POMS PRODUCTION AND OPERATIONS MANAGEMENT

PRODUCTION AND OPERATIONS MANAGEMENT POMS

Vol. 26, No. 8, August 2017, pp. 1585–1603
ISSN 1059-1478 | EISSN 1937-5956 | 17 | 2608 | 1585
DOI 10.1111/poms.12709

Design of the Reverse Channel for Remanufacturing: Must Profit-Maximization Harm the Environment?

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A key attribute of a remanufacturing strategy is the division of labor in the reverse channel, especially whether remanufacturing is performed in-house or outsourced. We investigate this decision for a retailer who accepts returns of a remanufacturable product. Our formulation considers the cost structures of the two strategies, uncertainty in the input quality of the collected/returned used products, consumer willingness-to-pay for remanufactured product, the extent to which the remanufactured product cannibalizes demand for a new product, and the power structure in the channel. For the profit-maximizing retailer, the differentials in variable remanufacturing costs drive strategy choice, and higher fixed costs of in-house remanufacturing favors outsourcing. The variable remanufacturing costs and the balance of power in the prospective outsourced reverse channel are the key drivers of environmental impact, as measured by the retailer's propensity to remanufacture. While profitability and environmental goals often conflict, they align under certain conditions. These include (a) the third party has less bargaining power; or (b) the fixed cost for in-house remanufacturing is relatively high. All else equal, when remanufacturing is outsourced, the environment fares better if the third party has leadership power. We generalize to the cases when remanufacturing achieves a quality level less than "good-as-new" and when used items have non-zero salvage value. Analysis of these extensions illuminates how relative power in the reverse channel drives the firms' preferences, as well as the end customers' consumption experience.

Key words: reverse channel design; remanufacturing; outsourcing; environmental impact
History: Received: August 2016; Accepted: February 2017 by Kalyan Singhal and Subodha Kumar, after 2 revisions.

1. Introduction

Sustainability initiatives are at the forefront of many firms' agendas today. Consumers and government mandates are both calling for environment-friendly business practices. Remanufacturing[1] is one approach to sustainability, with benefits that include the diversion of discarded products from landfills, reduced virgin raw material usage, and energy consumption lower than in original manufacturing (USEPA 1997). It is perceived as an environment-friendly end-of-use management option for many product categories (Örsdemir et al. 2014). For example, remanufacturing in the auto industry saves over 80% of the energy and raw material required to manufacture a new part, and keeps used parts ("cores") out of landfills.[2] Gutowski et al. (2011) find that remanufacturing consumes less energy than does manufacturing of new products, and evidence suggests that remanufacturing can be superior to recycling in material consumption and overall environmental impact (Fullerton and Wu 1989, Calcott and Walls 2000, Dinan 2005). Remanufactured products can be made to perform as well as new products.[3]

This research is motivated by GameStop, a consumer electronics retailer that specializes in video game consoles among other related products. GameStop is the world's largest multi-channel video game retailer. It has more than 6600 retail stores in 15 countries, including more than 4500 stores in the United States. GameStop earns significant profit from refurbishing and reselling hardware. In 2013 these activities accounted for more than a quarter of its 9 billion USD in revenue and roughly half its 2.66 billion USD in gross profit.[4]

The company's retail stores serve as collection centers for used game consoles. Collected consoles are sent to a facility dedicated to testing and refurbishing. Those consoles that undergo refurbishing are sent back to the retail stores to be sold for less than the retail price of new consoles. These less expensive consoles help the company reach consumers who could not or would not buy the new product. Success in this part of the business model has motivated the company to build its own remanufacturing facility in Grapevine, Texas.

Superiority of an in-house approach to remanufacturing is not a foregone conclusion. A significant number of third party firms offer remanufacturing/refurbishing expertise, making viable the outsourcing of these activities. As a general business practice, outsourcing is attractive due to its avoidance of direct ownership of workforce, assets, and infrastructure, which increases financial and operational flexibility. Outsourcing may also provide access to specialized and focused expertise. Potential hazards include a reduction in product quality, communication and coordination difficulties, and dependence on an outside party (Tsay 2014).

This study evaluates whether a retailer should remanufacture in-house or outsource this reverse channel activity, an important question for GameStop and the many other firms who currently remanufacture in-house (Hauser and Lund 2003, Martin et al. 2010). As environmental concerns are presumably part of the motivation for remanufacturing, we consider the consequences not just for retailer profitability but also environmental impact as measured by the level of remanufacturing activity. Under the premise that per-unit environmental harm is less for a remanufactured product than for a new product, in our setting, greater remanufacturing activity will lead to a better environmental outcome.

Our research addresses the following questions:

- What are the key drivers of the performance of the remanufacturing strategy (i.e., in-house vs. outsourcing)?
- Could one of the strategy choices dominate the other in both profit and environmental impact?
- How does the retailer's bargaining power (in dealing with an independent provider of remanufacturing services) factor into the choice of strategy?
- What is the impact of a quality level differential between remanufactured and new products on our results?
- How does the salvage value of non-remanufactured cores affect the performance of each strategy?

Our analysis has several noteworthy features. First, we consider uncertainty in the quality of collected products, which makes the cost of each strategy a function of this quality level. Second, we endogenize the specification of a threshold quality level for qualifying for remanufacture. This allows prediction of the percentage of collected products that will be remanufactured, providing a measure of environmental impact. Third, our model of consumer behavior incorporates the possibility that remanufactured product may cannibalize the sales of the new product.

Some of our findings confirm intuition, but a number are surprising. For the profit-maximizing retailer the differentials in variable remanufacturing costs drive strategy choice, and higher fixed costs of In-house remanufacturing favors Outsourcing. The variable remanufacturing costs and the balance of power in the prospective outsourced reverse channel are the key drivers of the alternative strategies' relative environmental impact.

While profitability and environmental goals are often in conflict, they align in certain scenarios. These include: (a) the third party has less bargaining power; or (b) the fixed cost for In-house remanufacturing is relatively high. The first scenario emerges because when remanufacturing is outsourced, the environment fares better if the third party has leadership power. Meanwhile, when the third-party has less power, the retailer commands a larger share of the profit. So if outsourcing is less costly, it will be preferred by the retailer. Lower outsourcing costs also increase the amount of remanufacturing. Hence, profitability and environmental goals will be aligned in this scenario. Regarding the second scenario, high fixed costs for the In-house strategy will make Outsourcing more attractive to the retailer. This will also increase the remanufacturing activity, thereby aligning the profit and environmental goals.

The retailer prefers a decrease in the differential between new and remanufactured quality levels since this elevates demand and profit margin by more than enough to offset an increase in remanufacturing cost. However, the third party may dislike this when remanufacturing costs are high since in this case the retailer can extract a larger portion of the third-party's gains. The salvage value of non-remanufactured cores will impact the optimal decisions only when variable remanufacturing costs are relatively high. Under the In-house and Retailer-led Outsourcing strategies, the retailer's profit increases with an increase in salvage value due to the extra salvage revenue. When Outsourcing to a third party with leadership power, however, the retailer's profit decreases with the salvage value since the third party reacts by elevating the wholesale price.

The remainder of this study is organized as follows. The next section reviews the relevant literature. Section 3 presents our model that characterizes each strategy choice. Section 4 evaluates the two strategies in terms of retailer profitability and environmental impact. Section 5 examines the impact of setting a remanufactured product quality level which is lower than that for new products, and introducing a disposal/salvage value for collected used goods that do not undergo remanufacturing. Section 6 discusses managerial implications and identifies future research directions.

2. Relevant Literature

Atasu et al. (2008), Guide and Van Wassenhove (2009), Tang and Zhou (2012) and Souza (2013) provide broad reviews of extant literature on reverse supply chains. This section comments specifically on the four distinguishing features that position our research in this literature: (a) consumer choice, (b) uncertainty in product returns, (c) in-house vs. outsourced remanufacturing, and (d) the environmental impact of remanufacturing.

In the area of consumer choice, the vertical differentiation framework has been deployed to examine whether an OEM should offer remanufactured versions of its products. As with the introduction of any new competing/substitutable product, adding a remanufactured product to a firm's product portfolio has two possible impacts on demand: (i) a market expansion effect, since a remanufactured product sold at a lower price can reach a segment of consumers who are not willing to pay the new product's full price; and (ii) a cannibalization effect, as some customers choose the remanufactured product over the new product (Ferguson and Toktay 2006, Ferrer and Swaminathan 2006, Vorasayan and Ryan 2006, Yin and Tang 2014, Vakharia and Wang 2014). Our study also uses a vertical differentiation framework to depict cannibalization. With the presupposition that consumers in our model always value the remanufactured product less than they do the new product, we examine two scenarios for how the products differ in (functional) quality: (i) parity between the two types, and (ii) the remanufactured product is strictly not "good-as-new."

Uncertainty in the quality and quantity of returns is a major concern in product recovery (Fleischmann et al. 2001, Guide 2000, Thierry et al. 1995). Guide and Van Wassenhove (2009) observe that the decision to introduce a remanufactured product depends more on market (demand) or supply (quantity and quality) constraints than on technical operating constraints. Martin et al. (2010) argue that volume uncertainty is of lesser concern since managers can leverage historical data to reduce such uncertainty. Guide and Van Wassenhove (2001) note that the key to controlling profitability is the *quality* of used products collected by the firm. We align with these researchers by the following: (a) treating the quantity of product returns as exogenous; and (b) per Guide and Van Wassenhove (2001), allowing incoming product return quality to be stochastic and remanufacturing costs to depend on each item's quality. We also endogenize the retailer and/or third-party determination of the threshold quality level that used products must surpass to qualify for remanufacture.

The general in-house vs. outsourcing decision is the subject of a vast amount of study in multiple disciplines, for which Tsay (2014) can serve as an overview. Regarding the decision for remanufacturing in particular, the available research is sparse since the options have been limited. That is, remanufacturing activities have until recently been carried out primarily by small, independent, and privately-owned outside service providers (Guide 2000, Hauser and Lund 2003, Martin et al. 2010). As the volume of remanufacturing has grown, more firms have begun performing these activities in-house or evaluating the ramifications of doing so. Our research directly informs this possibility. Our model of the outsourced approach has the third party charging the retailer a per-unit fee for remanufacturing, and deciding how much of the collected used goods to actually remanufacture.

The literature on the environmental impact of remanufacturing is growing (e.g., Atasu et al. 2008, Corbett and Kleindorfer 2001a, b, Guide and Van Wassenhove 2006a, b). Several papers assess environmental impact in terms of volume multiplied by a per-unit "impact" cost (e.g., Agrawal et al. 2012, Thomas 2011, White et al. 1999). While this approach has logical appeal, an obvious difficulty is the estimation of this per-unit "impact" cost. We obviate the need for this estimation, using the level of remanufacturing activity as the metric of impact. We thereby focus on the remanufacturing process rather than end customer usage of the product. In considering profitability along with environmental impact, our work aligns with that of Tang and Zhou (2012), who formulate a "PPP ecosystem" to illuminate the triple-bottom-line objective (profit, people, and planet).

In sum, we draw upon and extend prior research in remanufacturing to study a retailer's strategic choice between remanufacturing in-house and outsourcing to a third party. Rather than assume one particular power relationship between the retailer and third party, as is common in the literature, we consider a spectrum of governance options for the outsourcing relationship: retailer as leader, third party as leader, and bargaining when each party has some negotiating power. We also integrate a combination of salient factors that has not previously been studied: uncertainty in the quality of product returns; costs specific to each strategy choice; endogenization of the quality threshold that dictates the fraction of the collected used items that will be remanufactured; and cannibalization effects when remanufactured and new products are both available to consumers. The next section describes our analytical framework.

3. Analytical Framework

3.1. Model Primitives

A retailer sells a new product (identified by subscript n) as well as a remanufactured version of the same product (identified by subscript r)[5], and sets their respective prices p_n and p_r. The retailer can source new product at an exogenous wholesale price w_n, while the cost for obtaining remanufactured product depends on the reverse channel strategy, as specified below. The selling prices must satisfy $p_n > w_n$ and $p_r < p_n$. All events transpire within a single period.

The pair of selling prices interacts with consumer preferences regarding product quality to determine the market demand for each item. This entails looking at each consumer's net utility from each type of item and then aggregating the decisions of all potential consumers, which we develop next.

Each type of product has a specified performance capability when functioning properly, which we call "functional quality" and denote as q subscripted with n or r. We assume that remanufacturing activity restores the used products to the quality level that exactly match with the functional quality of a new product[6] and we normalize this to 1 (i.e., $q_n = q_r = 1$) to simplify analysis.[7]

A consumer derives one of the following two net utility levels from purchasing a new or remanufactured item, respectively:

$$\begin{aligned} u_n &= \gamma q_n - p_n \\ &= \gamma - p_n \end{aligned}, \qquad (1)$$

$$\begin{aligned} u_r &= \alpha\gamma q_r - p_r \\ &= \alpha\gamma - p_r \end{aligned}, \qquad (2)$$

γ represents the consumer's willingness-to-pay for quality. In equation (2), $\alpha \in (0, 1)$ is a parameter conveying consumer *perception* that the remanufactured product is inferior to the new product quality-wise, which is reminiscent of what Garvin (1984) terms "perceived quality." Any subsequent use of the term "quality" will refer to functional quality. Perceived quality will always be explicitly labeled as such.

A consumer will buy the type of item that delivers higher utility, and will not buy at all if neither type delivers positive utility. The retailer's p_n and p_r directly drive these utilities, and hence the market demands. We restrict consideration to prices such that ($p_r \leq \alpha p_n$), meaning that the remanufactured item is discounted enough relative to the new item to offset the difference in perceived quality.[8] The utility functions in equation (1) and equation (2) indicate that consumers with willingness-to-pay $\gamma \in [\frac{p_r}{\alpha}, \frac{p_n - p_r}{1-\alpha})$ prefer to buy a remanufactured product while those with $\gamma \geq \frac{p_n - p_r}{1-\alpha}$ will buy a new product.[9]

Consistent with prior research on vertical differentiation which allows for heterogeneity in the individual consumer's willingness-to-pay for quality (see, e.g., Debo , et al. 2005, 2006, and Ferguson and Toktay 2006), we assume γ to be distributed uniformly on the interval (0, 1). Normalizing market size to 1 leads to the following demand functions for the two product types:

$$D_n = 1 - \frac{p_n - p_r}{1 - \alpha}, \qquad (3)$$

$$D_r = \frac{\alpha p_n - p_r}{\alpha(1 - \alpha)}. \qquad (4)$$

Total market coverage ($D_n + D_r$) is then $1 - \frac{p_r}{\alpha}$. These demand variables (as well as the various decision variables and performance outcomes) will later be further subscripted with i to indicate dependence on the design of the reverse channel, i.e., whether the retailer remanufactures in-house (i = 1) or outsources to a third party (i = 2). We refer to the former strategy as "In-house" and the latter as "Outsourcing."

The term S denotes the amount of collected (used) product, an item which is sometimes called a "core." Whatever portion of this undergoes remanufacturing will be available to fulfill D_r. $S > 0$ implies that remanufacturing is an option. S is normalized so as to remain strictly less than 1 (i.e., $0 < S < 1$). We follow numerous past researchers who have treated their equivalent of S as an exogenous parameter (e.g., Inderfurth 1997, Krikke et al. 1999, Laan et al. 1999, Spengler et al. 1997). Our specific reasonsare as follows. First, in many settings (including GameStop's), the process of collecting used the product is decoupled from the remanufacturing process. Second, volume uncertainty has less impact on the collections process than does quality uncertainty (Martin et al. 2010). Third, a fixed and exogenous S allows a "fair" comparison between the In-house and Outsourcing strategies.

The decision of whether to remanufacture a used item depends on the item's quality, which we represent with θ, a random variable with finite support in the range [0, 1]. $f(\theta)$ and $F(\theta)$ are respectively the density and distribution function for θ, with $F(0) = 0$ and $F(1) = 1$. We assume $F(\theta)$ to strictly increase in θ.[10] As the collection process is the same regardless of which party performs the remanufacturing, $f(\theta)$ and $F(\theta)$ need not be indexed with i. The fraction of collected items remanufactured is a function of the strategy choice and is given by $\int_{\theta=\tilde{\theta}_i}^{1} f(\theta)d\theta = 1 - F(\tilde{\theta}_i)$, where

$\tilde{\theta}_i$ represents the endogenously determined threshold such that all collected items with at least this level of quality will be remanufactured.

Since $F(\theta)$ is a monotone mapping, we can use $\tilde{\theta}_i$ as our metric of environmental impact, for which lower values are better. The "best" environmental outcome occurs at $\tilde{\theta}_i = 0$ (remanufacturing of 100% of collected items) while the "worst" occurs at $\tilde{\theta}_i = 1$ (no remanufacturing). And the strategy with the smaller $\tilde{\theta}_i$ will be regarded as environmentally superior.

We acknowledge the need to precisely qualify this approach. As a general rule, introducing remanufactured goods at a lower price should expand the overall market. The additional buyers can be segmented into two pools: those who would otherwise have bought new but instead buy the remanufactured item (good for the environment) and those who thought the new item was too expensive but are willing to buy the remanufactured item (bad for the environment since remanufacturing's environmental harm, while less than that of new manufacturing, is not zero). Galbreth et al. (2013) make such an argument. The following two conditions justify our approach: (a) We consider the environmental impact of only the manufacturing/remanufacturing process and not the buyer's use of the item. No model can assess the latter without additional assumptions and information. The product could be an energy and resource hog, in which case growing the market would clearly be harmful. Or perhaps the product would save energy and resources relative to how the buyers would act sans the product. (b) We assume that remanufacturing has a per-unit environmental harm that is much smaller than that for manufacturing a new item. This is especially plausible for consumer electronics, where oftentimes collected used items need little or no actual refurbishing, in which case remanufacturing is mostly just verifying the proper functionality. Under these conditions, increased remanufacturing will be a net positive for the environment since the benefits of preventing some new production will vastly outweigh the harm due to the remanufacturing that drives the net market growth.

Figure 1 illustrates the sequence of events in the reverse channel. This makes explicit that a perfect assessment of quality (remanufacturability) often cannot be done at the initial point of collection, with the full diagnosis possible only at the point of remanufacture.[11]

The two strategies (In-house and Outsourcing) differ in the cost of technology and processes needed to perform the remanufacturing. Strategy i has per-unit cost of $C_i(\theta) = c_i(1-\theta)$ to restore an item of quality level θ ($0 \le \theta \le 1$) to "good-as-new" condition. We call c_i the "variable cost of remanufacturing" to emphasize that this expense is incurred on a per-unit basis, but with the understanding that the actual cost for each unit depends on that unit's quality shortfall prior to remanufacturing (measured by $(1-\theta)$).[12] In expectation, the variable element of the cost of remanufacturing for strategy i is proportional to c_i, so comparisons of c_1 and c_2 will directly convey the relative cost efficiency of each strategy's remanufacturing capabilities. The total expected variable remanufacturing cost of the respective strategies are as follows:

- *In−house*: $\int_{\theta=\tilde{\theta}_1}^{1} C_1(\theta)Sf(\theta)d\theta = \int_{\theta=\tilde{\theta}_1}^{1} c_1(1-\theta)Sf(\theta)d\theta$ and,
- *Outsourcing*: $\int_{\theta=\tilde{\theta}_2}^{1} C_2(\theta)Sf(\theta)d\theta = \int_{\theta=\tilde{\theta}_2}^{1} c_2(1-\theta)Sf(\theta)d\theta.$

For the In-house strategy, maintaining remanufacturing capability burdens the retailer with an additional fixed cost of $\beta(1-c_1)$ with $\beta > 0$.[13] This functional form imposes the property that a lower variable cost comes at the expense of a higher fixed cost.

Table 1 summarizes the notation for our variables. An asterisk attached to a variable will indicate the optimal/equilibrium value for the given context. The next sub-sections present our analysis of the In-house and Outsourcing strategies.

3.2. In-House Remanufacturing

The retailer's three decision variables are the prices of the new and remanufactured product (p_{n1}, p_{r1}) and

Figure 1 Reverse Flow of Materials [Color figure can be viewed at wileyonlinelibrary.com]

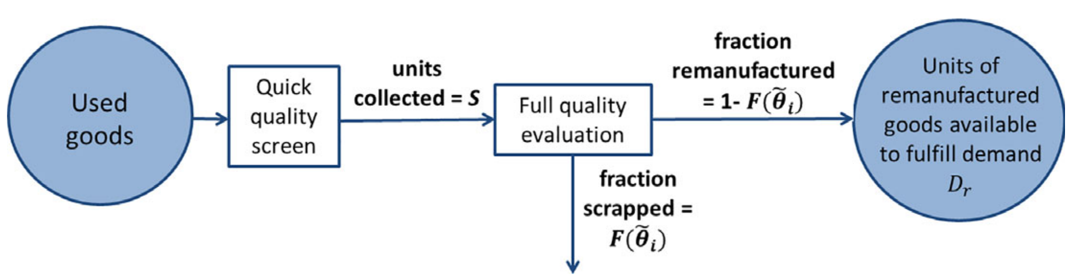


Table 1 Notation (Attaching an Asterisk to any of these Variables will Indicate the Optimal/Equilibrium Value for the Given Context)

Notation	Description
Indices	
j	Index for product type ($j = n$ for new product; $j = r$ for remanufactured product)
i	Index for remanufacturing strategy ($i = 1$ for In-house; $i = 2$ for Outsourcing)
Product price	
p_{ji}	Retail price for product type j under strategy i
Quality	
q_j	Functional quality of item of type j
θ	Functional quality of used item at time of collection, $\theta \in [0, 1]$
μ	Mean functional quality of collected (used) items
$f(\theta)$	Probability density function for θ
$F(\theta)$	Probability distribution function for θ
$\tilde{\theta}_i$	Quality threshold to qualify for remanufacturing under strategy i
Consumers	
u_j	Consumer's net utility for purchasing item of type j
γ	Consumer's willingness-to-pay for the product's quality; $\gamma \sim U(0, 1)$
α	Willingness-to-pay multiplier for perception of the remanufactured product's quality handicap; $\alpha \in (0, 1)$
Market	
D_{ji}	Demand for product type j under strategy i
Remanufacturing	
S	Total collections of used product, normalized to the range (0, 1]
$C_i(\theta)$	Unit remanufacturing cost for a used product of quality θ under strategy i
c_i	Remanufacturing cost coefficient for strategy i
g	Unit disposal/salvage value for collected items not remanufactured
β	Fixed-cost coefficient for maintaining remanufacturing technology In-house
w_r	Wholesale price for remanufactured product (only relevant with Outsourcing)
δ	Bargaining power for third party ($0 < \delta < 1$) (only relevant with Outsourcing)
Profit	
π_i	Retailer profit under strategy i
π_{2o}	Third-party profit (only relevant with Outsourcing)
Placeholders	
x	Placeholder to represent αw_n
y	Placeholder to represent $2\alpha(1 - \alpha)S$

the quality threshold ($\tilde{\theta}_1$) such that all collected items with at least that level of quality will be remanufactured. The quantity of used items available for remanufacturing is S. The cost of acquiring these items would show up in the retailer's profit function as a fixed cost regardless of the strategy choice, so we set this to zero. We assume that used items that do not undergo remanufacturing have negligible salvage value. Section 5.2 will relax that assumption.

The retailer's total profit is revenue generated from selling new and remanufactured goods, less the variable costs of procuring new product and remanufacturing used items as well as the fixed cost for maintaining remanufacturing capability In-house. The following constrained profit maximization problem is the result, in which the constraint specifies that sales volume of the remanufactured product cannot exceed the total collections of used items:

$$\begin{aligned}\max_{0 \le p_{r1} < \alpha p_{n1}; 0 \le \tilde{\theta}_1 \le 1} \quad \pi_1 &= (p_{n1} - w_n)D_{n1} + p_{r1}D_{r1} \\ &\quad - [S \int_{\theta=\tilde{\theta}_1}^{1} c_1(1-\theta)f(\theta)d\theta] \\ &\quad - \beta(1 - c_1) \\ &= (p_{n1} - w_n)D_{n1} + p_{r1}D_{r1} \\ &\quad - c_1 S[1 - F(\tilde{\theta}_1) - \mu \\ &\quad + H(\tilde{\theta}_1)] - \beta(1 - c_1),\end{aligned} \tag{5}$$

$$s.t.\ D_{r1} \le S \int_{\theta=\tilde{\theta}_1}^{1} f(\theta)d\theta = S[1 - F(\tilde{\theta}_1)], \tag{6}$$

where $D_{n1} = 1 - \frac{p_{n1} - p_{r1}}{1 - \alpha}$ and $D_{r1} = \frac{\alpha p_{n1} - p_{r1}}{\alpha(1 - \alpha)}$ as stated in equations (3) and equation (4), and $H(\tilde{\theta}_1) = \int_{0}^{\theta=\tilde{\theta}_1} \theta f(\theta)d\theta$.

Defining $x = \alpha w_n$, $y = 2\alpha(1 - \alpha)S$, and $H(\tilde{\theta}_1^*) = \int_0^{\tilde{\theta}_1^*} \theta f(\theta)d\theta$ to make the presentation more compact, Table 2 reports the optimal solution, with proofs in section A.1 of the Appendix S1.

Table 2 shows how c_1 drives the optimal solution for In-house remanufacturing, as interpreted below:

- *Low variable cost of remanufacturing* (*i.e.*, $c_1 \in (0, x - y]$): Prices and demands for the new and remanufactured product do not depend on c_1, and all collected items are remanufactured. The total market served by both products is greater than when only the new product is offered, although total retailer profit declines (linearly) with c_1 in this range.[14] The underlying intuition is that when remanufacturing can be done at low variable cost, all collected products will be remanufactured ($\tilde{\theta}_1^* = 0$) and put on the market ($D_{r1}^* = S$). Given this fixed demand, the retailer's selling price for the remanufactured product and corresponding revenue are both invariant to the remanufacturing costs. Any increase in the variable cost of remanufacturing will simply decrease the retailer's profit.
- *High variable cost of remanufacturing* (*i.e.*, $c_1 \in (x - y, 1)$): As c_1 increases, the retailer will raise the selling price of remanufactured product (to pass some of the cost increase on to customers) which reduces the amount of collected product that is remanufactured. Since the price for the new product does not change, the net effect is to decrease demand for the

Table 2 Optimal Solution for the In-House Remanufacturing Strategy

	Range for c_1	
	$c_1 \in (0, x - y]$	$c_1 \in (x - y, 1)$
$\tilde{\theta}_1^*$	0	Solution of $c_1\tilde{\theta}_1 + yF(\tilde{\theta}_1) = c_1 - x + y$
p_{n1}^*	$\frac{1 + w_n}{2}$	$\frac{1 + w_n}{2}$
p_{r1}^*	$\frac{\alpha + x - y}{2}$	$\frac{\alpha + x - y[1 - F(\tilde{\theta}_1^*)]}{2}$
D_{n1}^*	$\frac{1-w_n}{2} - \alpha S$	$\frac{1-w_n}{2} - \alpha S[1 - F(\tilde{\theta}_1^*)]$
D_{r1}^*	S	$S[1 - F(\tilde{\theta}_1^*)]$
π_1^*	$\frac{(1 - w_n)^2}{4} + \frac{S}{2}(2x - y) - c_1S(1 - \mu) - \beta(1 - c_1)$	$\frac{(1 - w_n)^2}{4} + \frac{S[1 - F(\tilde{\theta}_1^*)]}{2} \times [2x - y[1 - F(\tilde{\theta}_1^*)]] - -c_1S[1 - F(\tilde{\theta}_1^*) - \mu + H(\tilde{\theta}_1^*)] - ;\beta(1 - c_1)$

$x = \alpha w_n$, $y = 2\alpha(1 - \alpha)S$, $H(\tilde{\theta}_1^*) = \int_0^{\tilde{\theta}_1^*} \theta f(\theta)d\theta$, and μ is the mean of θ.

remanufactured product while increasing demand for the new product. As in the case of low variable cost of remanufacturing, the retailer cannot avoid a decline in profit when c_1 increases.

These results provide some managerial insights. When remanufacturing can be done at low variable costs, all collected used products will be remanufactured. As these costs increase, the retailer will become more selective about which items to remanufacture, thus reducing the volume of remanufactured products in the marketplace. The implications for the price of the remanufactured product stem directly from this dynamic.

Three parameters moderating these relationships are α (which scales consumer willingness-to pay for the remanufactured product vs. the new product), w_n (wholesale price for the new product), and S (used products available for remanufacturing). Table 3 shows how these parameters impact the solution in Table 2.

Table 3 Comparative Statics for Optimal Solution for In-House Remanufacturing

	Key decisions					
Parameter	$\tilde{\theta}_1^*$	p_{n1}^*	p_{r1}^*	D_{n1}^*	D_{r1}^*	π_1^*
$\alpha\uparrow$	NC/↓	NC	↑	↓	NC/↑	↑
$S\uparrow$	NC/↑	NC	↓	↓	↑	↑
$w_n\uparrow$	NC/↓	↑	↑	↓	NC/↑	Mixed

The directional relationships are abbreviated as follows, and apply over all $c_1 \in (0, 1)$ unless otherwise noted: (a) NC indicates no change; (b) NC/↑ indicates NC when $c_1 \in (0, x - y]$ and ↑ when $c_1 \in (x - y, 1)$; (c) NC/↓ indicates NC when $c_1 \in (0, x - y]$ and ↓ when $c_1 \in (x - y, 1)$; (d) Mixed indicates that the optimal profit decreases with w_n when $c_1 \in (0, x - y]$ and $\alpha < \frac{1-w_n}{2S}$, and increases otherwise.

The results in Table 3 align with expectations. Recall that the quality threshold defines the total amount of collected products that will be remanufactured (i.e., lowering that threshold means more used items will qualify for remanufacturing). When c_1 is low enough, the threshold is set to 0 so that all collected used items will be remanufactured regardless of the other three parameters. Only when c_1 is sufficiently large will the other factors matter. Specifically, increasing either consumer willingness-to-pay for the remanufactured product or the new product's wholesale price stimulates remanufacturing activity (i.e., a decrease in the quality threshold), while an increase in the total used product collections allows the retailer to be more discriminating in which products to remanufacture (i.e., a increase in the quality threshold).

The new product's retail price is impacted only by its wholesale price and is invariant to the consumer's relative willingness-to-pay for the remanufactured product and the total collected used products. The remanufactured product's retail price increases with the new product's wholesale price (since this allows the retailer to increase the remanufactured item's margin to compensate for the loss in the new product's margin), decreases with the total used product (since more used products are then available for remanufacturing), and increases with the consumer willingness-to-pay for the remanufactured product (since this reduces the differentiation between the two product types). Increases in the new product's wholesale price reduces that product's margin, so that the retailer ramps up remanufacturing by decreasing the quality threshold. As the consumer becomes willing to pay more for the remanufactured product, the retailer raises that product's retail price or increases the volume available for sale.

3.3. Outsourcing of Remanufacturing

This section analyzes the Outsourcing approach, in which the retailer finds an outside entity (third party) to perform the remanufacturing. Rather than assume one particular power relationship between the retailer and this third party, as is common in the literature (usually with one of the parties as the Stackelberg leader), we consider a spectrum of possibilities. Specifically, we adopt the Nash bargaining framework (Myerson 1997), whereby each party obtains whatever payoff it would get from noncooperation along with a share of any benefits due to cooperation. Let δ $(0 \leq \delta \leq 1)$ denote the normalized bargaining power for the third party so that $(1 - \delta)$ represents the same for the retailer, π_2 and π_{2o} represent the respective profits for the retailer and third party, and π_1^* and 0 represent the respective retailer and third-party profits if bargaining fails (i.e., their disagreement points, with π_1^* being the retailer's optimal profit under the In-house strategy as shown in Table 2). The Pareto-efficient Nash bargaining solution is the π_2 and π_{2o} combination that maximizes the following Nash product:

$$N_\delta = (\pi_{2o} - 0)^\delta (\pi_2 - \pi_1^*)^{(1-\delta)}, \tag{7}$$

$$s.t.$$

$$D_{r2} \le S \int_{\theta=\tilde{\theta}_2}^{1} f(\theta)d\theta = S[1 - F(\tilde{\theta}_2)]. \tag{8}$$

We assume a two-stage decision making process.[15] At the first stage, the retailer and the third party negotiate on the quality threshold ($\tilde{\theta}_2$) and remanufactured product wholesale price (w_r) to optimize the joint Nash product in equation (7). These are taken as given at the second stage, in which the retailer chooses the retail prices for the new and remanufactured products (p_{n2} and p_{r2}) to maximize its own profit.

We solve the game by backward induction. The mathematical details are in section A.2 of the Appendix S1. These establish both profit expressions as simply functions of $\tilde{\theta}_2$, so that the Nash bargaining optimization problem reduces to:

$$\max_{0 \le \tilde{\theta}_2 \le 1} \quad N_\delta = (\pi_{2o} - 0)^\delta (\pi_2 - \pi_1^*)^{(1-\delta)}, \tag{9}$$

where $\pi_2 = \frac{(1-w_n)^2}{4} + \frac{yS}{2}[1-F(\tilde{\theta}_2)]^2$ and $\pi_{2o} = xS[1 - F(\tilde{\theta}_2)] - yS[1 - F(\tilde{\theta}_2)]^2 - c_2S[1 - F(\tilde{\theta}_2) - \mu + H(\tilde{\theta}_2)]$ (see section A.2 of the Appendix S1).

We analyze this problem for three cases that represent the range of possible power relationships between the retailer and the third party: (a) Retailer-led Outsourcing (δ = 0); (b) Third party-led Outsourcing (δ = 1); and (c) Collaborative Outsourcing (0 < δ < 1). These cases reflect the competitive standing of the two firms in their own sectors and in relation to each other. Consider Apple, which sells refurbished items in its Apple Stores, controls the market for iOS products, and famously dominates its dealings with suppliers and channel partners. If Apple were our model's retailer that outsourced remanufacturing, δ = 0 would be a reasonable approximation. GameStop, while a Fortune 500 company, does not have the same leverage, in part because it is but one retailer of the manufacturer-branded game consoles (e.g., Sony PlayStation, Nintendo Wii, Microsoft XBox) it carries. For GameStop a large δ and even δ = 1 are plausible. A large δ could be questionable for a niche remanufacturer such as Alotech (components for industrial machinery and heavy commercial vehicles) due to the many alternative service providers accessible through ReMaTec's online catalogue.[16] Of course, once outsourcing relationships are underway, factors such as asset specificity influence the true balance of power. The following subsections develop the equilibrium for the three cases of δ.

3.3.1. Outsourcing with Retailer as the Leader (δ = 0). When δ = 0 the Nash bargaining optimization in equation (9) reduces to:

$$\max_{0 \le \tilde{\theta}_2 \le 1} \quad \pi_2 - \pi_1^*, \tag{10}$$

which is equivalent to maximizing just the retailer's profit π_2. The complete profit-maximization is as follows:

$$\max_{0 \le p_{r2} < \alpha p_{n2}; 0 \le \tilde{\theta}_2 \le 1} \quad \pi_2 = (p_{n2} - w_n)D_{n2} + p_{r2}D_{r2} - c_2S[1 - F(\tilde{\theta}_2) - \mu + H(\tilde{\theta}_2)], \tag{11}$$

$$s.t.$$

$$D_{r2} \le S[1 - F(\tilde{\theta}_2)]. \tag{12}$$

This matches the In-house profit-maximization problem in equation (5) and equation (6), except with three points of deviation: (a) c_2 replaces c_1 since remanufacturing occurs at the third-party's variable cost; (b) $\tilde{\theta}_2$ replaces $\tilde{\theta}_1$ to match the subscript to the strategy; and (c) β = 0 because the retailer no longer maintains internal manufacturing capability. The solution is, therefore, what appears in Table 2, adjusted in these three ways.

3.3.2. Outsourcing with the Third Party as Leader (δ = 1). When δ = 1 the Nash bargaining optimization in equation (15) simply maximizes the third party's profit as follows:

$$\max_{0 \le \tilde{\theta}_2 \le 1} \quad \pi_{2o}. \tag{13}$$

Table 4 presents the resulting equilibrium, with proof in section A.3 of the Appendix S1. The equilibrium is shaped by c_2, which conveys the third party's variable cost for performing remanufacturing, in the following ways:

- *Outsourcing to a third party with low variable cost of remanufacturing* (*i.e.*, $c_2 \in (0, x - 2y]$): Here the third party charges a wholesale price for the remanufactured product that does not depend on the cost of remanufacturing, and remanufactures all collected products. The total market served by both products will be greater than when only the new product is offered. Within

Table 4 Nash Bargaining Equilibrium for the Outsourcing Remanufacturing Strategy When $\delta = 1$

	Range for c_2	
	$c_2 \in (0, x - 2y]$	$c_2 \in (x - 2y, 1)$
$\tilde{\theta}_2^*$	0	Solution of $c_2\tilde{\theta}_2 + 2yF(\tilde{\theta}_2) = c_2 - x + 2y$
w_r^*	$x - y$	$x - y[1 - F(\tilde{\theta}_2^*)]$
p_{n2}^*	$\frac{1 + w_n}{2}$	$\frac{1 + w_n}{2}$
p_{r2}^*	$\frac{\alpha + x - y}{2}$	$\frac{\alpha + x - y[1 - F(\tilde{\theta}_2^*)]}{2}$
D_{n2}^*	$\frac{1-w_n}{2} - \alpha S$	$\frac{1-w_n}{2} - \alpha S[1 - F(\tilde{\theta}_2^*)]$
D_{r2}^*	S	$S[1 - F(\tilde{\theta}_2^*)]$
π_2^*	$\frac{(1 - w_n)^2}{4} + \frac{yS}{2}$	$\frac{(1 - w_n)^2}{4} + \frac{yS}{2}[1 - F(\tilde{\theta}_2^*)]^2$
π_{2o}^*	$S(x - y) + c_2S(1 - \mu)$	$S[1 - F(\tilde{\theta}_2^*)]\{x - y[1 - F(\tilde{\theta}_2^*)]\} - c_2S[1 - F(\tilde{\theta}_2^*) - \mu + H(\tilde{\theta}_2^*)]$

$x = \alpha w_n$, $y = 2\alpha(1 - \alpha)S$, $H(\tilde{\theta}_2^*) = \int_0^{\tilde{\theta}_2^*} \theta f(\theta) d\theta$, and μ is the mean of θ.

the stated range, the third-party profit decreases with c_2 while the retailer profit is constant. With demand being constant, the retailer's selling price for the remanufactured product is invariant to c_2 in the given range. The constant demand for both products and constant product prices together make the third-party profit decline as c_2 increases.

- *Outsourcing to a third party with high variable cost of remanufacturing* (*i.e.*, $c_2 \in (x - 2y, 1)$): As c_2 increases, the third-party remanufactures a smaller quantity and raises the wholesale price. In turn, the retailer also increases the remanufactured product's selling price (to cover increases in the wholesale price), which decreases demand for this item. The new product's selling price is invariant to c_2 but the increase in remanufactured product price enhances demand for the new product. Adding the remanufactured product to the portfolio increases total market coverage. Profits for both the third party and the retailer decline as c_2 increases.

The managerial insights stemming from these results are similar to those for the In-house strategy. Likewise, changes to the key parameters (i.e., α, w_n, S) have impact similar to what Table 3 documents. When the third party can remanufacture at relatively low variable cost, the retailer sets the quality threshold so that all collected used items will be remanufactured. As this cost increases, the retailer raises the threshold so as to reduce the amount of remanufacturing. As before, the remanufactured product price decreases with the volume of remanufactured product made available.

3.3.3. Collaborative Outsourcing ($0 < \delta < 1$). To characterize the solution to equation (9), we examine the first-order condition of N_δ with respect to $\tilde{\theta}_2$:

$$\frac{\partial N_\delta}{\partial \tilde{\theta}_2} = (\pi_{2o})^\delta (\pi_2 - \pi_1^*)^{-\delta} \left\{ \left[(\pi_2 - \pi_1^*)\delta(\pi_{2o})^{-1} \frac{\partial \pi_{2o}}{\partial \tilde{\theta}_2} \right] + (1 - \delta)\frac{\partial \pi_2}{\partial \tilde{\theta}_2} = 0. \right.$$

Substituting in $\frac{\partial \pi_2}{\partial \tilde{\theta}_2} = -Sf(\tilde{\theta}_2)y(1 - F(\tilde{\theta}_2))$ and $\frac{\partial \pi_{2o}}{\partial \tilde{\theta}_2} = -Sf(\tilde{\theta}_2)[x - 2y(1 - F(\tilde{\theta}_2)) - c_2(1 - \tilde{\theta}_2)]$, a necessary (and sufficient if $N_\delta(\tilde{\theta}_2)$ has a global optimum) condition for an optimum for N_δ is:

$$\delta[\frac{\pi_2 - \pi_1^*}{\pi_{2o}}][x - 2y(1 - F(\tilde{\theta}_2)) - c_2(1 - \tilde{\theta}_2)] + [1 - \delta][y(1 - F(\tilde{\theta}_2))] = 0.$$

The general solution to equation (14) is difficult to analytically characterize. Thus, we investigate the case of egalitarian bargaining, which allocates payoffs based on each party's relative bargaining power (Cai et al. 2012, Dukes et al. 2006, Kalai and Smorodinsky 1975, Myerson 1997). Specifically, at equilibrium the ratio of net gains for the parties will match the ratio of their relative bargaining power, i.e., $\frac{1-\delta}{\delta} = \frac{\pi_2 - \pi_1^*}{\pi_{2o} - 0}$. We rearrange the terms to form the following additional condition on $\tilde{\theta}_2$:

$$(1 - \delta)(\pi_{2o} - 0) = \delta(\pi_2 - \pi_1^*). \tag{15}$$

We substitute $\pi_2 = \frac{(1-w_n)^2}{4} + \frac{yS}{2}[1 - F(\tilde{\theta}_2)]^2$, $\pi_{2o} = xS[1 - F(\tilde{\theta}_2)] - yS[1 - F(\tilde{\theta}_2)]^2 - c_2S[1 - F(\tilde{\theta}_2) - \mu + H(\tilde{\theta}_2)]$, and π_1^* from Table 2 into equation (15) and then seek the $\tilde{\theta}_2$ which solves the following equation:

$$\frac{1 - \delta}{\delta}[xS(1 - F(\tilde{\theta}_2)) - c_2S(1 - F(\tilde{\theta}_2) - \mu + H(\tilde{\theta}_2)] - \frac{2 - \delta}{2\delta}\left[yS(1 - F(\tilde{\theta}_2))^2\right] = -A, \tag{16}$$

where:

$$A = \begin{cases} \frac{S}{2}(2x - y) - c_1S(1 - \mu) - \beta(1 - c_1), \\ \quad \text{when } c_1 \in (0, x - y] \\ \frac{S[1 - F(\tilde{\theta}_1^*)]}{2}[2x - y[1 - F(\tilde{\theta}_1^*)]] \\ -c_1S[1 - F(\tilde{\theta}_1^*) - \mu + H(\tilde{\theta}_1^*)] - \beta(1 - c_1), \\ \quad \text{when } c_1 \in (x - y, 1) \end{cases}$$

and, for the case of $c_1 \in (x - y, 1)$, $\tilde{\theta}_1^*$ is a solution to $c_1\tilde{\theta}_1 + yF(\tilde{\theta}_1) = c_1 - x + y$. The next section describes the implications of each remanufacturing strategy for retailer profitability and the environment.

4. Design of the Reverse Channel for Remanufacturing

This section characterizes how the retailer's choice between In-house and Outsourcing impacts retailer profitability and the environment (as measured by the amount of remanufacturing). Due to the complexity of the model, all subsequent analytic conclusions assume θ is uniformly distributed in [0, 1] so that $f(\theta) = 1$ and $F(\theta) = \theta$.[17] All our graphs use $\alpha = 0.8$, $w_n = 0.2$, and $S = 0.2$, which guarantees positive demand for both types of products in all scenarios. Experimentation across a broad range of parameter combinations has demonstrated the robustness of our findings. Proofs of all propositions appear in Appendix S3.

4.1. In-House vs. Retailer-Led Outsourcing ($\delta = 0$)

The following propositions characterize the choice between the In-house approach and the Outsourcing strategy in which the retailer has leadership power.

Proposition 1. *In-house remanufacturing and Retailer-led Outsourcing have the following ordering with respect to retailer profit:*

(*a*) *If* $c_1, c_2 \in (0, x - y]$, *then if* $c_2 \geq \frac{2\beta}{S} + c_1(1 - \frac{2\beta}{S})$, *In-house gives the retailer greater profit; otherwise Outsourcing does;*
(*b*) *If* $c_1 \in (0, x - y]$ *and* $c_2 \in (x - y, 1)$, *then if* $c_2 \geq \frac{Sx^2}{S(2x-y-c_1)-2\beta(1-c_1)} - y$, *In-house gives the retailer greater profit; otherwise Outsourcing does;*
(*c*) *If* $c_1 \in (x - y, 1)$ *and* $c_2 \in (0, x - y]$, *then if* $c_2 \geq (2x - y) + \frac{2\beta(1-c_1)}{S} - \frac{x^2}{y+c_1}$, *In-house gives the retailer greater profit; otherwise Outsourcing does;*
(*d*) *If* $c_1, c_2 \in (x-y, 1)$, *then if* $c_2 \geq \frac{2Sx^2c_1+4y\beta(1-c_1)(y+c_1)}{2Sx^2-4\beta(1-c_1)(y+c_1)}$, *In-house gives the retailer greater profit; otherwise Outsourcing does;*

where $x = \alpha w_n$ *and* $y = 2\alpha S(1 - \alpha)$.

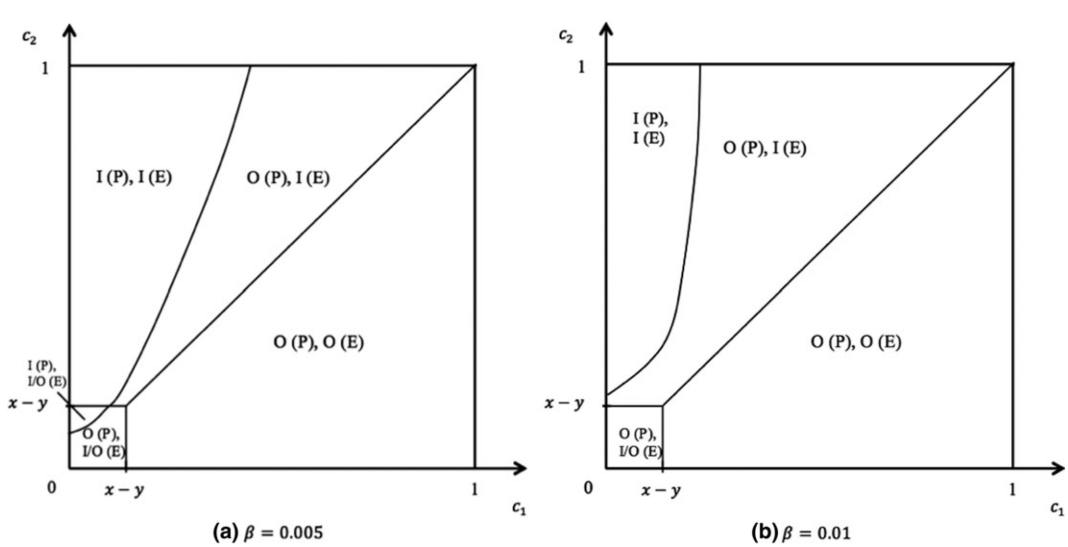
Proposition 2. *In-house remanufacturing and Retailer-led Outsourcing have the following ordering with respect to environmental impact:*

(*a*) *If* $c_1, c_2 \in (0, x - y]$, *then both In-house and Outsourcing yield an equal (and "best" possible) environmental outcome;*
(*b*) *If* $c_1 \in (0, x - y]$ *and* $c_2 \in (x - y, 1)$, *then In-house is better for the environment;*
(*c*) *If* $c_1 \in (x - y, 1)$ *and* $c_2 \in (0, x - y]$, *then Outsourcing is better for the environment; and*
(*d*) *If* $c_1, c_2 \in (x - y, 1)$, *then if:*
- $c_1 = c_2$, *both In-house and Outsourcing yield an equal environmental outcome;*
- $c_1 < c_2$, *In-house is better for the environment; and*
- $c_1 > c_2$, *Outsourcing is better for the environment;*

where $x = \alpha w_n$ *and* $y = 2\alpha S(1 - \alpha)$.

Figure 2 uses Propositions 1 and 2 to compare the two strategies with respect to the two criteria, for different combinations of c_1 and c_2. The regions bear tags with the format *STRATEGY(METRIC)*, with *STRATEGY* $\in$ *(I, O)* referring to In-house or Outsourcing, respectively, and *METRIC* $\in$ *(P, E)* referring to (retailer) Profit or Environment, respectively. So *I(P)* and *O(P)* identify regions in which In-house and Outsourcing, respectively, generate higher retailer profit; *I(E)* and *O(E)* label regions in which In-house

Figure 2 Retailer Profit and Environmental Impact When the Outsourcing Option is Retailer-Led ($\delta = 0$) (with $\alpha = 0.8$, $w_n = 0.2$, $S = 0.2$): Regions of Congruence and Conflict



and Outsourcing, respectively, are more environment-friendly. The *STRATEGY* slot may also display a composite label, such as in *I/O(E)* which indicates parity between In-house and Outsourcing in environmental impact. The two panels of Figure 2 depict different levels of β: low ($\beta = 0.005$) and high ($\beta = 0.01$).

Figure 2 yields the following insights. There are distinct areas we call "congruence regions," to mean that one of the strategy choices (at least weakly) dominates the other in both retailer profitability and environmental impact. In our notation, this entails the same letter appearing in the *STRATEGY* slot of all tags for the region. For example, In-house remanufacturing is dominant in congruence regions labeled [*I(P), I(E)*] and [*I(P), I/O(E)*], while Outsourcing does better in congruence regions labeled [*O(P), O(E)*] and [*O(P), I/O(E)*]. These regions reflect the relative magnitudes of c_1 and c_2 (i.e., relatively small c_1 and relatively large c_2 make In-house remanufacturing dominant, while the reverse favors Outsourcing). The existence of congruence regions demonstrates that profitability and environmental performance are not always in conflict. However, there may be "conflict regions" such as [*O(P), I(E)*] in which the retailer must decide the relative importance of profit vs. environment. Such regions are a consequence of the additional fixed cost the retailer must bear if remanufacturing In-house. Note that this region exists even when $c_1 < c_2$ (In-house has a lower variable cost of remanufacturing than does the third-party channel) and expands with β, the parameter that scales the fixed cost of In-house remanufacturing.

4.2. In-House vs. Third Party-Led Outsourcing ($\delta = 1$)

The following propositions characterize the choice between the In-house approach and the Outsourcing strategy in which the third party has leadership power.

Proposition 3. *In-house remanufacturing and Third party-led Outsourcing have the following ordering with respect to retailer profit:*

- (*a*) *When* $c_1 \in (0, x - y]$ *and* $c_2 \in (0, x - 2y]$, *then if* $c_1 \le \frac{2S(x-y)-2\beta}{S-2\beta}$, *In-house gives the retailer greater profit; otherwise Outsourcing does;*
- (*b*) *When* $c_1 \in (0, x - y]$ *and* $c_2 \in (x - 2y, 1)$, *then if* $c_1 \le \frac{S(2x-y)-2\beta}{S-2\beta} - \frac{x^2 yS}{(S-2\beta)(2y+c_2)^2}$, *In-house gives the retailer greater profit; otherwise Outsourcing does;*
- (*c*) *When* $c_1 \in (x - y, 1)$ *and* $c_2 \in (0, x - 2y]$, *then if* $2\beta(1 - c_1)(y + c_1) + yS(y + c_1) \le x^2 S$, *In-house gives the retailer greater profit; otherwise Outsourcing does; and*
- (*d*) *When* $c_1 \in (x - y, 1)$ *and* $c_2 \in (x - 2y, 1)$, *then if* $\frac{x^2S[(2y+c_2)^2-y(y+c_1)]}{2(y+c_1)(2y+c_2)^2} - \beta(1 - c_1) \ge 0$, *In-house gives the retailer greater profit; otherwise Outsourcing does;*

where $x = \alpha w_n$ *and* $y = 2\alpha S(1 - \alpha)$.

Proposition 4. *In-house remanufacturing and Third party-led Outsourcing have the following ordering with respect to environmental impact:*

- (*a*) *If* $c_1 \in (0, x - y]$ *and* $c_2 \in (0, x - 2y]$, *then both In-house and Outsourcing yield an equal (and "best" possible) environmental outcome;*
- (*b*) *If* $c_1 \in (0, x - y]$ *and* $c_2 \in (x - 2y, 1)$, *then In-house is better for the environment;*
- (*c*) *If* $c_1 \in (x - y, 1)$ *and* $c_2 \in (0, x - 2y]$, *then Outsourcing is better for the environment;*
- (*d*) *If* $c_1 \in (x - y, 1)$ *and* $c_2 \in (x - 2y, 1)$, *then if:*
  - $c_1 - c_1 < y$, *In-house is better for the environment;*
  - $c_1 - c_2 = y$, *both In-house and Outsourcing yield an equal environmental outcome; and*
  - $c_1 - c_2 > y$, *Outsourcing is better for the environment;*

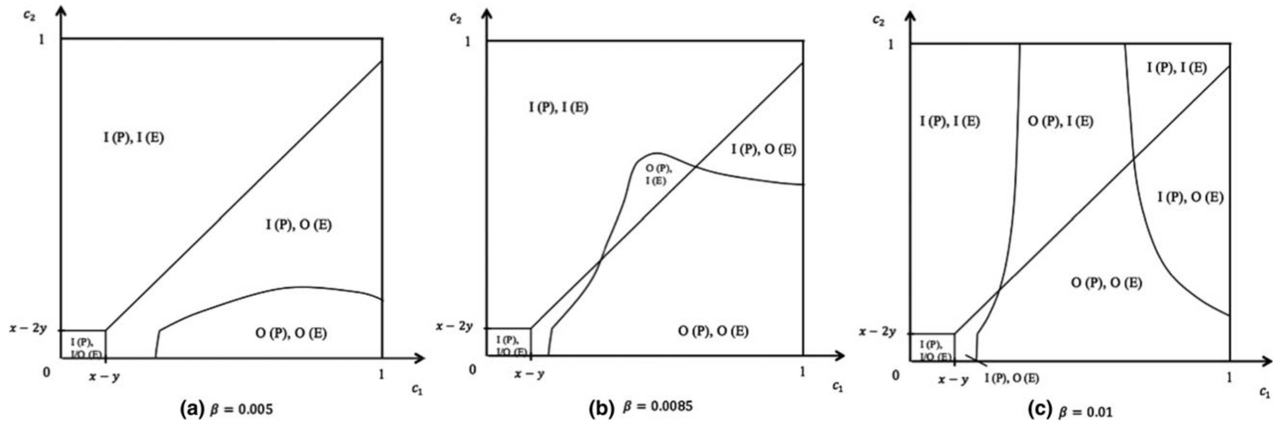
where $x = \alpha w_n$ *and* $y = 2\alpha S(1 - \alpha)$.

Figure 3 illustrates the findings of Propositions 3 and 4. The individual panels walk through the progression β = 0.005, 0.0085, and 0.01 to show how the congruence and conflict regions evolve as the In-house remanufacturing fixed cost increases.

The panels in Figure 3 demonstrate some trends. As the fixed cost increases (proportionally to β for any given c_1 and c_2): (a) the [*O(P), O(E)*] region (Outsourcing congruence) generally grows while the [*I(P), I(E)*] region (In-house congruence) shrinks; and (b) the [*I(P), O(E)*] conflict region surrenders some ground to the new conflict region [*O(P), I(E)*]. The evolution of the congruence regions aligns with expectations since an increase in fixed costs for In-house remanufacturing should reduce In-house congruence while expanding Outsourcing congruence.

Comparing the two panels of Figure 2 with their counterparts in Figure 3 (panels (a) and (c)) reveals some consequences of the power dynamic in an outsourcing relationship, since the figures differ only in δ. First, the region for which both strategies yield an equal environmental outcome (denoted with a label containing *I/O(E)*) is larger when the retailer has complete power than when the third party does. That is, the environment is more often better off under Outsourcing when the retailer is the leader. Second, the region where In-house generates greater retail profit than does Outsourcing (denoted with a label containing *I(P)*) is generally larger when the third party has power in the

Figure 3 Retailer Profit and Environmental Impact When the Outsourcing Option is Third Party-Led (δ = 1) (with $\alpha = 0.8$, $w_n = 0.2$, $S = 0.2$): Regions of Congruence and Conflict



outsourced relationship. This is because ceding control handicaps the retailer's ability to properly trade off the costs and benefits of the decisions that drive its own profit. Outsourcing already erodes the retailer's control, and shifting power to the third party (from $\delta = 0$ to $\delta = 1$) does so further. This finding is consistent with a theme in the modern understanding of outsourcing in general: one might well be better off insourcing if the outsourced alternative requires giving up too much control (Tsay 2014). Of course, a countervailing factor in our model, as in reality, is the fixed cost represented by β that handicaps the In-house approach. Indeed, all the figures contain regions in which retailer profit is higher with Outsourcing (denoted with a label containing *O(P)*), including Figure 3 where the third party has all the power.

4.3. In-House vs. Collaborative Outsourcing ($0 < \delta < 1$)

As seen in section 4, we do not have closed forms for the equilibrium under Collaborative Outsourcing. Thus, for this power structure, we go directly to numerical analysis to characterize the choice between the In-house approach and Outsourcing. We maintain consistency by using the same values of α, w_n, and S as in the previous sections. To increase generality, we consider broad ranges for β (β = 0.005, 0.0085, and 0.01) and δ (δ = 0.25, 0.50, and 0.75). Figures 4, 5, and 6 show the resulting regions of congruence and conflict.

The figures show that the congruence and conflict regions reflect a complex interplay among the parameters conveying the remanufacturing variable cost (c_1 and c_2), the fixed cost associated with the In-house strategy (β), and the relative bargaining power between the retailer and the third party (δ). For small and medium β (Figures 4 and 5), an increase in δ shrinks the congruence region for In-house ([*I(P), I(E)*] and [*I(P), I/O(E)*]) and expands the conflict region ([*I(P), O(E)*]). When β is large (Figure 6), an increase in δ reduces the congruence regions for Outsourcing ([*O(P), O(E)*]) while giving rise to a new conflict region in which Outsourcing gives greater retailer profit while In-house is better for the environment ([*O(P), I(E)*]). This occurs because the high fixed

Figure 4 Retailer Profit and Environmental Impact When the Outsourcing Option has Shared Power ($0 < \delta < 1$), with $\beta = 0.005$ (with $\alpha = 0.8$, $w_n = 0.2$, $S = 0.2$): Regions of Congruence and Conflict

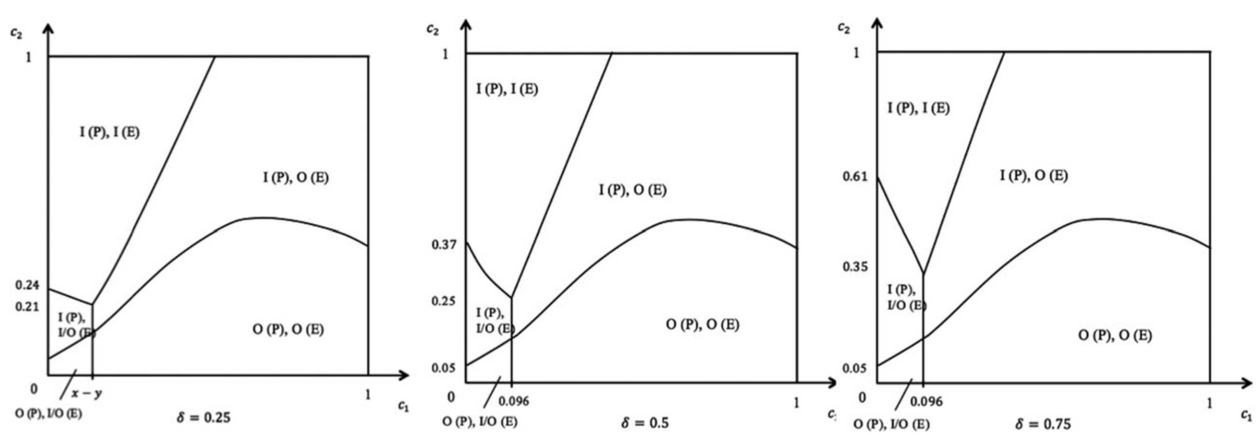


Figure 5 Retailer Profit and Environmental Impact When the Outsourcing Option has Shared Power ($0 < \delta < 1$), with $\beta = 0.0085$ (with $\alpha = 0.8$, $w_n = 0.2$, $S = 0.2$): Regions of Congruence and Conflict

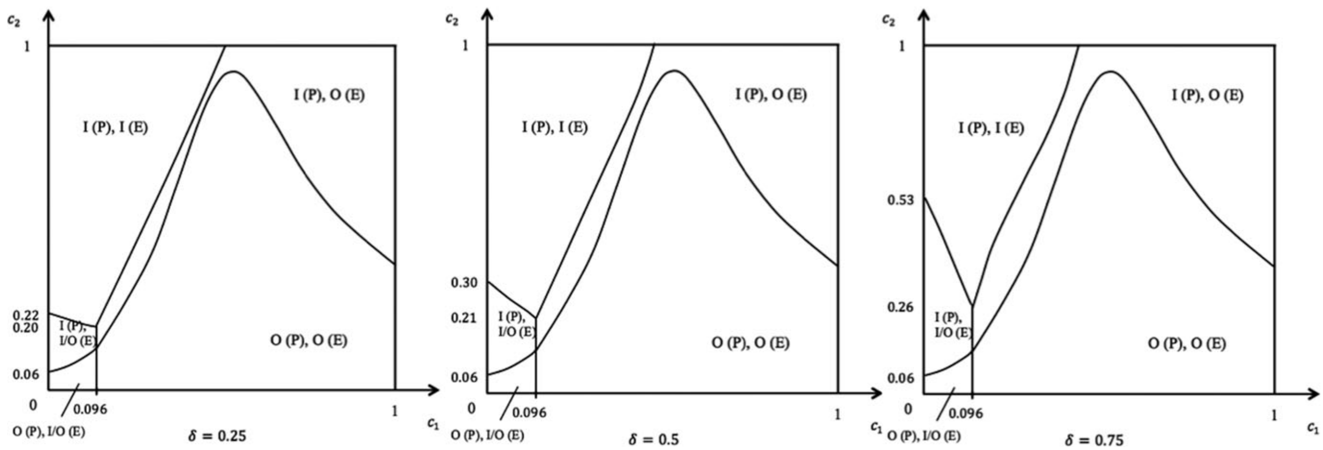
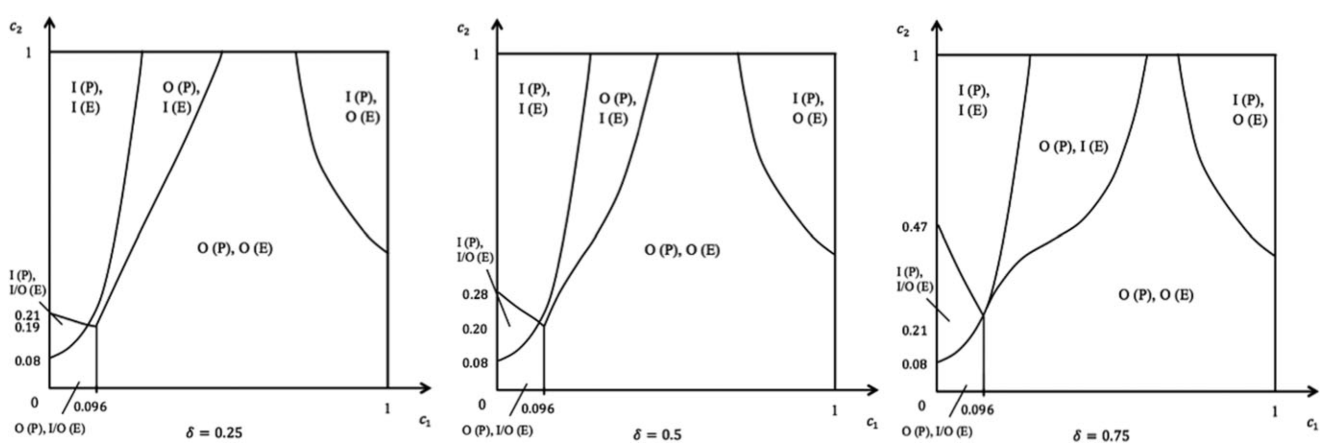


Figure 6 Retailer Profit and Environmental Impact When the Outsourcing Option has Shared Power ($0 < \delta < 1$), with $\beta = 0.01$ (with $\alpha = 0.8$, $w_n = 0.2$, $S = 0.2$): Regions of Congruence and Conflict



cost for In-house remanufacturing compels the retailer to adopt Outsourcing even though the In-house variable cost is relatively low.

For a fixed δ, increases in β reduce the conflict region ([$I(P)$, $O(E)$]) and expand the congruence region for Outsourcing ([$O(P)$, $O(E)$]).

A message emerging from our extensive analysis is that there are always parameter combinations for which both profitability and environmental goals are in conflict, which might not be surprising. Our contribution is to show that these regions are smaller (making profitability and environmental goals more likely to align organically) when: (a) the third party has less bargaining power; or (b) the fixed cost for In-house remanufacturing is relatively high.

5. Impact of Remanufactured Product Quality and Salvage Value

This section explores two extensions to our modeling framework. The first posits that the remanufactured product is strictly inferior to the new product in functional quality, i.e., $q_r < q_n = 1$. The second introduces the prospect of "salvaging" the collected used items that are not sent into remanufacture. We study each extension separately, rather than incorporating both into the same model.

5.1. Impact of Remanufactured Product Quality

Thus far we have assumed that remanufacturing will make any used item "good-as-new" (i.e., $q_r = q_n = 1$) We now relax this assumption to $q_r < q_n$, indicating perhaps that restoring that level of quality would require a cost-prohibitive complete rebuild. Now the collected used products have quality θ that is random with finite support in the range $[0, q_r]$. The cumulative distribution function of θ is $F(\theta)$, with $F(0) = 0$ and $F(q_r) = 1$. The consumer surpluses of buying new product and remanufactured product become, respectively, the following:

$$u_n = \gamma - p_n,$$
$$u_r = \alpha q_r \gamma - p_r.$$

Folllowing the development of the original model, the consumer surpluses give rise to the following demands for new and remanufactured product, respectively:

$$D_n = 1 - \frac{p_n - p_r}{1 - \alpha q_r},$$

$$D_r = \frac{\alpha q_r p_n - p_r}{\alpha q_r(1 - \alpha q_r)}.$$

Strategy i has a per-unit cost of $c_i(q_r - \theta)$ to restore an item of quality level θ to q_r. The total expected remanufacturing cost is $S \int_{\theta=\tilde{\theta}_i}^{q_r} c_i(q_r - \theta) f(\theta) d\theta$. The approach of the original analysis provides closed forms for the optimum/equilibrium for In-house and (Retailer-led and Third party-led) Outsourcing strategies. Technical details and proofs appear in sections D.1 and D.2 of the Appendix S4.

Proposition 5. *The impact of q_r is as follows:*

(*a*) *Under In-house and Outsourcing strategies* (i = 1 *and* 2, *respectively*), *increases in relative quality for remanufactured products* (q_r) *leads to increases in: the retail price* (p_{ri}) *and demand* (D_{ri}) *for the remanufactured product, and retailer profit* (π_i).
(*b*) *Under Third party-led Outsourcing, if the third-party's remanufacturing cost is sufficiently low* (*i.e.,* $c_2 \in (0, \alpha w_n - 4\alpha(1 - \alpha q_r)S]$), *the third-party's profit increases with* q_r; *otherwise* (*i.e.,* $c_2 \in (\alpha w_n - 4\alpha(1 - \alpha q_r)S, 1)$), *the third-party's profit will first increase and then decrease with* q_r.

For the remanufactured product, higher quality (q_r) commands a higher retail price due to the quality premium, while also taking some market share from the new product. The net effect on retailer profitability turns out to be positive regardless of whether the remanufacturing is done In-house or through Outsourcing. This creates an incentive for the retailer to improve the restorative capabilities of the remanufacturing process, which must be balanced against any required investment.

The comparative statics reported in section D.2 of the Appendix S4 indicate that under both strategies the quality threshold $\tilde{\theta}_i$ increases with q_r. This is because the total remanufacturing cost ($S \int_{\theta=\tilde{\theta}_i}^{q_r} c_i (q_r - \theta) f(\theta) d\theta$) increases with q_r, so whichever party is performing the remanufacturing will prefer to raise the threshold to qualify for remanufacture ($\tilde{\theta}_i$). For the In-house strategy, the revenue growth from the remanufactured product outweighs the increased remanufacturing cost. This is also true under Third party-led Outsourcing if the remanufacturing cost is sufficiently low (i.e., $c_2 \in (0, \alpha w_n - 4\alpha(1 - \alpha q_r)S]$). However, for higher values of c_2, (i.e., $c_2 \in (\alpha w_n - 4\alpha(1 - \alpha q_r)S, 1)$), the third-party's profit first increases with q_r then decreases. So preferences of the third party reflect a tension between the increase in the total remanufacturing cost and the benefit of a higher wholesale price. When q_r increases from a sufficiently small base value, the benefit due to increasing the wholesale price will dominate, making the third party favor a larger q_r. This effect reverses when q_r becomes sufficiently large.

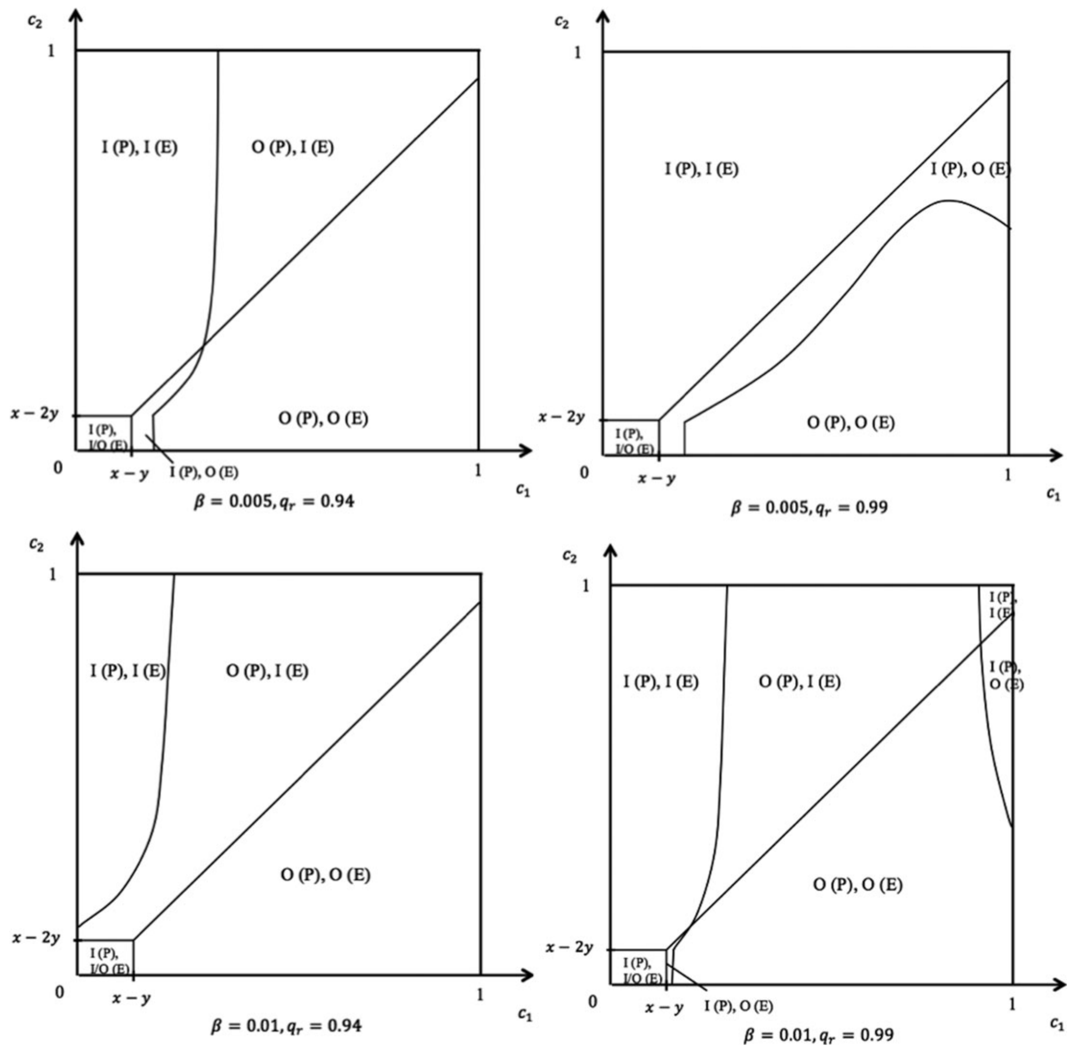
The preceding analysis reveals a conflict between the retailer and the third party regarding the relative quality for remanufactured products, at least for sufficiently high c_2. While the retailer prefers to aim for "good-as-new," the third party would use a looser standard. In this way the outsourcing strategy affects the end customer's experience of the product not only through the price but also the functional performance.

To examine how q_r affects the alignment or conflict between retailer profit and environmental impact, we compare the In-house strategy with both Retailer-led Outsourcing ($\delta = 0$) and Third party-led Outsourcing ($\delta = 1$). When $\delta = 0$ the impact of q_r is minimal because the indifference curve mainly depends on the fixed cost, which is independent of q_r. The comparison between In-house and Third party-led Outsourcing is more complicated. The trend from the left to the right panels in Figure 7 show the impact of increasing q_r while β is held fixed: an expansion of the region where In-house is more profitable. This occurs because the retailer can extract more value from the higher remanufactured product quality when performing the remanufacturing itself than when outsourcing to a third party. In doing so, however, the retailer is choosing the strategy that becomes less often favorable for the environment as q_r grows.

5.2. Impact of Salvage Value

This section assumes a non-zero per-unit "salvage" value of g for the portion of S that is not sent into remanufacture. As in standard inventory models, a positive g implies some alternative use or willing buyer while a negative g represents disposal at some expense. We first examine how this parameter shapes the optimal/equilibrium solutions then compare across the remanufacturing strategies. Technical details appear in sections D.3 and D.4 of the Appendix S4.

Figure 7 Retailer Profit and Environmental Impact When the Outsourcing Option is Third Party-Led (δ = 1) (with α = 0.8, w_n = 0.2, S = 0.2): Regions of Congruence and Conflict When Remanufactured Product is not "Good-as-New"



Proposition 6. *The impact of per-unit salvage value g is as follows:*

(*a*) *When $c_1 \in (0, x - y - g]$ for In-house; $c_2 \in (0, x - y - g]$ for Retailer-led Outsourcing; or $c_2 \in (0, x - 2y - g]$ for Third party-led Outsourcing, there is no impact of g on the optimal/equilibrium solutions.*

(*b*) *When $c_1 \in (x - y - g, 1)$ for In-house; $c_2 \in (x - y - g, 1)$ for Retailer-led Outsourcing; or $c_2 \in (x - 2y - g, 1)$ for Third party-led Outsourcing, a higher g leads to higher retail price (p_{ri}), higher demand for new product (D_{ni}), and lower demand for remanufactured product (D_{ri}). Under In-house and Retailer-led Outsourcing, the retailer's profit (π_i) increases with g. Under Third party-led Outsourcing, the retailer's profit decreases with g while the third-party's profit (π_{2o}) increases with g.*

Under low remanufacturing costs, both new and remanufactured products alike will be sold out, so there is nothing to salvage and g is irrelevant. Otherwise, any increases in g will dampen the incentive to remanufacture, which manifests in an increase in $\tilde{\theta}_i$. This reduces the demand for remanufactured product D_{ri} and, in turn, the retailer's revenue from the remanufactured product. Under In-house and Retailer-led Outsourcing strategies, the retailer is in control and can thereby jointly optimize the sales of new product and salvaging the un-remanufactured items to reflect the value of g. In contrast, under Third party-led Outsourcing the third party interferes by controlling the wholesale price w_{r2}. A higher g motivates the third party to raise w_{r2}, which hurts the retailer by elevating $\tilde{\theta}_2$. But unlike the In-house case, the retailer no longer receives the benefits of increased salvage value so will react by increasing the retail prices, which dampens demand and retail profit.

We first compare In-house and Retailer-led Outsourcing (i.e., $\delta = 0$) in Figure 8. This shows that a non-zero salvage value does not change the [*O(P), O(E)*] congruence region. Relative to the base-case of zero salvage value (center panels), an increase (decrease) in g decreases (increases) the [*I (P), I(E)*] congruence region with a corresponding increase (decrease) in the [*O(P), I(E)*] conflict region. This is because the demand for remanufactured product D_r declines more steeply under the In-house strategy than under Retailer-led Outsourcing. Consequently, the retailer's profit increases more quickly with g under Retailer-led Outsourcing strategy, as indicated by how the *O(P)* region increases with g.

Figure 9 makes an analogous comparison between In-house remanufacturing and Third party-led Outsourcing (i.e, $\delta = 1$). Relative to the base-case of zero salvage value (center panels), an increase (decrease) in g decreases (increases) the [*O(P), O(E)*] congruence region and increases (decreases) the [*I(P), O(E)*] conflict region while leaving the [*I(P), I(E)*] congruence region mostly unchanged. The driver of these properties is that the retailer's profit declines with g under Third party-led Outsourcing.

6. Implications and Conclusions

Must profit maximization harm the environment? This is a fundamental question in the sustainability movement. A firm's every decision, big or small, might change depending on the relative priority given to these ostensibly conflicting goals. We have investigated this question for what certainly qualifies as a big decision, that of designing a mechanism that institutionalizes and facilitates product reuse. Specifically, we have systematically compared In-house and Outsourcing options for remanufacturing, with both profit and environmental impact in mind. Although our original motivation was a retailer (GameStop) selling both new and remanufactured goods, our managerial insights will also be meaningful for the many other nodes in the supply chain (e.g., an OEM) that face analogous decisions.

We have analytically characterized the optimal/equilibrium values of the selling price of

Figure 8 Retailer Profit and Environmental Impact When the Outsourcing Option is Retailer-Led ($\delta = 0$) (with $\alpha = 0.8$, $w_n = 0.2$, $S = 0.2$): Regions of Congruence and Conflict as Salvage Value Varies

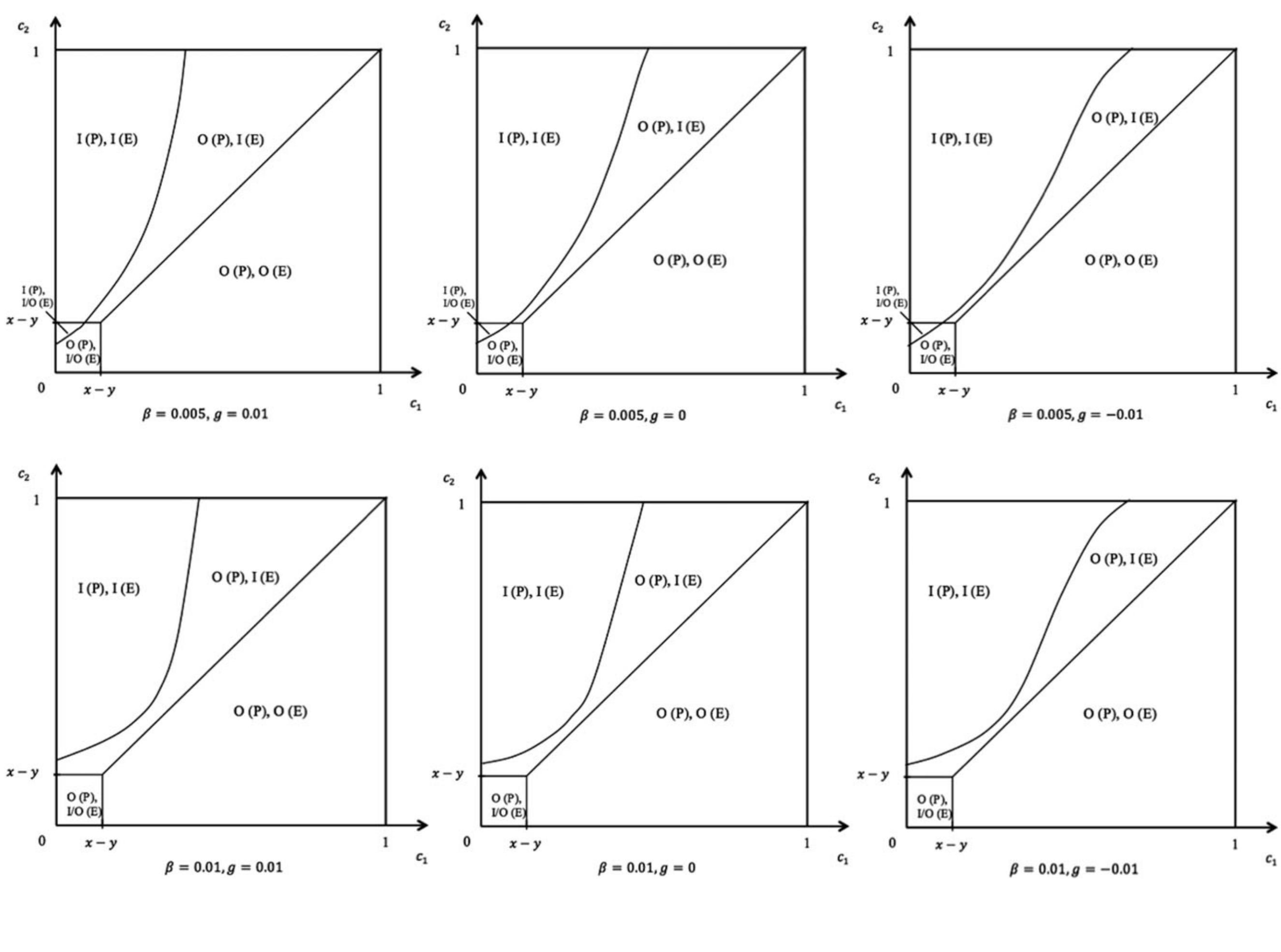
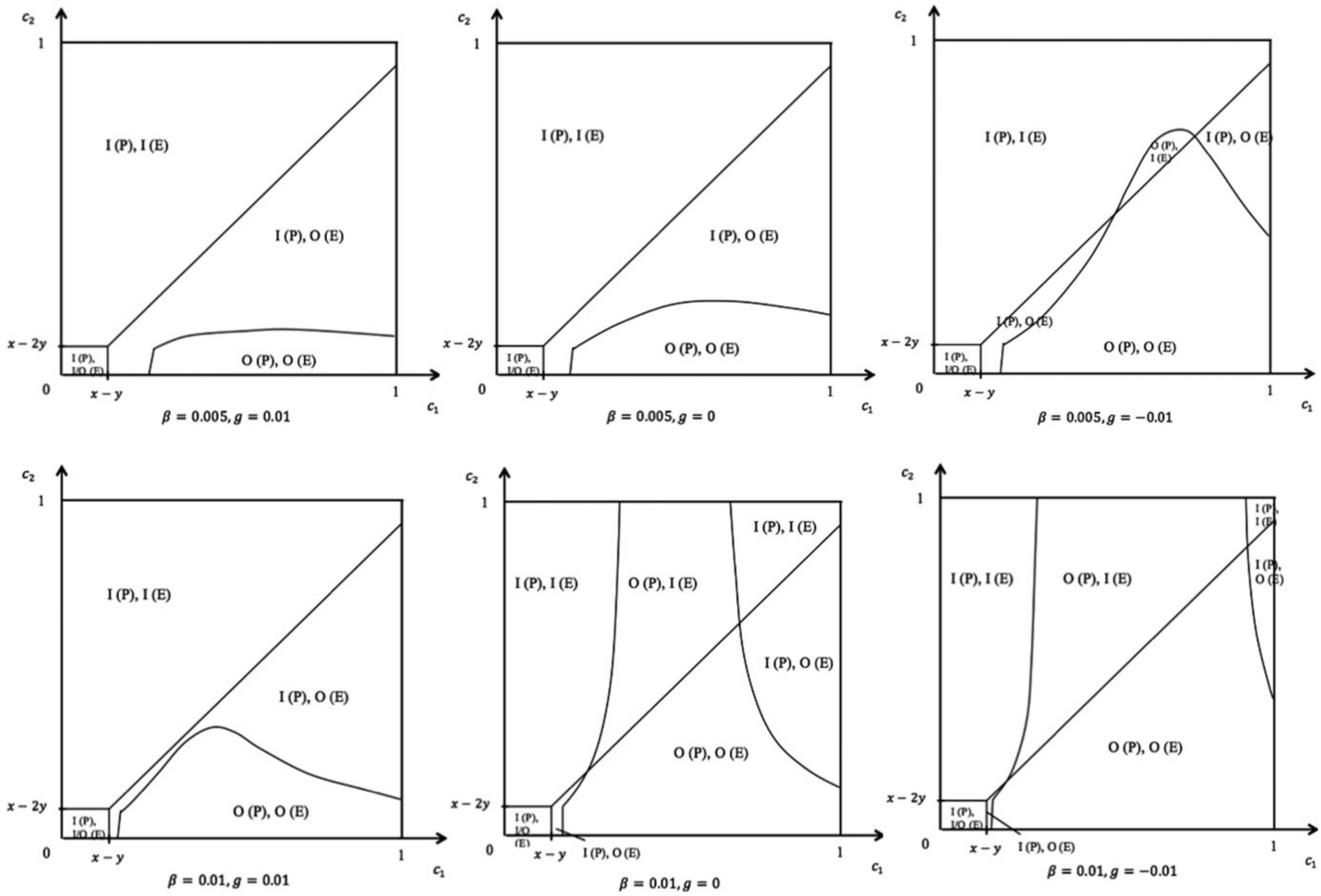


Figure 9 Retailer Profit and Environmental Impact When the Outsourcing Option is Third Party-Led ($\delta = 1$) (with $\alpha = 0.8$, $w_n = 0.2$, $S = 0.2$): Regions of Congruence and Conflict as Salvage Value Varies



remanufactured product, the quality threshold to qualify for remanufacturing, the retailer profit, and the market shares for new and remanufactured products under each strategy choice. We have done this within a feature-rich model formulation that includes diverse cost elements and a spectrum of scenarios for the allocation of decision power.

We have shown how the profitability of each strategy choice depends on the relative magnitude of variable remanufacturing costs, the fixed cost associated with the In-house strategy, and the power structure in the reverse channel. In-house remanufacturing is favored by some combination of the following conditions: low variable cost, low fixed cost, and powerful third party.

We have also characterized how the environmental impact of the two strategy options depends on the relative magnitude of variable remanufacturing costs and the balance of power in the reverse channel. All else being equal, the strategy with lower variable remanufacturing costs is better for the environment. Shifting power to the third party favors the choice of Outsourcing.

These findings validate intuition, but we go beyond that in quantifying the tradeoffs in this feature-rich setting. As one case in point, an accepted principle is that higher fixed costs of conducting an activity internally will favor Outsourcing, but this directional statement is generally made qualitatively and is rarely formalized in existing analytic models. Our model also confirms the In-house approach to be attractive due to the loss of control that results from Outsourcing. Without a sense of the magnitude of each impact, such as we provide, there is no way to prioritize these countervailing factors. Separately, this study may be unique in the analytic literature in addressing the question of how Outsourcing impacts the environment.

To help firms reconcile profitability and environmental goals, we identify regions of "conflict" where each strategy is better by one of the criteria and worse by the other. Conflicts are more likely when the third party has greater channel power or the In-house strategy has a small fixed-cost. Specifically we determined that a more powerful profit-minded retailer tends to prefer the less environment friendly remanufacturing strategy. This insight could offer guidance to policy-makers or industry organizations whose actions influence the amount of power held by individual firms.

When the remanufacturing process does not necessarily restore used product to "good-as-new" quality, the retailer performing in-house remanufacturing prefers a higher relative remanufactured product quality level, while in some scenarios the third party would prefer a lower level. In this way, the outsourcing strategy affects the end customers' experience of the product not only through the price but also the functional performance. When used product can be salvaged for a positive salvage value instead of being remanufactured, the retailer's profit increases with the salvage value under the In-house strategy or Retailer-led Outsourcing but decreases with this value with this value under Third party-led Outsourcing. Managerially, this points to the interaction between salvage values and channel power in terms of strategy choice. Higher salvage values are preferred in settings where the retailer is more powerful, while the retailer actually likes lower salvage values when the third party has greater channel power.

Future research can examine the mechanism by which the retailer acquires used items and how this interacts with the choice of remanufacturing strategy. For instance, the terms of GameStop's trade-in program impact both the quantity and quality of used game consoles that the retailer can obtain, which our analysis identified as key determinants of the relative performance of the In-house and Outsourcing approaches. Another open issue is the moderating role of product lifecycle, i.e., how Outsourcing and In-house remanufacturing compare as the product moves through the stages of launch, growth, maturity, and decline.

Acknowledgments

Asoo Vakharia gratefully acknowledges support from the Summer Research Grant Program of the Warrington College at the University of Florida. Gangshu (George) Cai gratefully acknowledges support from the National Natural Science Foundations of China through grant 71629001.

Notes

[1]This study uses the term remanufacturing to encompass all activities in the reverse channel, including testing, refurbishing, and/or recycling, as in Guide and Van Wassenhove (2009) and Souza (2013).

[2]http://www.cardone.com/about-us/environmental-commitment, accessed December 2013.

[3]http://www.baileysdiesel.com/on-highway/remanufacturing-is-green-manufacturing, accessed August 2013.

[4]http://www.star-telegram.com/2014/08/16/6047649/gamestops-roc-is-hub-for-multibillion.html, accessed October 2014.

[5]By focusing on a single firm rather than a competitive setting, we are able to focus on the key issue at hand, which is to provide insights into the strategic decision to either pursue in-house remanufacturing or outsource this activity.

[6]GameStop's VP of refurbishment has said, "We're looking at repairing it; getting it back to that original factory condition. Not upgrading it, not downgrading it, but getting it back to where it is...you're not just trying to get it working, you're not trying to sell it to a customer and in 30 or 60 days they have a bad experience with it, because they'll never come back to you again." (http://www.gamespot.com/articles/inside-gamestops-refurbishment-center/1100-6389498/, accessed February 2014).

[7]Section 5.1 relaxes this assumption by examining $q_r < q_n = 1$.

[8]If instead $p_r > \alpha p_n$ then $u_n > u_r$ for any consumer with $\gamma \geq p_n$, while both u_n and u_r are negative for any consumer with $\gamma \leq p_n$. That is, all consumers with $\gamma \geq p_n$ will buy new products while the remainder will buy nothing. Then remanufacturing will not be necessary at all, making irrelevant the decision of how to do it.

[9]This statement of the interval boundaries implies that a consumer who derives equal utility from either item will buy the new one. This is inconsequential when γ has a continuous distribution.

[10]This holds for several increasing failure rate (IFR) distributions, including normal, triangular, and uniform.

[11]In GameStop's Refurbishment Operations Center in Grapevine, Texas, "where 1200 employees work each week over two shifts to process, repair and repackage the old electronics equipment for new users," devices that need repairs "are sent to a bank of trained technicians, who will either make the repair or scrap the device and harvest its parts for recycling." (http://www.star-telegram.com/2014/08/16/6047649/gamestops-roc-is-hub-for-multibillion.html, accessed October 2014).

[12]Since γ (consumer willingness-to-pay for quality) is bounded above by 1, the market size is 1, and in order to ensure positive consumer utilities and firm profits, the product prices (p_n, p_r) and wholesale prices (w_n, w_r) also cannot exceed 1. So to prevent negative profit margins, it is necessary to assume $c_i \in (0, 1)$.

[13]The linearity does not impact our key findings. The only condition on β is that it must be bounded in a way that enables the firms to realize positive profits.

[14]The retailer will always earn more from selling both both types of product than from carrying just the new product.

[15]We can alternatively think of this as a sub-problem of the retailer's overall three-stage problem, with the first stage being the retailer's choice to keep the reverse channel In-house or use Outsourcing. Section 4 implicitly solves the retailer's master problem.

[16]http://www.alotechinc.com/product-remanufacturing/ and http://www.rematec.com/products-and-services/, accessed August 23, 2016.

[17]Appendix S2 tests sensitivity to this assumption.

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Supporting Information

Additional supporting information may be found online in the supporting information tab for this article:

Appendix S1: Analytical Proofs for Section 3.

Appendix S2: Comparison of Uniform versus Triangular Distributions for θ.

Appendix S3: Analytical Proofs of Proposition 1–4.

Appendix S4: Analytical Proofs for Section 5.