M\left(-\alpha^2(-1+\beta)+\beta\right)^2\theta^4}{16c(1+m_c)^2} > \frac{M\beta\theta^4}{16c(1+m_c)^2}$. This can be reorganized as $x_1 \triangleq \alpha^4+\left(-1+2\alpha^2-2\alpha^4\right)\beta+\left(1-2\alpha^2+\alpha^4\right)\beta^2 > 0$. $\frac{\partial^3 x_1}{\partial\alpha^3} = 24\alpha(-1+\beta)^2 > 0$, and $\frac{\partial^2 x_1}{\partial\alpha^2}|_{\alpha=0} = -4(-1+\beta)\beta > 0$. Therefore, $\frac{\partial^2 x_1}{\partial\alpha^2} > 0$. $\frac{\partial x_1}{\partial\alpha}|_{\alpha=0} = 0$, and hence, $\frac{\partial x_1}{\partial\alpha} > 0$. Therefore, x_1 is monotone increasing in α for $\alpha \in (0,1)$. $x_1|_\alpha = 0$. $x_1(\alpha=0) = (-1+\beta)\beta < 0$ and $x_1(\alpha=1) = (1-\beta) > 0$. Hence, there exist a $\alpha_c \in (0,1)$ such that the firm sells both segments when $\alpha > \alpha_c$; otherwise, it sells high end segment. We define $\gamma_f = \frac{\alpha_c}{\beta}$.

If the firm uses servicization strategy and serves to both segments, only individual rationality constraints bind for the both consumer segments. The firm sets the prices of the contracts $F_H = \tau_H\left(\theta-\frac{\tau_H}{2\delta}\right)$ and $F_L = \tau_L\left(\alpha\theta-\frac{\tau_L}{2\delta}\right)$. When we plug these into the profit function, we have $\pi_{v,B} = M\beta\left(-c\delta^2+\tau_H\left(\theta-\frac{\tau_H}{2\delta}\right)\right)+M(1-\beta)\left(-c\delta^2+\tau_L\left(\alpha\theta-\frac{\tau_L}{2\delta}\right)\right) - \frac{m_f}{2\delta}\left({\tau_L}^2(1-\beta)M+{\tau_H}^2\beta M\right)$. $\frac{\partial^2\pi_{v,B}}{\partial\tau_L} = \frac{M(-1+\beta)\left(1+m_f\right)}{\delta}$, and hence, profit is strictly concave in τ_L. From FOC, $\tau_L = \frac{\alpha\delta\theta}{1+m_f}$. $\frac{\partial^2\pi_{v,B}(|\tau_L)}{\partial\tau_H^2} = -\frac{M\beta\left(1+m_f\right)}{\delta}$, and hence, from FOC, $\tau_H = \frac{\delta\theta}{1+m_f}$. Similarly δ can be found as $\frac{\left(-\alpha^2(-1+\beta)+\beta\right)\theta^2}{4c\left(1+m_f\right)}$. From here, it is easy to see that the firm serves both segments if and only if $\gamma_f < \frac{\alpha}{\beta}$.

If we compare the selling and servicization strategy, the firm uses servicization if and only if $r > 1$; otherwise, it uses selling strategy. By comparing, the firms profits when it serves to both segments in full information, with the one in the asymmetric information, one can show that $\gamma_f < \gamma$. $\square$

APPENDIX C

RESPONSIBLE SOURCING VIA VERTICAL INTEGRATION: THE IMPACTS OF SCRUTINY, DEMAND EXTERNALITY, AND CROSS SOURCING

We first define the following difference functions:

$$\Delta_1 = \pi^A_{vr|dn} - \pi^A_{vn|dn}, \tag{C.0.1}$$

$$\Delta_2 = \pi^A_{vr|dn} - \pi^A_{dn|dn}, \tag{C.0.2}$$

$$\Delta_3 = \pi^A_{vn|dn} - \pi^A_{dn|dn}, \tag{C.0.3}$$

$$\Delta_4 = \pi^A_{vrc|drc} - \pi^A_{vn|dn}, \tag{C.0.4}$$

$$\Delta_5 = \pi^A_{vrc|drc} - \pi^A_{vr|dn}, \tag{C.0.5}$$

$$\Delta_6 = \pi^A_{vnc|dnc} - \pi^A_{vn|dn}, \tag{C.0.6}$$

$$\Delta_6 = \pi^A_{vrc|dnc} - \pi^A_{vnc|dn}. \tag{C.0.7}$$

C.1 Proofs

Proof of Proposition 17

Suppose that $f = 0$. In this case, $\Delta_3 > 0$. When $0 < \alpha < \frac{\beta p + c_r}{p - c_r}$ we can show that Δ_1 is a concave function and $\Delta_1 > 0$ if and only if $\sigma^1_{vr,vn} < \sigma < \sigma^2_{vr,vn}$ where $\sigma^1_{vr,vn}$, $\sigma^2_{vr,vn}$ are such that $\Delta_1(\sigma) = 0$. Therefore, as long as f is small enough, (V, N) is the optimum strategy for $\sigma < \sigma^1_{vr,vn}$ and $\sigma > \sigma^2_{vr,vn}$, and (V, R) is the optimum for the rest.

As f increases (D, N) would start arising in the equilibrium. The threshold f for this is determined by the minimum value of Δ_3. Δ_3 takes its minimum at $\sigma = 1$, and $\lim_{\sigma \to 1} \Delta_3 = Qw(1 + \beta)$. Therefore, as long as $f \leq Qw(1 + \beta)$, optimal strategy described above would not change.

Define $f_1 = \Delta_3(\sigma^2_{vr,vn})$. As long as $Qw(1 + \beta) \leq f < f_1$, (D, N) is in the equilibrium if only if $1 > \sigma > \sigma_{vn,dn}$ where $\sigma_{vn,dn}$ is such that $\Delta_3(\sigma_{vn,dn}) = 0$.

Define $f_2 = \Delta_3(\sigma^1_{vr,vn})$ and suppose that $f_1 \leq f < f_2$. In this case, when $\sigma^2_{vr,dn} < \sigma < 1$,

$\Delta_3 < 0$ and $\Delta_2 < 0$ where $\sigma_{vr,dn}$ is such that $\Delta_2(\sigma) = 0$. Hence, (D, N) is the optimal strategy. When $\sigma_{vr,vn} \leq \sigma < \sigma_{vr,dn}$, $\Delta_3 > 0$ and $\Delta_1 > 0$, and hence (V, R) is the optimal strategy.

When $f_2 \leq f < \min\{Qw, f_m\}$, (D, N) becomes optimal strategy for $\sigma_{vn,dn} < \sigma < \sigma^1_{vr,dn}$. This leads to the optimal structure stated in the proposition. Note that $f_m = \max_{\sigma} \Delta_2$. The upper bound essentially ensures that staying disintegrated does not dominate (V, R) and (V, N). $\square$

Proof of Proposition 18

We will prove the proposition only for $\alpha > 0$. However, similar analysis can be performed for $\min\{\frac{c_r+\beta(p-w)}{p-c_r}, \frac{\beta(p-w)}{-c_r+2p+w}\} < \alpha \leq 0$. Suppose that $f = 0$. When $0 < \alpha < -\beta$, $\frac{d\Delta_1}{d\sigma} = -Q\left(\alpha c_r + p(\beta - 2\alpha\sigma)\right) > 0$, $\lim_{\sigma\to 0} \Delta_1 = -Qc_r < 0$ and
$\lim_{\sigma\to 1} \Delta_1 = -Q\left(\alpha c_r + c_r + \alpha(-p) + \beta p\right) > 0$. Hence, $\Delta_1 < 0$ if and only if $\sigma^1_{vr,vn} > \sigma > 0$ where $\Delta_1(\sigma^1_{vr,vn}) = 0$. Similarly, $\frac{d\Delta_2}{d\sigma} = Q\left(-\alpha c_r + 2\alpha p\sigma + \beta(-p) + w(-2\alpha\sigma + \alpha + \beta)\right) > 0$, $\lim_{\sigma\to 0} = Q\left(w - c_r\right) < 0$ and $\lim_{\sigma\to 1} = Q\left(-(\alpha+1)c_r + \alpha p - \beta p + \beta w + w\right) > 0$. Hence, $\Delta_2 < 0$ if and only if $\sigma^2_{vr,dn} > \sigma > 0$ where $\Delta_2(\sigma^2_{vr,dn}) = 0$. Since when $f = 0$, $\pi^A_{vn|dn} > \pi^A_{dn|dn}$, it must be that $\sigma^2_{vr,dn} > \sigma_{vn,dn}$. And these are true as long as $f \leq f_2$, where f_2 is defined as $f_2 = \Delta_2(\sigma^1_{vr,vn})$. Note that $\Delta_2(\sigma^2_{vr,vn}) > \lim_{\sigma\to 1} \Delta_3$ but (V, R) is more profitable than (D, N) for $\sigma \geq \sigma^2_{vr,vn}$ when $f \leq f_2$. Hence, when $f \leq f_2$, for $\sigma < \sigma^1_{vr,vn}$, (V, N) is the optimum strategy. Otherwise, (V, R) is the optimum strategy.

When $f > f_2$, from the definition of f_2 we can see that $\sigma^2_{vr,dn} > \sigma^1_{vr,vn} > \sigma_{vn,dn}$. Hence the proposition is proved. $\square$

Proof of Proposition 19

First lets find the equilibrium wholesale prices and profits of firm A for equilibriums $(V, R)_c$ and $(V, N)_c$. Note that the wholesale price offered to the firm B will make firm B indifferent between sourcing from firm A or from an outside supplier. Hence, $\pi^B_{dn|vn} = \pi^B_{dnc|vnc}$ and $\pi^B_{dn|vr} = \pi^B_{drc|vrc}$. From these we can find the wholesale prices stated in the equilibrium. The profits are as follows:

$$\pi^A_{vrc} = Q\left(-c_r - \beta\sigma(p - w) + w\right) + Q\left(p - c_r\right) - f \tag{C.1.1}$$

$$\pi^A_{vnc} = \sigma(\alpha(-p)Q + \beta pQ + \alpha Qw + \beta Qw) + \sigma^2(\alpha pQ - \alpha Qw) + pQ + Qw - f \tag{C.1.2}$$

Lets look at how functions Δ_4, Δ_5 and Δ_6 behave. $\frac{d^2\Delta_4}{d\sigma^2} = 2\alpha p Q$, and hence, this function is concave for $\alpha < 0$, linear for $\alpha = 0$, and convex for $\alpha > 0$. $\frac{d\Delta_4}{d\sigma}|_{\sigma=0} = Q(\beta w - p(\alpha + 2\beta)) > 0$, $\frac{d\Delta_4}{d\sigma}|_{\sigma=1} = Q(p(\alpha - 2\beta) + \beta w) > 0$, $\Delta_4|_{\sigma=0} = Q\,(w - 2c_r) < 0$, and $\Delta_4|_{\sigma=1} = Q\,(-2c_r - 2\beta p + \beta w + w) > 0$. Therefore, There exists a single $\sigma_{vrc,vn}$ such that $\Delta_4 > 0$ if and only if $\sigma > \sigma_{vrc,vn}$. Similarly, we can show that when $\alpha \geq \frac{-c_r+(-\beta)(p-w)+w}{p-c_r}$, $\Delta_5 < 0$. And when $\alpha < \frac{-c_r+(-\beta)(p-w)+w}{p-c_r}$, there exists a $\sigma_{vrc,vr}$ such that $\Delta_5 > 0$ if and only if $\sigma > \sigma_{vrc,vr}$.

$\frac{d^2\Delta_6}{d\sigma^2} = 2\alpha Q(2p - w)$, then it is concave for $\alpha < 0$, convex for $\alpha > 0$ and linear for $\alpha = 0$. We can show that as long as $\alpha \leq \frac{\left(\beta+2\sqrt{\beta+1}+2\right)w}{2p-w}$, $\Delta_6 \geq 0$. Otherwise, There exist $\sigma^1_{vnc,vn}$ and $\sigma^2_{vnc,vn}$ such that $\Delta_6 < 0$ if and only if $\sigma^1_{vnc,vn} < \sigma < \sigma^2_{vnc,vn}$. Therefore, as long as $\alpha \leq \frac{\left(\beta+2\sqrt{\beta+1}+2\right)w}{2p-w}$, (V,N) cannot be in the equilibrium.

From above, we can see that when $\alpha \leq \frac{\left(\beta+2\sqrt{\beta+1}+2\right)w}{2p-w}$, $(V,N)_c$ is the equilibrium for $\sigma < \sigma_{vrc,vnc}$; otherwise, $(V,N)_c$ is the equilibrium.

Now, we will show that there exists a $\alpha_1 > \frac{\left(\beta+2\sqrt{\beta+1}+2\right)w}{2p-w}$ such that (V,N) and (V,R) cannot arise in the equilibrium and the equilibrium structure described above continue to hold for this region as well. From the implicit differentiation:

$$\frac{d\sigma_{vrc,vnc}}{d\alpha} = -\frac{\frac{\partial\Delta_7}{\partial\alpha}}{\frac{\partial\Delta_7}{\partial\sigma}} = -\frac{(\sigma-1)\sigma(p-w)}{\alpha(-p)+2\beta p+2\alpha\sigma(p-w)+\alpha w}|_{\sigma=\sigma_{vrc,vnc}} < 0, \tag{C.1.3}$$

$$\frac{d\sigma_{vrc,vn}}{d\alpha} = -\frac{\frac{\partial\Delta_4}{\partial\alpha}}{\frac{\partial\Delta_4}{\partial\sigma}} = -\frac{p(\sigma-1)\sigma}{\beta w - p(-2\alpha\sigma+\alpha+2\beta)}|_{\sigma=\sigma_{vrc,vn}} > 0. \tag{C.1.4}$$

In addition, we can show that $\sigma_{vrc,vnc} = \sigma_{vrc,vn}$ if and only if

$$\alpha = \alpha_1 = \frac{2\beta^2 w\left(4p^2 - 3pw + w^2\right)(c_r - p)}{\left(-w\,(2c_r + p) + 4pc_r + w^2\right)\left(c_r(4p - 2w) + 4\beta p^2 - p(3\beta w + w) + (\beta+1)w^2\right)}. \tag{C.1.5}$$

When $\frac{\left(\beta+2\sqrt{\beta+1}+2\right)w}{2p-w} < \alpha \leq \alpha_1$, $\pi^A_{vn} > \pi^A_{vnc}$ for $\sigma^1_{vnc,vn} < \sigma < \sigma^2_{vnc,vn}$; however, we can show that $\pi^A_{vrc} > \pi^A_{vn}$ for the same region. Therefore, (V,N) cannot be in the equilibrium.

For $\alpha > \alpha_1$, we can proceed in the same manner to show the rest of the proposition. Note that α_2 is such that $\sigma_{vrc,vr} = \sigma_{vrc,vn}$.

In order to show that $\frac{\left(\beta+2\sqrt{\beta+1}+2\right)w}{2p-w} < \alpha_2$, consider $\hat{\alpha} = \frac{2(\beta+2)w}{2p-w} > \frac{\left(\beta+2\sqrt{\beta+1}+2\right)w}{2p-w}$. Then we can directly compare $\sigma_{vrc,vr}$ and $\sigma_{vr,vn}$ at $\alpha = \hat{\alpha}_d$ to show that at this α value $\sigma_{vrc,vr} < \sigma_{vr,vn}$ which essentially proves that $\frac{(\beta+2\sqrt{\beta+1}+2)w}{2p-w} < \alpha_2$. $\square$

Proof of Proposition 20

By using the implicit function theorem we can show that $\frac{d\sigma^1_{vr,vn}}{d\alpha} < 0$, $\frac{d\sigma^1_{vr,dn}}{d\alpha} < 0$, $\frac{d\sigma^2_{vr,vn}}{d\alpha} > 0$, $\frac{d\sigma^2_{vr,dn}}{d\alpha} > 0$. This proves that the region where (V, R) is the equilibrium expands. $\square$

Proof of Proposition 21

This can be shown similar to the previous proposition. $\square$

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