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Abstract

Despite documented benefits of remanufacturing, many manufacturers have yet to embrace the idea of tapping into remanufactured-goods markets. In this paper, we explore this dichotomy and analyze the effect of remanufacturable product design on market segmentation and product and trade-in prices by studying a two-stage profit-maximization problem in which a price-setting manufacturer can choose whether or not to open a remanufactured-goods market for its product. Our results suggest that it is optimal for a manufacturer to design a remanufacturable product when the value-added from remanufacturing is relatively high but product durability is relatively low and innovation is nominal. In addition, we find that entering a remanufactured-goods market in and of itself does not necessarily translate into environmental friendliness. On the one hand, the optimal trade-in program could result in low return and/or remanufacturing rates. On the other hand, a low price for remanufactured products could attract higher demand and thereby potentially result in more damage to the environment. Meanwhile, external restrictions imposed on total greenhouse gas emissions draw criticism in their own right because they risk stifling growth or reducing overall consumer welfare. Given these trade-offs, we therefore develop and compare several measures of environmental efficiency and conclude that emissions per revenue can serve as the best proxy for emissions as a metric for measuring overall environmental stewardship.

Keywords: Product Design; Remanufacturing; Market Segmentation; Trade-in Program; Return Rate; Environmental Impact

1 Introduction

The demand for remanufactured products has grown tremendously in recent years. According to United States International Trade Commission (USITC) estimates, the U.S. market for remanufactured goods increased by 15 percent from $36.0 billion in 2009 to $41.5 billion in 2011, and the value of U.S. remanufactured production grew by 15 percent to at least $43.0 billion during that same period, thus supporting 180,000 full-time U.S. jobs and contributing to $11.7 billion U.S. exports (USITC, 2012). Accordingly,

a growing number of manufacturers are actively engaging in remanufacturing, many of which offer trade-in programs to promote sales of upgraded products, use collected used products for remanufacturing, and maintain sufficient control over the entire product life cycle (Li *et al.*, 2011). As a case in point, Oracle makes available its Upgrade Advantage Program (UAP) to the users of its servers, storage systems, and select components. This program provides trade-in discounts toward new Oracle hardware when customers return qualified used equipment, which includes both originally new and remanufactured products. Meanwhile, Oracle's Remanufactured Products Program targets customers who require same-as-new quality and warranty products but can afford only reduced prices. Oracle currently offers over 70 items across 11 different product lines on its factory remanufactured products listing, with list prices ranging from $250 to $220,000 per unit (Oracle, 2013). Moreover, through these programs, Oracle has secured exclusive control over its remanufactured-goods market for itself and its partner (Oraiopoulos *et al.*, 2012) and it has boosted sales of new products as well.

For many manufacturers, offering remanufactured products is an approach that not only can attract new end-customers by expanding product lines to include less expensive alternatives, but also can help protect the environment by consuming fewer resources and by reducing overall carbon emissions. For instance, the Bosch eXchange workshop is a program that replaces faulty vehicle parts with certified remanufactured parts, at a price that is between 30 and 40 percent lower than the price of new parts. But, in addition, this program also has resulted in Bosch emitting 23,000 fewer metric tons of CO_2 in 2009 because it remanufactured 2.5 million parts in lieu of manufacturing them anew (Bosch, 2010). Similarly, Cummins' remanufacturing business, also known as ReCon, reclaimed 50 million pounds of product in 2012 and avoided 200 million pounds of greenhouse gas (GHG) emissions by offering 1,000 components and 2,000 engine part numbers as alternatives to their new-product counterparts (Cummins, 2012).

Despite these documented benefits of remanufacturing, many manufacturers have yet to embrace the idea of tapping into remanufactured-goods markets (Ferguson, 2010). Indeed, as Ferguson (2010) reports, Hauser and Lund estimated in 2008 that only 6% of over 2000 remanufacturing firms in their database were original equipment manufacturers (OEMs). And from 2009 to 2011, only 2% among total sales of all manufactured products by U.S. firms in seven remanufacturing-intensive sectors was estimated to be remanufactured goods (USITC, 2012). One major reason why manufacturers have been reluctant to introduce remanufacturing operations is the apprehension that the sale of remanufactured products would cannibalize their new product offerings (Atasu *et al.*, 2010). But, in addition, other technical and management issues include uncertainty in the quantity, quality and timing of returned products (Guide, 2000; Toktay *et al.*, 2004; Clottey *et al.*, 2012), high core and labor costs and lack of skilled workers (USITC, 2012), and possible theft of intellectual

property (Martin *et al.*, 2010).

As highlighted above, there are trade-offs involved in a manufacturer's decision to open a remanufactured-goods market for its product. Thus, the decision is a function of the system and market parameters. Therefore, in this paper, we ask the following research questions: Under what conditions should a manufacturer expand its product line to include making a remanufactured good available to its market? Moreover, if the manufacturer does enter into remanufacturing, then what should be the optimal trade-in program? What would be the resulting return rate through the trade-in program? Regardless, what would be the optimal market segmentation strategy and what would be the environmental implications of that strategy?

To answer these questions, we develop and study a two-stage profit-maximization problem in which a price-setting manufacturer can choose whether or not to open a remanufactured-goods market for its product by designing its product either to be remanufacturable or non-remanufacturable, respectively. If the manufacturer designs its product to be remanufacturable, then it also must determine its optimal pricing strategy, which involves a price for selling new products in the first period, a trade-in allowance for new products returned after the first period in exchange for either a new or remanufactured product in the second period, a price for selling new products in the second period, and a price for selling remanufactured products in the second period. If the manufacturer instead designs its product to be non-remanufacturable, then it still must determine its corresponding optimal pricing strategy, but in this case the optimal pricing strategy requires specification only of first and second period prices of new products.

Given this modeling construct, we explore and draw implications from the optimal market segmentation policies. Upon doing so, we find that it is optimal for a manufacturer to design a remanufacturable product (and thus open a remanufactured-goods market for its products) when the value-added from remanufacturing is relatively high but product durability is relatively low and innovation is nominal. In many cases, however, we find that it is not optimal for the manufacturer to design its product to be remanufacturable, which helps validate to some extent the documented evidence indicating the reluctance of so many manufacturers to enter the remanufactured-goods market.

In addition, we find that the optimal trade-in program is such that the return rate could be low, depending on the problem parameters. In particular, we find that when the production cost of a non-remanufacturable product is high but the remanufacturing cost is low, the manufacturer designs its new products to be remanufacturable but then limits the incentive for customers to return those products in exchange for a new or remanufactured replacement by virtue of offering a relatively low trade-in price. In addition, under such circumstances, not only is a small fraction of products returned through the trade-in program, but also is only a small fraction of those returns then remanufactured. Hence, under such circumstances, the return rate

and the remanufacturing rate of returned products are low.

Thus, we emphasize that entering a remanufactured-goods market in and of itself does not necessarily translate into environmental friendliness. Despite the fact that the negative environmental impact of a given unit of a remanufactured product is usually less than that of a new one, a low price for remanufactured products could attract demand from consumers who otherwise would not purchase new products at higher prices. This demand increase in remanufactured products thus would mean that additional resources may be consumed to fulfill customer demand, thereby potentially resulting in a more damaging environmental impact overall (e.g., more GHG emissions). Meanwhile, restrictions imposed on GHG emissions draw criticism in their own right because they risk stifling growth or reducing overall consumer welfare. Given these trade-offs, we therefore develop and compare several measures of environmental efficiency that take into consideration both environmental issues and economic performance or social welfare. Among these measures, we conclude that a manufacturer that remanufactures its products generally produces lower GHG emissions per dollar of revenue than a manufacturer that does not remanufacture. In fact, manufacturers such as Apple (2013), Cummins (2012) and Dell (2013) have been measuring their environmental performance using such an efficiency ratio.

Our paper is organized as follows. We first review related literature in Section 2. We then formulate our model and provide structural results in Section 3, and we provide detailed analysis in Section 4 to identify the optimal design decision, market segmentation, return rate and remanufacturing rate. We then investigate and compare several environmental impact measures in Section 5. We conclude our paper with a summary of our findings, implications, and limitations in Section 6.

2 Relation to Literature

A large number of studies in recent years have focused on the strategic, tactical, and operational issues of remanufacturing, as comprehensively reviewed by Guide and Van Wassenhove (2009) and by Souza (2013). Among this literature, several themes have emerged to establish why and how OEMs voluntarily enter remanufacturing markets including, but not limited to, the following reasons: to enhance profit opportunities (Toffel, 2004), to better manage demand (Ferrer and Swaminathan 2006, 2010), to help segment consumer markets (Debo *et al.*, 2005; Atasu *et al.*, 2008) and to mitigate the effects of external remanufacturing competition (Majumder and Groenevelt, 2001; Ferguson and Toktay, 2006) while prudently managing potential cannibalization within its own product line (Moorthy 1984; Guide and Li, 2010). We contribute to this literature by endogenizing the decision to design for remanufacturability (*i.e.,* whether or not to design a product

that can be remanufactured). In doing so, we incorporate a cost trade-off by recognizing that producing a remanufacturable product is usually more costly than producing a non-remanufacturable product, but that is in exchange for potential savings when the product is remanufactured. Meanwhile, we endogenize the trade-in price, which serves as both an incentive for customers to return used products and as a lever for the manufacturer to further segment the market.

We also contribute to the remanufacturing literature that investigates trade-in programs and their implications for pricing and discounting strategies. Along this theme, Oraiopoulos *et al.* (2012) and Agrawal *et al.* (2008) consider the role of a trade-in program in facilitating product returns (for remanufacturing) and in providing a lever to segment vertical markets through price. Ray *et al.* (2005) study the trade-in strategy for remanufacturing products by considering both durability and the age of products. They find that if the trade-in allowance is age-independent, then the trade-in allowance first increases in durability but after a certain threshold, it starts decreasing. They conclude that a firm should offer the maximum trade-in allowance when products are of medium durability. Moreover, with an optimized trade-in program, some customers carry back used products for resale value and others may continue using their products for another period. In a related vein, return rates can be modeled exogenously because manufacturers often must comply with laws and regulations such as the Waste Electrical and Electronic Equipment (WEEE) Directive, which specifies a minimum percentage of e-waste that needs to be collected by manufacturers. However, firms can actually benefit from actively controlling the return rate of used products (Guide, 2000; 2001). Atasu and Souza (2013) show that the optimal recovery rate (*i.e.*, the return rate multiplied by the fraction of returned products that are recovered) can be zero or positive but the firm never chooses high product quality or price when the rate is endogenous. We relax their assumption that the return rate is independent of prices and instead model it as the proportion of new products sold in the first period that are later returned by customers who maximize their surplus. Hence, our return rate is related to customer utility from new, used and remanufactured products, to the retail prices of new and remanufactured products as well as to the trade-in price. Furthermore, we then examine the remanufacturing rate, which we define as the proportion of returned products that are eventually remanufactured by the manufacturer.

Although environmental performance can be positively correlated to financial performance (Klassen and McLaughlin, 1996; Corbett and Klassen, 2006), these two metrics often lead to conflict for manufacturers (Kleindorfer *et al.*, 2005). Moreover, environmentally responsible practices such as leasing and product recovery are not necessarily superior to no-leasing or no-recovery scenarios (Agrawal *et al.*, 2012; Atasu and Souza, 2013). As to remanufacturing, Gu *et al.* (2012) show that the presumed environmental efficiency of remanufactured products could be compromised if either the ratio of per-unit environmental impact as-

sociated with remanufactured or new products is high, or the remanufacturing cost is high. The studies mentioned above limit their discussion by using aggregated measure of environmental impact. A common belief is that environmental regulations based on such a measure erode competitiveness (Porter and van der Linde, 1995). Hence, we contribute to the literature by defining and evaluating different environmental efficiency measures that relate them to other outcomes such as profit, revenue or social welfare.

Our paper is most closely related to Oraiopoulos *et al.* (2012), who explore the conditions under which an OEM should allow or restrict the opening of a secondary market for remanufactured products operated by third-party entrants and how such decisions and trade-in prices are affected by the relicensing fee. By examining combined effects of inherent product durability, added value of remanufacturing process, innovation and cost, they show that when consumers' willingness to pay for a remanufactured product is sufficiently high compared to inherent product durability, it is not optimal for the OEM to eliminate the secondary market because cannibalization effects are outweighed by relicensing revenue and resale value effects. Our paper differs from their paper in several ways. First, product design is endogenous to our model, that is, our manufacturer decides whether or not to design its new products to be remanufacturable. If the manufacturer chooses a remanufacturable design, a higher production cost of new products incurs to the firm due to R&D expenses and additional resource consumption. Second, we consider the manufacturer to be a price-setter for both new and remanufactured products. Under this assumption, we therefore have no relicensing fee, but instead introduce a new consumer type, namely consumers who buy a new product in the first period and replace it with a remanufactured product in the second period. Third, our paper emphasizes the environmental implications of an optimal strategy.

3 Assumptions and Models

3.1 Modeling Framework

Manufacturer. We consider a two-period, profit-maximization problem for a price-setting manufacturer. The manufacturer makes design decision k at the beginning of the time horizon, where $k = 0$ denotes a non-remanufacturable design (in which case new products are non-remanufacturable) and $k = 1$ denotes a remanufacturable design (in which case new products are remanufacturable). In the first period, the manufacturer determines the price p_1 at which new products are sold in the period. In the second period, if $k = 0$, then the manufacturer only determines the price p_2 at which new products are sold in the period; however, if $k = 1$, then the manufacturer determines the prices p_2 and p_r at which new and remanufactured products are respectively sold in the period. Meanwhile, if $k = 1$, then the manufacturer also determines the

trade-in allowance s for buyers who return a used product to buy either a new or a remanufactured one in the second period. Only returned products may be remanufactured and therefore the number of remanufactured products cannot exceed the number of products returned.

The production cost of a new product depends on the design decision k. We assume that the unit cost to produce a new non-remanufacturable product (defined by $k = 0$) and a new remanufacturable product (defined by $k = 1$) is c_0 and c_1, respectively, where $c_1 \geq c_0$ reflects the increased complexity required to make a product remanufacturable (Subramanian, 2012). The unit cost to remanufacture a product is c_r. We assume $c_r < c_0$ because the per-unit remanufacturing cost can be as low as 40 to 65 percent less than that of its new products (Ginsburg, 2001).

Consumers. Willingness-to-pay (WTP) θ for a new product in the first period is heterogeneous and uniformly distributed in the interval $[0,1]$, with market size normalized to 1. We assume θ to be independent of k since a consumer's sustainability considerations are normally separate from the attribute of the products themselves (Galbreth and Ghosh, 2013). We call a customer with WTP equal to θ a customer of type θ. Consistent with Oraiopoulos *et al.* (2012), we make the following five assumptions: First, we assume that the new product in the second period (if offered) is an upgraded version of the one produced and sold in the first period, characterized by innovation factor α, where $\alpha \geq 1$. Thus, if a consumer is willing to pay θ for the new product in the first period, then her WTP for an upgraded new product in the second period is $\alpha \cdot \theta$. Second, we assume that a new product in the first period depreciates with use and is characterized by durability factor δ, where $\delta < 1$. Thus, if the customer's WTP is θ for a new product in the first period, then her valuation associated with keeping the product in the second period is $\delta \cdot \theta$. Third, we assume that a consumer's WTP for a remanufactured product is less than her WTP for a new product. Thus, if a consumer is willing to pay θ for a new product in the first period, then her WTP for a remanufactured product in the second period is $\delta_r \cdot \theta$, where remanufacturing valuation factor $\delta_r \in (0,1)$. Fourth, we assume that remanufacturing improves the condition of a used product. Thus, $\delta_r > \delta$. Fifth, we assume that the one-period utility from an upgraded product is less than the combined utility from a new product bought in the first period and used for two periods. Thus, $\alpha < 1 + \delta$.

If a new product is remanufacturable ($k = 1$), then a customer purchases at most one new unit in each period. If the customer makes a purchase in the first period, then in the second period, she can either trade it in for a new product (segment *nn*), trade it in for a remanufactured product if one is available (segment *nr*) or keep it and thereby exit the market (segment *nu*). If the customer does not make a purchase in the first period, then in the second period, she can either buy a new product (segment *on*), buy a remanufactured product if available (segment *or*), or remain out of the market altogether (segment *oo*). Therefore, in principle, there

exist six customer segments distinguished by different customer buying strategies for the two periods. We use "customer segment" and "customer strategy" interchangeably unless otherwise distinguished.

Consumers are strategic in the sense that they make purchase decisions based on the total consumer surplus associated with both periods, which we define as the product valuations net of trade-in price s (if applicable) minus the product prices p_1, p_2 and p_r, as applicable. Thus, like Oraiopoulos *et al.* (2012), we essentially assume that consumers know the trade-in program as well as the price list for both periods before making decisions. Note that consumers who otherwise would have a negative consumer surplus do not make any purchases (segment *oo*). We denote segment size by d with a subscript to refer to the segment, e.g., d_{nn} denotes the size of customer segment *nn*. Therefore, we have $d_{nn} + d_{nr} + d_{nu} + d_{on} + d_{or} + d_{oo} = 1$. For parsimony, we assume that used products cannot be directly traded between customers. If a new product is non-remanufacturable ($k = 0$), then the market segmentation is analogous except that $k = 0$ means that $d_{nr} = d_{or} = 0$ by definition. Table 1 summarizes the total consumer surplus associated with each strategy for a customer of type θ, given p_1, p_2, p_r and s, as applicable for a given k.

Table 1: Consumer Surplus of Each Strategy for Consumers of Type θ

Strategy	1st Period	2nd Period	Consumer Surplus $S(\theta)$
nn	buy new	buy new	$(\theta - p_1) + s + (\alpha\,\theta - p_2)$
nr	buy new	buy remanufactured	$(\theta - p_1) + s + (\delta_r\theta - p_r)$
nu	buy new	continue to use	$(\theta - p_1) + \delta\,\theta$
on	inactive	buy new	$\alpha\,\theta - p_2$
or	inactive	buy remanufactured	$\delta_r\theta - p_r$
oo	inactive	inactive	0

Profit-maximization Problem: Let Π^k be the manufacturer's total profit over the two periods, given design decision k. If new products are designed to be non-remanufacturable ($k = 0$), then the manufacturer's problem is

$$\begin{aligned} \Pi^0 &= \max_{p_1,p_2} (p_1 - c_0)\cdot(d_{nn} + d_{nu}) + (p_2 - c_0)\cdot(d_{nn} + d_{on}) \qquad (1) \\ s.t. \quad & d_{nn} + d_{nu} + d_{on} \le 1 \\ & d_{nn}, d_{nu}, d_{on} \ge 0 \\ & p_1, p_2 \ge 0 \end{aligned}$$

Alternatively, if new products are designed to be remanufacturable ($k = 1$), then the manufacturer's problem

becomes

$$\begin{aligned}
\Pi^1 &= \max_{p_1,p_2,p_r,s} (p_1-c_1)\cdot(d_{nn}+d_{nr}+d_{nu})+(p_2-c_1)\cdot(d_{nn}+d_{on}) \\
&\qquad +(p_r-c_r)\cdot(d_{nr}+d_{or})-s\cdot(d_{nn}+d_{nr}) \qquad (2)\\
s.t. \quad & d_{or}\le d_{nn} \\
& d_{nn}+d_{nr}+d_{nu}+d_{on}+d_{or}\le 1 \\
& d_{nn},d_{nr},d_{nu},d_{on},d_{or}\ge 0 \\
& p_1,p_2,p_r,s\ge 0
\end{aligned}$$

where $d_{or}\le d_{nn}$ is true because the number of units remanufactured cannot exceed the number of units returned, i.e., $d_{nr}+d_{or}\le d_{nn}+d_{nr}$ or, equivalently, $d_{or}\le d_{nn}$. Design decision k is determined by maximizing $\Pi^*=\max\left\{\Pi^0,\Pi^1\right\}$ and the corresponding optimal decisions are denoted as k^*,p_1^*,p_2^*,p_r^* and s^*.

3.2 Solution Procedure

For any given product design, we use Table 1 to obtain the indifference point θ between any pair of customer segments such that a customer of type θ is indifferent between two strategies, and under the assumption that $\alpha<1+\delta$, we produce Table 2 accordingly. In Table 2, customers with WTP above the indifference point θ in a cell belong to the customer segment of the corresponding row and those with WTP below the indifference point θ belong to the customer segment of the corresponding column. We can derive the size of each segment by comparing the indifference points. For example, if products are remanufacturable, then Table 2(a) establishes that, for a customer to choose strategy nr, her WTP θ must satisfy

$$\theta \in \left[\max\left\{\frac{p_r-s}{\delta_r-\delta},\frac{p_1-p_2+p_r-s}{1+\delta_r-\alpha},p_1-s,\frac{p_1+p_r-s}{1+\delta_r},0\right\},\min\left\{\frac{p_2-p_r}{\alpha-\delta_r},1\right\}\right]. \qquad (3)$$

In other words, if $k=1$, then for a customer to choose strategy nr, that strategy must yield a higher consumer surplus than would strategies nu,on,or,oo. As per the "nr" row of Table 2(a), this would be true if

$$\theta\ge\max\left\{\frac{p_r-s}{\delta_r-\delta},\frac{p_1-p_2+p_r-s}{1+\delta_r-\alpha},p_1-s,\frac{p_1+p_r-s}{1+\delta_r}\right\}.$$

Meanwhile, for the customer to choose strategy nr, that strategy also must yield a higher consumer surplus than would strategy nn, which would be true if $\theta\le\frac{p_2-p_r}{\alpha-\delta_r}$, as per the "$nr$" column of Table 2(a). Note that

$\theta \in [0,1]$, thus Equation 3 follows. Given (3), then, the size of customer segment *nr* is

$$d_{nr} = \max\left\{\min\left\{\frac{p_2 - p_r}{\alpha - \delta_r}, 1\right\} - \max\left\{\frac{p_r - s}{\delta_r - \delta}, \frac{p_1 - p_2 + p_r - s}{1 + \delta_r - \alpha}, p_1 - s, \frac{p_1 + p_r - s}{1 + \delta_r}, 0\right\}, 0\right\} \tag{4}$$

The size of all other customer segments, for a given value of k, can be derived in the same fashion.

Table 2: Indifference Point θ for Any Pair of Strategies

(a) Remanufacturable Design

$k=1$	nr	nu	on	or	oo
nn	$\frac{p_2-p_r}{\alpha-\delta_r}$	$\frac{p_2-s}{\alpha-\delta}$	$p_1 - s$	$\frac{p_1+p_2-p_r-s}{1+\alpha-\delta_r}$	$\frac{p_1+p_2-s}{1+\alpha}$
nr		$\frac{p_r-s}{\delta_r-\delta}$	$\frac{p_1-p_2+p_r-s}{1+\delta_r-\alpha}$	$p_1 - s$	$\frac{p_1+p_r-s}{1+\delta_r}$
nu			$\frac{p_1-p_2}{1+\delta-\alpha}$	$\frac{p_1-p_r}{1+\delta-\delta_r}$	$\frac{p_1}{1+\delta}$
on				$\frac{p_2-p_r}{\alpha-\delta_r}$	$\frac{p_2}{\alpha}$
or					$\frac{p_r}{\delta_r}$

(b) Non-remanufacturable Design

$k=0$	nu	on	oo
nn	$\frac{p_2}{\alpha-\delta}$	p_1	$\frac{p_1+p_2}{1+\alpha}$
nu		$\frac{p_1-p_2}{1+\delta-\alpha}$	$\frac{p_1}{1+\delta}$
on			$\frac{p_2}{\alpha}$

Let **M=**$(sgn(d_{nn}), sgn(d_{nr}), sgn(d_{nu}), sgn(d_{on}), sgn(d_{or}))$ denote a specified market configuration, where $sgn(x) = 1$ if $x > 0$ and $sgn(x) = 0$ if $x \leq 0$. Thus, for example, **M=**(1,1,0,0,0) represents the market configuration in which some customers buy new products in the first period and then trade them in for either new or remanufactured products in the second period ($d_{nn}, d_{nr} > 0$) but no customer exits the market after the first period or enters it in the second period ($d_{nu} = d_{on} = d_{or} = 0$). Given this definition of **M**, note that $k = 0$ if and only if **M=**(*,0,*,*,0), where * can be 0 or 1; all other configurations correspond to $k = 1$. In principle, there are $2^5 - 1 = 31$ non-trivial possible market configurations of which 7 are associated with non-remanufacturable design ($k = 0$) and 24 are associated with remanufacturable design ($k = 1$). However, the following two propositions establish that certain configurations cannot exist in an optimal solution, thus eliminating them from consideration. The proofs of both propositions are provided in Appendix A.

Proposition 1 *Given any product specification and market condition ($c_0, c_1, c_r, \alpha, \delta$ and δ_r), the following are true:*

(i) $d_{or} > 0 \Rightarrow d_{nn} > 0$, *i.e.,* ***M=****(0,*,*,*,1) does not exist, where * can be 0 or 1.*

(ii) $d_{nr} > 0 \Rightarrow d_{on} = 0$ *and* $d_{on} > 0 \Rightarrow d_{nr} = 0$, *i.e.,* ***M=****(*,1,*,1,*) does not exist, where * can be 0 or 1.*

(iii) $d_{nr} = d_{nu} = d_{on} = d_{or} = 0 \Rightarrow d_{nn} = 0$, *i.e.,* ***M=****(1,0,0,0,0) does not exist.*

Intuitively, Proposition 1(i) is a result of the fact that the manufacturer cannot remanufacture more products than are returned ($d_{or} \leq d_{nn}$). According to the proof of Proposition 1(ii), the existence of segment *on* effectively requires that $p_1 - s$ (the price of new products in the first period net of their trade-in value) must be relatively large while $p_2 - p_r$, the price difference of new and remanufactured products in the second

period, must be relatively small, which in turns makes it irrational to buy a new product in the first period and then trade it in for a remanufactured product because $p_1 - s + p_r$ is relatively large. Similarly, for segment *nr* to exist, $p_1 - s$ must be relatively small and $p_2 - p_r$ must be relatively large, in which case there would be no demand for new products in the second period because p_2 is relatively large. The proof of Proposition 1(iii) indicates that if products are designed to be non-remanufacturable ($k = 0$) and if there exist customers who makes purchases in both periods, then it means that p_1 must be sufficiently low so as to entice some other customers to purchase new products in the first period without then purchasing anew in the second period, thus rendering it impossible to sell products only to customers with the highest valuation (segment *nn*).

In all, Proposition 1 eliminates 15 of the 31 theoretically possible market configurations from consideration. Next, Proposition 2 eliminates 2 more of the remaining 16.

Proposition 2 *Given any product specification and market condition ($c_0, c_1, c_r, \alpha, \delta, \delta_r$), the following are true:*

(i) *It is more profitable to offer only new products in the first period ($d_{nu} > 0$ and $d_{nn} = d_{nr} = d_{on} = d_{or} = 0$) than it is to offer only new products in the second period ($d_{on} > 0$ and $d_{nn} = d_{nr} = d_{nu} = d_{or} = 0$), i.e.,* ***M****=(0,0,1,0,0) dominates* ***M****=(0,0,0,1,0).*

(ii) *If new products are non-remanufacturable ($d_{nr} = d_{or} = 0$), then it is more profitable to offer new products for one-time purchase only in the first period ($d_{nu} > 0$ and $d_{nn} = d_{on} = 0$) than it is to offer new products for one-time purchase in either the first period or the second period ($d_{nu}, d_{on} > 0$ and $d_{nn} = 0$), i.e.,* ***M****=(0,0,1,0,0) dominates* ***M****=(0,0,1,1,0).*

To help explain Proposition 2(i), note that the assumption $1 + \delta > \alpha$ suggests that if a manufacturer offers only new products, either in the first period or in the second period, then it should be optimal to produce and sell the products earlier rather than later, everything else being equal. In other words, if innovation is not sufficient, then it does the firm no benefit to delay the introduction of a new product for a minor update. Moreover in such a case, new products will be non-remanufacturable because the firm will not remanufacture them. In a similar vein, Proposition 2(ii) is a byproduct of product cannibalization in our two-period model. In particular, if the manufacturer offers new products that are non-remanufacturable in both periods, then some customers will prefer to buy new products in the first period rather than to buy in the second period. Note the unit profit of selling one new product in the second period is usually smaller than the unit profit of selling one in the first period that can be used in both periods (see proof for details). Consequently, the manufacturer prefers to price products such that customers will only make purchases in

the first period rather than in the second.

Although Propositions 1 and 2 analytically eliminate all but 14 possible market configurations from the search for the optimal solutions to (1) and (2), we find that we need to rely on a numerical search routine to complete the optimization over the remaining feasible set of configurations. To that end, we condition the remaining search on the different feasible market configurations. In particular, for any given feasible market configuration, we numerically solve either (1) or (2), as applicable, by applying the Matlab build-in quadratic programming function *quadprog*. We then compare the profit associated with each of the resulting solutions (one for each feasible market configuration) to obtain the optimal solution k^*, p_1^*, p_2^*, p_r^* and s^* for any given parameter set. (See Technical Supplement for algorithm details and justification.) Finally, we repeat this process for an exhaustive set of input parameters to populate a comprehensive database of solutions to the manufacturer's maximization problem. Table 3 summarizes the specific parameter ranges used in the process for which we solved the firm's optimization problem. Given Table 3, the total number of parameter combinations $(c_0, c_1, c_r, \alpha, \delta, \delta_r)$ using an increment $I = 0.1$ for all parameters is 18,720. However, in addition, we solved another approximately 36,000 instances by applying a smaller increment $I = 0.005$. Thus our analysis below is based on solutions to approximately 54,000 instances of the problem.

Table 3: Parameter Ranges for Numerical Study

Parameter	**Increment (I)**	**Min**	**Max**
c_0	0.1^*	I	$1-I$
c_1	0.1^*	g_0	$1-I$
c_r	0.1^*	I	c_0-I
α	0.1^*	1	$2-3\times I$
δ	0.1^*	$\alpha-1+I$	$1-2\times I$
δ_r	0.1^*	$\delta+I$	$1-I$

* we choose increment $I = 0.005$ in the cases when more than one parameters are fixed.

4 Analysis

In this section, we compile and explore the database of optimal designs and market configurations as well as the corresponding optimal profits and return rates produced by the numerical optimization routine applied to the comprehensive set of problem instances as described above. To set the stage, we note first that, although 14 possible market configurations survive the elimination procedure implied by Propositions 1 and 2, we find that seven of those that remain never appear in our database of optimal solutions. Thus, we find that, of the 31 non-trivial possible market configurations that can exist in principle, only eight remain as potentially optimal for a given set of problem parameters taken from Table 3. We label these 8 configurations as M1

through M8, and we provide each of their specifications in Table 4. From Table 4, note that M1, M2 and M3 each have $d_{nr} = d_{or} = 0$, which implies that $k^* = 0$ when any one of these configurations is optimal; and M4 to M8 each of have either or both $d_{nr} > 0$ or $d_{or} > 0$, which implies that $k^* = 1$ when any one of these configurations is optimal.

Table 4: Taxonomy of Optimal Solution

k^*	$k^* = 0$			$k^* = 1$				
Mkt Conf.	M1	M2	M3	M4	M5	M6	M7	M8
d_{nn}	+	+		+	+	+		
d_{nr}					+	+	+	+
d_{nu}	+	+	+	+	+		+	
d_{on}	+							
d_{or}				+		+		

Notes: + means the segment size is positive; blank cell means the segment size is zero.

4.1 Optimal Market Segmentation

We first investigate the effects of exogenous parameters (production cost c_0 and c_1, remanufacturing cost c_r, innovation factor α, durability factor δ and remanufacturing factor δ_r) on the size of each customer segment in an optimal solution, as depicted in Figures 1 and 2. In Figure 1, we use base values of $c_0 = 0.5, c_1 = 0.55$ and $c_r = 0.2$ and explain the effect of varying c_0, c_1 and c_r on the optimal customer segmentation. In Figure 2 we repeat this by varying parameters α, δ and δ_r.

We find that the cost parameters c_0, c_1 and c_r have an indirect impact on consumer behavior. In particular, the cost structure first affects the manufacturer's optimal design and market configuration, which in turn influences the size of various customer segments (see Figure 1). If the production cost of non-remanufacturable products c_0 is low relative to c_1, the manufacturer designs its products to be non-remanufacturable (*i.e.,* $k^* = 0$). Intuitively, this is true because the cost premium of making the product remanufacturable is significant. Therefore, segment *nr* and *or* exist only when c_0 is relatively large (see Figure 1(a)). On the contrary, as shown in Figures 1(b) and 1(c), if the production cost of remanufacturable products c_1 is close to c_0 or the remanufacturing cost c_r is low, the manufacturer designs its products to be remanufacturable, which makes sense because, then, the manufacturer can reap the added value of remanufacturing without incurring much additional cost. As a result, customers buy remanufactured products when c_1 or c_r is relatively low. Moreover, the lower is c_r, the more are the customers who buy remanufactured products (*i.e.,* the larger is segment *nr*) and the fewer are the customers who buy new products (*i.e.,* the smaller is segment

nn). Intuitively, a lower c_r allows the manufacturer to lower the price of remanufactured products. Interestingly, however, the size of segment *or* also increases as c_r increases (see Figure 1(c)). This is because some customers who otherwise would choose strategy *nr* when c_r is small switch to strategy *or* when c_r is large, which results in a higher p_r and a lower s. Nevertheless, as a whole, the overall sale of remanufactured products reduces as c_r increases (see Figure 1(c)). In a similar vein, the overall sale of remanufactured products initially increases as c_1 increases because some customers who otherwise would choose strategy *nn* when c_1 is small switch to purchase remanufactured products in the second period when c_1 (and, correspondingly p_1 and p_2) grow larger. Eventually, however, if c_1 is sufficiently large, then the manufacturer's optimal design becomes $k^* = 0$ in which case segments *nr* and *or* necessarily disappear altogether because remanufactured products are not available.

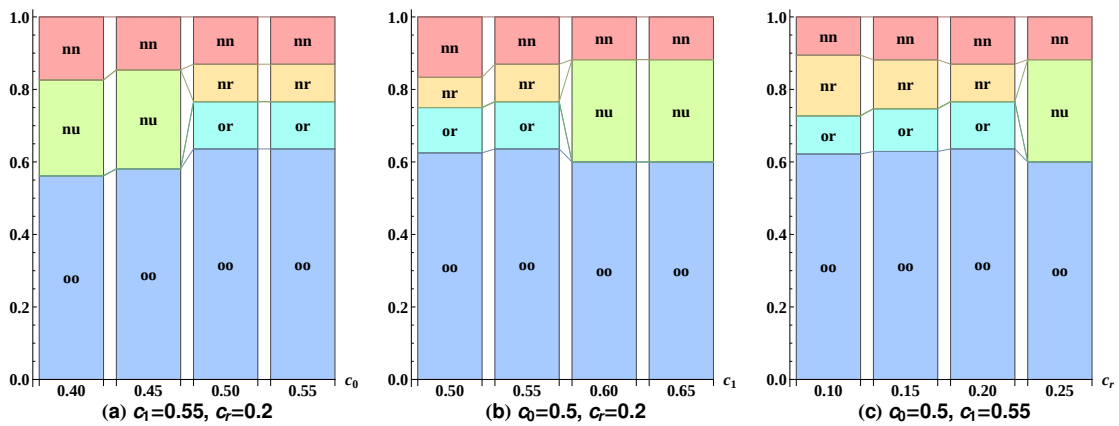

Figure 1: Customer Segments ($\alpha = 1.25$, $\delta = 0.4$ and $\delta_r = 0.8$)

Looking next at Figure 2, we find that when innovation factor α increases, more customers buy new products in both periods (*i.e.,* d_{nn} increases), but fewer customers buy remanufactured products (*i.e.,* $d_{nr} + d_{or}$ decreases). This is because customers are willing to pay more for upgraded products when α is larger. Interestingly, however, we find that although the overall demand for remanufactured products ($d_{nr} + d_{or}$) decreases in α, the size of segment *or* increases in α. Intuitively, this happens because, as α increases, the manufacturer can provide less incentive to attract previous buyers (*i.e.,* provide smaller s), which enables it to reduce its price for remanufactured products (*i.e.,* reduce p_r) to expand segment *or*. Similarly, a larger durability factor δ means that more customers find it optimal to continue using the old product in the second period (*i.e.,* d_{nu} increases), while fewer customers buy upgraded or remanufactured products (*i.e.,* d_{nn}, d_{nr} and d_{or} all decrease). In general, δ_r produces the mirror effect that c_r produces as shown in Figure 2(c). In particular, as δ_r increases, while d_{nr} increases and d_{nu} decreases; and the progressions of d_{or} and d_{nn} are

monotonically decreasing as long as $k^* = 1$.

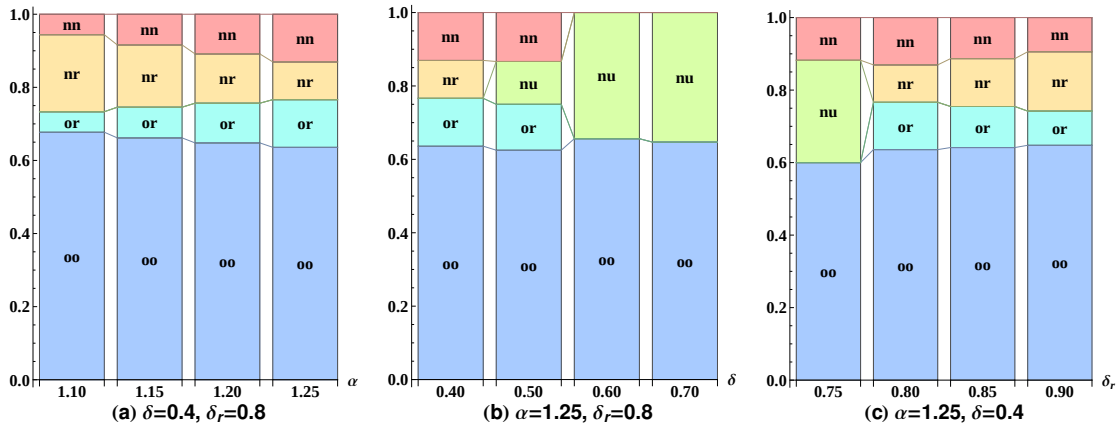

Figure 2: Customer Segments ($c_0 = 0.5, c_1 = 0.55$ and $c_r = 0.2$)

4.2 Optimal Product Design

As seen from Figure 2, the manufacturer tends to design a non-remanufacturable product ($k^* = 0$) when product durability δ is relatively large or remanufacturing valuation factor δ_r is relatively small. We next examine more closely the effect of these two parameters on the optimal product design. Toward that end, Figure 3 illustrates the optimal product design and market configurations as functions of (δ, δ_r) space for various values of c_1, given that $c_0 = 0.5, c_r = 0.2$ and $\alpha = 1.25$. Each solid curve in the figure represents the threshold above which $k^* = 1$.

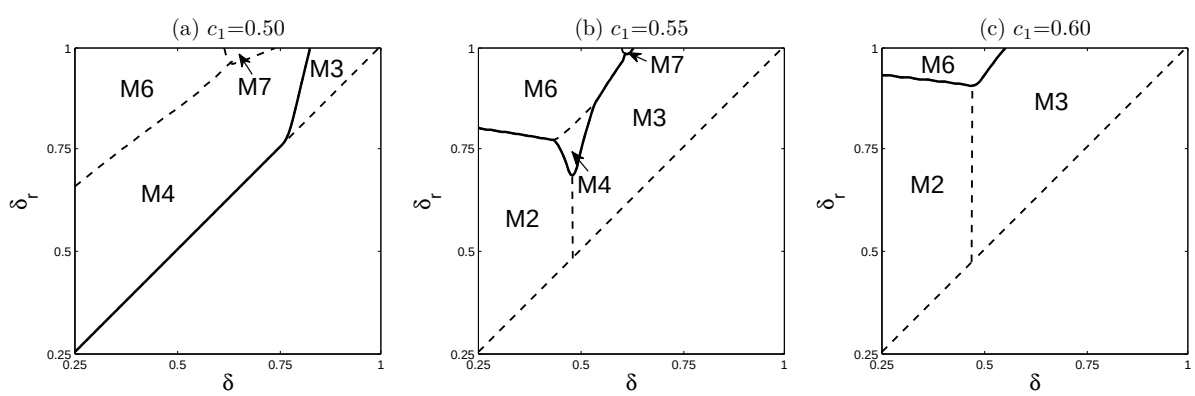

Figure 3: Optimal Product Design and Market Configurations when $c_0 = 0.5$, $c_r = 0.2$, $\alpha = 1.25$.
Notes: The southeast area is outside the bounds of discussion because $\delta < \delta_r$. In each plot, $k^* = 1$ when (δ, δ_r) lies above the bold solid curve and $k^* = 0$ when (δ, δ_r) lies below the bold solid curve.

Table 5: Characterization of the Optimal Solution: $c_0 = 0.5$, $c_r = 0.2$, $\alpha = 1.25$

Mkt Conf.	M1	M2	M3	M4*	M5*	M6*	M7*	M8*	
Figure 3(a) $c_1 = 0.50$ (%)	0.0	0.0	7.0	64.4	0.0	27.2	1.4	0.0	100%
Figure 3(b) $c_1 = 0.55$ (%)	0.0	34.0	40.1	2.1	0.0	23.5	0.3	0.0	100%
Figure 3(c) $c_1 = 0.60$ (%)	0.0	45.9	45.4	0.0	0.0	8.7	0.0	0.0	100%

Notes: * indicates market configurations corresponding to $k^* = 1$. Each row represents the percentage of cases (varying δ and δ_r) for which the given market configuration constitutes the optimal solution for given c_1.

As Figure 3 illustrates, it is optimal to design new products to be remanufacturable ($k^* = 1$) only when the product durability δ is sufficiently low and the remanufacturing valuation factor δ_r is sufficiently high. Moreover, the higher is the cost to produce remanufacturable products c_1, the more dramatic is this effect. Hence, it is optimal for the manufacturer to produce remanufacturable products not only when a customer's WTP is high for a remanufactured product and low for a used product, but also when the production cost is sufficiently low to justify the endeavor. Intuitively, if new products were to provide relatively high utility in the second period, as compared to remanufactured products, then it would be difficult for the manufacturer to attract customers to the remanufactured products in the second period. Indeed, notice from Figure 3 that although it is predominately optimal for the manufacturer to design a remanufacturable product when there is no cost premium associated with that decision (*i.e.,* when $c_1 = c_0$), if c_1 is even just 10%-15% higher than c_0, the product design threshold moves northwest rapidly, thus leaving a much smaller region in which $k^* = 1$. To quantify this observation, we probe deeper using Table 5. In Table 5, we specify as percentages the optimal market configuration areas depicted in Figure 3. For example, in reference to Figure 3(a), of all the problem instances derived from Table 5 by setting $c_1 = 0.5$ (and $c_0 = 0.5$, $c_r = 0.2$, $\alpha = 1.25$), but varying δ and δ_r, market configuration M3 is optimal for only 7% (whereas M4 is optimal for 64.4%, M6 is optimal for 27.2%, and M7 is optimal for 1.4%). Given Table 5, then, note that as c_1 increases from 0.50 to 0.55 to 0.60, the corresponding percentage of problem instances for which $k^* = 1$ (M4-M8) decreases rapidly, but at a decreasing rate, from 93% to 25.9% to 8.7%.

To further relate the above observation to optimal design, we next find the upper bound of c_1 beyond which the manufacturer chooses not to design a remanufacturable product. Figure 4 depicts this threshold as a function of various problem parameters. In Figure 4, values of c_1 below a given threshold function correspond to $k^* = 1$ and values above the threshold function correspond to $k^* = 0$. Intuitively, when customers are willing to pay more for a remanufactured product (*i.e.,* the larger is δ_r) or when the remanufacturing cost is lower (*i.e.,* the smaller is c_r), the manufacturer will continue to design and produce remanufacturable products at higher costs (*i.e.,* at higher values of c_1). However, it is interesting to note from Figure 4(a) that

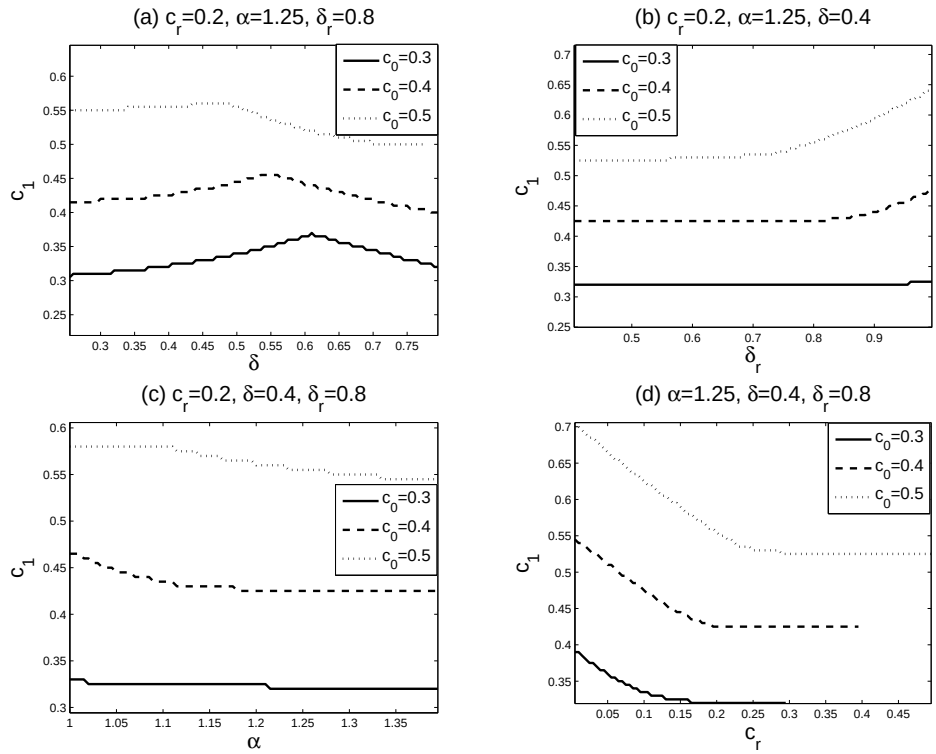

Figure 4: Maximum Threshold of c_1 for a Remanufacturable Design

the remanufacturable design threshold of c_1 is not a monotone function of product durability δ. To help explain this observation, it is useful to examine the corresponding optimal market configuration when $k^* = 0$. In doing so, we find that when δ is small, the profit associated with selling new products in both periods is higher than that associated with selling new products only in the first period because customers who keep using old products do not pay a large premium for product durability. But, if new products are available in both periods when customers also have the option to continue using used products, then any increase in δ essentially intensifies product cannibalization. As a result, when δ is small and increases, the manufacturer will choose to remanufacture even for increased costs c_1 associated with doing so. In contrast, segment *nu* is sufficiently lucrative to deter the manufacturer from selling new products in the second period, in which case, any increase in δ essentially means that the manufacturer can charge a higher price for new products and generate higher profits without worrying about product cannibalization. Consequently, when δ is large and increases, the manufacturer, ceteris paribus, requires a lower c_1 to justify remanufacturing.

4.3 Optimal Return and Remanufacturing Rates

Environmental laws such as the Waste Electrical and Electronic Equipment (WEEE) Directive requires its member states to recollect a specific percent of e-waste put on their markets (WEEE Directive, 2012). Nev-

ertheless, manufacturers recollect used products not only to comply with laws and regulations, but also to remanufacture them to boost economic success. In our model setting, the return rate is determined by the trade-in allowance s. Hence, in this section, we study the implied return rate corresponding to the manufacturer's optimal product design and market segmentation strategy. However, the return rate in and of itself is not necessarily the same as the remanufacturing rate, meaning that not all returned products are necessarily remanufactured upon their return. Hence, in this section, we also study the resulting remanufacturing rate associated with the manufacturer's optimal strategy.

4.3.1 Return Rate

We define return rate (r) as the proportion of new products sold in the first period that are later recollected by the manufacturer, that is,

$$r = \frac{d_{nn} + d_{nr}}{d_{nn} + d_{nr} + d_{nu}}$$

Because $r \in (0,1]$ if new products are remanufacturable (*i.e.* if $k^* = 1$) and $r = 0$ if (and only if) new products are non-remanufacturable (*i.e.* if $k^* = 0$), we restrict our discussion only to cases in which new products are remanufacturable. In other words, we focus here on the cases from Sections 4.1-4.2 in which the optimal market configuration is a member of the set $\{$M4, M5, M6, M7, M8$\}$. Table 6 aggregates and summarizes the return rates associated with those cases. As Table 6 highlights, if the manufacturer designs its product to be remanufacturable, then it is optimal for the manufacturer to set s such that all first-period customers return the product (*i.e.*, $r = 1$) in only 44.7% of the corresponding solutions. Note that $r = 1$ means that no customer who makes a purchase in the first period keeps the product for further use in the second period (*i.e.*, $r = 1 \Rightarrow d_{nu} = 0$). Thus, $r = 1$ corresponds to cases in which either market configuration M6 or M8 is optimal. Alternatively, if for any given set of parameters, either M4, M5, or M7 is the optimal configuration, then it means that $r < 1$. For these cases, given that $r < 1$, Table 6 further identifies whether or not r is especially low. There are two reasons why the optimal market configuration can be such that r is especially low. On the one hand, r can be low if a sufficiently large portion of the consumer market values continued use of products enough relative to their trade-in value not to make it worth the trade. This is reflected in Table 6 by the case in which M7 is the optimal configuration. On the other hand, r can be low if it is optimal for the manufacturer to design its trade-in program primarily as a mechanism to fine tune the segmentation of its markets through its pricing tactics. This is reflected in Table 6 by the cases in which M4 and M5 are the optimal configurations.

To probe deeper, consider Figure 5, which depicts how the return rate r, as well as and the associated

Table 6: Return Rate when $k^* = 1$

Opt Mkt Conf.	$r < 0.5$	$0.5 \leq r < 1$	$r = 1$	Subtotal
M4	22.8%	23.0%	0%	45.8%
M5	1.2%	2.3%	0%	3.5%
M6	0%	0%	19.3%	19.3%
M7	1.2%	4.8%	0%	6.0%
M8	0%	0%	25.4%	25.4%
Total	25.2%	30.1%	44.7%	100%

trade-in price s required to induce that return rate, change as selected parameters change. As Figure 5(a) shows, both r and s generally increase as δ_r increases. This basically reflects the fact that, the higher is δ_r, the more profit the manufacturer can gain from remanufactured products and, thus, the more incentive the manufacturer has to increase its trade-in price so that it can recollect enough used products to sufficiently endow its remanufacturing operation. However, as δ increases, r actually decreases despite increases in s. The intuition is as follows. The higher is δ, the more a consumer values ownership of a previous purchase relative to a replacement purchase, regardless of whether that replacement would be new or remanufactured. Hence, the higher is δ, the higher the trade-in price needs to be to stimulate any returns, but, at the same time, the less willing are consumers to respond to that incentive. Conversely, Figure 5(b) indicates that r generally increases, while s generally decreases, with increases in α. Intuitively, if α is relatively large, then it means that consumers are more willing to buy new products in the second period, thus they are willing to trade-in previous purchases without deterrence from a relatively lower s. Nevertheless, as Figure 5(c) illustrates, r and s both grow comparatively larger when a high c_0 is coupled with a small c_r. Intuitively, in such a scenario, the potential benefit of cost savings (*i.e.*, $c_0 - c_r$) dominates the potential negative effect of product cannibalization; hence, it is profitable to recollect more used products for remanufacturing and that requires a relatively larger s to fuel the process.

4.3.2 Remanufacturing Rate

Although the return rate r effectively reveals how much incentive a manufacturer provides consumers through its trade-in price s to return used products for replacement purchases, not all recollected products will necessarily be remanufactured, particularly if the manufacturer uses its trade-in program simply as a way to more finely segment its market through pricing tactics. Therefore, it is important also to examine the remanufacturing rate (rm), which we define as the proportion of returned products that are actually

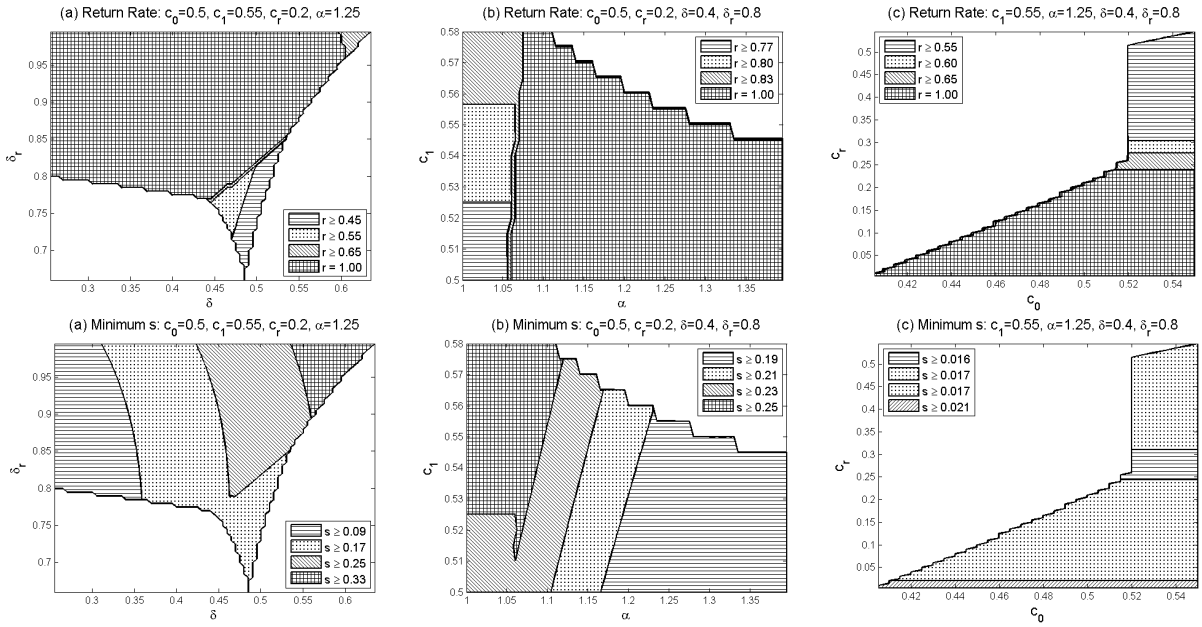

Figure 5: Return Rate and Minimum s

Notes: Pattern areas represent when it is optimal for the manufacturer to design and produce remanufactured products.

remanufactured. That is,

$$rm = \frac{d_{nr} + d_{or}}{d_{nn} + d_{nr}}$$

By definition, $rm \in (0,1]$ and is only valid if $k^* = 1$. If $rm = 1$, then it means that the manufacturer recollects used products solely for the purpose of remanufacturing rather than for the purpose of fine-tuning its market segmentation. According to Table 7, we find that $rm = 1$ in more than half of the optimal solutions corresponding to $k^* = 1$ (58.4%). On the contrary, we also find that $rm < 0.5$ in more than one third of optimal solutions corresponding to $k^* = 1$ (37.5%). It is these cases, in particular, that suggest that it very well could be in the manufacturer's interest to use its trade-in program not for the purpose of endowing its remanufacturing process, per se, but rather for the purpose of stimulating repurchases of new products while reducing the cannibalization of those repurchases. As Table 7 illustrates, this occurs when M4 or M5 is the optimal market configuration. Indeed, according to Table 7, M5 is especially likely to be associated with a low rm. Intuitively, this is true because M5 is optimal when α is relatively small, which signifies that remanufactured products intensively cannibalize the sale of new products, when c_1 is close to c_0, which signifies that the cost of offering a trade-in program is low, and when c_r is large, which signifies that the cost of producing remanufactured products is high.

Given Table 7, Figure 6 further illustrates how rm changes as selected parameters change. Like the return rate r, and for analogous reasons, the remanufacturing rate rm increases in δ_r and decreases in δ

Table 7: Remanufacturing Rate when $k^* = 1$

Opt Mkt Conf.	$rm < 0.5$	$0.5 \leq rm < 1$	$rm = 1$	Subtotal
M4	32.9%	2.1%	10.8%	45.8%
M5	3.5%	0.0%	0%	3.5%
M6	1.1%	2.0%	16.2%	19.3%
M7	0%	0%	6.0%	6.0%
M8	0%	0%	25.4%	25.4%
Total	37.5%	4.1%	58.4%	100%

(see Figure 6(a)). However, unlike the return rate r, the remanufacturing rate rm generally decreases in α (see Figure 6(b)). This is true because, when α is relatively large, it means that customers prefer upgraded products to remanufactured products, thus a remanufacturable product design primarily serves the purpose of more finely segmenting the market, and this drives rm down. Nevertheless, Figure 6(b) also suggests that rm generally increases as c_1 increases. This is true because, as c_1 increases, it becomes more costly for the manufacturer to produce remanufacturable products. As a result, the manufacturer will choose a remanufacturable product design only if it is profitable to sell remanufactured products, which drives rm up. By comparing Figure 6(c) to 5(c), we find that although the manufacturer recollects more than half of the products it sells in the first period when c_0 and c_r are both high (Figure 5 (c)), the manufacturer actually remanufactures less than 10% of those recollected units (Figure 6 (c)). This is because when the cost of producing non-remanufacturable products c_0 is high, switching to a remanufacturable design does not significantly increase the associated production cost (*i.e.*, $c_1 - c_0$ is relatively small) but it does enable the manufacturer to extract additional value by further segmenting its market through its trade-in program. However, because of the relatively high remanufacturing cost c_r, it is not profitable to remanufacture the recollected products. As a result, although r is sufficiently large, rm is nevertheless close to zero.

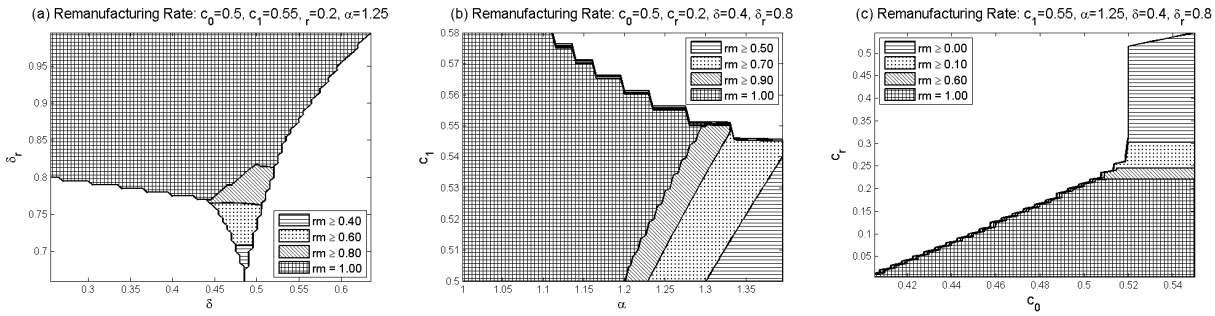

Figure 6: Remanufacturing Rate

Notes: Pattern areas represent when it is optimal for the manufacturer to design and produce remanufactured products.

5 Environmental Impact

Among other reasons, return rates in general, and remanufacturing rates in particular, are important because they serve as useful metrics that help gauge how a manufacturer's product design affects its environmental impact. However, metrics for assessing environmental impact have yet to be standardized. For example, whereas the EPA focuses on establishing standards that essentially limit the emissions released through per-unit consumption (United States Environmental Protection Agency, 2012), the EU Emissions Trading System (EU ETS) focuses on establishing standards that essentially limit the emissions released during production (EU ETS, 2012). Moreover, regardless of laws and regulations, manufacturers sometimes adopt their own environmental performance metrics for internal control. For example, one such metric, adopted by Apple Inc., is emissions per revenue (Apple, 2013). Accordingly, in this section, we assess the environmental impact of the manufacturer's optimal product design and market segmentation strategy from Section 4 by considering its performance across several commonly applied metrics introduced by government or industry. Toward that end, we compare the manufacturer's optimal product design $k^* \in \{0,1\}$ from Section 4 to the environmentally friendly design $k^{ef} \in \{0,1\}$ associated with a given environmental impact metric, where the definition of k^{ef} depends on the specific metric ef under consideration. For example, if $ef(k)$ denotes the specific metric under consideration such that the lower is $ef(k)$ the more environmentally friendly is the product design, then we say that $k^{ef} = 1$ if and only if $ef(k=1) \leq ef(k=0)$. For each environmental impact measure ef that we consider in this section, we compare k^* to k^{ef} for each of the 18,720 problem instances defined by Table 3 when using the increment $I = 0.1$; and for any given problem instance and specified value of k, we assume that the manufacturer chooses the optimal market segmentation conditioned on that value of k.

Within this context, we compare k^* and k^{ef} across the comprehensive set of problem instances to assess the extent to which a manufacturer's remanufacturable product design (whether optimal or not) will be environmentally friendly (*i.e.*, $k^{ef} = 1$), on the one hand, and the extent to which a manufacturer's optimal product design is consistent with the environmentally friendly design (*i.e.*, $k^* = k^{ef}$), on the other hand, for different definitions of environmental impact metric ef. Moreover, we compare and contrast these assessments across the various definitions of ef to ascertain the virtues associated with adopting or imposing any particular metric over another. We begin by establishing the notion of total emissions within the context of our model.

5.1 Emissions

Given that one of the most acknowledged environmental impact metrics is total emissions, we model emissions in a similar spirit as Agrawal *et al.* (2012), Atasu and Souza (2013) and Gu *et al.* (2012). In particular, we assume that the emissions of producing one unit of new product is e_p, the emissions associated with remanufacturing (if applicable) and with consuming a unit of product is e_r and e_c, respectively, and the emissions associated with disposing the remains of a unit of product is e_d. Given this construct and the sizes of all customer segments ($d_{nn}, d_{nr}, d_{nu}, d_{on}$ and d_{or}), the total emissions of producing new products is $e_p\,(2 \cdot d_{nn} + d_{nr} + d_{nu} + d_{on})$ and the total emissions of producing remanufactured products is $e_r\,(d_{nr} + d_{or})$. Correspondingly, the total emissions associated with the consumption of those new and remanufactured products is $e_c\,(2 \cdot d_{nn} + 2 \cdot d_{nr} + d_{nu} + d_{on} + d_{or})$. Note that all products originally produced are eventually disposed, however the sources of disposal are twofold: on the one hand, consumers dispose the products in their possession at the end of the second period ($d_{nn} + d_{nr} + d_{nu} + d_{on} + d_{or}$), but they do not dispose any products at the end of the first period because, at that time, they either keep the product for another period of use or they return the product to the manufacturer for a trade-in allowance toward the purchase of a different one. On the other hand, the manufacturer disposes products at the end of the first period that it recollects from returns but does not remanufacture ($d_{nn} + d_{nr} - (d_{nr} + d_{or}) = d_{nn} - d_{or}$). Accordingly, the emissions associated with disposing product remains is $e_d\,(2 \cdot d_{nn} + d_{nr} + d_{nu} + d_{on})$. Thus, all told, the total emissions for a given product design $EI\,(k)$ is as follows

$$EI\,(k) = 2e_1 \cdot d_{nn} + (e_1 + e_2) \cdot d_{nr} + e_1 \cdot d_{nu} + e_1 \cdot d_{on} + e_2 \cdot d_{or} \tag{5}$$

where $e_1 = e_p + e_c + e_d$ and $e_2 = e_r + e_c$ denote the life-cycle emissions per-unit (EPU) of a new and a remanufactured product, respectively, and $e_2 < e_1$ to reflect that remanufacturing is inherently environmentally efficient in the sense that remanufacturing a unit of product is more environmentally friendly than disposing a unit of product and then manufacturing a new one in its place (*i.e.*, $e_r < e_d + e_p$). This inherent efficiency, however, could potentially fuel an associated downside in the form of Jevons Paradox or the Rebound Effect (Owen, 2010; Small and Van Dender, 2007). The essence of these paradoxical phenomena is as follows: if technological advances enhance the efficiency of production, then profits would rise and investment in capacity expansion would occur as a result, thus driving prices down and pushing consumption higher (Goldberg, 1998). Therefore, the end effect very well could be a higher total energy consumption than that before the efficiency improvements. Accordingly, we focus attention on total emissions $EI\,(k)$ rather than EPU.

Given (5), let k^{EI} be defined such that $k^{EI} = 1$ if and only if $EI(k = 1) \leq EI(k = 0)$ so that $k^{EI} \in \{0, 1\}$ denotes the product design that is more environmentally friendly in terms of total emissions. Then, by comparing k^* and k^{EI} for each of the 18,720 problem instances from Table 3, we obtain Table 8, where each subtable corresponds to a different value of $E := \frac{e_2}{e_1}$. According to Table 8, for example, if $E = 0.5$, then it means that although a remanufacturable product design is environmentally friendly ($k^{EI} = 1$) in 66.20% of the 18,720 problem instances considered, that design is also optimal ($k^* = k^{EI} = 1$) in only 1.86% of the 18,720 instances.

Table 8: k^* vs. k^{EI}: Comparison of Profit and Emissions

$E = 0.2$	$k^{EI} = 0$	$k^{EI} = 1$
$k^* = 1$	15.08%	4.04%
$k^* = 0$	12.50%	68.38%

$E = 0.5$	$k^{EI} = 0$	$k^{EI} = 1$
$k^* = 1$	17.27%	1.86%
$k^* = 0$	16.53%	64.34%

$E = 0.8$	$k^{EI} = 0$	$k^{EI} = 1$
$k^* = 1$	18.96%	0.16%
$k^* = 0$	20.04%	60.84%

We make several observations from Table 8. First, although a remanufacturable product design generally results in lower emissions as compared to a non-remanufacturable product design (in the sense that $k^{EI} = 1$ in approximately 60%-70% of the problem instances), a remanufacturable product design in and of itself is not necessarily synonymous with environmental friendliness (in the sense that $k^{EI} = 0$ in approximately 30%-40% of the problem instances). Second, by and large, the optimal product design k^* is not particularly environmentally friendly in terms of total emissions (in the sense that $k^* \neq k^{EI}$ in approximately 79%-83% of the the problem instances). Third, as E increases, although the proportion of cases for which $k^* = 0 \neq k^{EI}$ decreases, the proportion for which $k^* = 1 \neq k^{EI}$ increases. Thus, all told, Table 8 suggests that maximizing profit typically comes at the expense of increased total emissions. And by extrapolation, this means that one potential drawback of a purely regulatory approach to limiting total emissions is that it could force manufacturers to reduce its production level to the point that it fails to meet customer needs (James, 1994). For this reason, government and industry alike often consider metrics of emissions efficiency in lieu of total emissions, where emissions efficiency accounts for the economic benefits generated in exchange for a unit of emissions. In other words, as an alternative to total emissions, environmental impact can be measured by $\frac{Emissions}{Economic\ Benefits}$, where *Economic Benefits* can refer either to manufacturer benefits (such as revenue or profit) or to societal benefits (such as consumer surplus or social welfare). Accordingly, we next introduce four such measures before proceeding to assess their relative significance in Section 5.2.

Emissions Per Revenue (ER). ER is an important environmental efficiency metric that manufacturers not only strive to reduce, but also publish voluntarily to communicate their environmental stewarding. See, for example, Apple (2013), Cummins (2012) and Dell (2013). Introduced by Klassen and McLaughlin (1996), ER gauges environmental impact by comparing a manufacturer's total emissions associated with

the sales of its products to the total revenue derived from those sales. Thus, in our context, $ER(k) = \frac{EI(k)}{R(k)}$, where

$$R(k) = \begin{cases} p_1(d_{nn} + d_{nr} + d_{nu}) + p_2(d_{nn} + d_{on}) + p_r(d_{nr} + d_{or}) - s(d_{nn} + d_{nr}) & \text{if } k = 1 \\ p_1(d_{nn} + d_{nu}) + p_2(d_{nn} + d_{on}) & \text{if } k = 0 \end{cases} \tag{6}$$

Accordingly, let k^{ER} be defined such that $k^{ER} = 1$ if and only if $ER(k = 1) \leq ER(k = 0)$ so that $k^{ER} \in \{0, 1\}$ denotes the product design that is more environmentally friendly in terms of the emissions per revenue efficiency ratio.

Emissions Per Profit (EP). EP is a related environmental efficiency metric that focuses on value added in lieu of total revenue (see, for example, Bosch 2012). Specifically, in our context, $EP(k) = \frac{EI(k)}{\Pi^k}$, where Π^k is given by (1) and (2), depending on whether $k = 0$ or $k = 1$, respectively. Accordingly, let k^{EP} be defined such that $k^{EP} = 1$ if and only if $EP(k = 1) \leq EP(k = 0)$ so that $k^{EP} \in \{0, 1\}$ denotes the product design that is more environmentally friendly in terms of the emissions per profit efficiency ratio.

Emissions Per Consumer Surplus (EC). EC is an environmental efficiency metric that relates emissions to the net economic benefits derived directly from the consumption rather than the sales of the manufacturer's products. Given that overregulation of reuse and recycling rates has been shown to have potentially deleterious effects on consumer surplus under certain circumstances (Karakayali *et al.*, 2012), EC has particular relevance to social planners. In our context, $EC(k) = \frac{EI(k)}{CS(k)}$, where $CS(k)$ is derived in detail in Appendix B. Accordingly, let k^{EC} be defined such that $k^{EC} = 1$ if and only if $EC(k = 1) \leq EC(k = 0)$ so that $k^{EC} \in \{0, 1\}$ denotes the product design that is more environmentally friendly in terms of the emissions per consumer surplus efficiency ratio.

Emissions Per Social Welfare (EW). EW is an environmental efficiency metric similar to EC except that it relates emissions to the combined net economic benefits derived from both the consumption and the sales of the manufacturer's products (Örsdemir *et al.*, Forthcoming). In our context, $EW(k) = \frac{EI(k)}{SW(k)}$, where $SW(k)$ is derived in detail in Appendix B. Accordingly, let k^{EW} be defined such that $k^{EW} = 1$ if and only if $EW(k = 1) \leq EW(k = 0)$ so that $k^{EW} \in \{0, 1\}$ denotes the product design that is more environmentally friendly in terms of the emissions per consumer surplus efficiency ratio.

5.2 Assessment of Environmental Impact and Optimal Product Design

In this section, to assess the relative merits of the various environmental efficiency metrics and their potential significance to industry and government, we systematically compare k^* to k^{ef} for the four ef ratios defined in Section 5.1 in the same spirit that we compared k^* to k^{EI} in Table 8. Toward that end, we fo-

cus on the same 18,720 problem instances previously compiled, and we present our results in Table 9 for the representative case in which $E = 0.5$. Recall that, for any given metric $ef(k)$, $k^{ef} = 1$ if and only if $ef(k=1) \leq ef(k=0)$. Thus, in this section, if $k^{ef} = x$ for metric ef, then we say that x is the product design that is more environmentally friendly in terms of ef.

Table 9: Environmental Efficiency Metrics

$E = 0.5$	k^{EI}		k^{ER}		k^{EP}		k^{EC}		k^{EW}	
	0	1	0	1	0	1	0	1	0	1
$k^* = 1$	17.27%	1.86%	11.56%	7.57%	9.61%	9.52%	15.68%	3.45%	16.05%	3.08%
$k^* = 0$	16.53%	64.34%	17.86%	63.01%	77.06%	3.81%	80.27%	0.60%	24.72%	56.15%
Total	33.80%	66.20%	29.42%	70.58%	86.67%	13.33%	95.95%	4.05%	40.77%	59.23%

According to Table 9, EP is the environmental efficiency metric that is most consistent with a manufacturer's optimal product design in the sense that $k^* = k^{ef}$ is true for the highest percentage of problem instance (86.58%) when $ef = EP$ as compared to when $ef \in \{\text{ER,EC,EW}\}$. This can be explained intuitively because $EP(k)$ includes profit in its denominator, which means that, everything else being equal, EP decreases as profit increases. In this sense, environmental efficiency metric EP is particularly well aligned with profit maximization, thus it stands to reason that $k^* = k^{EP}$ would be true as a general rule. By contrast, it is the closely related environmental efficiency metric ER that is most aligned with the reduction of total emissions in the sense that the percentage of problem instances in which $k^{EI} = 1$ (66.20%) is closer in magnitude to the percentage of problem instances in which $k^{ER} = 1$ (70.58%) than it is to the percentage of problem instances in which $k^{ef} = 1$ for $ef \in \{\text{EP,EC,EW}\}$. Indeed, the percentage of cases for which $k^{ef} = 1$ is greatest for $ef = ER$ among all environmental impact measures ef considered here. Intuitively, this makes sense because a production cost premium is required to produce a unit of a remanufacturable product as compared to producing a unit of a non-remanufacturable product (i.e., $c_1 > c_0$), which in turn means that $k = 1$ typically corresponds to a higher associated per-unit revenue as compared to $k = 0$, everything else being equal. Correspondingly, $ER(k=1)$ typically will be lower than $ER(k=0)$ because $ER(k)$ is a metric that explicitly includes revenue in its denominator.

On the opposite end the spectrum relative to ER, environmental efficiency metric EC results in the lowest percentage of cases in which $k^{ef} = 1$ among all environmental impact measures ef considered here. In particular, $k^{EC} = 1$ in only 4.05% of the problem instances (as compared to $k^{ER} = 1$ in 70.58% of problem instances). Nevertheless, given that metric EC includes consumer surplus, as opposed to manufacturer surplus in its denominator, and given that it is natural for consumer surplus to decrease when the breadth of a product line increases, it makes sense that, everything else being equal, the consumer surplus associated

with $k = 1$ typically would be lower than the consumer surplus associated with $k = 0$ because, in our context, $k = 0$ reflects a lower product line breadth as compared to $k = 1$. By comparison, environmental efficiency metric EW appears to be similar to metric ER in the sense that, like metric ER, metric EW is predominately aligned with the reduction of total emissions as measured by EI. In particular, according to Table 9, $k^{EW} = 1$ for a percentage of problem instances (59.23%) that is relatively close in magnitude to the percentage of problem instances for which $k^{EI} = 1$ (66.20%). Nevertheless, unlike metric ER, metric EW is unlikely to gain wide-spread adoption in practice because of the computational difficulty associated with measuring social welfare accurately.

Thus, all told, we conclude that among the four available environmental efficiency ratios defined in Section 5.1, ER can serve as the best proxy for EI as a metric for measuring overall environmental stewardship. In addition, interestingly, $k^* = k^{ER}$ in a higher percentage of cases (25.43%) than $k^* = k^{EI}$ (18.39%). Thus, this helps explain in part why some manufacturers might be more inclined to publish their overall environmental stewarding performance with respect to ER in lieu of publishing their performance with respect to EI.

6 Conclusion

Introducing a remanufacturable product to its market not only increases a manufacturer's profits by attracting a new customer segment to its product offerings, but also provides spillover benefits to the environment by consuming less resources. Yet, despite these noted benefits of remanufacturing, many manufacturers have yet to expand their operations to enter the remanufactured-goods industry. Therefore, in this paper, we analyze this apparent dichotomy by formulating and studying a remanufacturable design problem when consumers are vertically heterogeneous with respect to their willingness to pay. Toward that end, we develop a stylized economic model in which a price-setting manufacturer can choose whether or not to enter into remanufacturing by designing its product to be either remanufacturable or non-remanufacturable, respectively, and then designing a corresponding pricing policy and trade-in program accordingly. Given this construct, we specifically explore and draw implications from the market segmentation strategy that results. Upon doing so, we find that as a general rule of thumb it is optimal for a manufacturer to design a remanufacturable product when the value-added from remanufacturing is relatively high, when product durability is relatively low, and when innovation is nominal. In a similar vein, remanufacturability typically is justified when the production cost of a remanufacturable product is comparatively low relative to the production cost of a non-remanufacturable product or when the cost to remanufacture a returned product is relatively low.

Otherwise, however, it is not optimal for the manufacturer to design a remanufacturable product, which helps explain in part the documented evidence that reflects some manufacturer reluctance to expand into the remanufactured-goods industry.

In addition, we find that a remanufacturable product design is not synonymous with high return and remanufacturing rates. Indeed, we find that even if it is optimal for the manufacturer to design a remanufacturable product and to establish a trade-in program to induce a high return rate, a high level of remanufacturing activity is not a foregone conclusion. A high return rate but low remanufacturing rate would be the case, for example, if the production cost of a remanufacturable product is low while product innovation is high. This phenomenon suggests that regulating return rates in the name of environmental stewardship could potentially result in ineffective or even counterproductive policy. In a similar vein, we find that despite remanufacturing's inherent environmental benefits per unit of production, its associated countereffect is an increase in overall production volume to meet demand from an expanded market. Moreover, we find that, as a result, the manufacturer's increased profit potential very well could come at the net expense of environmental deterioration because of increased total GHG emissions. Thus, regulatory restrictions focused solely on overall emission totals run the risk of a social cost if they essentially force manufacturers to reduce production levels to the point at which they cannot affordably meet customer needs. Nevertheless, if environmental cost efficiency is taken into account, which in this context means emissions produced per unit of economic benefit extracted in return for the manufacturer, society, or both, then we find a happy middle ground. In particular, we find that the efficiency ratio ER (emissions per revenue) is a metric that can serve as an especially good proxy for monitoring and controlling environmentally responsible manufacturing operations.

In closing, we note that our results and insights are based in part on the modeling stipulation that the manufacturer allows its trade-in allowance for a returned product to be applied toward the purchase of either a new or a remanufactured product. Nevertheless, we also considered as a modeling extension if, instead, the manufacturer restricted trade-ins to be applied only toward the purchase of a new product (but not a remanufactured one). For this extension, we found that, by and large, our qualitative results and insights continue to apply. However, one notable difference is that the resulting optimal market segmentation strategy would be such that sales of remanufactured products would decrease and thus, cannibalization actually would decrease, thereby leading to an increase in the overall sales of new products (relative to the baseline situation in which trade-ins may be applied toward the purchase of either new or remanufactured products). Yet, interestingly, the manufacturer's profit would decrease as a result. One explanation of this somewhat counterintuitive implication is as follows: When trade-ins are not restricted such that they may be applied

either toward the purchase of a new product or toward the purchase of a remanufactured product, some consumers who otherwise would opt for continued use of a previously purchased product over trading in that used product for a new product become willing to trade in the used product for a less expensive (but, often, more profitable) remanufactured product. In fact, given that remanufactured product sales often contribute as much as two-to-three times more earnings before interest and taxes than new product sales contribute (Giuntini, 2008), the profits generated from the increase in the sales of remanufactured products more than offset the opportunity cost of losing profits from the cannibalization of new product sales.

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APPENDIX A. PROOF OF PROPOSITIONS

Proof of Proposition 1. Part (i) follows directly from the constraint that the manufacturer cannot remanufacture more products than returned products as follows: $d_{or}+d_{nr} \le d_{nn}+d_{nr} \Rightarrow d_{or} \le d_{nn}$. Thus, $d_{or} > 0$ implies that $d_{nn} > 0$.

Part (ii) is by contradiction. From Table 1, $d_{nr} > 0 \Rightarrow \exists \theta_1$ such that $S_{nr}(\theta_1) \ge S_{nn}(\theta_1) \Leftrightarrow \theta_1 \le \frac{p_2-p_r}{\alpha-\delta_r}$ and $S_{nr}(\theta_1) \ge S_{or}(\theta_1) \Leftrightarrow \theta_1 \ge p_1 - s$. Thus, the existence of θ_1 requires that $p_1 - s \le \frac{p_2-p_r}{\alpha-\delta_r}$. Note $p_1 - s = \frac{p_2-p_r}{\alpha-\delta_r} \Rightarrow d_{nr} = 0$. Thus, $d_{nr} > 0$ requires that $p_1 - s < \frac{p_2-p_r}{\alpha-\delta_r}$. Similarly, $d_{on} > 0 \Rightarrow \exists \theta_2$ such that $S_{on}(\theta_2) \ge S_{nn}(\theta_2) \Leftrightarrow \theta_2 \le p_1 - s$ and $S_{on}(\theta_2) \ge S_{or}(\theta_2) \Leftrightarrow \theta_2 \ge \frac{p_2-p_r}{\alpha-\delta_r}$. Thus, the existence of θ_2 requires that $\frac{p_2-p_r}{\alpha-\delta_r} \le p_1 - s$, which is a contradiction.

To prove part (iii), we use Table 2(a) because $d_{nr} = d_{or} = 0$, by assumption. Assume $d_{nn} > 0$. If $d_{on} = 0$, then $d_{nu} = 0$ only when $\frac{p_2}{\alpha-\delta} - \frac{p_1}{1+\delta} \le 0$; if $d_{nu} = 0$, then $d_{on} = 0$ only when $p_1 - \frac{p_2}{\alpha} \le 0$. Therefore, after some algebra, we must have $\alpha p_1 \le p_2 \le \frac{\alpha-\delta}{1+\delta} p_1$, which is impossible if $p_1 \ne 0$ or $p_2 \ne 0$ because $\alpha > \frac{\alpha-\delta}{1+\delta} > 0$. ■

Proof of Proposition 2. Part (i). In both cases, customers either buy the only offered product or do not purchase. We first consider when the offered product is available only in the second period. The object function can be written as $\Pi_{00010} = \max_{p_2}(p_2 - c_0) \cdot d_{on}$ subject to $d_{on} > 0, p_2 \ge 0$. Since $d_{nr} = d_{or} = 0$, $s = 0$ and $d_{on} = 1 - \frac{p_2}{\alpha}$. It is easy to show that $p_2^* = \frac{\alpha+c_0}{2}$ and $\Pi^*_{00010} = \frac{(\alpha-c_0)^2}{4\alpha}$ when $c_0 < \alpha$ and $\Pi^*_{00010} = 0$ (no production) when $c_0 \ge \alpha$. Similarly, when the offered new product is available only in the first period. It is straightforward to show that $p_1^* = \frac{1+\delta+c_0}{2}$ and $\Pi^*_{00100} = \frac{(1+\delta-c_0)^2}{4(1+\delta)}$ when $c_0 < 1+\delta$ and $\Pi^*_{00100} = 0$ (no production) when $c_0 \ge 1+\delta$.

When $c_0 < \alpha$, we must have $c_0 < 1+\delta$ because $\alpha < 1+\delta$. Thus, $\Pi^*_{00100} > 0$ whenever $\Pi^*_{00010} > 0$. Moreover, $\Pi^*_{00010} = \frac{(\alpha-c_0)^2}{4\alpha} > \Pi^*_{00100} = \frac{(1+\delta-c_0)^2}{4(1+\delta)}$ only when $\alpha(1+\delta) > c_0^2$, which is impossible as $c_0 < \alpha, c_0 < 1+\delta$. When $c_0 \ge \alpha$, $\Pi^*_{00010} = 0$ and $\Pi^*_{00100} \ge 0$. Therefore, the statement follows.

Part (ii). We first solve the manufacturer's problem when M=(0,0,1,1,0):

$$\begin{aligned}
\Pi_{01010} &= \max_{p_1,p_2} (p_1-c_0)\cdot d_{nu} + (p_2-c_0)\cdot d_{on} \\
s.t \quad & d_{nn}=0 \\
& d_{nu}, d_{on} > 0 \\
& p_1, p_2 \geq 0
\end{aligned}$$

Since $d_{nr}=d_{or}=0$, $s=0$. Note $d_{nn}=0$ if $\frac{p_2}{\alpha-\delta}\geq 1$. The problem can be further expressed as

$$\Pi_{00110} = \max_{p_1,p_2} (p_1-c_0)\cdot\left(1-\frac{p_1-p_2}{1+\delta-\alpha}\right)+(p_2-c_0)\cdot\left(\frac{p_1-p_2}{1+\delta-\alpha}-\frac{p_2}{\alpha}\right) \tag{7}$$

$$s.t. \quad \frac{p_2}{\alpha-\delta}-1\geq 0 \tag{8}$$

$$1-\frac{p_1-p_2}{1+\delta-\alpha}>0, \frac{p_1-p_2}{1+\delta-\alpha}-\frac{p_2}{\alpha}>0 \tag{9}$$

$$p_1\geq 0, p_2\geq 0 \tag{10}$$

Consider the relaxed problem where (9) is replaced by $1-\frac{p_1-p_2}{1+\delta-\alpha}\geq 0, \frac{p_1-p_2}{1+\delta-\alpha}-\frac{p_2}{\alpha}\geq 0$ and denote the corresponding optimal profit as $\tilde{\Pi}^*_{00110}$. Thus, the Lagrangian function of the relaxed problem can be written as

$$\begin{aligned}
L &= (p_1-c_0)\cdot\left(1-\frac{p_1-p_2}{1+\delta-\alpha}\right)+(p_2-c_0)\cdot\left(\frac{p_1-p_2}{1+\delta-\alpha}-\frac{p_2}{\alpha}\right) \\
&\quad +\mu_1\left(\frac{p_2}{\alpha-\delta}-1\right)+\mu_2\left(1-\frac{p_1-p_2}{1+\delta-\alpha}\right)+\mu_3\left(\frac{p_1-p_2}{1+\delta-\alpha}-\frac{p_2}{\alpha}\right)
\end{aligned}$$

Based on the KKT conditions, we obtain two KKT points:

Case 1: if $a\geq\frac{2\delta(1+\delta)}{1+\delta-c_0}$, then $p_1^*=\frac{(\alpha-\delta)(1+\delta)}{\alpha}$ and $p_2^*=\alpha-\delta$ and $\tilde{\Pi}^*_{00110}=\frac{\delta[(\alpha-\delta)(1+\delta)-\alpha c_0]}{\alpha^2}$. Note when $c_0\geq\frac{(\alpha-\delta)(1+\delta)}{\alpha}$, the profit is negative and hence we assume no production. We can further prove that $\tilde{\Pi}^*_{00110}\leq\Pi^*_{00100}=\frac{(1+\delta-c_0)^2}{4(1+\delta)}$ when $c_0<\frac{(\alpha-\delta)(1+\delta)}{\alpha}$ and $2\delta<\alpha<1+\delta$.

Case 2: if $a<\frac{2\delta(1+\delta)}{1+\delta-c_0}$, then $p_1^*=\frac{1+\delta+c_0}{2}$ and $p_2^*=\frac{\alpha(1+\delta+c_0)}{2(1+\delta)}$ and $\tilde{\Pi}^*_{00110}=\frac{(1+\delta-c_0)^2}{4(1+\delta)}$. In such a case $\tilde{\Pi}^*_{00110}=\Pi^*_{00100}$.

The proposition thus follows because $\Pi^*_{00110}\leq\tilde{\Pi}^*_{00110}$. ■

APPENDIX B. DERIVATIONS OF $CS(k)$ AND $SW(k)$

Derivation of $CS(k)$. Given $d_{nn}, d_{nr}, d_{nu}, d_{on}, d_{or}$, first consider the case in which $k=1$. Let $\theta_1 = 1 - d_{nn}, \theta_2 = \theta_1 - d_{nr}, \theta_3 = \theta_2 - d_{nu}, \theta_2 = \theta_3 - d_{on}, \theta_5 = \theta_4 - d_{or}$. Then, by definition of consumer surplus, $CS(k=1)$ can be expressed as follows:

$$\begin{aligned}
CS(k=1) &= \int_{\theta_1}^{1} \theta(1+\alpha) - (p_1+p_2-s)\,d\theta + \int_{\theta_2}^{\theta_1} \theta(1+\delta_r) - (p_1+p_r-s)\,d\theta + \int_{\theta_3}^{\theta_2} \theta(1+\delta) - p_1 d\theta \\
&\quad + \int_{\theta_4}^{\theta_3} (\theta\alpha - p_2)\,d\theta + \int_{\theta_5}^{\theta_4} (\theta\delta_r - p_r)\,d\theta \\
&= \frac{(1-\theta_1^2)(1+\alpha)}{2} - (p_1+p_2-s)(1-\theta_1) + \frac{(\theta_1^2-\theta_2^2)(1+\delta_r)}{2} - (p_1+p_r-s)(\theta_1-\theta_2) \\
&\quad + \frac{(\theta_2^2-\theta_3^2)(1+\delta)}{2} - p_1(\theta_2-\theta_3) + \frac{(\theta_3^2-\theta_4^2)\alpha}{2} - p_2(\theta_3-\theta_4) + \frac{(\theta_4^2-\theta_5^2)\delta_r}{2} - p_r(\theta_4-\theta_5)
\end{aligned}$$

Next, for the case in which $k=0$, let $\theta_1 = 1 - d_{nn}, \theta_2 = \theta_1 - d_{nu}, \theta_3 = \theta_2 - d_{on}$. Then

$$\begin{aligned}
CS(k=0) &= \int_{\theta_1}^{1} \theta(1+\alpha) - (p_1+p_2)\,d\theta + \int_{\theta_2}^{\theta_1} \theta(1+\delta) - p_1 d\theta + \int_{\theta_3}^{\theta_2} (\theta\alpha - p_2)\,d\theta \\
&= \frac{(1-\theta_1^2)(1+\alpha)}{2} - (p_1+p_2)(1-\theta_1) + \frac{(\theta_1^2-\theta_2^2)(1+\delta)}{2} - p_1(\theta_1-\theta_2) \\
&\quad + \frac{(\theta_2^2-\theta_3^2)\alpha}{2} - p_2(\theta_2-\theta_3)
\end{aligned}$$

Derivation of $SW(k)$. Given $d_{nn}, d_{nr}, d_{nu}, d_{on}, d_{or}$, first consider the case in which $k=1$. Let $\theta_1 = 1 - d_{nn}, \theta_2 = \theta_1 - d_{nr}, \theta_3 = \theta_2 - d_{nu}, \theta_2 = \theta_3 - d_{on}, \theta_5 = \theta_4 - d_{or}$. Then $SW(k=1)$ is defined as the sum of manufacturer profit and consumer surplus as follows:

$$\begin{aligned}
SW(k=1) &= \int_{\theta_1}^{1} \theta(1+\alpha)\,d\theta + \int_{\theta_2}^{\theta_1} \theta(1+\delta_r)\,d\theta + \int_{\theta_3}^{\theta_2} \theta(1+\delta)\,d\theta + \int_{\theta_4}^{\theta_3} \theta\alpha d\theta + \int_{\theta_5}^{\theta_4} \theta\delta_r d\theta \\
&= \frac{(1-\theta_1^2)(1+\alpha)}{2} + \frac{(\theta_1^2-\theta_2^2)(1+\delta_r)}{2} + \frac{(\theta_2^2-\theta_3^2)(1+\delta)}{2} + \frac{(\theta_3^2-\theta_4^2)\alpha}{2} + \frac{(\theta_4^2-\theta_5^2)\delta_r}{2}
\end{aligned}$$

Similarly, for the case in which $k=0$, let $\theta_1 = 1 - d_{nn}, \theta_2 = \theta_1 - d_{nu}, \theta_3 = \theta_2 - d_{on}$. Then

$$\begin{aligned}
SW(k=0) &= \int_{\theta_1}^{1} \theta(1+\alpha)\,d\theta + \int_{\theta_2}^{\theta_1} \theta(1+\delta)\,d\theta + \int_{\theta_3}^{\theta_2} \theta\alpha d\theta \\
&= \frac{(1-\theta_1^2)(1+\alpha)}{2} + \frac{(\theta_1^2-\theta_2^2)(1+\delta)}{2} + \frac{(\theta_2^2-\theta_3^2)\alpha}{2}
\end{aligned}$$