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When remanufacturing meets product quality improvement: The impact of production cost

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ABSTRACT

Remanufacturing as well as quality improving innovations are important activities to improve sustainability. However, when coexisting in one company, their interaction is not clear. On the one hand, past research found a positive impact of remanufacturing on product quality. On the other hand, remanufacturing was shown to be negatively affected by an industry's technology trajectory of quality improvements.

Using a stylized model of endogenous product quality improvement and remanufacturing we find that the main driver of the contradicting results is the change in manufacturing costs caused by improving product quality. A strong increase in manufacturing costs due to product quality improvement may induce the firm to take up remanufacturing when introducing the new product. Conversely, a small impact of product quality improvement on manufacturing costs reverses this effect and may indeed lead the firm to cease remanufacturing when introducing the new product. We find that the latter outcome is never beneficial from an environmental point of view, while the former always is. With endogenous product quality improving innovation we then characterize conditions where a remanufacturing manufacturer would take a different product quality improvement decision than a non-remanufacturing manufacturer. We observe that remanufacturing stifles (stimulates) product quality improvement when manufacturing cost of quality improved products are low (high). Neither of the two results are exclusively beneficial or detrimental from an environmental perspective and we characterize the conditions under which product quality improvement is preferable.

1. Introduction

Remanufacturing has been identified as a resource efficient and sustainable strategy within the circular economy: consumption of raw materials can be significantly reduced and energy use and emissions to air and water can be avoided by keeping the core components in use for longer (Parker et al., 2015). However, manufacturers, particularly in innovative industries, constantly invest in new products with improved quality to cater for consumer demands. Intuitively, if quality improvement cycles are short, consumers' propensity of purchasing the remanufactured products will be smaller since the improved quality features are not included. On the other hand, higher quality of the new product may – through an associated increase in new product price – reduce this effect in the short run. At the same time, increasingly harsh regulations posed on manufacturers regarding re-use and remanufacturing will have an impact on strategic decision making including new product quality improvement. Particularly, if remanufacturing is seen as a value proposition (as advocated in Guide Jr. & Van Wassenhove, 2009) a firm may find it less appealing to constantly improve product quality if that reduces remanufacturing profitability.

However, the underlying tradeoffs are not yet fully understood in both academia and practice as indicated by contradicting results. While companies like Xerox and Apple have been remanufacturing and reselling used products for a long time, Samsung only recently started to remarket its remanufactured smartphones (Etherington, 2016). Moreover, while the smartphone industry is fast moving and Apple as well as Samsung are at the forefront of innovation, Xerox has been less of a success story in terms of capitalizing on its inventions (Mui, 2012). The example of Xerox is also used as a motivation in two scientific papers that come up with opposing results. Galbreth, Boyaci, and Verter (2013) mention that a key element, the explicit consideration of incremen-

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tal quality improving innovation, is missing in the extant body of academic work on remanufacturing. They investigate the impact of the rate of quality improvements on the product reuse decision and find that quality improving innovation can reduce the quantity of remanufactured products. On the contrary, Atasu and Souza (2013), the first study to analyse the impact of product recovery on quality choice under voluntary and mandated product take-back environments, show that remanufacturing may increase the optimal quality provision of a manufacturer. Note that, while quality choice is only one aspect of innovation in general (besides timing, product or process innovation, among many others), in Galbreth et al. (2013) incremental innovation is synonymous to quality choice/improvement. Moreover, though Galbreth et al. (2013) focus on quality improvement through incremental innovation, while Atasu and Souza (2013) study a one-shot quality choice decision, the market impact, based on the evaluations of products with different quality, are analogous in the two models.

Our paper aims at contributing to further our understanding about the critical relationship between product quality improvement and remanufacturing by revisiting these contradictory results.

In particular, we aim to answer the following questions:

- (Under what conditions) Will product quality improvement stimulate or reduce the manufacturer's remanufacturing efforts?
- Does remanufacturing increase or decrease the manufacturer's propensity to improve product quality?
- What are the environmental implications of the manufacturer's profit-optimal strategy?

As mentioned above, in Galbreth et al. (2013) quality improvement is exogenously modeled by an industry trajectory and Atasu and Souza (2013) use a static setting, which means the quality decision is taken once and for all and there is no upgrade over time. In this paper, we endogenize the product quality improvement decision in a remanufacturing setting and develop a generalized model to resolve the before mentioned contradicting results from these two papers.

Specifically, we consider a manufacturer facing the decision to invest in product quality improvement and/or remanufacture its used products. The situation is modelled as a two-period decision problem. At the outset, the manufacturer has the first generation of a new product available. At the beginning of the first period, the manufacturer takes an investment decision that would make a quality improved second generation of the new product available in period 2. Further, the manufacturer makes its first period quantity decision for (first generation) new products to sell to the market. At the end of the first period, used products are collected. In the second period, those used products can then be remanufactured and sold on the market to consumers with lower willingness-to-pay for the product. Besides, the manufacturer again decides its quantity of new products to manufacture and sell to the market. Depending on the investment decision taken prior to period 1, these new products will be first (if no investment was taken) or second (if the manufacturer did invest) generation of the product. We assume that consumers' willingness-to-pay for second generation units is larger than for first generation units. Note that the same assumption is also adopted by Atasu and Souza (2013) and Galbreth et al. (2013). In both periods, the products' prices are determined by the manufacturer's quantity decisions.

Using this stylized model, we explore the interaction between remanufacturing and product quality improvement. Specifically, we focus on the impact of quality-dependent manufacturing cost on the relationship between remanufacturing and new product quality improvement. We find that when manufacturing efficiency is high (i.e. quality has little impact on manufacturing cost), if committed to remanufacturing, the manufacturer has less willingness to invest in product quality improvement. On the other hand, product quality improvement indeed hurts remanufacturing, in that it may induce the manufacturer to give up remanufacturing after introducing the second generation new product. These results are completely reversed when manufacturing efficiency is low (i.e. quality has a strong impact on manufacturing cost). Similarly, for high manufacturing efficiency we find that increased quality increases resource consumption which we use as a proxy for environmental impact, while it reduces total resource consumption when manufacturing efficiency is low. Moreover, we find that under certain conditions giving up remanufacturing after improving product quality may benefit the environment when compared with remanufacturing and foregoing quality improvement.

Our results have important implications for both firm decision makers and policy makers. Understanding the implications product quality improvement will have on remanufacturing, manufacturers can better focus their R&D efforts on projects that ideally perform on both economic and environmental aspects. Moreover, the results support firms in deciding which products may be worth remanufacturing. From a policy-maker's point of view, our results highlight the fact that encouraging remanufacturing through legislation ultimately aimed at improving product design may in fact have the inverse effect of stifling product quality improvement. Moreover, from an environmental point of view, encouraging product quality improvement may be preferable over encouraging remanufacturing.

Overall, we make the following contributions: first, we endogenize the product quality improvement decision in a remanufacturing setting and develop a stylised model to study the interaction between remanufacturing and product quality improvement. Second, we derive the conditions under which remanufacturing and product quality improvement are mutually beneficial or exclusive. Third, we investigate the environmental implications of improving product quality and remanufacturing in terms of the total resource consumption and show what is preferred by the manufacturer might not be environmentally friendly. The results can help to inform policy makers in terms of environmental regulations.

The remainder of the paper is organised as follows. Section 2 reviews the related literature and posits our research in the literature. Section 3 provides the problem setting and modelling framework. We analyse the model, derive managerial insights and discuss environmental implications in Section 4. Section 5 concludes the paper. Proofs of all our theoretical results are provided in the appendix.

2. Literature review

Our study builds on three streams of literature: remanufacturing and closed-loop supply chains, product design in CLSCs as well as the interaction between product innovation and remanufacturing.

Remanufacturing and closed-loop supply chain management have been extensively studied in the past decades. Souza (2013) and Govindan, Soleimani, and Kannan (2015) provide very comprehensive literature reviews in this area. Atasu (2016) integrates the latest and most influential research in an edited book.

Traditionally, the research on remanufacturing and closed loop supply chain management mostly focuses on the competition and market segmentation between new and remanufactured products (Atasu, Sarvary, & Van Wassenhove, 2008; Ferrer & Swaminathan, 2006; 2010; Souza, 2013), inventory management (Corum, Vayvay, & Bayraktar, 2014; Hsueh, 2011; Toktay, Wein, & Zenios, 2000; Zanoni, Ferretti, & Tang, 2006; Zhou & Yu, 2011), or pricing for used products (Guide Jr., Teunter, & Van Wassenhove, 2003; Liang, Pokharel, & Lim, 2009; Xiong et al., 2014). This stream of research usually assumes that the technology and product design are exogenously given and do not change during the decision horizon. Therefore, the main focus is the interaction between new and remanufactured products. Although remanufactured products may cannibalize the new product market, the overall profit may increase due to the low cost of remanufactured products (Souza, 2013). As indicated above, none of these models consider the product design or product quality improvement issues in a remanufacturing context.

Green product design, also known as design for environment, addresses environmental issues through product design (Chen, 2001). Chen (2001) develop a quality-based model to analyse the conflicts between traditional and environmental attributes. Krishnan and Lacourbe (2011) model firm's product decisions including both functional and environmental quality dimensions, and identify the conditions under which both profit and environmental quality are maximized. Raz, Druehl, and Blass (2013) analyse the design for environment issues in a newsvendor setting. The firm can invest in manufacturing stage environmental improvement and usage stage environmental improvement. They show that overproduction may increase the overall environmental impact although the unit environmental impact decreases due to the investment in the design. These papers include the environmental attributes in product design decisions, however, ignore product reuse options.

Recent years witnessed a growing trend in researching the interaction between product design and used product recovery. Atasu and Souza (2013) investigate how product reuse impacts product quality choice, and find that recovery may lead to higher product quality. They also show the role that the form of product recovery, recovery cost structure and product take-back legislation play for firm's quality choice. Örsdemir, Kemahlolu-Ziya, and Parlaktürk (2014) extend Atasu and Souza (2013) to the oligopoly setting and study the competitive quality choice in presence of remanufacturing. They find that when an OEM competes with an independent remanufacturer, remanufacturing may reduce the quality and increase environmental impact. Debo, Toktay, and Van Wassenhove (2005) study the joint pricing and remanufacturability decision faced by a manufacturer introducing a remanufacturable product. While the optimal remanufacturability level is determined by the consumer profile (Debo et al., 2005), if the firm can make both product quality and remanufacturability decisions, the firm would couple increased remanufacturing with higher product quality (Gu, Chhajed, Petruzzi, & Yalabik, 2015). Subramanian, Ferguson, and Toktay (2013) investigate the impact of remanufacturing on the component commonality decision, and derive the conditions under which the OEM's commonality decision may be reversed. Wu (2012) studies the design-for-disassembly problem in a supply chain formed by an original equipment manufacturer producing new products and a remanufacturer remanufacturing the used products. Using a two-period model, the author derives managerial insights for the manufacturer and remanufacturer. The product design decision in the above papers is made once and for all at the beginning of the decision period, either for functional improvement or environmental improvement. Conversely, we assume that the manufacturer can improve product quality over time.

The interaction between product innovation and remanufacturing is rarely studied in the literature. Limited research only focuses on the impact of product innovation on remanufacturing (Boyaci, Verter, & Galbreth, 2016; Galbreth et al., 2013). Galbreth et al. (2013) show that incremental innovation may reduce the value of remanufacturing and thus can have a negative economic effect. This is also true under radical innovation (Boyaci et al., 2016). Boyaci et al. (2016) investigate a manufacturer's decision regarding the design for reusability and the product reuse decision considering exogenous innovation including a deterministic incremental innovation rate and a stochastic radical innovation that may occur over time. However, given that innovation in the above two papers is exogenous it is not part of the manufacturer's strategic decision space.

Extending existing research, we consider endogenous product quality improvement, thereby studying product quality decisions in a simple dynamic setting, and model consumer preferences for new and remanufactured products as a function of new product quality. Summarizing, our research investigates the mutual impacts between product quality improvement and remanufacturing.

3. Problem setting

We consider a monopolist manufacturer's joint strategic decisions on remanufacturing and product quality improvement and abstract from the optimal timing decisions for new product introductions by focusing on a two-period model. Every period corresponds to a life-cycle of the product. In the first period the manufacturer sells the first generation of new products at price p_{1n} to heterogeneous consumers with a willingness-to-pay of $v_n \sim U[0, 1]$. Per unit manufacturing cost is given by $c_{1n} < 1$.

Prior to the beginning of period 1 (i.e. at time $t = 0$) the manufacturer can take the strategic decision whether or not to invest in new product R&D. Without investment, the manufacturer still sells the first generation new product in period 2 under unchanged consumer valuation. If he invests a quality improved second generation new product will be available for period 2 (i.e. at time $t = 1$). Following the extant literature we assume that the product quality improvement cycle coincides with the product life cycle (see e.g. in Atasu & Souza, 2013; Ovchinnikov, Blass, & Raz, 2014) and that consumers are willing to pay a premium for improved goods and services (see e.g. Atasu & Souza, 2013; Galbreth et al., 2013). We model this by a parameter $\theta_{2n} \geq 1$, such that a consumer's willingness-to-pay in period 2 is given by $\theta_{2n} v_n$. If the manufacturer sticks with the first generation product we have $\theta_{2n} = 1$, while we mimic product quality improvement by letting $\theta_{2n} > 1$. Our goal is to analyse the maximum R&D investment k a manufacturer is willing to undertake to obtain a given level of $\theta_{2n} > 1$ associated with the second generation quality improved product. Consequently, the relationship between k and θ_{2n} will be a result of our analysis.

The manufacturing cost in period 2 also depends on the generation of new products offered and in general is given by $c_{2n} = c_{1n}\theta_{2n}^{\xi}$. This functional form is commonly used in modelling production cost of a product with improved quality (see Krishnan & Lacourbe, 2011 and references therein). Here $\xi \geq 0$ corresponds to the second generation manufacturing efficiency associated with the improved product features. For example, in Atasu and Souza (2013) a convex-increasing relationship is modeled by setting $\xi = 2$. In our analysis below, we will show that the choice of ξ crucially influences the structural insights about the relationship between product quality improvement and remanufacturing. Clearly, without quality improvement, i.e. when the generation 1 product is sold in period 2, the cost is given by $c_{2n} = c_{1n}$.

At the end of the first period used units are returned by the consumers. Without loss of generality, and in line with our assumption concerning the product life-cycle, we assume that all first period sales q_{1n} are returned. The manufacturer can remanufacture those units at per unit cost $c_r = \alpha c_{1n}$ and sell them on a secondary market at price p_{2r}.[1] Here $\alpha < 1$ models the remanufacturing efficiency compared to new production. Following the extant literature we assume that consumers are homogeneous

[1] To simplify the analysis we assume that collection cost are zero. Since adding collection cost will, regardless of any other decisions, just reduce the profitability of remanufacturing this simplification will not alter the qualitative insights we provide.

in their discounted valuation for remanufactured products. Their willingness-to-pay for remanufactured products is given by $\theta_r v_n$, where $\theta_r < 1$.

Summarizing, the manufacturer decides: (i) at time 0, whether or not to invest in R&D to obtain a 2nd generation quality improved new product for period 2, as well as how many 1st generation new units q_{1n} to manufacture and offer to the market; (ii) at time 1, how many new and remanufactured units q_{2n} and q_{2r}, respectively, to offer to the market.

3.1. The demand model

As mentioned above, we consider heterogeneous consumers with willingness-to-pay $v_n \sim U[0, 1]$ for the first generation new product. The valuations for new products of the same generation are the same across different periods because only one new product exists in the market at any given time (this is in line with Debo et al., 2005).

In the first period, the net utility of a consumer buying the new product is $U_{1n} = v_n - p_{1n}$. The condition $U_{1n} \geq 0$ yields the inverse market demand for first generation new products in period 1 as $p_{1n} = 1 - q_{1n}$.

In the second period, new and remanufactured products will compete for market share. Given the willingness-to-pay for remanufactured products mentioned above, the net utility of a consumer buying a remanufactured product is $U_{2r} = \theta_r v_n - p_{2r}$. The consumer's net utility of buying a new product depends on whether the new product will be first or second generation (i.e. whether or not the manufacturer undertook product R&D at time $t = 0$) and, the same as Atasu and Souza (2013), is given by $U_{2n} = \theta_{2n} v_n - p_{2n}$. Note that also in Galbreth et al. (2013) an analogous consumer utility model is used to study incremental product innovation. While in their context the new product evaluation is normalized to 1 (to reflect the industry trajectory) and remanufactured products are devalued with increased quality of the new product (yielding an evaluation of $\frac{\theta_r}{\theta_{2n}}$), the relative evaluations of new over remanufactured products are the same as in our model, namely $\frac{\theta_{2n}}{\theta_r}$.

Using consumer rationality in their purchasing decisions we obtain the second period inverse demand functions:

$$p_{2r} = \theta_r(1 - q_{2n} - q_{2r}) \tag{1}$$

and

$$p_{2n} = \theta_{2n}(1 - q_{2n}) - \theta_r q_{2r}. \tag{2}$$

3.2. The manufacturer's decision problem

Under these demand functions the manufacturer's profit before investment cost can be written as

$$\Pi(\theta_{2n}, q_{1n}, q_{2n}, q_{2r}) = (p_{1n} - c_{1n})q_{1n} + (p_{2n} - c_{2n})q_{2n} + (p_{2r} - c_r)q_{2r}. \tag{3}$$

Using the indicator function $\mathbb{1}_{\theta_{2n}>1}$ to reflect whether the manufacturer undertook product R&D or not, the optimization problem then is to maximize profits including investment cost as follows:

$$\max_{\theta_{2n}, q_{1n}, q_{2n}, q_{2r}} \Pi(\theta_{2n}, q_{1n}, q_{2n}, q_{2r}) - k\mathbb{1}_{\theta_{2n}>1} \tag{4}$$

$$s.t. \quad 0 \leq q_{2r} \leq q_{1n} \tag{5}$$

$$q_{2n} \geq 0 \tag{6}$$

Here k is the investment cost. Note that remanufacturing can only be profitable at all under the assumption $\theta_r > \alpha c_{1n}$.

3.3. Measuring (virgin) resource consumption

Our model shown above maximizes the firm's profit as a function of its product quality improvement and remanufacturing decisions. We follow some of the extant literature and measure total resource (virgin material) consumption as a proxy for environmental impact (see e.g. Galbreth et al., 2013).

Assume that the unit resource consumption of new products in both periods – i.e. regardless of their generation – is γ_n and the unit resource consumption of the remanufactured product is $\gamma_r < \gamma_n$. Note that the assumption about the identical resource consumption of new first and second generation products is reasonable for functional quality improvement, for example the iPhone series, which is quite common in current practice.

The total resource consumption of a firm in our model is then given by

$$TEI = (q_{1n} + q_{2n})\gamma_n + q_{2r}\gamma_r.$$

4. Model analysis

We can solve the firm's problem by first obtaining the optimal first period production decision q_{1n} as well as the optimal second period production decision q_{2n} and remanufacturing decision q_{2r} for given θ_{2n}. Afterwards, by comparing the differential of profits with ($\theta_{2n} > 1$) and without ($\theta_{2n} = 1$) quality improvement with the investment cost k, we can obtain the optimal product quality improvement decision θ_{2n}.

Lemma 1 provides the optimal production strategy along with the associated quantities and prices for a given level of θ_{2n}.

Lemma 1. *To exclude the meaningless solution where the manufacturer stops new production in period 2 when $\theta_{2n} = 1$ (i.e. there is no innovation) we assume $\alpha > \frac{c_{1n}+\theta_r^2-1}{c_{1n}\theta_r}$.*

Case 1: $\xi \leq 1$: The manufacturer's optimal second period quantity decisions for given θ_{2n} are characterized by three different operational regions:

I *No remanufacturing but new production*
$\alpha > \theta_r\theta_{2n}^{\xi-1}$

II *Partial remanufacturing and new production*
$\theta_r\theta_{2n}^{\xi-1} - \frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{c_{1n}\theta_{2n}} \leq \alpha \leq \theta_r\theta_{2n}^{\xi-1}$

III *Full remanufacturing and new production*
$\alpha < \theta_r\theta_{2n}^{\xi-1} - \frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{c_{1n}\theta_{2n}}$

Case 2: $\xi > 1$: The manufacturer's optimal second period quantity decisions for given θ_{2n} are characterized by five different operational regions:

$\alpha > \theta_r$:

I *No remanufacturing but new production*
$\alpha > \theta_r\theta_{2n}^{\xi-1}$

II *Partial remanufacturing and new production*
$\theta_{2n}^{\xi} - \frac{\theta_{2n}-\theta_r}{c_{1n}} < \alpha \leq \theta_r\theta_{2n}^{\xi-1}$

IV *Partial remanufacturing but no new production*
$\alpha \leq \theta_{2n}^{\xi} - \frac{\theta_{2n}-\theta_r}{c_{1n}}$

$\alpha \leq \theta_r$:

II *Partial remanufacturing and new production*
$\alpha \geq \theta_r\theta_{2n}^{\xi-1} - \frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{c_{1n}\theta_{2n}}$

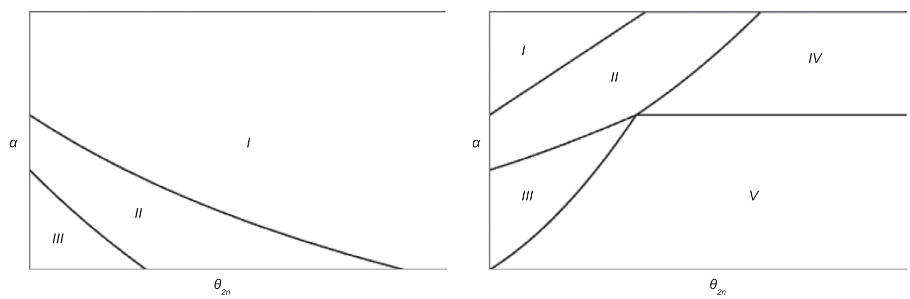
III *Full remanufacturing and new production*
$(1+\theta_r)\frac{c_{1n}\theta_{2n}^{\xi}-(\theta_{2n}-\theta_r)}{c_{1n}\theta_r} - 1 < \alpha < \theta_r\theta_{2n}^{\xi-1} - \frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{c_{1n}\theta_{2n}}$

V *Full remanufacturing but no new production*
$\alpha \leq (1+\theta_r)\frac{c_{1n}\theta_{2n}^{\xi}-(\theta_{2n}-\theta_r)}{c_{1n}\theta_r} - 1$

The associated quantities and prices are shown in Table 1.

Table 1
Production quantities and associated prices.

	Optimal quantities and prices		
Regions	q_{1n} p_{1n}	q_{2n} p_{2n}	q_{2r} p_{2r}
I	$\frac{1-c_{1n}}{2}$	$\frac{1-c_{1n}\theta_{2n}^{\xi-1}}{2}$	0
	$\frac{1+c_{1n}}{2}$	$\frac{\theta_{2n}(1+c_{1n}\theta_{2n}^{\xi-1})}{2}$	–
II	$\frac{1-c_{1n}}{2}$	$\frac{\theta_{2n}-c_{1n}\theta_{2n}^{\xi}-(\theta_r-\alpha c_{1n})}{2(\theta_{2n}-\theta_r)}$	$\frac{\theta_{2n}^{\xi}\theta_r c_{1n}-\theta_{2n}\alpha c_{1n}}{2\theta_r(\theta_{2n}-\theta_r)}$
	$\frac{1+c_{1n}}{2}$	$\frac{\theta_{2n}(1+c_{1n}\theta_{2n}^{\xi-1})}{2}$	$\frac{\alpha c_{1n}+\theta_r}{2}$
III	$\frac{(1-c_{1n}(1+\alpha))\theta_{2n}+c_{1n}\theta_r\theta_{2n}^{\xi}}{2[\theta_r(\theta_{2n}-\theta_r)+\theta_{2n}]}$	$\frac{c_{1n}(1+\alpha)\theta_r+(\theta_{2n}-\theta_r-c_{1n}\theta_{2n}^{\xi})(1+\theta_r)}{2[\theta_r(\theta_{2n}-\theta_r)+\theta_{2n}]}$	q_{1n}
	$1-\frac{(1-c_{1n}(1+\alpha))\theta_{2n}+c_{1n}\theta_r\theta_{2n}^{\xi}}{2[\theta_r(\theta_{2n}-\theta_r)+\theta_{2n}]}$	$\frac{\theta_{2n}(1+c_{1n}\theta_{2n}^{\xi-1})}{2}$	$\frac{\theta_r[(\theta_{2n}-\theta_r)(c_{1n}(1+\alpha)+\theta_r)+c_{1n}\theta_{2n}^{\xi}+\theta_r]}{2[\theta_r(\theta_{2n}-\theta_r)+\theta_{2n}]}$
IV	$\frac{1-c_{1n}}{2}$	0	$\frac{\theta_r-c_{1n}\alpha}{2\theta_r}$
	$\frac{1+c_{1n}}{2}$	–	$\frac{\theta_r+c_{1n}\alpha}{2}$
V	$\frac{1-c_{1n}(1+\alpha)+\theta_r}{2(1+\theta_r)}$	0	q_{1n}
	$\frac{1+c_{1n}(1+\alpha)+\theta_r}{2(1+\theta_r)}$	–	$\frac{\theta_r(1+c_{1n}(1+\alpha)+\theta_r)}{2(1+\theta_r)}$



a) ξ=0 b) ξ=2

Fig. 1. Operational regions under high ($\xi = 0$) and low ($\xi = 2$) second generation manufacturing efficiency ($\theta_r = 0.8, c_{1n} = 0.6$).

4.1. The impact of product quality improvement on the remanufacturing decision

Using Lemma 1 we can derive a strong result with respect to the impact of θ_{2n} on the optimal production strategy (given by q_{1n}, q_{2n} and q_{2r}) as a function of ξ.

Proposition 1. *When $\xi \le 1$, an increase in θ_{2n} will have a detrimental impact on remanufacturing.*

For $\xi > 1$, an increase in θ_{2n} will increase remanufacturing whenever $c_{1n} > \frac{\theta_r}{\theta_r+(\xi-1)\theta_{2n}^{\xi}}$.

Fig. 1 visualizes these results for two special cases, namely $\xi = 0$ and $\xi = 2$, respectively. Note that, as mentioned above, the latter case corresponds to the setting used in Atasu and Souza (2013).

While for $\xi \le 1$ the manufacturer would switch from full remanufacturing to partial remanufacturing to no remanufacturing, the opposite is true for $\xi > 1$. Note that for $\xi > 1$ the impact of increasing θ_{2n} on the manufacturing cost of the product might not be large enough when $c_{1n} \le \frac{\theta_r}{\theta_r+(\xi-1)\theta_{2n}^{\xi}}$. As a result, similar to the case $\xi \le 1$, a switch from full remanufacturing to partial remanufacturing can take place under $\xi > 1$ for relatively small c_{1n}. Furthermore, observe that for $\xi > 1$ the manufacturer would actually find it optimal to cease manufacturing new units in the second period when θ_{2n} is too large (regions IV and V). Clearly, this implies that the associated manufacturing cost of the second generation product would be prohibitive and the manufacturer would never invest in such a level of θ_{2n}. Thus, we need not further consider the corresponding regions in our analysis.

Comparing the decisions for low and high second generation manufacturing efficiency under the remaining cases I–III we observe that q_{1n} and q_{2r} are never smaller, while q_{2n} is always smaller under low second generation manufacturing efficiency. This is straightforward, as the increased manufacturing cost under $\xi > 1$ induce the manufacturer to increase the price of second generation new products p_{2n} which reduces their appeal to consumers. Consequently remanufactured products are more sought after. To cover the increased demand for remanufactured products without having to increase first period supply too much, the manufacturer even charges a higher price for remanufactured products when $\xi > 1$.

Unfortunately, further closed form analytical results for general ξ are not possible. Thus, in the following we will focus on the two cases used in Fig. 1 to exemplify the results for low and high second generation manufacturing efficiency.

Let us first turn to sensitivity analysis with respect to θ_{2n}. Under $\xi = 0$ an increase in θ_{2n} will always decrease the volume of remanufacturing both under partial and full remanufacturing. On the other hand, under $\xi = 2$ the opposite is true, i.e. an increase in θ_{2n} will always increase the volume of remanufacturing under partial as well as full remanufacturing whenever $\alpha \ge \theta_r^2$. In the remainder of this paper we will restrict ourselves to this case $\alpha \ge \theta_r^2$ for the sake of readability.[2]

Note that for $\xi = 0$ our results are identical with the findings from Galbreth et al. (2013) – who use a linear relationship between quality and manufacturing cost, which is equivalent to setting $\xi = 1$ in our model – whereafter a steeper industry trajectory (in our case a higher θ_{2n}) reduces the value of remanufacturing. However, our more general formulation shows that these results switch completely when $\xi > 1$. From a practical perspective this implies that the manufacturer needs to carefully analyse the relationship between product quality and manufacturing cost to evaluate the operational implications on the production quantities.

[2] When $\alpha < \theta_r^2$ the result may hold but also may be reversed and gets quite unintelligible. If requested, these results can be obtained from the authors.

When looking at the resource consumption associated with the above discussion we get the following clear-cut result.

Proposition 2. *When $\xi = 0$, improving product quality always increases total resource consumption.*

When $\xi = 2$, improving product quality always decreases total resource consumption for the remanufacturing firm.

From Proposition 2, we can see that when $\xi = 0$, improving product quality is always bad for the environment. The explanation to that comes from the relative importance of two counteracting effects. On the one hand, we have the demand inducing, market enlarging effect of introducing the second generation product (and associated increase in total resource consumption). On the other hand, we observe the reduction in market share with low willingness-to-pay customers (and associated decrease in total resource consumption) who would only have bought the remanufactured product whenever $\xi = 0$. When $\xi = 0$, the former effect is dominant, explaining the finding.

When ξ is high, the opposite can be observed. The demand shrinking effect of introducing the second generation new product due to increased manufacturing cost outweighs the market expansion due to sales of remanufactured products to consumers who would otherwise not have bought any product, thus driving the environmental result. Note that this result also holds when remanufacturing itself is not environmentally beneficial (as shown in e.g. Galbreth et al., 2013).

To summarize, our results so far suggest that higher product quality which induces less remanufacturing is always bad for the environment. Conversely, when higher quality enhances remanufacturing the environmental effect is positive. Below we will extend our analysis to product quality improvement decision.

Based on our theoretical analysis above, we can now move to the quality-improvement/investment decision. We are interested in the question under what conditions the manufacturer is actually better off by introducing the second generation product, and under what conditions he should stick with his first generation new product. To do so, we can compute a threshold cost $k' = \Pi(\theta_{2n} > 1, q_{1n}, q_{2n}, q_{2r}) - \Pi(\theta_{2n} = 1, q_{1n}, q_{2n}, q_{2r})$ which corresponds to the profit differential between the cases with and without quality improvement. Clearly, the manufacturer is better off by introducing the second generation product as long as the associated investment cost k is lower than the threshold k'.

Proposition 3 summarizes the results.

Proposition 3. *When $\xi = 0$, the threshold k' is non-negative and strictly increasing in θ_{2n}. When $\xi = 2$, the threshold k' is non-positive and strictly decreasing in θ_{2n} whenever $\alpha < \theta_r - \frac{(1-c_{1n})\theta_r(1-\theta_r)}{c_{1n}}$.*

Thus, when $\xi = 0$, higher product quality is always beneficial and the manufacturer is willing to invest more for higher quality. For $\xi = 0$ we also find that with increasing α the firm is willing to invest more for the same quality θ_{2n} of the new product, yet at a diminishing rate. This is due to the reduced cannibalization between new and remanufactured products under low remanufacturing efficiency (i.e. high α). In that case, the manufacturer can charge a higher price for second generation new units without facing too many consumers switching to remanufactured products. Summarizing, product quality improvement hurts remanufacturing, and the effect increases when remanufacturing efficiency decreases, i.e. α increases.

Together with the fact that higher quality reduces the manufacturer's propensity to remanufacture this leads to a case where the manufacturer would remanufacture without improving new product quality, but instead prefers to introduce the second generation product and consequently stops to remanufacture when quality improvement of the new product is sufficiently radical, and second generation manufacturing efficiency as well as remanufacturing efficiency are high.

On the other hand, for $\xi = 2$ the investment relationship is less clear cut. Due to low second generation manufacturing efficiency, a higher θ_{2n} may actually reduce the profits even before accounting for the investment cost. Thus, the manufacturer may be better off by sticking with the first generation product even if investment cost were zero. This is always true when α is low as given by the condition in the proposition. In that case, the efficient remanufacturing would be hurt by quality improvement of the new product. Yet, if improving new product quality were profitable after accounting for the investment cost, the manufacturer introducing the second generation product may actually start remanufacturing. When remanufacturing efficiency decreases (α increases), the manufacturer is willing to invest progressively less for the same quality θ_{2n} of the new product. Here quality improvement of the new product boosts remanufacturing, and the effect increases when remanufacturing efficiency increases, i.e. α decreases.

Above, we have seen that – depending on ξ – introducing a sufficiently radical product quality improvement (i.e. a large θ_{2n}) may induce the manufacturer to stop or take-up remanufacturing. This informs the managers that product quality improvement is the better choice if second generation manufacturing is efficient. Otherwise, the trade-off between product quality improvement and remanufacturing is less clear-cut and needs more careful analysis. From the government policy maker's perspective, the above result shows that for some industry (with low efficiency of new generation manufacturing), it is not necessary to incentivize the firm to do remanufacturing. However, for competitive industries, where new generation manufacturing is efficient (e.g. smart phones), product quality improvement is preferred and hurts remanufacturing. Moreover, product quality improvement always increases total resource consumption. In this situation, necessary actions should be taken from the government (e.g. WEEE directive) so that remanufacturing is considered by firms.

4.2. The impact of remanufacturing on the decision of product quality improvement

Up to now we have investigated the decision of product quality improvement under the assumption that the firm in question is willing to remanufacture. In this section we want to understand how the strategic decision to engage in remanufacturing affects the decision of product quality improvement. To do so we consider two firms. The first firm is the one we have looked at so far, i.e. it is willing to remanufacture when c_r is small enough. Its optimization problem is characterized by the regions shown in Fig. 1. Alternatively, we will consider a second firm that has taken the strategic decision not to remanufacture at all. As an example, in practice such a firm may fear cannibalization of their new product sales through the offering of remanufactured units, or it may not have, or want to set up, the necessary logistics infrastructure for collecting the used units.

Our research question then can be reformulated to: Does the first firm invest more in product quality improvement than the second firm and if so under what conditions?

Proposition 4 answers this question with a strong result.

Proposition 4. *Under high second generation manufacturing efficiency ($\xi = 0$), the remanufacturing firm will **never** be willing to **invest more** in new product quality improvement than the firm that does not remanufacture.*

*Under low second generation manufacturing efficiency ($\xi = 2$), the remanufacturing firm will **never** be willing to **invest less** in new product quality improvement than the firm that does not remanufacture, if $\alpha \geq \theta_r$.*

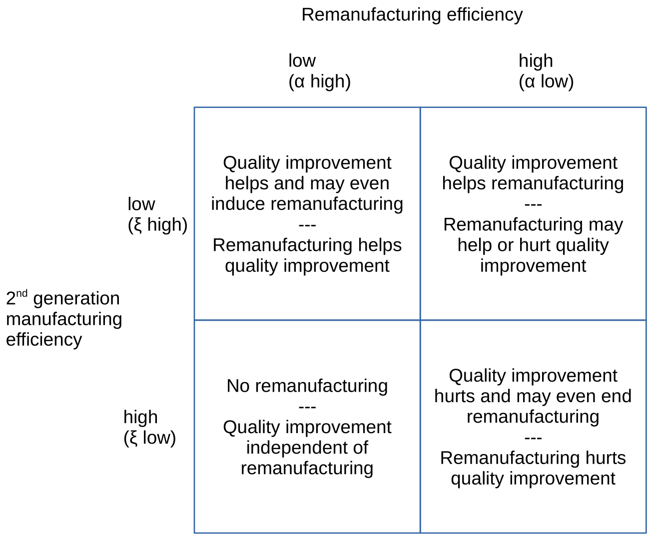


Fig. 2. The relationship between remanufacturing and product quality improvement as a function of (quality-improvement-induced) manufacturing efficiency and remanufacturing efficiency.

When $\xi = 0$, the main driver for the result is the fact that for the diversified firm the positive effect of quality improvement on the market for new products is partly offset by the negative effect this quality improvement has on the remanufactured product. Moreover, increased remanufacturing efficiency – i.e. smaller α – magnifies the negative effect of remanufacturing on product quality improvement since this implies more competition between the two products.

On the other hand, when $\xi = 2$ the condition $\alpha \geq \theta_r$ implies that without improving quality of the new product the remanufacturing firm would not remanufacture (due to low remanufacturing efficiency). Thus, without quality improvement the two firms are identical in their decisions. However, above we have seen that under quality improvement the remanufacturing firm may be willing to take up remanufacturing. Since it would not do so if it were not profitable, its profit must be larger than without remanufacturing. Thus, we get the proposed result. In other words, the market expansion effect of introducing the remanufactured product dominates the cannibalization effect reducing new product sales when the 2nd generation product is introduced.

Finally, Fig. 2 summarizes our main economic insights on the relationship between remanufacturing and product quality improvement.

Summarizing, product quality improvement and remanufacturing are always mutually beneficial when second generation manufacturing efficiency and remanufacturing efficiency are both low (ξ and α are high). In that case competition between the new and remanufactured products is weak and the market expansion effects of both product quality improvement and remanufacturing dominate. When second generation manufacturing efficiency and remanufacturing efficiency are both high, the opposite is true since the cannibalization effect between the two products drives the result. Thus, either product quality improvement without remanufacturing or remanufacturing without product quality improvement is preferable.

When second generation manufacturing efficiency is high but remanufacturing efficiency is low we get the trivial result that there is no remanufacturing. Consequently, the product quality improvement decision only depends on the primary market effects it induces. Finally, when second generation manufacturing efficiency is low but remanufacturing efficiency is high, which of the above mentioned two scenarios applies depends on the initial manufacturing cost for first generation products c_{1n}. When c_{1n} is high, remanufacturing and product quality improvement are mutually beneficial, while when c_{1n} is low they are mutually exclusive. Clearly, in the former case the competition between the new and remanufactured product is weak, while in the latter case it is strong, thereby driving the result.

4.3. Product quality improvement without remanufacturing or remanufacturing without product quality improvement: Which is more environmentally beneficial?

Above, Fig. 2 summarizes that product quality improvement and remanufacturing are either independent or mutually beneficial in most cases. Only for $\xi = 0$ and low α we find that product quality improvement may actually hurt remanufacturing and vice versa. In that situation the interesting question arises whether product quality improvement or remanufacturing is to be favored from an environmental point of view. The following proposition summarizes our findings.

Proposition 5. *Under high second generation manufacturing efficiency ($\xi = 0$), product quality improvement by the non-remanufacturing firm is environmentally preferable over remanufacturing by the non-quality-improvement firm when*

- *the remanufacturing firm's optimal decision is partial remanufacturing and*
  $\theta_{2n} \leq \frac{1-\theta_r}{1-\alpha}$ ***or***
  $\theta_{2n} > \frac{1-\theta_r}{1-\alpha}$ *and*
  $\frac{\gamma_n}{\gamma_r} \leq \frac{\theta_{2n}(\theta_r-\alpha)}{\theta_r(\theta_{2n}-1+\theta_r-\theta_{2n}\alpha)}$
- *the remanufacturing firm's optimal decision is full remanufacturing and*
  $\theta_{2n} \leq \frac{c_{1n}[1+\theta_r(1-\theta_r)]}{\theta_r(2-\theta_r)+c_{1n}(1-\theta_r)(1+\alpha-\theta_r)}$ ***or***
  $\theta_{2n} > \frac{c_{1n}[1+\theta_r(1-\theta_r)]}{\theta_r(2-\theta_r)+c_{1n}(1-\theta_r)(1+\alpha-\theta_r)}$ *and*
  $\frac{\gamma_n}{\gamma_r} \leq \frac{\theta_{2n}[1-c_{1n}(1+\alpha-\theta_r)]}{\theta_{2n}[\theta_r(2-\theta_r)+c_{1n}(1-\theta_r)(1+\alpha-\theta_r)]-c_{1n}[1+\theta_r(1-\theta_r)]}$

Thus, when the second generation manufacturing efficiency is high ($= 0$), remanufacturing that disencourages product quality improvement may actually be bad from a sustainability point of view. This is particularly true when product quality improvement is incremental. In that case, the non-remanufacturing firm will enjoy a large environmental advantage from not serving the lower-end consumers. This advantage dominates as long as the market increase in the demand for new units due to product quality improvement is not too large. In all other cases, i.e. when product quality improvement is of a more radical type, the environmental results depend on the relative per unit resource consumption advantage of remanufactured products over new units in the obvious way.[3]

This result has important implications for policy makers. Although remanufacturing is good for the environment on a per unit basis due to the reduced consumption of materials, energy etc. it is not necessarily good when considering the total quantity, because it may induce more consumption which may cause more environmental impact. Therefore, overincentivizing on remanufacturing is not a good idea. In this sense, encouraging product quality improvement could be preferable from the environment's perspective.

[3] Note that we have analysed this question as well as some of the other results from a social perspective as well. We focused on consumer surplus but the results are not clear-cut and little insightful in general. For the sake of completeness we present the more interesting ones in Appendix B.

5. Conclusions

In this paper we have studied the joint decision making about product quality improvement and remanufacturing by a monopolist manufacturer. Product quality improvement increases consumer's willingness-to-pay for the new product, which at the same time reduces the attractiveness of remanufactured products. Going beyond the existing literature we endogenize the product quality improvement decision and investigate the impact of the manufacturing efficiency associated with improving product quality. We confirm the findings from previous research concerning the negative impact of improving product quality on remanufacturing, yet only for the case where manufacturing efficiency associated with quality improved product is high. When manufacturing efficiency for the second generation product is low, the result reverses in that introducing that product will actually stimulate remanufacturing. Therefore, whether product quality improvement and remanufacturing co-exist in one company depends on the efficiency of product quality improvement.

In a second step we analyse how the strategic decision to remanufacture influences a manufacturer's propensity to improve product quality. Again, the effect will be positive or negative depending on the manufacturing cost for the second generation product. Thus, we characterize the conditions under which remanufacturing and product quality improvement are mutually beneficial or mutually exclusive. We further link these findings with environmental (in terms of resource consumption) performance and show that what is economically preferable may not be beneficial with respect to resource consumption. Specifically, we find that from an environmental point of view product quality improvement by a non-remanufacturing firm may be preferable over remanufacturing without product quality improvement.

From a policy-maker's perspective these results highlight an intriguing dilemma. Short product quality improvement cycles are seen as one key element in the planned obsolescence debate and our results suggest that remanufacturing may counteract (too) early introduction of new product generations when manufacturing efficiency of the quality improved product is low. But when manufacturing efficiency is high, remanufacturing is not preferred compared to product quality improvement. Moreover, from the perspective of the environment, although remanufacturing is good on a per unit basis, it may actually be harmful in terms of the total resource consumption by foregoing some quality improvement if remanufacturing promotes that. Our results suggest that the answer to this dilemma crucially depends on the type of product quality improvement and its impact on manufacturing cost.

Clearly our model is not without limitations to provide answers to the more general aspects with respect to industry dynamics and environmental policy. However, our work can be seen as a first step towards a richer understanding of sustainability, by linking short-term (through remanufacturing) and long-term (through quality improvement) economic and environmental effects. The next step will be to extend the model by incorporating competition through an oligopolistic setting. Clearly, product quality improvement is driven by competitive pressure as much as by consumer demand. It will be interesting to see whether our results about foregoing product quality improvement still hold under such a setting. Moreover, in an oligopolistic setting we can also study whether heterogeneity about the strategic decision to remanufacture prevails and how it affects the industry dynamics with respect to product quality improvement. A second possible research thread is to make the model more comprehensive by including the decision which type of product quality improvement to pursue. In this paper we have focused on product quality improvement that has no direct effect on the per unit environmental impact of new products. Clearly, this contrasts with green product quality improvement, where a new product generation may reduce the energy consumption in the use phase (e.g. washing machines). Understanding those things in more detail will further enhance firm and public decision making.

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Appendix A. Proofs

Proof of Lemma 1. Using the shadow prices λ_1 for the remanufacturing constraint as well as λ_n and λ_r for the non-negativity constraints on q_{2n} and q_{2r} we can write the Lagrangean of the problem as

$$\begin{aligned}\mathcal{L} = {} & (1 - q_{1n} - c_{1n})q_{1n} + (\theta_{2n}(1 - q_{2n}) - \theta_r q_{2r} - c_{1n}\theta_{2n}^{\xi})q_{2n} \\ & + (\theta_r(1 - q_{2n} - q_{2r}) - \alpha c_{1n})q_{2r} - \lambda_1(q_{2r} - q_{1n}) \\ & + \lambda_n q_{2n} + \lambda_r q_{2r}. \end{aligned} \tag{7}$$

From the first-order-conditions of $\mathcal{L}$ from Eq. (7) we obtain

$$q_{1n} = \frac{1 - c_{1n} + \lambda_1}{2} \tag{8}$$

$$q_{2n} = \frac{(c_{1n}\alpha + \theta_{2n} - c_{1n}\theta_{2n}^{\xi} - \theta_r + \lambda_1 + \lambda_n - \lambda_r)}{2(\theta_{2n} - \theta_r)} \tag{9}$$

$$q_{2r} = \frac{-c_{1n}\alpha\theta_{2n} + c_{1n}\theta_{2n}^{\xi}\theta_r - \theta_{2n}\lambda_1 - \theta_r\lambda_n + \theta_{2n}\lambda_r}{2\theta_r(\theta_{2n} - \theta_r)} \tag{10}$$

$$\lambda_1(q_{2r} - q_{1n}) = 0 \tag{11}$$

$$\lambda_n q_{2n} = 0 \tag{12}$$

$$\lambda_r q_{2r} = 0 \tag{13}$$

$$0 \le q_{2r} \le q_{1n} \tag{14}$$

$$q_{2n} \ge 0. \tag{15}$$

It is easy to verify that the objective function is jointly concave in the production quantities such that a solution of the system of Eqs. (8)–(15) will be an optimum. Given the three lagrangean multipliers λ_1, λ_n and λ_r there are eight possible cases. Note that the two cases where $\lambda_r > 0$ and $\lambda_1 > 0$ at the same time do not exist, since they imply that $q_{2r} = q_{1n} = 0$. This is impossible, since $q_{1n} = 0$ is excluded by the assumption $c_{1n} < 1$. Thirdly, the case where $\lambda_r > 0$ and $\lambda_n > 0$ does not make sense either since it would imply that there is no production at all in the second period, i.e. $q_{2r} = q_{2n} = 0$. This could only happen when $\theta_r \le \alpha c_{1n}$ which is again excluded by assumption.

Thus five possible cases remain. The quantities q_{1n}, q_{2n} and q_{2r} and associated prices p_{1n}, p_{2n} and p_{2r} for each of these cases are readily obtained by plugging the values for λ_1, λ_n and λ_r into conditions (8)–(10) as well as the inverse demand functions.

Let us now consider the case existence conditions. The first case (denoted by I) implies that $\lambda_r > 0$ while $\lambda_1 = \lambda_n = 0$. Solving the condition (10) for λ_r at $q_{2r} = 0$ we obtain $\lambda_r = \frac{c_{1n}(\alpha\theta_{2n} - \theta_{2n}^{\xi}\theta_r)}{\theta_{2n}}$. $\lambda_r \ge 0$ whenever $\alpha \ge \theta_{2n}^{\xi-1}\theta_r$. Moreover, when $\xi > 1$ this implies that $\alpha > \theta_r$. This concludes the proof for this case.

Let us now turn to the other extreme case V, where $\lambda_1 > 0$ and $\lambda_n > 0$, while $\lambda_r = 0$. From the conditions $q_{2r} = q_{1n}$ and $q_{2n} = 0$ we can compute λ_1 and λ_n as $\lambda_1 = \frac{c_{1n}(\theta_r - \alpha)}{1+\theta_r}$ and $\lambda_n = \frac{-\theta_{2n}(1+\theta_r) + c_{1n}\theta_{2n}^{\xi}(1+\theta_r) + \theta_r(1 - c_{1n}(1+\alpha) + \theta_r)}{1+\theta_r}$. From $\lambda_1 > 0$ we get directly

$\theta_r > \alpha$ while $\lambda_n > 0$ yields $\alpha < (1+\theta_r)\frac{c_{1n}\theta_{2n}^{\xi}-(\theta_{2n}-\theta_r)}{c_{1n}\theta_r} - 1$. Moreover, the FOC of λ_n w.r.t. θ_{2n} is strictly negative when $\xi \le 1$. Together with the fact that – by model assumption – this case does not exist for $\theta_{2n} = 1$, we get that case V only exists when $\xi > 1$ which concludes the proof for this case.

Case IV implies that $\lambda_1 = \lambda_r = 0$, while $\lambda_n > 0$. Setting $q_{2n} = 0$ we obtain $\lambda_n = -c_{1n}\alpha - \theta_{2n} + c_{1n}\theta_{2n}^{\xi} + \theta_r \ge 0$. This condition holds whenever $\alpha \le \theta_{2n}^{\xi} - \frac{\theta_{2n}-\theta_r}{c_{1n}}$. Plugging λ_n into the condition (10) for q_{2r} and subsequently checking the condition $q_{2r} < q_{1n}$ it turns out that this only holds when $\alpha > \theta_r$. Analogous to case V, the FOC of λ_n w.r.t. θ_{2n} is strictly negative when $\xi \le 1$. Together with the fact that –by model assumption– this case does not exist for $\theta_{2n} = 1$, we get that case IV only exists when $\xi > 1$. This concludes the proof for this case.

In case II none of the constraints is binding, hence $\lambda_1 = \lambda_n = \lambda_r = 0$. From the condition $q_{2r} > 0$ we get $\alpha \le \theta_{2n}^{\xi-1}\theta_r$, which is dominated by $\alpha \le \theta_r$ whenever $\xi > 1$. Analogously, the condition $q_{2n} > 0$ yields $\alpha > \theta_{2n}^{\xi} - \frac{\theta_{2n}-\theta_r}{c_{1n}}$ while from the condition $q_{2r} < q_{1n}$ we obtain $\alpha > \theta_r\theta_{2n}^{\xi-1} - \frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{c_{1n}\theta_{2n}}$. Together with the results for case IV above this concludes the proof for this case.

Finally, let us turn to case III, where $\lambda_r = \lambda_n = 0$ while $\lambda_1 > 0$. From the condition $q_{2r} = q_{1n}$ we can compute $\lambda_1 = \frac{\theta_r(-\theta_{2n}+\theta_r)+c_{1n}(-\alpha\theta_{2n}+(\theta_{2n}+\theta_{2n}^{\xi}-\theta_r)\theta_r)}{\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2}$. The requirement $\lambda_1 > 0$ yields $\alpha < \theta_r\theta_{2n}^{\xi-1} - \frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{c_{1n}\theta_{2n}}$. The requirement $q_{2n} > 0$ yields $\alpha > (1+\theta_r)\frac{c_{1n}\theta_{2n}^{\xi}-(\theta_{2n}-\theta_r)}{c_{1n}\theta_r} - 1$. Both of these conditions on α can only be jointly satisfied when $c_{1n} \le \frac{\theta_{2n}-\theta_r}{\theta_{2n}^{\xi}-\theta_r}$. It is easy to verify that under this condition the upper bound on α satisfies $\theta_r\theta_{2n}^{\xi-1} - \frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{c_{1n}\theta_{2n}} \le \theta_r$. Thus, when $\theta_r \ge \alpha$ the case always exists while when $\theta_r < \alpha$ it can never exist. This concludes the proof for this case.

To conclude the proof let us consider the condition to ensure $q_{2n} > 0$ when $\theta_{2n} = 1$. This implies that we have to rule out regions IV and V when $\theta_{2n} = 1$. Let us first consider region IV. Plugging $\theta_{2n} = 1$ into the threshold for α yields $\alpha \le 1 - \frac{1-\theta_r}{c_{1n}}$. However, observe from Lemma 1 that region IV can only exist when $\alpha > \theta_r$. These two constraints are mutually exclusive, whenever $c_{1n} < 1$ which holds by assumption. Thus, when $\theta_{2n} = 1$ region IV does not exist. Using the same analysis for region V yields $\alpha \le \frac{c_{1n}-1+\theta_r^2}{c_{1n}\theta_r}$ which is consistent with the condition $\alpha \le \theta_r$, implying that region V may exist when $\theta_{2n} = 1$. Thus, we obtain our threshold to ensure positive second period new production under $\theta_{2n} = 1$. □

Proof of Proposition 1. Using the results from Lemma 1 we will address the two cases $\xi \le 1$ and $\xi > 1$ separately.

When $\xi \le 1$ the lower boundary on α for Case I is non-increasing in θ_{2n} and strictly decreasing whenever $\xi < 1$. The lower boundary on α for Case II is strictly decreasing in θ_{2n}. Thus, an increase in θ_{2n} will induce the manufacturer to switch from full remanufacturing to partial remanufacturing and ultimately to no remanufacturing.

When $\xi > 1$ the lower boundary on α for Case I is strictly increasing in θ_{2n}. Similarly, the lower bound on α for Case II is strictly increasing in θ_{2n} whenever $\alpha > \theta_r$. When $\alpha \le \theta_r$ the lower bound on α for Case II increases whenever $c_{1n} > \frac{\theta_r}{\theta_r+(\xi-1)\theta_{2n}^{\xi}}$. Note that this constraint is softened as ξ or θ_{2n} increase. Finally, the lower bound on α for Case III is again strictly increasing in θ_{2n}. In other words an increase in θ_{2n} will induce the manufacturer to switch from no remanufacturing to partial remanufacturing and ultimately to full remanufacturing in general. This concludes the proof. □

Proof of Proposition 2. When $\xi = 0$, the total environmental impacts TEI in regions I-III respectively are $\frac{\gamma_n(2\theta_{2n}-c_{1n}\theta_{2n}-c_{1n})}{2\theta_{2n}}$, $\frac{(2-c_{1n})\gamma_n}{2} - \frac{c_{1n}(1-\alpha)(\gamma_n-\gamma_r)}{2(\theta_{2n}-\theta_r)} - \frac{\alpha c_{1n}\gamma_r}{2\theta_r}$, and

$$\frac{\theta_{2n}\gamma_r+c_{1n}[-\gamma_n-(\alpha+1)\theta_{2n}(\gamma_n+\gamma_r)+\theta_r((\alpha+1)\gamma_n+\gamma_r)]+\gamma_n[\theta_{2n}(\theta_r+2)-\theta_r(\theta_r+1)]}{2(\theta_{2n}(\theta_r+1)-\theta_r^2)}.$$

The corresponding first derivatives with respect to θ_{2n} are $\frac{c_{1n}\gamma_n}{2\theta_{2n}^2}$, $\frac{c_{1n}(1-\alpha)(\gamma_n-\gamma_r)}{2(\theta_{2n}-\theta_r)^2}$, and $\frac{(\gamma_n-\gamma_r\theta_r)[c_{1n}(1-\alpha\theta_r)+\theta_r]}{2[\theta_r^2-\theta_{2n}(\theta_r+1)]^2}$. Obviously, all of them are positive. As a result, when $\xi = 0$, product quality improvement always increases total environmental impact.

When $\xi = 2$, the total environmental impact TEI in region I is $-\frac{1}{2}\gamma_n[c_{1n}(\theta_{2n}+1)-2]$. The first derivative of TEI in region I with respect to θ_{2n} is $-\frac{1}{2}c_{1n}\gamma_n$ which is negative. The total environmental impact TEI in region II is $\frac{c_{1n}[\gamma_n\theta_r(\alpha-\theta_{2n}^2-\theta_{2n}+\theta_r)+\theta_{2n}\gamma_r(\theta_{2n}\theta_r-\alpha)]+2\gamma_n\theta_r(\theta_{2n}-\theta_r)}{2\theta_r(\theta_{2n}-\theta_r)}$. The first derivative of TEI in region II with respect to θ_{2n} is $-\frac{c_{1n}(\gamma_n-\gamma_r)(\alpha+\theta_{2n}^2-2\theta_{2n}\theta_r)}{2(\theta_{2n}-\theta_r)^2} < 0$. This holds, since for $\alpha \ge \theta_r^2$ we can easily show that $\alpha + \theta_{2n}^2 - 2\theta_{2n}\theta_r > (\theta_{2n}-\theta_r)^2 > 0$. The total environmental impact TEI in region III is

$$\frac{\gamma_n[\theta_r((\alpha+1)c_{1n}+\theta_{2n}-1)-\theta_{2n}(c_{1n}(\alpha+\theta_{2n}+1)-2)-\theta_r^2]+\theta_{2n}\gamma_r[1-c_{1n}(\alpha-\theta_{2n}\theta_r+1)]}{2[\theta_{2n}(\theta_r+1)-\theta_r^2]}.$$

The first derivative of TEI in region III with respect to θ_{2n} is $\frac{(\gamma_n-\gamma_r\theta_r)[\theta_r-c_{1n}(\theta_{2n}^2(\theta_r+1)-2\theta_{2n}\theta_r^2+(\alpha+1)\theta_r)]}{2[\theta_r^2-\theta_{2n}(\theta_r+1)]^2}$. From the case existence condition $\alpha < \theta_{2n}\theta_r - \frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{c_{1n}\theta_{2n}}$, we know $c_{1n} > \frac{\theta_{2n}\theta_r-\theta_r^2}{-\alpha\theta_{2n}+\theta_{2n}^2\theta_r+\theta_{2n}\theta_r-\theta_r^2}$. Some algebraic manipulation yields

$$\frac{\theta_{2n}\theta_r-\theta_r^2}{-\alpha\theta_{2n}+\theta_{2n}^2\theta_r+\theta_{2n}\theta_r-\theta_r^2} - \frac{\theta_r}{\theta_{2n}^2+\theta_{2n}^2\theta_r-2\theta_{2n}\theta_r^2+\alpha\theta_r+\theta_r}$$
$$= \frac{\theta_r(\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2)(\alpha+\theta_{2n}^2-2\theta_{2n}\theta_r)}{(-\alpha\theta_{2n}+\theta_{2n}^2\theta_r+\theta_{2n}\theta_r-\theta_r^2)(\theta_{2n}^2+\theta_{2n}^2\theta_r-2\theta_{2n}\theta_r^2+\alpha\theta_r+\theta_r)}$$
$$> \frac{\theta_r(\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2)(\theta_{2n}-\theta_r)^2}{(-\alpha\theta_{2n}+\theta_{2n}^2\theta_r+\theta_{2n}\theta_r-\theta_r^2)(\theta_{2n}^2+\theta_{2n}^2\theta_r-2\theta_{2n}\theta_r^2+\alpha\theta_r+\theta_r)} > 0.$$

Here $\theta_{2n}^2 + \theta_{2n}^2\theta_r - 2\theta_{2n}\theta_r^2 + \alpha\theta_r + \theta_r = \theta_{2n}(\theta_{2n} + \theta_{2n}\theta_r - 2\theta_r^2) + (\alpha+1)\theta_r > 0$. So $c_{1n} > \frac{\theta_r}{\theta_{2n}^2+\theta_{2n}^2\theta_r-2\theta_{2n}\theta_r^2+\alpha\theta_r+\theta_r}$. In other words, $\theta_r - c_{1n}[\theta_{2n}^2(\theta_r+1) - 2\theta_{2n}\theta_r^2 + (\alpha+1)\theta_r] < 0$. As a result, The first derivative of TEI in region III with respect to θ_{2n} is negative. In sum, product quality improvement always decreases total environmental impact when $\xi = 2$. □

Proof of Proposition 3. Note that the shape of k' only depends on the profit $\Pi(\theta_{2n} > 1, q_{1n}, q_{2n}, q_{2r})$ since the profit $\Pi(\theta_{2n} = 1, q_{1n}, q_{2n}, q_{2r})$ is a constant for given parameters. Thus, we now focus on the impact of θ_{2n} on $\Pi(\theta_{2n} > 1, q_{1n}, q_{2n}, q_{2r})$.

From Lemma 1 we know that the manufacturer can be in one of the five cases I, II, III, IV, V after improving product quality. We also know that cases IV and V imply that the manufacturer stops manufacturing new units in the second period. Clearly in those cases any investment k would be lost, i.e. $k' = 0$ and we need not further consider those two cases.

Let us analyse the remaining three cases for $\xi = 0$ and $\xi = 2$, separately. When $\xi = 0$, the profit in the three cases is given by

Case I:

$$\Pi(\theta_{2n} > 1, q_{1n}, q_{2n}, q_{2r}) = \frac{c_{1n}^2+\theta_{2n}+(-4+c_{1n})c_{1n}\theta_{2n}+\theta_{2n}^2}{4\theta_{2n}}$$

Case II:

$$\Pi(\theta_{2n} > 1, q_{1n}, q_{2n}, q_{2r}) = \frac{(1+\theta_{2n}-4c_{1n})(\theta_{2n}-\theta_r)\theta_r+c_{1n}^2(\alpha^2\theta_{2n}-2\alpha\theta_r+(1+\theta_{2n}-\theta_r)\ \theta_r)}{4(\theta_{2n}-\theta_r)\theta_r}$$

Case III:

$$\Pi(\theta_{2n} > 1, q_{1n}, q_{2n}, q_{2r}) = \frac{\theta_{2n}(1+\theta_{2n}-\theta_r)(1+\theta_r)+c_{1n}^2(1+(1+\alpha)^2\theta_{2n}-\theta_r-2\alpha\theta_r)}{4(\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2)} + \frac{2c_{1n}(\theta_r+\theta_r^2-\theta_{2n}(2+\alpha+\theta_r))}{4(\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2)}$$

It is easy to verify that in all three cases the first derivative w.r.t. θ_{2n} is strictly positive over the respective feasible ranges. This concludes the proof for $\xi = 0$.

Now we turn to $\xi = 2$. The profit in the three cases is given by

Case I:

$\Pi(\theta_{2n} > 1, q_{1n}, q_{2n}, q_{2r}) = \frac{1+\theta_{2n}+c_{1n}(-2+c_{1n}-2\theta_{2n}^2+c_{1n}\theta_{2n}^3)}{4}$

Case II:

$\Pi(\theta_{2n} > 1, q_{1n}, q_{2n}, q_{2r}) = \frac{(1+\theta_{2n}-2c_{1n}(1+\theta_{2n}^2))(\theta_{2n}-\theta_r)\theta_r}{4(\theta_{2n}-\theta_r)\theta_r} + \frac{c_{1n}^2(\alpha^2\theta_{2n}-2\alpha\theta_{2n}^2\theta_r+(\theta_{2n}+\theta_{2n}^4-\theta_r)\theta_r)}{4(\theta_{2n}-\theta_r)\theta_r}$

Case III:

$\Pi(\theta_{2n} > 1, q_{1n}, q_{2n}, q_{2r}) = \frac{\theta_{2n}(1+\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2+c_{1n}^2((1+\alpha)^2+\theta_{2n}^3+\theta_{2n}(-2-2\alpha+\theta_{2n}^2)\theta_r))}{4(\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2)} - \frac{\theta_{2n}(2c_{1n}(1+\alpha+\theta_{2n}(\theta_{2n}-\theta_r)(1+\theta_r)))}{4(\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2)}$

In case I, the first derivative w.r.t. θ_{2n} is positive over the entire case domain whenever $c_{1n} \le \frac{\theta_r}{3\alpha}$. It is positive for $\theta_{2n} < \frac{1}{3c_{1n}}$ if $\frac{\theta_r}{3\alpha} < c_{1n} < \frac{1}{3}$. Whenever $c_{1n} \ge \frac{1}{3}$ it is always negative. In that latter case it implies that k' is negative for the entire case domain.

In case II, we get an increasing k' as θ_{2n} increases whenever $\alpha \ge \theta_r^2$ and $c_{1n} < \frac{\theta_{2n}-\theta_r}{\alpha+3\theta_{2n}^2-4\theta_{2n}\theta_r}$.

In case III, k' is strictly decreasing in θ_{2n} over the entire case domain when $\alpha \ge \theta_r^2$. □

Proof of Proposition 4. Observe that the firm that never remanufactures is always in region I. Without product quality improvement, i.e. when $\theta_{2n} = 1$, its optimal strategy and profit are given by

$q_{1n} = \frac{1-c_{1n}}{2},\ p_{1n} = \frac{1+c_{1n}}{2}$

$q_{2n} = \frac{1-c_{1n}}{2},\ p_{2n} = \frac{1+c_{1n}}{2}$

$q_{2r} = 0$

$\Pi(1, q_{1n}, q_{2n}, q_{2r}) = \frac{(1-c_{1n})^2}{2}$.

Obviously this profit is independent of ξ.

From the proof of Proposition 3 we know that under product quality improvement the firm's optimal profit depends on ξ. For $\xi = 0$ we get

$$\Pi(\theta_{2n}, q_{1n}, q_{2n}, q_{2r}) = \frac{(1-c_{1n})^2}{4} + \frac{(\theta_{2n}-c_{1n})^2}{4\theta_{2n}}.$$

Thus, for the firm that does not remanufacture at all the maximum investment for improving product quality at $\xi = 0$ is given by

$$k \le \frac{(\theta_{2n}-c_{1n})^2}{4\theta_{2n}} - \frac{(1-c_{1n})^2}{4}.$$

Analogously, for $\xi = 2$ we get the profit

$$\Pi(\theta_{2n}, q_{1n}, q_{2n}, q_{2r}) = \frac{(1-c_{1n})^2}{4} + \frac{\theta_{2n}(1-c_{1n}\theta_{2n})^2}{4}$$

and the maximum investment for a given θ_{2n} is given by

$$k \le \frac{\theta_{2n}(1-c_{1n}\theta_{2n})^2}{4} - \frac{(1-c_{1n})^2}{4}.$$

Now observe that our focal firm willing to remanufacture could be in region I, II or III before and after improving product quality. When the firm is in region I before and after improving product quality its strategy, profits and maximum investment are obviously identical to the non-remanufacturing firm (since remanufacturing is just not profitable). We need not further consider that case.

For the remaining analysis let us first consider the situation $\xi = 0$. In that setting, the firm will be in case II or III before product quality improvement, i.e. when $\theta_{2n} = 1$, whenever $\alpha < \theta_r$. Observe that by definition this implies that the first firm makes a larger profit than it would make without remanufacturing, i.e. before product quality improvement our focal firm makes a larger profit than firm 2.

After improving product quality firm 1 could end up in regions I, II or III. Observe first that when it ends up in region I, the maximum investment k the manufacturer is willing to make in order to reach a given $\theta_{2n} > 1$ is then determined by the profit differential with and without product quality improvement. From Lemma 1 we can infer that the manufacturer will be in region II for $\theta_{2n} = 1$ whenever $\theta_r - \frac{(1-c_{1n})\theta_r(1-\theta_r)}{c_{1n}} \le \alpha \le \theta_r$. In that case the maximum acceptable investment k is computed as

$k \le \Pi_I(\theta_{2n}, q_{1n}, q_{2n}, 0) - \Pi_{II}(1, q_{1n}, q_{2n}, q_{2r})$. Plugging in all the prices and quantities yields $k \le \frac{(\theta_{2n}-c_{1n})^2}{4\theta_{2n}} - \frac{(1-c_{1n})^2}{4} - \frac{c_{1n}^2(\theta_r-\alpha)^2}{4\theta_r(1-\theta_r)}$. Analogously, when $\theta_r - \frac{(1-c_{1n})\theta_r(1-\theta_r)}{c_{1n}} > \alpha$ the manufacturer will be in region III without investment and the associated maximum acceptable investment k is computed by $k \le \Pi_I(\theta_{2n}, q_{1n}, q_{2n}, 0) - \Pi_{III}(1, q_{1n}, q_{2n}, q_{2r})$. Again, by simply plugging in all the prices and quantities associated with the two scenarios, we obtain $k \le \frac{(\theta_{2n}-c_{1n})^2}{4\theta_{2n}} - \frac{(1-\theta_r)^2(1-c_{1n})^2+(1-\alpha c_{1n})^2}{4[\theta_r(1-\theta_r)+1]} + \frac{(1-\theta_r)[(1-\theta_r)+2c_{1n}(\theta_r-\alpha c_{1n})]}{4[\theta_r(1-\theta_r)+1]}$. Comparing the above bounds on k with the bound $k \le \frac{(\theta_{2n}-c_{1n})^2}{4\theta_{2n}} - \frac{(1-c_{1n})^2}{4}$ obtained for firm 2 we get that product quality improvement is hindered by remanufacturing whenever:

- $\theta_r - \frac{(1-c_{1n})\theta_r(1-\theta_r)}{c_{1n}} \le \alpha < \theta_r$
  $\frac{(\theta_{2n}-c_{1n})^2}{4\theta_{2n}} - \frac{(1-c_{1n})^2}{4} \ge k \ge \frac{(\theta_{2n}-c_{1n})^2}{4\theta_{2n}} - \frac{(1-c_{1n})^2}{4} - \frac{c_{1n}^2(\theta_r-\alpha)^2}{4\theta_r(1-\theta_r)}$
- $\alpha < \theta_r - \frac{(1-c_{1n})\theta_r(1-\theta_r)}{c_{1n}}$
  $\frac{(\theta_{2n}-c_{1n})^2}{4\theta_{2n}} - \frac{(1-c_{1n})^2}{4} \ge k \ge \frac{(\theta_{2n}-c_{1n})^2}{4\theta_{2n}} - \frac{(1-\theta_r)^2(1-c_{1n})^2+(1-\alpha c_{1n})^2}{4[\theta_r(1-\theta_r)+1]} + \frac{(1-\theta_r)[(1-\theta_r)+2c_{1n}(\theta_r-\alpha c_{1n})]}{4[\theta_r(1-\theta_r)+1]}$.

In those cases, the firm that never remanufactures would improve product quality, while the remanufacturing firm would not improve product quality.

Similar analysis for the situations where the remanufacturing firm ends up in region II and III after improving product quality yields the following results. When the firm ends up in region II, product quality improvement is hindered by remanufacturing whenever:

- $\theta_r - \frac{(1-c_{1n})\theta_r(1-\theta_r)}{c_{1n}} \le \alpha < \theta_r$
  $\frac{(\theta_{2n}-c_{1n})^2}{4\theta_{2n}} - \frac{(1-c_{1n})^2}{4} \ge k \ge \frac{\theta_{2n}-2c_{1n}-(1-c_{1n})^2}{4} + \frac{c_{1n}^2\theta_r(1-\alpha)+\alpha c_{1n}^2(\theta_{2n}\alpha-\theta_r)}{4(\theta_{2n}-\theta_r)\theta_r} - \frac{c_{1n}^2(\theta_r-\alpha)^2}{4\theta_r(1-\theta_r)}$
- $\alpha < \theta_r - \frac{(1-c_{1n})\theta_r(1-\theta_r)}{c_{1n}}$
  $\frac{(\theta_{2n}-c_{1n})^2}{4\theta_{2n}} - \frac{(1-c_{1n})^2}{4} \ge k \ge \frac{\theta_{2n}-2c_{1n}+(1-c_{1n})^2}{4} + \frac{c_{1n}^2\theta_r(1-\alpha)+\alpha c_{1n}^2(\theta_{2n}\alpha-\theta_r)}{4(\theta_{2n}-\theta_r)\theta_r} - \frac{(2-\theta_r)(1+\theta_r)+c_{1n}^2[1+(1+\alpha)^2-\theta_r-2\alpha\theta_r]+2c_{1n}(\theta_r^2-2-\alpha)}{4[\theta_r(1-\theta_r)+1]}$.

When the firm ends up in region III, product quality improvement is hindered by remanufacturing whenever:

- $\alpha < \theta_r - \frac{(1-c_{1n})\theta_r(1-\theta_r)}{c_{1n}}$
  $\frac{(\theta_{2n}-c_{1n})^2}{4\theta_{2n}} - \frac{(1-c_{1n})^2}{4} \ge k \ge \frac{\theta_{2n}(1+\theta_{2n}-\theta_r)(1+\theta_r)+c_{1n}^2(1+(1+\alpha)^2\theta_{2n}-\theta_r-2\alpha\theta_r)+2c_{1n}(\theta_r+\theta_r^2-\theta_{2n}(2+\alpha+\theta_r))}{4(\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2)} - \frac{(2-\theta_r)(1+\theta_r)+c_{1n}^2[1+(1+\alpha)^2-\theta_r-2\alpha\theta_r]+2c_{1n}(\theta_r^2-2-\alpha)}{4[\theta_r(1-\theta_r)+1]}$.

This concludes the proof for $\xi = 0$.

Let us now turn to the case $\xi = 2$. Analogously to above we need to consider the possible combinations of optimal strategies before and after improving product quality. From Lemma 1 we know that for $\alpha > \theta_r$ the firm may switch from region I to region II. In that case, remanufacturing helps product quality improvement whenever

$\frac{(\theta_{2n}-1)(\theta_{2n}-\theta_r)\theta_r-2c_{1n}(\theta_{2n}^2-1)(\theta_{2n}-\theta_r)\theta_r+c_{1n}^2(\alpha^2\theta_{2n}+\theta_{2n}(-1-2\alpha\theta_{2n}+\theta_{2n}^3)\theta_r+\theta_r^2)}{4(\theta_{2n}-\theta_r)\theta_r}$
$\geq k \geq \frac{\theta_{2n}(1-c_{1n}\theta_{2n})^2}{4} - \frac{(1-c_{1n})^2}{4}$.

Under that condition the remanufacturing firm would improve product quality (and partially remanufacture first generation cores), while the non-remanufacturing firm would stick with its first generation product. □

Proof of Proposition 5. Note that we are only interested in a situation where $\alpha < \frac{\theta_r}{\theta_{2n}}$ as otherwise remanufacturing would never be beneficial. Under that condition the remanufacturing firm will either perform partial or full remanufacturing depending on α.

Let us first consider the case where the firm does partial remanufacturing. From Table 1 we can find the optimal quantities and, given that the firm does not improve product quality, compute total environmental impact TEI_{R-NI} for $\theta_{2n}=1$. Thus, we get $TEI_{R-NI} = \frac{\gamma_n[2(1-\theta_r)\theta_r-c_{1n}\theta_r(2-\alpha-\theta_r)]+\gamma_r c_{1n}(\theta_r-\alpha)}{2\theta_r(1-\theta_r)}$. Conversely for the non-remanufacturing firm who improves product quality, the total environmental impact

TEI_{NR-I} is given by $TEI_{NR-I} = \frac{\gamma_n(2\theta_{2n}-c_{1n}\theta_{2n}-c_{1n})}{2\theta_{2n}}$. Comparing the two, our proposed result holds when $TEI_{R-NI} > TEI_{NR-I}$. Straightforward algebraic manipulation yields $\frac{\gamma_r c_{1n}\theta_{2n}(\theta_r-\alpha)+\gamma_n c_{1n}\theta_r[1-\theta_r-(1-\alpha)\theta_{2n}]}{2\theta_{2n}(1-\theta_r)\theta_r} > 0$. Since $\alpha < \frac{\theta_r}{\theta_{2n}} < \theta_r$, obviously $TEI_{R-NI} > TEI_{NR-I}$ holds only when $1-\theta_r-(1-\alpha)\theta_{2n} \geq 0$ or $1-\theta_r-(1-\alpha)\theta_{2n} < 0$ and $\gamma_r c_{1n}\theta_{2n}(\theta_r-\alpha)+\gamma_n c_{1n}\theta_r[1-\theta_r-(1-\alpha)\theta_{2n}] > 0$. By simple algebraic manipulation, we obtain $\theta_{2n} \leq \frac{1-\theta_r}{1-\alpha}$ or $\theta_{2n} > \frac{1-\theta_r}{1-\alpha}$ and $\frac{\gamma_n}{\gamma_r} \leq \frac{\theta_{2n}(\theta_r-\alpha)}{\theta_r(\theta_{2n}-1+\theta_r-\theta_{2n}\alpha)}$.

Considering now the case where the remanufacturing firm remanufactures all available used cores, analogous reasoning leads to the condition
$\frac{\gamma_r[\theta_{2n}-c_{1n}\theta_{2n}(1+\alpha-\theta_r)]+\gamma_n[-\theta_{2n}\theta_r(2-\theta_r)-\theta_{2n}c_{1n}(1-\theta_r)(1+\alpha-\theta_r)+c_{1n}\theta_r(1-\theta_r)+c_{1n}]}{2\theta_{2n}[1+\theta_r(1-\theta_r)]}$.
Similarly, it is positive when $-\theta_{2n}\theta_r(2-\theta_r)-\theta_{2n}c_{1n}(1-\theta_r)(1+\alpha-\theta_r)+c_{1n}\theta_r(1-\theta_r)+c_{1n} \geq 0$ or $-\theta_{2n}\theta_r(2-\theta_r)-\theta_{2n}c_{1n}(1-\theta_r)(1+\alpha-\theta_r)+c_{1n}\theta_r(1-\theta_r)+c_{1n} < 0$ and $\gamma_r[\theta_{2n}-c_{1n}\theta_{2n}(1+\alpha-\theta_r)]+\gamma_n[-\theta_{2n}\theta_r(2-\theta_r)-\theta_{2n}c_{1n}(1-\theta_r)(1+\alpha-\theta_r)+c_{1n}\theta_r(1-\theta_r)+c_{1n}] > 0$. By simple algebraic manipulation, we obtain $\theta_{2n} \leq \frac{c_{1n}[1+\theta_r(1-\theta_r)]}{\theta_r(2-\theta_r)+c_{1n}(1-\theta_r)(1+\alpha-\theta_r)}$ or $\theta_{2n} > \frac{c_{1n}[1+\theta_r(1-\theta_r)]}{\theta_r(2-\theta_r)+c_{1n}(1-\theta_r)(1+\alpha-\theta_r)}$ and $\frac{\gamma_n}{\gamma_r} \leq \frac{\theta_{2n}[1-c_{1n}(1+\alpha-\theta_r)]}{\theta_{2n}[\theta_r(2-\theta_r)+c_{1n}(1-\theta_r)(1+\alpha-\theta_r)]-c_{1n}[1+\theta_r(1-\theta_r)]}$. □

Appendix B. Consumer surplus analysis

Consumer surplus results from the difference between a product's price and a consumer's willingness-to-pay for the product. Consequently, total consumer surplus is the aggregate of these differences over all consumers purchasing either a new or a remanufactured product.

Specifically, under remanufacturing total consumer surplus in our model is given by

$$CS = \int_{p_{1n}}^{1}(v-p_{1n})dv + \int_{\frac{p_{2n}-p_{2r}}{\theta_{2n}-\theta_r}}^{1}(\theta_{2n}v-p_{2n})dv + \int_{\frac{p_{2r}}{\theta_r}}^{\frac{p_{2n}-p_{2r}}{\theta_{2n}-\theta_r}}(\theta_r v-p_{2r})dv$$
$$= \frac{(1-p_{1n})^2}{2} + \frac{\theta_{2n}}{2} - p_{2n} + \frac{(p_{2n}-p_{2r})^2}{2(\theta_{2n}-\theta_r)} + \frac{p_{2r}^2}{2\theta_r}$$

Without remanufacturing this simplifies to

$$CS = \int_{p_{1n}}^{1}(v-p_{1n})dv + \int_{\frac{p_{2n}}{\theta_{2n}}}^{1}(\theta_{2n}v-p_{2n})dv$$
$$= \frac{(1-p_{1n})^2}{2} + \frac{(\theta_{2n}-p_{2n})^2}{2\theta_{2n}}$$

Following Proposition 2, we analyse the consumer surplus and get the following result.

Proposition B1. *When $\xi = 0$, consumers will benefit from product quality improvement.*

When $\xi = 2$, Consumers will benefit from product quality improvement when the manufacturer does not fully remanufacture if $\theta_{2n} < \frac{1}{3c_{1n}}$, and never benefits from product quality improvement under full remanufacturing.

Proof. When $\xi = 0$, the consumer surplus CS in region I is $\frac{c_{1n}^2\theta_{2n}-4c_{1n}\theta_{2n}+c_{1n}^2+\theta_{2n}^2+\theta_{2n}}{8\theta_{2n}}$. The first derivative of CS in region I with respect to θ_{2n} is $\frac{1}{8}[1-(\frac{c_{1n}}{\theta_{2n}})^2] > 0$.

The consumer surplus CS in region II is $\frac{1}{8}[c_{1n}(\frac{(\alpha-1)^2c_{1n}}{\theta_{2n}-\theta_r}+\frac{\alpha^2c_{1n}}{\theta_r}+c_{1n}-4)+\theta_{2n}+1]$. The first derivative of CS in region II with respect to θ_{2n} is $\frac{(\alpha c_{1n}-c_{1n}+\theta_{2n}-\theta_r)(c_{1n}-\alpha c_{1n}+\theta_{2n}-\theta_r)}{8(\theta_{2n}-\theta_r)^2}$. According to the region existence condition $\frac{\theta_r}{\theta_{2n}} - \frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{c_{1n}\theta_{2n}} \leq \alpha$, we know that $\theta_{2n} \geq \frac{(1-c_{1n})\theta_r^2+c_{1n}\theta_r}{\alpha c_{1n}+(1-c_{1n})\theta_r}$. So $\alpha c_{1n}-c_{1n}+\theta_{2n}-\theta_r \geq -(1-\alpha)c_{1n}+\frac{(1-c_{1n})\theta_r^2+c_{1n}\theta_r}{\alpha c_{1n}+(1-c_{1n})\theta_r}-\theta_r = \frac{(1-\alpha)c_{1n}^2(\theta_r-\alpha)}{\alpha c_{1n}+(1-c_{1n})\theta_r}$. From the case existence condition $\alpha < \frac{\theta_r}{\theta_{2n}}$, we know $\alpha < \theta_r$. As a result $\alpha c_{1n}-c_{1n}+\theta_{2n}-\theta_r > 0$. So the first derivative of CS in region II with respect to θ_{2n} is positive.

The consumer surplus CS in region III is
$\frac{c_{1n}^2[(\alpha+1)^2\theta_{2n}-(2\alpha+1)\theta_r+1]+2c_{1n}[\theta_r^2+\theta_r-\theta_{2n}(\alpha+\theta_r+2)]+\theta_{2n}(\theta_r+1)(\theta_{2n}-\theta_r+1)}{8[\theta_{2n}(\theta_r+1)-\theta_r^2]}$.
The first derivative of CS in region III with respect to θ_{2n} is $\frac{(\alpha c_{1n}\theta_r-c_{1n}+\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2-\theta_r)(-\alpha c_{1n}\theta_r+c_{1n}+\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2+\theta_r)}{8(\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2)^2}$.
Rewriting the first term in brackets in the nominator $(\alpha c_{1n}\theta_r-c_{1n}+\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2-\theta_r)$ we get $((\theta_r+1)(\theta_{2n}-\theta_r)-c_{1n}(1-\alpha\theta_r))$. According to the assumption $c_{1n} < \frac{1-\theta_r^2}{1-\alpha\theta_r}$, we know $(\theta_r+1)(\theta_{2n}-\theta_r)-c_{1n}(1-\alpha\theta_r) > (\theta_r+1)(\theta_{2n}-\theta_r)-(1-\theta_r^2) = (\theta_{2n}-1)(\theta_r+1) > 0$. As a result, the first derivative of CS in region III with respect to θ_{2n} is positive. In sum, when $\xi = 0$, consumers will always benefit from product quality improvement.

When $\xi = 2$, the consumer surplus CS in region I is $\frac{1}{8}[c_{1n}^2(\theta_{2n}^3+1)-2c_{1n}(\theta_{2n}^2+1)+\theta_{2n}+1]$. The first derivative of CS in region I with respect to θ_{2n} is $\frac{1}{8}(c_{1n}\theta_{2n}-1)(3c_{1n}\theta_{2n}-1)$. It is positive for $\theta_{2n} < \frac{1}{3c_{1n}}$ and negative for $\theta_{2n} > \frac{1}{3c_{1n}}$. Please note that $\theta_{2n} < \frac{1}{c_{1n}}$ because of $\alpha \geq \theta_{2n}\theta_r$ and $c_{1n} < \frac{\theta_r}{\alpha}$. Therefore, if there is no remanufacturing and $\theta_{2n} < \frac{1}{3c_{1n}}$ consumer surplus increases with θ_{2n}, which means product quality improvement benefits consumers.

The consumer surplus CS in region II is $\frac{1}{8}(1+\theta_{2n}+c_{1n}(-2(1+\theta_{2n}^2)+c_{1n}(1+\frac{(\alpha-\theta_{2n}^2)^2}{\theta_{2n}-\theta_r}+\frac{\alpha^2}{\theta_r})))$. The first derivative of CS in region II with respect to θ_{2n} is $\frac{1}{8(\theta_{2n}-\theta_r)^2}(-\theta_{2n}+c_{1n}(-\alpha+\theta_{2n}^2)+\theta_r)(-\theta_{2n}+\theta_r+c_{1n}(\alpha+3\theta_{2n}^2-4\theta_{2n\theta_r}))$. Let us now consider the two cases $\alpha > \theta_r$ and $\alpha \leq \theta_r$ in turn.

a) $\alpha > \theta_r$ From the case existence condition $\theta_{2n}^2 - \frac{\theta_{2n}-\theta_r}{c_{1n}} < \alpha$, we know $c_{1n}(\theta_{2n}^2-\alpha)-\theta_{2n}+\theta_r < 0$. Therefore the sign of the first derivative is determined by $-\theta_{2n}+\theta_r+c_{1n}(\alpha+3\theta_{2n}^2-4\theta_{2n}\theta_r)$. Because $\alpha < \theta_{2n}\theta_r$, we have $-\theta_{2n}+\theta_r+c_{1n}(\alpha+3\theta_{2n}^2-4\theta_{2n}\theta_r) < (-1+3c_{1n}\theta_{2n})(\theta_{2n}-\theta_r) < 0$ if $\theta_{2n} < \frac{1}{3c_{1n}}$. Therefore the first derivative is positive when $\theta_{2n} < \frac{1}{3c_{1n}}$.

b) $\alpha \leq \theta_r$ According to the case existence condition $\theta_r\theta_{2n} - \frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{c_{1n}\theta_{2n}} \leq \alpha$, we have

$$-\theta_{2n}+c_{1n}(-\alpha+\theta_{2n}^2)+\theta_r$$
$$\leq -\theta_{2n}-c_{1n}\theta_r\theta_{2n}+\frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{\theta_{2n}}+c_{1n}\theta_{2n}^2+\theta_r$$
$$=\frac{(\theta_{2n}-\theta_r)(-\theta_{2n}+c_{1n}\theta_{2n}^2+\theta_r-c_{1n}\theta_r)}{\theta_{2n}}.$$

From the case existence condition $\theta_r\theta_{2n} - \frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{c_{1n}\theta_{2n}} \le \alpha \le \theta_r$, we know $\theta_r - (\theta_r\theta_{2n} - \frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{c_{1n}\theta_{2n}}) = \frac{\theta_r(\theta_{2n}-c_{1n}\theta_{2n}^2-\theta_r+c_{1n}\theta_r)}{c_{1n}\theta_{2n}} > 0$. So $\theta_{2n}-c_{1n}\theta_{2n}^2-\theta_r+c_{1n}\theta_r > 0$. As a result, $-\theta_{2n}+c_{1n}(-\alpha+\theta_{2n}^2)+\theta_r < 0$. Therefore, the first derivative is determined by $-\theta_{2n}+\theta_r+c_{1n}(\alpha+3\theta_{2n}^2-4\theta_{2n}\theta_r)$. After some algebraic manipulation we get the desired result

$$\begin{aligned} &-\theta_{2n}+\theta_r+c_{1n}(\alpha+3\theta_{2n}^2-4\theta_{2n}\theta_r) \\ &\quad = -\theta_{2n}+\theta_r+c_{1n}\alpha+3c_{1n}\theta_{2n}^2-4c_{1n}\theta_{2n}\theta_r \\ &\quad > -\theta_{2n}+\theta_r+c_{1n}\theta_r\theta_{2n}-\frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{\theta_{2n}} \\ &\qquad +3c_{1n}\theta_{2n}^2-4c_{1n}\theta_{2n}\theta_r \\ &\quad = \frac{(\theta_{2n}-\theta_r)(-\theta_{2n}+3c_{1n}\theta_{2n}^2-\theta_r+c_{1n}\theta_r)}{\theta_{2n}} \\ &\quad < 0. \end{aligned}$$

The last inequality holds when $\theta_{2n} < \frac{1}{3c_{1n}}$.

Therefore, in region II, when $\theta_{2n} < \frac{1}{3c_{1n}}$ the first derivative of CS is positive, meaning consumers benefit from product quality improvement.

The consumer surplus CS in region III is

$$\frac{\theta_{2n}[c_{1n}^2((\alpha+1)^2-2(\alpha+1)\theta_{2n}\theta_r+\theta_{2n}^3(\theta_r+1))-2c_{1n}(\alpha+\theta_{2n}(\theta_r+1)(\theta_{2n}-\theta_r)+1)+(\theta_r+1)(\theta_{2n}-\theta_r+1)]}{8[\theta_{2n}(\theta_r+1)-\theta_r^2]}.$$

The first derivative of CS in region III with respect to θ_{2n} is

$$\frac{[(c_{1n}\theta_{2n}^2-\theta_{2n}+\theta_r)(\theta_r+1)-c_{1n}\theta_r(1+\alpha)][(3c_{1n}\theta_{2n}^2-\theta_{2n})(\theta_r+1)-4c_{1n}\theta_r^2\theta_{2n}+\theta_r((\alpha+1)c_{1n}+\theta_r-1)]}{8[\theta_r^2-\theta_{2n}(\theta_r+1)]^2}.$$

From the case existence condition $\alpha > \frac{(\theta_r+1)[c_{1n}\theta_{2n}^2-(\theta_{2n}-\theta_r)]}{c_{1n}\theta_r} - 1$, we know $(c_{1n}\theta_{2n}^2-\theta_{2n}+\theta_r)(\theta_r+1)-c_{1n}\theta_r(1+\alpha) < 0$. From the case existence condition $\alpha < \theta_{2n}\theta_r - \frac{(1-c_{1n})\theta_r(\theta_{2n}-\theta_r)}{c_{1n}\theta_{2n}}$, we know $c_{1n} > \frac{\theta_{2n}\theta_r-\theta_r^2}{-\alpha\theta_{2n}+\theta_{2n}^2\theta_r+\theta_{2n}\theta_r-\theta_r^2}$. From $c_{1n} > \frac{\theta_{2n}\theta_r-\theta_r^2}{-\alpha\theta_{2n}+\theta_{2n}^2\theta_r+\theta_{2n}\theta_r-\theta_r^2} > \frac{\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2+\theta_r}{3\theta_{2n}^2(\theta_r+1)-4\theta_{2n}\theta_r^2+(\alpha+1)\theta_r}$ and $3\theta_{2n}^2(\theta_r+1)-4\theta_{2n}\theta_r^2+(\alpha+1)\theta_r = \theta_{2n}(3\theta_{2n}+3\theta_{2n}\theta_r-4\theta_r^2)+(\alpha+1)\theta_r > 0$, we know $(3c_{1n}\theta_{2n}^2-\theta_{2n})(\theta_r+1)-4c_{1n}\theta_r^2\theta_{2n}+\theta_r[(\alpha+1)c_{1n}+\theta_r-1] > 0$. So the first derivative of CS in region III with respect to θ_{2n} is negative. Observe that $\frac{\theta_{2n}\theta_r-\theta_r^2}{-\alpha\theta_{2n}+\theta_{2n}^2\theta_r+\theta_{2n}\theta_r-\theta_r^2} - \frac{\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2+\theta_r}{3\theta_{2n}^2(\theta_r+1)-4\theta_{2n}\theta_r^2+(\alpha+1)\theta_r} = \frac{(\theta_{2n}+\theta_{2n}\theta_r-\theta_r^2)(\alpha\theta_{2n}+2\theta_{2n}^2\theta_r-4\theta_{2n}\theta_r^2-\theta_{2n}\theta_r+\alpha\theta_r+\theta_r^2)}{(-\alpha\theta_{2n}+\theta_{2n}^2\theta_r+\theta_{2n}\theta_r-\theta_r^2)(3\theta_{2n}^2+3\theta_{2n}^2\theta_r-4\theta_{2n}\theta_r^2+\alpha\theta_r+\theta_r)}$. Since $\alpha \ge \theta_r^2$, $\alpha\theta_{2n}+2\theta_{2n}^2\theta_r-4\theta_{2n}\theta_r^2-\theta_{2n}\theta_r+\alpha\theta_r+\theta_r^2 \ge \theta_{2n}\theta_r^2+2\theta_{2n}^2\theta_r-4\theta_{2n}\theta_r^2-\theta_{2n}\theta_r+\theta_r^3+\theta_r^2 = \theta_r(\theta_{2n}-\theta_r)(2\theta_{2n}-\theta_r-1) > 0$. □

The above result shows that for a low ξ, the gains for the high-end consumers willing to pay a lot for the second generation products outweigh the losses for the lower-end consumers who can no longer buy a remanufactured product, thereby driving the results on the social aspects.

However, when the manufacturing efficiency is low ($\xi = 2$), full remanufacturing is never good for consumers. Partial or no remanufacturing may benefit consumers only when product quality improvement is small.

Following Proposition 5, we analyse the implications on consumer surplus of those results. We have the following result.

Proposition B2. *Under high second generation manufacturing efficiency ($\xi = 0$), from a social point of view, the non-remanufacturing firm that improves product quality provides a higher consumer surplus than the remanufacturing firm that foregoes product quality improvement only when the quality improvement is sufficiently radical (i.e. θ_{2n} is large enough).*

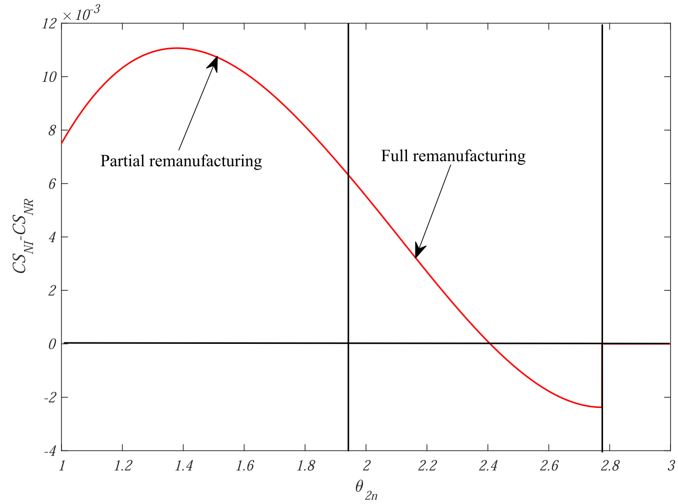

Fig. B.1. Consumer surplus difference when $\xi = 2$.

The proof of Proposition B2 is straightforward. When $\xi = 0$, consumer surplus is always increasing with θ_{2n}, therefore, there always exists a point above which the consumer surplus of the non-remanufacturing firm that improves product quality exceeds that from the remanufacturing firm that foregoes product quality improvement.

However, under $\xi = 2$, i.e. when second generation manufacturing efficiency is low, the result is not conclusive. We use a simple example to illustrate this case. Assume $\alpha = 0.2, c_{1n} = 0.3, \theta_r = 0.6$, we draw the difference of consumer surpluses from the two companies $CS_{NR-I} - CS_{R-NI}$ as a function of θ_{2n} in Fig. B.1, where CS_{NR-I} denotes consumer surplus with the non-remanufacturing firm that improves product quality and CS_{R-NI} denotes consumer surplus with the remanufacturing firm that forgoes product quality improvement. From Fig. B.1, we can see that different from the case of high manufacturing efficiency, when the manufacturing efficiency is low, radical product quality improvement (larger θ_{2n}) cannot guarantee a higher consumer surplus.

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