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Competitive Quality Choice and Remanufacturing

Adem Örsdemir, Eda Kemahlıoğlu-Ziya, Ali K. Parlaktürk
Kenan-Flagler Business School, The University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599, USA
adem_orsdemir@unc.edu, eda_kemahliogluziya@unc.edu, pturk@unc.edu

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.

Key words: product quality; remanufacturing; competition; environmental impact; social welfare
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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 United States, the majority of remanufacturing is done by IRs (Hauser and Lund 2008). The same study finds that the remanufacturing industry in the United States 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 (2011) 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 study is quality. Following Moorthy (1988) and Desai (2001), we define quality as an attribute that exhibits 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 studies that consider competition between *independent* products (e.g., Desai 2001, Moorthy 1988) do not immediately extend to the remanufacturing context. Thus, in this study we examine *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 (US Environmental Protection Agency 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 the competing remanufactured product. The OEM and the IR competitively determine their production outputs, which determine the prices of the new and remanufactured products. The remanufactured product can be perceived as 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 United States 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-à-vis* the new product and is explained in detail in section 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 to 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 the 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 limit 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; the perceptual quality gap between new and remanufactured products is independent of product quality; and 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. 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., Esenduran et al. 2010, Ferrer and Swaminathan 2010), an IR competing with an OEM (e.g., Esenduran et al. 2012, Ferrer and Swaminathan 2006, Majumder and Groenevelt 2001), or an OEM who faces competition from another firm (e.g., Atasu et al. 2008, Heese et al. 2005). 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-à-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 in 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 determines their relative competitive positioning, which plays a key role in our results.

In the operations management literature, a number of studies examine 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., Bernstein and Federgruen 2004, Tsay and Agrawal 2000) 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., Fishman and Rob 2000, Plambeck and Wang 2009, Souza et al. 2004). 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 studies 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 that uncertainty in remanufacturing cost may lead to higher reusability investment. Subramanian et al. (2011) study how remanufacturing threat of an IR affects the component commonality decision for an OEM selling two vertically differentiated products with exogenous qualities.

Atasu and Souza (2011) is the closest to our work. They consider a monopolist who remanufactures in-house and study the effect of three product recovery forms, that is, 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, that is, 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.

3. Model Overview

We consider an OEM selling a new product and an 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 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., Atasu and Souza 2011, Desai 2001, Moorthy 1988). 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 8.2 allows for such an additional cost term as in Atasu and Souza (2011). 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 (2011), Agrawal et al. (2011) and 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), and Atasu et al. (2009). 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 the following prices for the new and remanufactured products:

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

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 2011, 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

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

and the IR simultaneously solves

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

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

In addition to our base model, we consider the monopoly no-remanufacturing (NR), monopoly remanufacturing, and exogenous quality benchmarks. The monopoly 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 the 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 the Online Supplement.

4. Equilibrium

In this section, we discuss the decisions of the OEM and the IR in equilibrium. As will be evident, a 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 the α/δ ratio decreases, the IR's competitiveness increases and vice versa for the OEM. This is because increasing the α/δ ratio indicates that 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 equipment and printer cartridges for two examples that fall on two opposite ends of the spectrum. Remanufacturing medical imaging equipment (e.g., computer tomography and magnetic resonance imaging) has 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 equipment 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, the 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 and new and remanufactured product quantities are provided in Table 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.

Table 1 Equilibrium Product Quality and New and Remanufactured Product Quantities

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	$\frac{1}{3\beta}$	$\frac{2}{3(2+\delta)}$	$\frac{2}{3(2+\delta)}$

Figure 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 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 1 Characterization of Equilibrium Regions

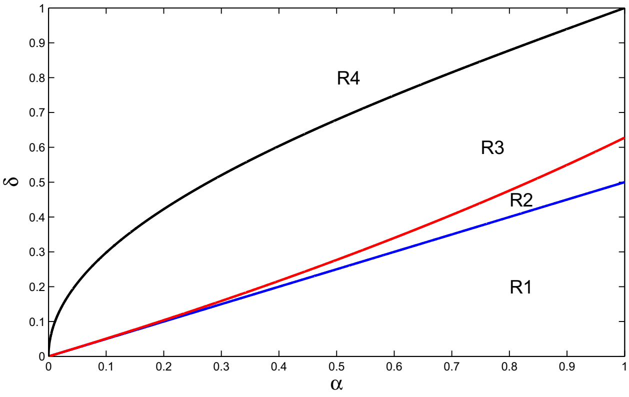


Figure 2 graphically demonstrates how the OEM's chosen quality level depends on the IR's cost of remanufacturing. We refer to the OEM's behavior in region *R*2 as entry deterrence because the OEM prevents the IR's entry by deviating from the NR benchmark. Note that entry deterrence does not exist in the exogenous quality benchmark (see section A in the Online Supplement). In other words, quantity alone is not sufficient to deter entry.

In region *R*3, the OEM can no longer deter the IR's entry. In this region, the OEM can 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, that is, $\frac{\alpha}{\delta} > 1$, 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, that is, $\frac{\alpha}{\delta} < 1$, the OEM chooses a lower quality level to de-emphasize its competitor's advantage.

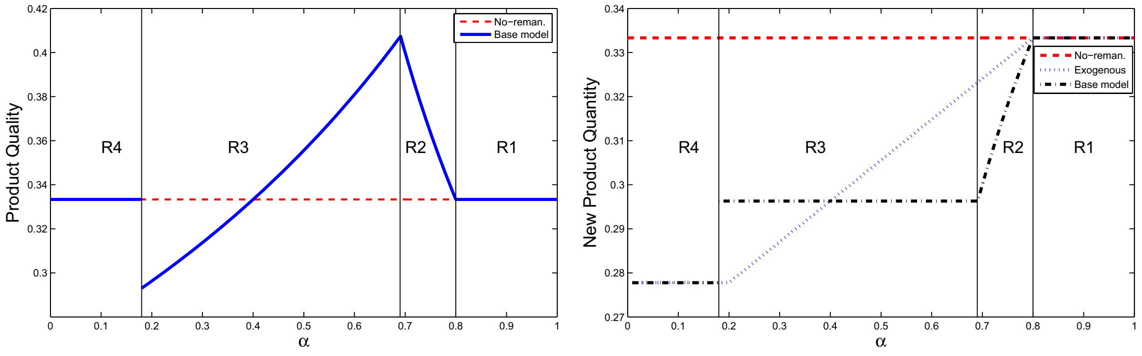
Finally, in region *R*4, the IR is very powerful and remanufactures all available cores. In this region, there is little perceived quality difference between the new and remanufactured products due to high δ, and the OEM cannot compete with the IR using the quality lever. Thus, the OEM keeps the quality at the NR benchmark level and instead competes with the IR by limiting the new product quantity and thereby the available cores for remanufacturing. We call this the quantity-limiting strategy. Figure 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 *R*4, there is discontinuity in the quantity and the quality levels in Figure 2 when moving from region *R*3 to *R*4 due to this strategy switch. We do not observe the same phenomenon in the order quantity of the exogenous quality benchmark shown in Figure 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 *R*2 and *R*4 demonstrate two extremes. In *R*2, 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 *R*4, 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.2 of the Online Supplement). 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 (2011) also find that a monopolist OEM engaging in quality recovery (of which

Figure 2 Equilibrium New Product Quality and Quantity ($\delta = 0.4$, $\beta = 1$, Exogenous Quality $s_f = \frac{1}{3\beta}$)



(a) Quality

(b) New Product Quantity

remanufacturing is an example) chooses a quality level that is weakly higher than the no-recovery scenario.

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

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

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 that 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 that 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 *R*3. Thus, CS is lower than or equal to the NR benchmark in regions *R*1 and *R*2. In region *R*1, the IR is not a threat and the outcome is identical to the NR benchmark. In region *R*2, however, CS is strictly smaller than that of the NR benchmark as shown in the second half of the proposition. Specifically, in region *R*2, the OEM inefficiently chooses higher quality to deter the IR's entry and therefore focuses on the higher valuation consumers, which in turn reduces CS. Interestingly, CS can also suffer in region *R*3 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.

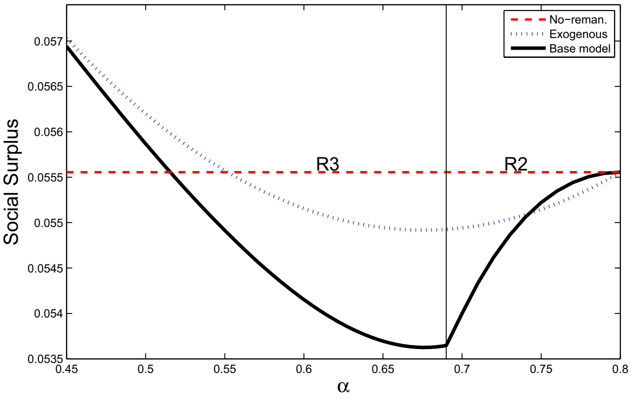
Proposition 3 indicates that an IR with a weak competitive position is not preferable for CS. In order for CS to benefit from remanufacturing, the IR must have a sufficiently strong cost-to-value advantage; otherwise the OEM's quality response hurts CS. This dynamic does not exist and CS always increases 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* $\frac{\alpha_s}{\delta} < \frac{\alpha}{\delta} < 2$.

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 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 that an IR's remanufacturing can decrease CS and SS. In contrast, our monopoly remanufacturing benchmark demonstrates that both CS and SS increase when a monopolistic OEM engages in remanufacturing. Likewise, our

Figure 3 Comparison of Social Surplus with No-Remanufacturing and Exogenous Quality Benchmarks ($\delta = 0.4$, $\beta = 1$, and Exogenous Quality $s_f = \frac{1}{3\beta}$)



extension in section 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 about 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 a 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 that 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.

6. Environmental Impact

We follow the convention in the literature (Agrawal et al. 2012, Atasu and Souza 2011, 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 $q_n E + q_r e$.

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

Proposition 5. *Table 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 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 the 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.

Table 2 Environmental Impact Comparative Statics

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

Figure 4 illustrates how the environmental impact depends on the IR's relative competitive position showing that environmental impact attains its worst level in region *R*3. 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 *R*2, as the OEM's cost-to-value advantage improves. Similarly at the other end, the environmental impact is also smaller in region *R*4, where the IR has a significant cost-to-value advantage.[2]

In region *R*4, the OEM follows the quantity scarcity policy to limit the IR's remanufacturing. Table 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. In both regions *R*2 and *R*4, quantity and, hence, the environmental impact decrease when the IR becomes more powerful. But there are different dynamics in place. In *R*2, quantity decreases because the OEM increases quality to deter the IR, whereas in region *R*4, the OEM creates scarcity to limit the IR's remanufacturing.

Comparisons with the monopoly remanufacturing benchmark (see section A.2 in the Online Supplement 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 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 (2011) 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 (2011) 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.

7. Additional Competitive Levers

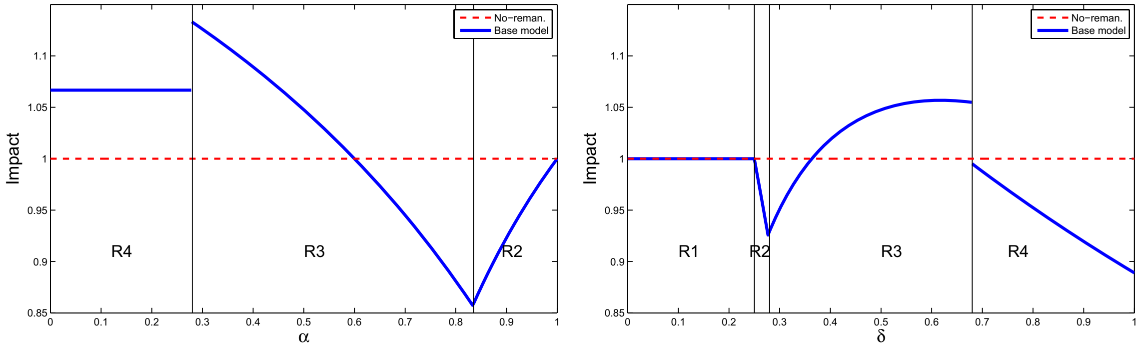
In this section, we study two additional levers an OEM can use to compete with an IR. Specifically, the OEM can also remanufacture its own product or it can collect cores to make them unavailable for the IR.

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

Figure 4 **Environmental Impact (e = 1, E = 3, δ = 0.5 in (a), α = 0.5 in (b))**



(a) Effect of α **(b)** Effect of δ

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]

Table 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 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, that is, $\alpha/\delta > 1$. It remanufactures some but not all available cores when the remanufactured product has the cost-to-value advantage, that is, $\alpha/\delta < 1$ but the advantage is not sufficiently big ($0.8 < \delta < 0.9$ in Table 3). Finally, when the remanufactured product has a significant cost-to-value advantage, a monopolist OEM remanufactures all available cores. Table 3 shows that 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 and 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 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 that 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 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.

Table 3 Equilibrium and the Resulting Consumer/Social Surplus and Environmental Impact when the OEM Can Also Remanufacture ($\beta = 1$, $\alpha = 0.8$)

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

The OEM increases quality when the remanufactured product has the cost-to-value advantage, that is, $\alpha/\delta < 1$. 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, that is, $\alpha/\delta > 1$, 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 ($0.40 < \delta < 0.49$).The NR benchmark is equivalent to the $\delta = 0.4$ outcome. 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 the 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 3. Thus a larger $\overline{e/E}$ indicates that remanufacturing is more likely to reduce the environmental impact. Improving the 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 is done by the OEM itself.

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 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.

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 the 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.

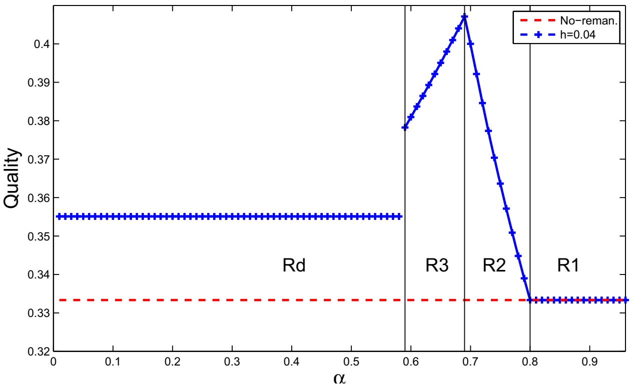
When the OEM uses quality to deter or compete with the IR (i.e., $0.59 \leq \alpha < 0.8$), the threat or actual entry can decrease the CS and SS compared to the NR benchmark. This behavior is similar to our base model. For $0 < \alpha < 0.59$, the OEM uses preemptive collection to deter the IR's entry, 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 B.1 of the Online Supplement, 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.

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, that is, quality choice, remanufacturing in-house, and preemptive collection, are available. In our study, we considered all combinations of

Figure 5 Equilibrium Quality when the OEM Can Collect and Dispose of the Used Cores ($\delta = 0.4$, $\beta = 1$, $h = 0.04$)



$\alpha \in \{0.1, 0.2, \ldots, 0.8, 0.9\}$ and $h \in \{0.04, 0.05, 0.06\}$. Table 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 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.

8. Extensions

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.

Table 4 Equilibrium when the OEM Can Remanufacture and Preemptively Collect ($\beta = 1$, $\alpha = 0.8$, $h = 0.04$)

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

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 B.2 of the Online Supplement). 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.

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, that is, $\frac{\alpha}{\delta} \geq 1$, and we state our result in Proposition 7. However, when the IR has the cost-to-value advantage, that is, $\frac{\alpha}{\delta} < 1$, the model is not analytically tractable; therefore we resort to a numerical study. Figure 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 have found that they are all consistent. We also study the impact of the quality independent remanufacturing cost on the CS and SS in the Online supplement (see section B.3) 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 that 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, that is, $\frac{-\alpha+2\delta}{9\beta} > n \geq n_0$. 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, that is, $\frac{2\delta-\alpha}{9\beta} \leq n$, the IR cannot enter at all, as expected.

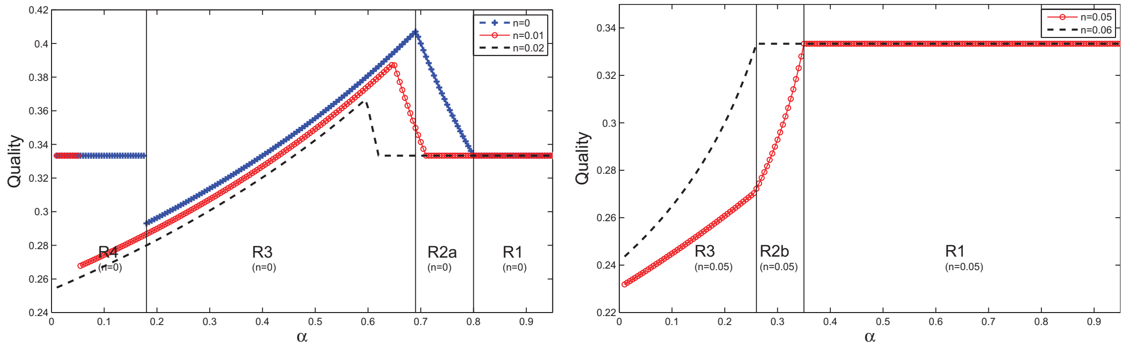
Figures 6a and 6b illustrate the equilibrium structure for $n \in \{0,0.01,0.02\}$ and $n \in \{0.05,0.06\}$ respectively. Figure 6a shows that when the IR has a strong cost-to-value position, the OEM may continue to rely on reducing production and limiting core availability (region $R4^i$). However, as intuition suggests, region $R4^i$ gets smaller as n increases. In fact, when $n \geq 0.02$, $R4^i$ disappears. Figure 7 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).

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 the 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 7 shows the equilibrium quality and quantity as quality gap ϕ varies for $\alpha = 0.4$. We find the behavior in

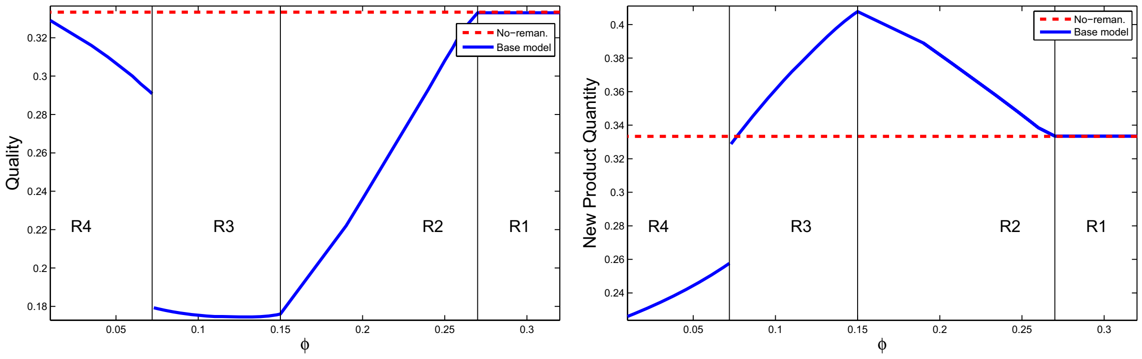
Figure 6 Equilibrium Quality Level when the IR Incurs Quality-Independent Cost (δ = 0.4, β = 1); (a) $n \in \{0,0.01,0.02\}$ (Partitions *R*1–*R*4 Are Shown for n = 0); (b) $n \in \{0,0.05,0.06\}$ (Partitions *R*1–*R*3 Are Shown for n = 0)



(a)

(b)

Figure 7 Equilibrium Quality and New Product Quantity when the Perceptual Quality Gap Is Independent of New Product Quality ($\alpha = 0.4$, $\beta = 1$)



(a) Quality **(b)** New Product Quantity

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 $R1$, the 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 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 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 B.4 of the Online Supplement).

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 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 that remanufacturing by an OEM always benefits the consumers (Atasu and Souza 2011 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 payoffs. Indeed, most studies looking at firms' quality choice consider stationary demand as we do (e.g., Atasu and Souza 2011, Johnson and Myatt 2006, Netessine and Taylor 2006, Plambeck and Wang 2009). 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 address in this study 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-à-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.

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Notes

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

[2] Although $e < E$ in Figure 4, the insights discussed here hold for $e \geq E$ as well.

[3] We know from section 5 and section A.2 in the Online Supplement 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.

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

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

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix A: Benchmarks

Appendix B: Consumer and Social Welfare Results for Extensions to the Base Model

Appendix C: Proofs