

Remanufacturing and the Component Commonality Decision

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Abstract

Firms often determine whether or not to make components common across products by focusing on the manufacturing and sales of new products only. However, component commonality decisions that ignore remanufacturing can adversely affect the profitability of the firm. In this paper, we analyze how remanufacturing could reverse the OEM's commonality decision that is based on the manufacturing and sales of new products only. Specifically, we determine the conditions under which the OEM's optimal decision on commonality may be reversed and illustrate how her profit can be significantly higher if remanufacturing is taken into account *ex ante*. We illustrate the implementation of our model for two products in the Apple iPadTM family.

Keywords: Component Commonality, Remanufacturing, Closed Loop Supply Chains

1 Introduction

Product line proliferation, where the variety of products offered increases (in order to sell to a broader customer base) but the sales volume of each product variant typically decreases (Swaminathan 2001), presents a major challenge for many firms today. Component commonality or standardization has been widely regarded as a mechanism for firms to mitigate the negative effects of product line proliferation. The benefits from making components common across different products include a reduction in unit production costs due to economies of scale, and savings in inventory carrying or shortage costs due to risk pooling. However, component commonality may also result in negative effects. For example, the production cost of a lower performance product may increase if a common component has to also meet the requirements of a higher performance product. Also, consumer perception of the high-end product may deteriorate if the high- and low-end products share common components. Thus, the typical decision as to whether a component should be made common or not involves considering both the cost and revenue-related effects, and evaluating if the decision results in an overall increase in the firm's profit (see Labro 2004 for a review of the costs and benefits of commonality identified in the related literature).

Indeed, in many ways the component commonality decision represents a classic supply chain problem for the Operations Management field. Thus, it is not surprising that it has been well studied (Swaminathan and Tayur 1999, Ramdas 2003). Missing, however, from the traditional component commonality strategy literature is any consideration of remanufacturing operations. Remanufacturing – a \$53 billion dollar industry in the US alone (Hauser and Lund 2003) – refers to the process of collecting, inspecting, disassembling, and refurbishing used products to their original or improved performance specifications. Examples of products that are commonly remanufactured include machine tools, consumer electronics, computers and peripherals, furniture, and tires. Some of these products are primarily remanufactured by their original manufacturers, but the majority are remanufactured by third parties.

Caterpillar is an often-cited example of an OEM that actively and profitably remanufactures its own products. In fact, Caterpillar has been shifting its strategy from solely manufacturing and selling construction equipment to one that has embraced remanufacturing (Gutowski et al. 2001). Building on this early success, Caterpillar established a remanufacturing division which had over \$2 billion in sales in 2007 and was the fastest growing among all of Caterpillar's divisions. Caterpillar also actively implements and promotes its use of component commonality. For example, Caterpillar's 2008 press release for the 785D Mining Truck states that "... improvements also focus on component commonality to keep parts stocking and maintenance simple..." (Caterpillar 2008). While the quote addresses the

benefits of component commonality to the customer, one can expect that Caterpillar itself benefits from managing and stocking fewer SKUs, both for its manufacturing and remanufacturing operations.

Given the prevalence of third-party remanufacturing (Hauser and Lund 2003), an interesting question is whether component commonality would also make it more economical for third parties to remanufacture the product. HP provides an interesting case in point. HP is well-known for its approach to managing product line proliferation, for which it was recently awarded the Edelman prize (Horner 2009). For example, HP advertises that its server designs use “the highest degree of component commonality in the industry” through its “universal design” approach. At the same time, HP adopts a contrasting strategy for its “business inkjet” printers (HP’s business inkjet printers are feature-rich and substantially more expensive than its other inkjet printers, making them attractive to third-party remanufacturers). HP uses different print heads (which, in turn, require different fixed ink cartridges) across different models. Since the print heads are fairly consistent in their functionality, customers are not likely to emphasize a specific print head as a differentiating factor in their purchase decision, relative to other printer features. Therefore, these print heads would appear to be prime candidates for commonality. However, making the print heads common will likely lower the costs of remanufacturing, leading third parties to be more competitive not only in the market for printers, but also in the market for replacement parts and supplies. Unlike printers, though, HP servers require special software to run, and the high relicensing fees charged by HP for this software limits the impact of third-party remanufacturers, regardless of HP’s commonality strategy. Thus, strategic considerations regarding remanufacturing competition and the different means available to HP for different products may explain HP’s divergent component commonality strategies.

This paper aims to uncover under what conditions and to what extent secondary market factors influence an OEM’s component commonality strategy. Our focus is OEM or third-party remanufacturing of end-products belonging to the same product line. Specifically, we aim to answer the following questions:

- i. *How does consideration of end-product remanufacturing affect the OEM’s component commonality decision? Under what circumstances would a decision that is based only on manufacturing considerations be reversed when remanufacturing is also taken into account?*
- ii. *If the OEM makes the component commonality decision without taking into account end-product remanufacturing, what is the economic significance of this omission? Under what circumstances is it most important to take remanufacturing considerations into account ex ante?*

To answer these questions, we analyze how the OEM’s optimal component commonality decision

is changed when the effects of end-product remanufacturing by either the OEM or a third party are included in the decision criteria. As is typical in the related literature, we do not model the firm's original product line design decision, but rather the decision as to whether to implement component commonality across an existing product line with given quality levels. We determine the conditions under which the OEM's optimal decision on commonality may be reversed and illustrate how her profit can be substantially higher if end-product remanufacturing is taken into account *ex ante*. We find that this profit impact is especially high if a third-party firm conducts the remanufacturing as opposed to the OEM.

The remainder of this paper is organized as follows. In Section 2, we position our work in relation to the extant literature. In Section 3, we introduce our model and its key assumptions. In Section 4, we derive the optimal results (prices and segment sizes) for the no remanufacturing, OEM remanufacturing, and third-party remanufacturing scenarios. In Section 5, we first numerically investigate the likelihood of commonality decision reversals and associated profit impacts if remanufacturing is taken into account, and contrast the same when the OEM does the remanufacturing versus when a third party does the remanufacturing. We then analytically derive conditions under which component commonality decisions could change with the consideration of remanufacturing. We discuss the implementation of our model for the example of iPadsTM in Section 6. Section 7 discusses extensions of our model and Section 8 concludes the paper. Proofs of all results are relegated to Appendix A and Tables pertaining to our numerical analysis are presented in Appendix B.

2 Relation to the Literature

In practice, managerial decisions are often made without consideration of the remanufacturing potential of the product. Possible reasons include: [i.] remanufacturing operations are often developed after-the-fact; [ii.] remanufacturing is not viewed as the firm's core business; and [iii.] the threat from third-party remanufacturers is not sufficiently appreciated. Thus, even at OEMs that do remanufacture, remanufacturing and remarketing operations are often handled separately from the manufacturing and marketing operations of new products, and are mostly managed as cost centers (Guide et al. 2006, Subramanian et al. 2010). The academic literature on closed-loop supply chains, however, demonstrates that firms that ignore remanufacturing operations in their decision making do so at their own detriment; the literature advocates an integrated approach to designing and managing forward and reverse supply chains: Fleischmann et al. (2001) address the question of designing the distribution network with considerations for collecting used products; Toktay et al. (2000) demonstrate the value of new component sourcing policies that take into account future product returns; Debo et al. (2005),

Ferguson and Toktay (2006), and Ferrer and Swaminathan (2006) argue that product pricing for new and remanufactured products should be undertaken jointly; Toktay and Wei (2010) develop cost allocation mechanisms to coordinate the production volumes of new and remanufactured products; Debo et al. (2006) address integrated capacity management under the joint diffusion of new and remanufactured products; and Savaşkan et al. (2004) and Atasu et al. (2010) analyze the manufacturer-retailer relationship under product collection. We contribute to this stream of literature by incorporating remanufacturing considerations into the classic component commonality decision, noting that the recent engineering-focused literature on design for remanufacturing also proposes component commonality and platform-based approaches to product design (King and Burgess 2005, Bras 2007). Furthermore, to the best of our knowledge, ours is the first work that discusses and contrasts the possible economic impacts of the omission of remanufacturing considerations in a product design decision when either the OEM or a third-party firm conducts the remanufacturing.

There is a rich body of literature that studies the trade-offs involved in commonality decisions in the context of new product manufacture and sales (see Ramdas 2003 and Labro 2004 for reviews of this literature). Seminal papers identifying the benefits of component commonality include Rutenberg (1969) that recognizes the economies of scale in production from using a common product module for multiple products, Baker et al. (1986) that recognizes the reduction in inventory costs due to the pooling effect under demand uncertainty, and Cooper (1994) and Pisano and Rossi (1994) that recognize the reduction in overall investments in production equipment. Lee and Billington (1994) discuss how higher component variety leads to higher forecast errors, excessive inventories for some parts and shortages for others, higher overhead and administrative costs, and higher manufacturing costs due to more specialized processes, materials, changeovers, and quality assurance methods. On the other hand, the literature also identifies the costs of component commonality to include the required over-design of components and demand cannibalization across differentiated products (Ulrich and Tung 1991, Moorthy and Png 1992, Robertson and Ulrich 1998, Kim and Chhajed 2000, Desai et al. 2001, Krishnan and Gupta 2001). However, the context of remanufacturing by either the OEM or a third-party firm has not been analytically studied in prior research. Also, while the above papers have addressed important dimensions of the component commonality decision, we integrate each of the key parameters into a single model and numerically test which ones have the most significant influence on the OEM's commonality decision and resulting profit. Thus, we contribute to this literature by developing an understanding of how remanufacturing would affect the commonality decision.

3 Model

In the base scenario, the OEM produces two vertically differentiated products that do not share any components. Similar to the established marketing literature, we assume that each consumer's valuation is a linear function of the product's quality q as perceived by the consumer (Mussa and Rosen 1978, Moorthy 1984, 1988). In particular, consumer type θ , where θ is uniformly distributed on $[0,1]$, obtains utility $\theta q - p$ from a product of quality q sold at price p . The high-end and low-end products are denoted by the subscripts h and l , respectively. As mentioned earlier, we do not model the original product quality choices but rather the OEM's decision of whether to implement component commonality in an existing product line. Thus, the original product qualities q_h and q_l are exogenous and satisfy $q_h > q_l$. The OEM determines the product prices p_h and p_l . While the product quality levels are exogenous, the resulting segment sizes, denoted by n_h and n_l , are endogenous and are determined by the OEM's pricing decisions. We normalize the market size to 1 without loss of generality. The unit costs to produce the two products are c_h and c_l , respectively.

Component Commonality:

If the products share common components, consumers may perceive a change in quality due to the similarity between the products, resulting in a lower willingness to pay for the high-end product and a higher willingness to pay for the low-end product (Kim and Chhajed 2000, Desai et al. 2001). To capture this phenomenon, we denote consumers' perceived qualities of the two products by $q'_h := q_h - \Delta$, and $q'_l := q_l + \Delta$, respectively, where $\Delta \geq 0$. Thus, consumer type θ has willingness to pay $\theta q'_h$ and $\theta q'_l$, respectively, for the high- and the low-end products that share common components.

Component commonality affects costs in two ways: an increase in the production cost of the low-end product (since the common components must at least meet the functionality required by the high-end product) and operational cost savings due to economies of scale or inventory risk pooling. For tractability of our strategic-level analysis, rather than explicitly modeling the latter operational effects, we propose to capture them in the unit production cost. In particular, we assume that the unit production costs of the two products with component commonality are $c'_h := c_h - s$ and $c'_l := \eta c_l - s$, where $s > 0$ and $\eta > 1$. While the total savings could potentially be convex in the number of units due to inventory risk pooling and economies of scale, the additive per-unit savings s allows us to capture a first-order approximation of these benefits while maintaining tractability. The multiplier increase in the per-unit cost of producing the lower quality product, η , reflects the fact that components often have to be oversized to implement commonality; $\eta > 1$ captures the increase in the cost of the low-end product since the common components must at least meet the functionality required by the

high-end product.

In practice, there may be a fixed cost associated with redesigning the products to allow the use of common components. However, this fixed cost does not influence market segmentation decisions and affects our results in the expected direction: commonality becomes less profitable as the fixed cost increases. Therefore, for exposition, we assume fixed costs to be zero and do not include them in our analysis.

Remanufacturing:

To clearly compare the commonality-related tradeoffs under OEM remanufacturing and under third-party remanufacturing, and to ensure tractability, we assume that either the OEM or a third party does the remanufacturing, but not both. This is observed in practice as well, because when the OEM remanufactures herself, she typically structures the sales process (using product leases or trade-in rebates) to ensure that the majority of the used products come back to her and not to a third party. Examples of industries where the OEM typically dominates the remanufactured product market include business and industrial equipment (e.g., commercial power tools, commercial copiers, and machine tools), cameras and photographic equipment, and home and garden products (e.g., vacuum cleaners); see, for example, Subramanian and Subramanyam (2010) and the remanufacturing industry profiles in Ferguson et al. (2010). On the other hand, when third-party firms are well established, the OEMs are typically hesitant to participate in the remanufactured product market either due to managerial and cost hurdles, or so as to not legitimize this market. Products that are observed to be mostly remanufactured by third parties include cellphones and personal digital assistants (PDAs), computers and networking equipment (e.g., routers and switches), and video game consoles (Subramanian and Subramanyam 2010).

We also assume that when either the OEM or the third party remanufactures, they use the high-end product for this purpose. This assumption is based on the observation from practice that remanufactured versions are typically offered for OEMs' higher-end products, since the lower willingness to pay for the remanufactured version of a product makes the low-end products less profitable to remanufacture. To capture possible constraints on collection and/or yields on collected product cores, we include a constraint on the size of remanufactured product segment, $n_r \leq \rho n_h$, where $\rho \in (0, 1]$. For simplicity, we analyze a base scenario where the third party's and the OEM's remanufacturing cost structures are the same; if the remanufacturing cost or access to product cores is less favorable for the third party, this would reduce the OEM's profit impact from a commonality decision that ignores remanufacturing.

Guide and Li (2010) and Subramanian and Subramanyam (2010) offer empirical evidence for the

lower valuation of remanufactured products by consumers. To model this, we assume that consumer type θ 's valuation per unit of quality for the remanufactured product is a fraction λ of its valuation for the high-end new product. Thus, $q_r := \lambda q_h$ (base scenario) and $q'_r := \lambda(q_h - \Delta)$ (with component commonality), with the valuation of the remanufactured product assumed to be located in-between the valuations of the high-end and low-end products (i.e., $q_l < q_r < q_h$, and $q'_l < q'_r < q'_h$, implying that we assume $\lambda > \frac{q_l + \Delta}{q_h - \Delta}$). The model can also be extended to include a fraction ξ of consumers who would not consider the remanufactured product at any price, but our qualitative results do not change with this generalization (please see Section 7 for a discussion). The unit cost to remanufacture is c_r for the base scenario and αc_r , on average, with component commonality ($\alpha < 1$). This captures the fact that sharing components across products should reduce the cost to remanufacture them because of reduced safety stocks, improved access to components, and a reduced effect of uncertainty in remanufacturing yields. In other words, a lower α reflects a setting for which such benefits are higher. For ease of reference, we summarize our notation in Table 1.

4 Analysis

Our objective is to understand how the OEM's choice of whether to implement component commonality or not is affected by secondary market considerations, namely remanufacturing by the OEM or by a third-party remanufacturer. Sections 4.1, 4.2, and 4.3, respectively, analyze the benchmark scenario with manufacturing only, the scenario with OEM remanufacturing, and the scenario with third-party remanufacturing. The optimal commonality decisions under these scenarios are contrasted in Section 5. To avoid end-of-horizon effects from affecting our insights, we develop a model of a representative period where both manufacturing and remanufacturing occur, as in Savaşkan et al. (2004).

4.1 Manufacturing Only (Forward Chain)

4.1.1 Forward Chain, No Commonality (“FN”):

This is the base scenario where the OEM only produces two vertically differentiated products. Recall that the product qualities (exogenous) are denoted by q_h and q_l and prices (decisions) are denoted by p_h and p_l . The net utilities that consumer type θ obtains from the high-end and low-end products are $u_h(\theta) = \theta q_h - p_h$ and $u_l(\theta) = \theta q_l - p_l$, respectively, from which the segment sizes n_h and n_l can be derived for given prices. Unit production costs are c_h and c_l . The OEM's profit is:

$$\Pi_M^{FN} = n_h(p_h - c_h) + n_l(p_l - c_l). \quad (1)$$

Symbol	Description
Subscripts	
h, l, r	<u>h</u> igh-end, <u>l</u> ow-end, <u>r</u> emanufactured product
M, T	<u>M</u> anufacturer (OEM), <u>T</u> hird-Party
Superscripts	Scenario
FN	Forward Chain (No Remanufacturing), No Commonality
FC	Forward Chain (No Remanufacturing), with Commonality
MN	OEM Remanufacturing, No Commonality
MC	OEM Remanufacturing, with Commonality
TN	Third-Party Remanufacturing, No Commonality
TC	Third-Party Remanufacturing, with Commonality
q_j	Perceived quality of product j with no commonality; $j \in \{h, l\}$
Δ	Effect of commonality on perceived product quality
$q'_h = q_h - \Delta$	Perceived quality of the high-end product under commonality
$q'_l = q_l + \Delta$	Perceived quality of the low-end product under commonality
$\lambda \in (0, 1)$	Valuation of the remanufactured product relative to the high-end product
$q_r = \lambda q_h$	Perceived quality of the remanufactured product with no commonality
$q'_r = \lambda q'_h$	Perceived quality of the remanufactured product under commonality
c_j	Unit production cost of product j ; $j \in \{h, l, r\}$
$s > 0$	Savings (on average) in unit production costs from commonality
$\eta > 1$	Effect of commonality on the base production cost of the low-end product
$c'_h = c_h - s$	Unit production cost of the high-end product under commonality
$c'_l = \eta c_l - s$	Unit production cost of the low-end product under commonality
$\alpha \in (0, 1)$	Effect of commonality (on average) on the unit remanufacturing cost
$c'_r = \alpha c_r$	Unit remanufacturing cost under commonality
$p_j(p'_j)$	Price of product j without (with) commonality; $j \in \{h, l, r\}$
$n_j(n'_j)$	Segment size for product j without (with) commonality; $j \in \{h, l, r\}$
$\rho \in (0, 1]$	Fraction of high-end product sales that can be remanufactured
$\xi \in (0, 1]$	Fraction of customers who would not consider the remanufactured product at any price (model extension)
Π_k^i	Profit of entity k under scenario i ; $k \in \{M, T\}$, $i \in \{FN, FC, MN, MC, TN, TC\}$
$\Pi_M^{FD} = \Pi_M^{FC} - \Pi_M^{FN}$	Benefit of commonality to the OEM under no remanufacturing
$\Pi_M^{MD} = \Pi_M^{MC} - \Pi_M^{MN}$	Benefit of commonality to the OEM under OEM remanufacturing
$\Pi_M^{TD} = \Pi_M^{TC} - \Pi_M^{TN}$	Benefit of commonality to the OEM under third-party remanufacturing
$[\cdot]_j^i$	Optimal/Equilibrium value of $[\cdot]$ for product j and scenario i ; $j \in \{h, l, r\}$, $i \in \{FN, FC, MN, MC, TN, TC\}$

Table 1: Notation

Proposition 1 *The optimal prices and segment sizes under no remanufacturing and no commonality*

are: $p_h^{FN} = \frac{1}{2}(q_h + c_h)$, $p_l^{FN} = \frac{1}{2}(q_l + c_l)$, and $n_h^{FN} = \frac{1}{2} \frac{(q_h - q_l) - (c_h - c_l)}{(q_h - q_l)}$, $n_l^{FN} = \frac{1}{2} \frac{(q_l c_h - q_h c_l)}{q_l(q_h - q_l)}$.

Note that all the propositions (and numerical analysis) are presented for parameter settings where the optimal/equilibrium segment sizes are positive ($n_h > 0$, $n_r > 0$ if applicable, and $n_l > 0$) and $n_r < \rho n_h$ holds such that the first-order conditions can be independently solved to obtain unconstrained

optimal (or equilibrium) solutions. We omit the associated explicit parameter conditions for brevity. We also analyze the case where $n_r = \rho n_h$ holds at optimality (or in equilibrium), and discuss the differences relative to the unconstrained case in Section 7.

4.1.2 Forward Chain, Commonality (“FC”):

Here, the OEM produces two vertically differentiated products that share common components. Recall that commonality results in changes in perceived qualities, captured as $q'_h = q_h - \Delta$ and $q'_l = q_l + \Delta$. Unit costs change to $c'_h = c_h - s$ and $c'_l = \eta c_l - s$, where $s > 0$ and $\eta > 1$. The OEM’s profit is:

$$\Pi_M^{FC} = n_h(p_h - c'_h) + n_l(p_l - c'_l). \quad (2)$$

Proposition 2 *The optimal prices and segment sizes under no remanufacturing and with commonality are: $p_h^{FC} = \frac{1}{2}(q'_h + c'_h)$, $p_l^{FC} = \frac{1}{2}(q'_l + c'_l)$, and $n_h^{FC} = \frac{1}{2} \frac{(q'_h - q'_l) - (c'_h - c'_l)}{(q_h - q_l)}$, $n_l^{FC} = \frac{1}{2} \frac{q'_l c'_h - q'_h c'_l}{q'_l (q'_h - q'_l)}$.*

4.2 OEM Remanufacturing

4.2.1 OEM Remanufacturing, No Commonality (“MN”)

In this scenario, the OEM produces two new products (high- and low-end) that do not share common components, and a remanufactured version of the high-end product. The perceived quality of the remanufactured product is $q_r := \lambda q_h$, where $q_h > q_r > q_l$. Prices (decisions) are p_h , p_r , and p_l , and the resulting segment sizes are n_h , n_r , and n_l . Net utilities from the products are $u_h(\theta) = \theta q_h - p_h$, $u_r(\theta) = \theta q_r - p_r$, and $u_l(\theta) = \theta q_l - p_l$. Unit production costs are c_h , c_r , and c_l . The OEM’s profit is:

$$\Pi_M^{MN} = n_h(p_h - c_h) + n_r(p_r - c_r) + n_l(p_l - c_l). \quad (3)$$

Proposition 3 *The optimal prices and segment sizes under OEM remanufacturing and no commonality are: $p_h^{MN} = \frac{1}{2}(q_h + c_h)$, $p_r^{MN} = \frac{1}{2}(q_r + c_r)$, $p_l^{MN} = \frac{1}{2}(q_l + c_l)$, and $n_h^{MN} = \frac{1}{2} \frac{(q_h - q_r) - (c_h - c_r)}{(q_h - q_r)}$, $n_r^{MN} = \frac{1}{2} \frac{q_r(c_h - c_l) - q_h(c_r - c_l) - q_l(c_h - c_r)}{(q_h - q_r)(q_r - q_l)}$, $n_l^{MN} = \frac{1}{2} \frac{q_l c_r - q_r c_l}{q_l (q_r - q_l)}$.*

4.2.2 OEM Remanufacturing, Commonality (“MC”)

Here, the OEM produces two new products that share common components, and a remanufactured version of the high-end product. Commonality results in changes in perceived qualities, $q'_h = q_h - \Delta$, $q'_r = \lambda q'_h$, and $q'_l = q_l + \Delta$. Unit costs change to $c'_h = c_h - s$, $c'_r := \alpha c_r$, and $c'_l = \eta c_l - s$, where $\alpha \in (0, 1)$ captures the reduction in remanufacturing costs from commonality (i.e., lower $\alpha \Rightarrow$ greater benefit of

commonality to the unit remanufacturing cost). The OEM's profit is:

$$\Pi_M^{MC} = n_h(p_h - c'_h) + n_r(p_r - c'_r) + n_l(p_l - c'_l). \quad (4)$$

Proposition 4 *The optimal prices and segment sizes under OEM remanufacturing and commonality are: $p_h^{MC} = \frac{1}{2}(q'_h + c'_h)$, $p_r^{MC} = \frac{1}{2}(q'_r + c'_r)$, $p_l^{MC} = \frac{1}{2}(q'_l + c'_l)$, and $n_h^{MC} = \frac{1}{2} \frac{(q'_h - q'_r) - (c'_h - c'_r)}{(q'_h - q'_r)}$, $n_r^{MC} = \frac{1}{2} \frac{q'_r(c'_h - c'_l) - q'_h(c'_r - c'_l) - q'_l(c'_h - c'_r)}{(q'_h - q'_r)(q'_r - q'_l)}$, $n_l^{MC} = \frac{1}{2} \frac{q'_l(c'_r - q'_r c'_l)}{q'_l(q'_r - q'_l)}$.*

4.3 Third-Party Remanufacturing

For this scenario, we assume that the OEM is the Stackelberg leader who chooses prices p_h and p_l for her new products. The third-party remanufacturer chooses price p_r for the remanufactured high-end product as a best response. We solve for the equilibrium prices and segment sizes by backward induction.

4.3.1 Third-Party Remanufacturing, No Commonality (“TN”)

The OEM's profit is:

$$\Pi_M^{TN} = n_h(p_h - c_h) + n_l(p_l - c_l). \quad (5)$$

And the third-party remanufacturer's profit is:

$$\Pi_T^{TN} = n_r(p_r - c_r). \quad (6)$$

Proposition 5 *The equilibrium prices and segment sizes under third-party remanufacturing and no commonality are:*

$$\begin{aligned} p_h^{TN} &= \frac{1}{2} \frac{2q_r q_l q_h + q_l c_h q_h + 2q_l q_r c_r - 3q_r^2 q_l + 3q_r q_l c_h + q_l q_h^2 - q_r c_l q_h + q_r^2 c_l}{q_r^2 - 4q_r q_h + 2q_r q_l + q_l q_h}, \\ &\quad + \frac{1}{2} \frac{4q_r^2 q_h - 4q_r c_h q_h - 2q_r q_h c_r - 4q_r q_h^2}{q_r^2 - 4q_r q_h + 2q_r q_l + q_l q_h}, \\ p_r^{TN} &= \frac{q_r (q_l q_h - q_r q_l + 2q_l c_r + q_l c_h - q_r c_h + q_r^2 - c_l q_h + q_r c_l - 2q_h c_r - q_r q_h)}{q_r^2 - 4q_r q_h + 2q_r q_l + q_l q_h}, \\ p_l^{TN} &= \frac{1}{2} \frac{q_l^2 q_h - 4q_r c_l q_h - q_r q_l q_h + q_r^2 q_l - 2q_l q_h c_r - q_r q_l c_h + 3q_r c_l q_l + 2q_l^2 c_r + q_r^2 c_l + q_l^2 c_h - q_l^2 q_r}{q_r^2 - 4q_r q_h + 2q_r q_l + q_l q_h}, \text{ and} \\ n_h^{TN} &= \frac{1}{2} \frac{2q_r q_l q_h - q_r q_l c_h - q_l c_h q_h - q_r c_l q_h + 2q_l q_r c_r + 4q_r c_h q_h - 2q_r q_h c_r + q_l q_h^2 - 3q_r^2 q_l + q_r^2 c_l}{(q_r^2 - 4q_r q_h + 2q_r q_l + q_l q_h)(q_h - q_r)}, \\ &\quad + \frac{1}{2} \frac{4q_r^2 q_h - 4q_r q_h^2 - 2q_r^2 c_h}{(q_r^2 - 4q_r q_h + 2q_r q_l + q_l q_h)(q_h - q_r)}, \\ n_r^{TN} &= \frac{q_h q_l^2 c_r - q_r c_l q_h^2 - q_l q_h^2 c_r + 2q_r q_h^2 c_r - q_r q_l^2 q_h - q_r q_l^2 c_h + q_r^2 q_l c_h - q_r^2 q_l c_l + q_l q_r q_h^2 - q_r^3 q_l}{(q_r^2 - 4q_r q_h + 2q_r q_l + q_l q_h)(q_h - q_r)(q_r - q_l)} \\ &\quad + \frac{q_r^2 q_l^2 + q_r^3 q_h - q_r^2 q_h^2 - 2q_r q_l q_h c_r + q_r q_l c_l q_h + q_l q_r c_h q_h + q_l q_r^2 c_r + q_r^2 c_l q_h - q_r^2 c_h q_h - q_r^2 q_h c_r}{(q_r^2 - 4q_r q_h + 2q_r q_l + q_l q_h)(q_h - q_r)(q_r - q_l)}, \end{aligned}$$

$$n_i^{TN} = \frac{1}{2} \frac{q_r (q_l^2 q_h - q_l^2 q_r + 2 q_l^2 c_r + q_l^2 c_h - q_r q_l c_h - 2 q_l c_l q_h - q_r c_l q_l)}{(q_r^2 - 4 q_r q_h + 2 q_r q_l + q_l q_h) (q_r - q_l) q_l} + \frac{1}{2} \frac{q_r (q_r^2 q_l - 2 q_l q_h c_r - q_r q_l q_h + 4 q_r c_l q_h - q_r^2 c_l)}{(q_r^2 - 4 q_r q_h + 2 q_r q_l + q_l q_h) (q_r - q_l) q_l}.$$

4.3.2 Third-Party Remanufacturing, Commonality (“TC”)

As in Section 4.2.2, commonality results in changes in perceived qualities, $q'_h = q_h - \Delta$, $q'_r = \lambda q'_h$, and $q'_l = q_l + \Delta$. Unit costs change to $c'_h = c_h - s$, $c'_r = \alpha c_r$, and $c'_l = \eta c_l - s$. Under commonality and third-party remanufacturing, the OEM’s profit is:

$$\Pi_M^{TC} = n_h(p_h - c'_h) + n_l(p_l - c'_l). \quad (7)$$

The third-party remanufacturer’s profit is:

$$\Pi_T^{TC} = n_r(p_r - c'_r). \quad (8)$$

Proposition 6 *The optimal prices and segment sizes under third-party remanufacturing and commonality are:*

$$\begin{aligned} p_h^{TC} &= \frac{1}{2} \frac{2 q'_r q'_l q'_h + q'_l c'_h q'_h + 2 q'_l q'_r c'_r - 3 q_r'^2 q'_l + 3 q'_r q'_l c'_h + q'_l q_h'^2 - q'_r c'_l q'_h + q_r'^2 c'_l}{q_r'^2 - 4 q'_r q'_h + 2 q'_r q'_l + q'_l q'_h}, \\ &\quad + \frac{1}{2} \frac{4 q_r'^2 q'_h - 4 q'_r c'_h q'_h - 2 q'_r q'_h c'_r - 4 q'_r q_h'^2}{q_r'^2 - 4 q'_r q'_h + 2 q'_r q'_l + q'_l q'_h}, \\ p_r^{TC} &= \frac{q'_r (q'_l q'_h - q'_r q'_l + 2 q'_l c'_r + q'_l c'_h - q'_r c'_h + q_r'^2 - c'_l q'_h + q'_r c'_l - 2 q'_h c'_r - q'_r q'_h)}{q_r'^2 - 4 q'_r q'_h + 2 q'_r q'_l + q'_l q'_h}, \\ p_l^{TC} &= \frac{1}{2} \frac{q_l'^2 q'_h - 4 q'_r c'_l q'_h - q'_r q'_l q'_h + q_r'^2 q'_l - 2 q'_l q'_h c'_r - q'_r q'_l c'_h + 3 q'_r c'_l q'_l + 2 q_l'^2 c'_r + q_r'^2 c'_l + q_l'^2 c'_h - q_l'^2 q_r'}{q_r'^2 - 4 q'_r q'_h + 2 q'_r q'_l + q'_l q'_h}, \text{ and} \\ n_h^{TC} &= \frac{1}{2} \frac{2 q'_r q'_l q'_h - q'_r q'_l c'_h - q'_l c'_h q'_h - q'_r c'_l q'_h + 2 q'_l q'_r c'_r + 4 q'_r c'_h q'_h - 2 q'_r q'_h c'_r + q_l q_h'^2 - 3 q_r'^2 q'_l + q_r'^2 c'_l}{(q_r'^2 - 4 q'_r q'_h + 2 q'_r q'_l + q'_l q'_h) (q'_h - q'_r)} \\ &\quad + \frac{1}{2} \frac{4 q_r'^2 q'_h - 4 q'_r q_h'^2 - 2 q_r'^2 c'_h}{(q_r'^2 - 4 q'_r q'_h + 2 q'_r q'_l + q'_l q'_h) (q'_h - q'_r)}, \\ n_r^{TC} &= \frac{q'_h q_l'^2 c'_r - q'_r c'_l q_h'^2 - q'_l q_h'^2 c'_r + 2 q'_r q_h'^2 c'_r - q'_r q_l'^2 q'_h - q'_r q_l'^2 c'_h + q_r'^2 q'_l c'_h - q_r'^2 q'_l c'_l + q'_l q'_r q_h'^2 - q_r'^3 q'_l}{(q_r'^2 - 4 q'_r q'_h + 2 q'_r q'_l + q'_l q'_h) (q'_h - q'_r) (q'_r - q'_l)} \\ &\quad + \frac{q_r'^2 q_l'^2 + q_r'^3 q'_h - q_r'^2 q_h'^2 - 2 q'_r q_l q_h c'_r + q'_r q_l c_l q_h + q_l q'_r c_h q_h + q_l q_r'^2 c'_r + q_r'^2 c_l q_h - q_r'^2 c_h q_h - q_r'^2 q_h c'_r}{(q_r'^2 - 4 q'_r q'_h + 2 q'_r q'_l + q'_l q'_h) (q'_h - q'_r) (q'_r - q'_l)}, \\ n_l^{TC} &= \frac{1}{2} \frac{q'_r (q_l'^2 q'_h - q_l'^2 q'_r + 2 q_l'^2 c'_r + q_l'^2 c'_h - q'_r q_l c'_h - 2 q_l c_l q_h - q_r c_l q_l)}{(q_r'^2 - 4 q'_r q'_h + 2 q'_r q'_l + q'_l q'_h) (q'_r - q'_l) q'_l} \\ &\quad + \frac{1}{2} \frac{q'_r (q_r'^2 q'_l - 2 q'_l q_h c'_r - q'_r q_l q_h + 4 q'_r c'_l q_h - q_r'^2 c'_l)}{(q_r'^2 - 4 q'_r q'_h + 2 q'_r q'_l + q'_l q'_h) (q'_r - q'_l) q'_l}. \end{aligned}$$

5 Investigating Reversals in the Commonality Strategy

Define $\Pi_M^{FD} := \Pi_M^{FC} - \Pi_M^{FN}$ as the difference in the OEM's profit from commonality when there is no remanufacturing. When this value is positive, the OEM benefits from component commonality in the no remanufacturing scenario. Similarly, define $\Pi_M^{MD} := \Pi_M^{MC} - \Pi_M^{MN}$ as the OEM's profit increase from commonality when the OEM undertakes the remanufacturing of her high-end product. When this value is positive, the OEM benefits from component commonality in the OEM remanufacturing scenario. Finally, define $\Pi_M^{TD} := \Pi_M^{TC} - \Pi_M^{TN}$ as the increase in the OEM's profit from commonality when the remanufacturing of her high-end product is conducted by a third-party remanufacturer. When this quantity is positive, the OEM benefits from investing in commonality despite the fact that the secondary market is exploited by a third party.

We focus on the cases where the OEM's preferred commonality strategy differs with and without remanufacturing. In particular, identifying whether the signs of Π_M^{FD} and Π_M^{MD} are reversed helps us answer the following question: *Will the OEM's commonality strategy be different if she takes into account that she will engage in remanufacturing?* Similarly, we investigate sign reversals between Π_M^{FD} and Π_M^{TD} to answer the following question: *Will the OEM's commonality strategy be different if she takes into account that a third party will engage in remanufacturing?* For ease of exposition, we summarize the reversals of interest in Table 2.

Remanufacturing by	Reversal Type	OEM preference if Reman ignored	OEM preference if Reman considered
OEM	$\Pi_M^{FD} > 0$ but $\Pi_M^{MD} < 0$	<u>C</u> ommonality	<u>N</u> o <u>C</u> ommonality
	$\Pi_M^{FD} < 0$ but $\Pi_M^{MD} > 0$	No Commonality	Commonality
Third Party	$\Pi_M^{FD} > 0$ but $\Pi_M^{TD} < 0$	Commonality	No Commonality
	$\Pi_M^{FD} < 0$ but $\Pi_M^{TD} > 0$	No Commonality	Commonality

Table 2: Types of reversals in the commonality decision when remanufacturing is taken into account.

We measure the profit impact or opportunity cost of a commonality decision that is made without consideration of remanufacturing, as:

$$\frac{\text{Profit from decision that considers remanufacturing} - \text{Profit from decision that ignores remanufacturing}}{\text{Profit from decision that ignores remanufacturing}} \times 100$$

First, in §5.1, we present a detailed numerical study that illustrates the likelihood of commonality decision reversals and the magnitude of associated profit impacts. The numerical study also identifies the parameters that most significantly explain decision reversals and profit impacts. We then analytically characterize the effects of parameters that capture the cost effects of commonality – namely, α , s , and η – on these reversals in §5.2. We numerically illustrate the effect of the market-related parameter Δ because analytical results cannot be obtained for it. Where possible, we relate the findings to specific

types of products that are remanufactured in practice, drawing from Subramanian and Subramanyam’s (2010) data on remanufactured products purchased on eBay across different product categories that include Business and Industrial, Cameras and Photo, Cellphones and PDAs, Computers and Networking, Consumer Electronics, Home and Garden, Musical Instruments, and Video Games. Finally, we present the analysis of a specific product (iPadsTM) in Section 6.

5.1 Numerical Study

We illustrate the likelihood of commonality decision reversals and the magnitude of associated profit impacts through a broad numerical study. Table 3 summarizes the parameter ranges used in the numerical study. To examine a range of separation in qualities between the high- and low-end products, we set $q_l = 10$ and vary q_h between 15 and 40. To examine the cannibalization effect, we vary Δ such that at its highest value, Δ brings the low- and high-end products close enough yet preserves the ordering of perceived qualities. To consider a range of margins from the products, we vary c_j between $0.3q_j$ and $0.9q_j \forall j \in \{h, l, r\}$. With respect to the other parameters, we vary α between 0.5 and 0.9 so that commonality reduces the cost of remanufacturing by up to 50%; we vary λ between 0.5 and 0.9 (as observed in Subramanian and Subramanyam 2010) provided the ordering of perceived qualities is maintained; we vary η such that commonality increases the cost of the low-end product by 10% to a maximum of 90%; and, we vary s from $0.1c_l$ to a maximum of $0.5c_l$ so that the savings in unit production costs from commonality is up to half the cost of the low-end product.

Table 3: Parameter Values/Ranges for Numerical Study

Parameter	Min	Max
η	1.1	1.9
λ	0.5	0.9
q_l	10	10
q_h	15	40
Δ	0	$\frac{q_h - q_l}{3}$
c_l	$0.3q_l$	$0.9q_l$
c_r	$0.3q_r$	$0.9q_r$
c_h	$0.3q_h$	$0.9q_h$
α	0.5	0.9
s	$0.1c_l$	$0.5c_l$

We vary all parameters from their minimum to their maximum values in five equispaced increments in a full-factorial fashion and omit those parameter combinations that violate any one of the conditions $n_h, n_r, n_l, \rho n_h - n_r > 0$ at the solution of the first-order conditions. This yields a set of 5,939 parameter

combinations. Analyzing these instances with respect to the prevalence of different types of reversals and their profit impacts, we develop the following managerial guidelines:

1. It is much more important to take remanufacturing into account when it is a third party that remanufactures: The component commonality decision changed in 34.7% of the numerical instances in our set with third-party remanufacturing, while this percentage was only 2% with OEM remanufacturing. Further, the median opportunity cost of ignoring remanufacturing was 18.20% with third-party remanufacturing but only 0.33% under OEM remanufacturing.

This is an intriguing finding in that the impact of component commonality is dramatically different between the two scenarios: If the OEM anticipates that she will be able to monopolize the remanufactured product market, then she can afford to ignore remanufacturing in determining the commonality decision. However, if she expects third parties to dominate, component commonality should be elevated to a more strategic level, and the effect of third-party remanufacturing should be taken into account at the outset. Products that are observed to be largely remanufactured by OEMs include business and industrial equipment (e.g., commercial power tools), cameras and photographic equipment, and home and garden products (e.g., vacuum cleaners), while products that are observed to be mostly remanufactured by third parties include cellphones and PDAs, computers and networking equipment (e.g., routers and switches), and video game consoles: Subramanian and Subramanyam (2010) find that more than 65% of the products in the former categories are remanufactured by OEMs, while more than 65% of the products in the latter categories are remanufactured by third parties. Thus, OEM attention for the design of the latter types of products should be focused on the eventuality of third-party remanufacturing at the outset.

2. If the OEM anticipates third-party remanufacturing, it is much more important to review an “Implement Commonality” decision than a “Do Not Implement Commonality Decision”: In our numerical set, 88% of all reversals (or, 30.5% of all parameter combinations) were of the $C \rightarrow NC$ type under third-party remanufacturing. While this dominance may not have been anticipated, it can be explained by considering who reaps the benefits of commonality (if any) at the remanufacturing stage: When it is a third party, commonality becomes less attractive to the OEM when remanufacturing is taken into account because some of the benefits accrue to the third party.

The larger implication of this result is that not investing in component commonality can be used as an entry deterrent strategy (see Ferguson and Toktay (2006) for other such strategies). Indeed, an examination of our numerical data reveals cases where the equilibrium size of the remanufactured product segment is 0 if the OEM does not choose commonality, but the segment is in fact served by the third party if the OEM chooses commonality. Our numerical analysis suggests that such preemption

(where it is optimal for the OEM to not choose commonality, which causes the third party to be forced out of the market) is facilitated if the savings in unit production costs s from commonality is relatively small but the benefit of commonality to the third party is high (i.e., α is low). The same effect is seen if Δ is low, which makes the low-end product of the OEM less competitive compared to the remanufactured product if commonality is chosen. In contrast, as the remanufactured product becomes more competitive (i.e., as the relative willingness to pay λ increases), the prospect of preemption by not choosing commonality diminishes.

3. The profit improvement obtained from optimally adopting commonality in the absence of third-party competition is dominated by the opportunity cost of this strategy being suboptimal should third-party remanufacturing emerge: In 71.85% of the instances in our numerical study where Commonality is the optimal strategy for the forward chain, if third-party remanufacturing emerges and Commonality ceases to be optimal, the profit loss from having chosen Commonality dominates the anticipated benefit of this strategy calculated under the assumption of no remanufacturing. While the average profit improvement for the forward chain from adopting commonality is 10.45%, the average opportunity cost of this decision ceasing to be optimal if third-party remanufacturing emerges is 24.62%.

The reason for this strong effect is the following: Commonality only has a cost-reduction benefit for the OEM when there is no third-party remanufacturing. In contrast, the benefit of commonality to the third party allows him to price the remanufactured product more aggressively, putting downward pressure on new product prices and/or helping the third party obtain greater market share. The negative competitive effects dominate the positive cost effect, resulting in a large opportunity cost for the OEM from having chosen commonality.

5.2 Comparative Statics for Third-Party Remanufacturing

Given their prevalence and significant profit impact, we further investigate the reversals under third-party remanufacturing using the regression approach employed in Global Sensitivity Analysis (Wagner 1995 and Souza et al. 2004). Global Sensitivity Analysis (GSA) involves running a regression of the metric of interest (i.e., dependent variable such as indicator of change in the commonality decision or profit impact in our context) on the model's parameters (i.e., independent variables) and examining the regression coefficients in order to assess the significance of various parameters in explaining the metric of interest. Our results are summarized in Table 4 below. Tables B1 – B4 in Appendix B present the regression coefficients and t-statistics for the four regressions.

An examination of Table 4 yields the following recommendations for OEMs facing third-party

Type of Decision Reversal	Parameters that explain Decision Reversal	Parameters that explain Profit Impact given Decision Reversal occurs
$C \rightarrow NC$	$\downarrow \alpha, \uparrow \eta, \downarrow s$	$\downarrow \alpha, \downarrow s, \uparrow \eta$
$NC \rightarrow C$	$\uparrow \Delta, \downarrow \eta \uparrow \alpha$	$\uparrow \Delta, \downarrow \eta, \uparrow s$

Table 4: Three most significant parameters (in decreasing order of t -statistic magnitude) that explain commonality decision reversals and profit impacts under third-party remanufacturing. A downward \downarrow (upward \uparrow) arrow in front of a parameter means that as that parameter decreases (increases), the metric of interest increases.

remanufacturing:

1. *It is important to review the “Implement Commonality” decision for products that promise larger savings from commonality to the third-party remanufacturer (α low) or whose production cost savings to the OEM from commonality are low (s low). The associated profit impacts of ignoring remanufacturing, too, are significantly influenced by these cost factors.*

This observation is further supported by Proposition 7, which indicates that if commonality is preferable under no remanufacturing, but is not preferable under third-party remanufacturing, this happens below a threshold value of α or s . The intuition is that as α decreases, the cost of remanufacturing decreases. Thus, under third-party remanufacturing, low values of α enhance third-party competition and, in turn, hurt the OEM. Also, as s decreases, the OEM faces the disadvantage of a lower reduction in the manufacturing cost from commonality.

Proposition 7 *All else being equal, the case where $\Pi_M^{FD} > 0$ but $\Pi_M^{TD} < 0$ ($C \rightarrow NC$ reversal) can exist: [i.] below a threshold value of α , or [ii.] below a threshold value of s . Further, [iii.] the manufacturing savings threshold $\bar{s}(\alpha)$ below which a $C \rightarrow NC$ reversal takes place decreases as α increases.*

Figure 1 illustrates this proposition and provides insight about interaction effects not captured by the GSA approach, namely, that $\bar{s}(\alpha)$ decreases in α . The rationale is the following: As α decreases, remanufacturing increasingly benefits from commonality. Since the third party becomes more competitive, the OEM chooses to not implement component commonality over a larger range of manufacturing savings s that accrue to herself.

Ferrer and Whybark (2003) discuss how product complexity may affect the economics of remanufacturing. The number of components across different product modules – including the *casing*, the *functional module*, *functional connectors*, and *structural connectors* – affect product complexity. Since remanufacturing is typically labor intensive, greater complexity and component diversity across a product line entail greater worker skills and training and, thus, higher costs of remanufacturing. Such

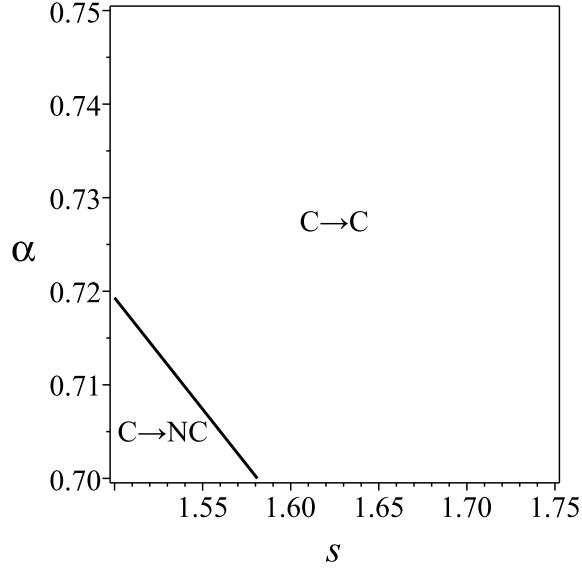


Figure 1: Parameter regions depicting $C \rightarrow NC$ reversals in the s - α space
(Parameter values: $q_h = 20$, $q_l = 10$, $\lambda = 0.7$, $\Delta = 1$, $c_h = 7$, $c_l = 3$, $c_r = 5$, $\eta = 1.2$)

products, in turn, afford greater savings in remanufacturing from commonality (i.e., low α). A similar level of savings from commonality may not be derived in new production (i.e., s is low) if flexible automation or delayed differentiation is employed.

2. *It is important to review the “Do not Implement Commonality” decision if, with commonality, the low-end product’s contribution margin and competitiveness vis-à-vis the remanufactured product are high, i.e., η is low and Δ (or, equivalently, q_l') is high.*

This is an interesting result that underlines the potential for commonality to provide a competitive advantage vis-à-vis the third party. The low-end product’s market position is elevated through commonality such that it cannibalizes the third party’s remanufactured product. If the production cost increase of the low-end product is low enough, a commonality strategy is beneficial to the OEM despite the remanufacturing cost advantage it confers on the third party. Proposition 8 provides support for this result with respect to η ; however, the effect of Δ can only be characterized numerically.

Proposition 8 *All else being equal, [i] the case where $\Pi_M^{FD} < 0$ but $\Pi_M^{TD} > 0$ ($NC \rightarrow C$ reversal) can exist below a threshold value of η . Further, [ii.] the threshold $\bar{\eta}(\alpha)$ below which an $NC \rightarrow C$ reversal takes place increases as α increases.*

Figure 2 illustrates the above results and highlights interaction effects with α . Under third-party remanufacturing, as α increases (giving a smaller cost advantage to the third party), commonality is preferable for the OEM for a larger range of increase in the low-end product’s cost, i.e., $\bar{\eta}(\alpha)$ increases

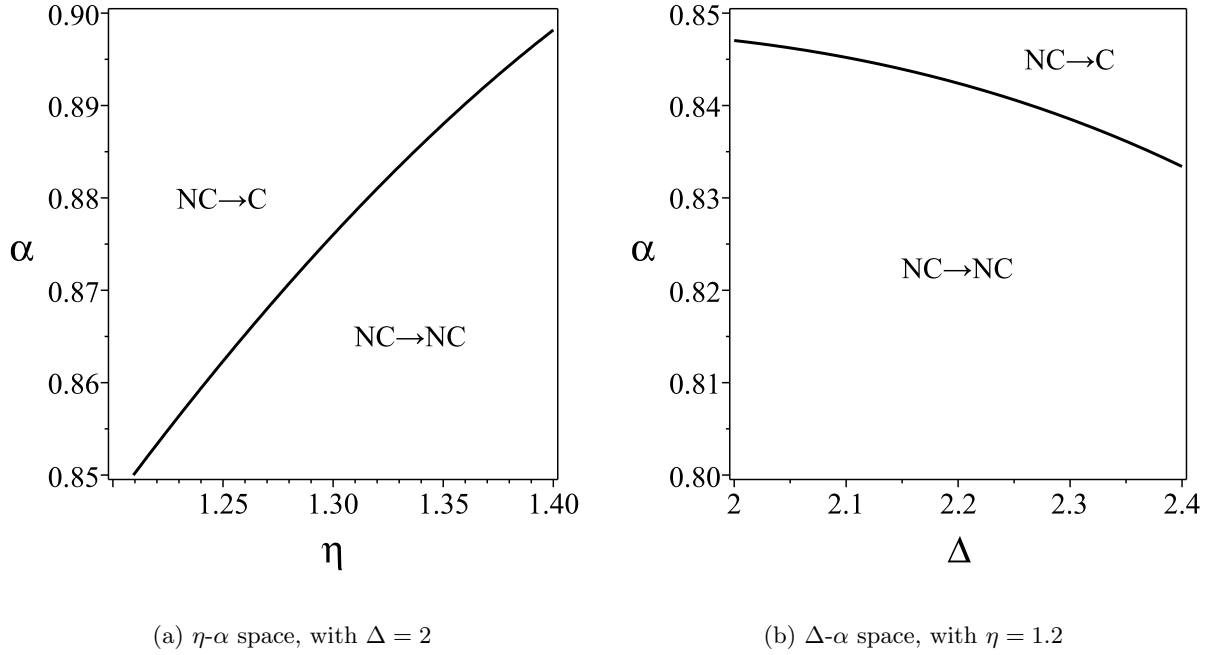


Figure 2: Parameter regions depicting $NC \rightarrow C$ reversals in the η - α and Δ - α spaces
(Parameter values: $q_h = 20$, $q_l = 10$, $\lambda = 0.8$, $c_h = 7$, $c_l = 3$, $c_r = 5$, $s = 1$)

in α . In other words, the OEM has a greater opportunity to use the low-end product to compete with the third party when the third party's gain from commonality is low. On the other hand, as α increases, the threshold for Δ above which the OEM would switch to a commonality strategy, decreases, i.e., $\bar{\Delta}(\alpha)$ decreases in α . This is because a higher degree of cannibalization of the remanufactured product by the low-end product and a higher remanufacturing cost are substitutes; they both reduce the threat from the third-party remanufacturer.

An example to the situation discussed here is any product family that uses common product casings. Product casings are typically the least expensive to make common (i.e., η low) yet may significantly impact perceived value (i.e., Δ high) because of immediate visibility. Common casings across low- and high-end products are employed in a wide variety of products, including computers and networking equipment, consumer electronics, cellphones and PDAs, and cameras. Numerous news articles and discussion forums show up in a simple Internet search with “same chassis” as the search phrase; the discussions evidence the potentially high cannibalization effect between the low- and high-end products (e.g., Tom's Hardware 2007); the corresponding cannibalization effect between the low- and remanufactured high-end products would be even more pronounced.

We add the interaction effects discussed above to update the findings summarized in Table 4.

Type of Decision Reversal	Parameters that explain Decision Reversal	Interaction Effects
$C \rightarrow NC$	$\downarrow \alpha, \uparrow \eta, \downarrow s$	$\bar{s}(\alpha) \downarrow$ in α
$NC \rightarrow C$	$\uparrow \Delta, \downarrow \eta \uparrow \alpha$	$\bar{\eta}(\alpha) \uparrow$ in α ; $\bar{\Delta}(\alpha) \downarrow$ in α

Table 5: Significant parameters that explain commonality decision reversals, and selected interaction effects.

6 Numerical Illustration: Example of iPads

In this section, we discuss the implementation of our model using the example of iPadsTM. We use iPads as an example because: [1.] iPads had a greater than 90% market share of the tablet market in 2010 (Business Insider 2011); [2.] cost estimates for different iPad models are available through product teardowns by market research firms such as iSuppli Corporation (Crothers 2010, see Table 6); [3.] the teardowns reveal a significant extent of commonality across the different iPad models; and [4.] iPads are sold to end customers only as complete units (i.e., parts are not available separately).

For our illustration, we consider the 16GB version of the iPad as the low-end product and the 64GB version as the high-end product. To validate the relevance of our research questions, we interviewed a practitioner familiar with the remanufacturing of Apple[®] products (Mr. Brian Gventer, former Director, ATC Logistics & Electronics). From these interviews, we learned that [1.] third-party remanufacturers face greater costs for parts than Apple does in manufacturing, in some cases up to 10 times as much (e.g., the LCD screen). Further, “the cost for getting at the parts [from product cores] is very low since a relatively unskilled temp can take the unit apart once shown how”. Thus, component commonality can significantly benefit third parties since their remanufacturing yields increase due to access to greater volumes across components; and [2.] certain steps of the remanufacturing process, such as diagnosing what it would take to fix the device and performing board-level work, are complex, requiring skilled technicians with a low throughput rate. Apart from the NAND flash memory difference, the 16GB and 64GB models are essentially identical. The high degree of component commonality can be expected to reduce the overall complexity of problem diagnosis across the product models. At the same time, the ability to salvage a greater number of usable parts (including entire boards) from product cores would decrease replacement parts costs and/or increase the remanufacturing process throughput.

Calibrating the Model to Known Parameters/Decisions

We assume that the prices of the 16GB and 64GB iPads at the time of product release (April 2010) correspond to the prices in our “manufacturing only” scenario or the forward chain (Section 4.1).

Components	16GB	64GB
Core Components		
Display and Touchscreen	\$80.00	\$80.00
Electromechanical and Mechanical	\$35.30	\$35.30
Battery	\$17.50	\$17.50
MPU and Memory		
A4 Processor	\$17.00	\$17.00
Supporting DRAM	\$11.90	\$11.90
WLAN n + BT + FM	\$8.05	\$8.05
User Interface Components	\$10.20	\$10.20
Other Power Management Components	\$2.40	\$2.40
Configuration-Dependent Components		
NAND Flash	\$29.50	\$118.00
Other Costs		
Box Contents	\$7.50	\$7.50
Totals		
Total Materials Cost	\$219.35	\$307.85
Total Manufacturing Cost	\$10.00	\$10.00
Grand Total	\$229.35	\$317.85
Retail Price	\$499.00	\$699.00

Table 6: iPad™ Bill of Materials, Cost Breakdown, and Retail Prices
Source: iSuppli Corporation (Crothers 2010)

Further, the product teardowns reveal that many components are shared across the 16GB and 64GB models, including the display and touchscreen; electromechanical and mechanical components; battery; processor and supporting DRAM (memory); wireless LAN, bluetooth, and FM circuitry; user interface components; and power management components (see Table 6). We therefore assume that the OEM (Apple) has made an optimal decision to choose Commonality for the forward chain. Thus, Proposition 2 is the relevant analytical result for calibration purposes.

iSuppli's total materials and manufacturing cost estimate for the 16GB model is \$229.35 and that for the 64GB model is \$317.85 (Crothers 2010). However, these cost estimates do not include potential savings from inventory pooling and economies of scale from having common components (i.e., the value of s in $c'_h = c_h - s$ and $c'_l = \eta c_l - s$ is not accounted for by iSuppli). Therefore, we set $c_h = 229.35$ and $\eta c_l = 317.85$. Due to the high level of commonality between the 16GB and 64GB models, we assume that $s = 50$, i.e. the benefit of inventory pooling and economies of scale is 20-25% of product cost. With regard to the cannibalization effect Δ , we observe that most comments in Apple's discussion forums cite the memory difference as being an important differentiating factor; in other words, that commonality

in the other components is not a significant reason to move away from the 64GB model. Therefore, we assume a moderate value of 50 for Δ (this works out post facto to a 4-7% effect of commonality on perceived qualities). The prices of the 16GB and 64GB models at product release were \$499 and \$699, respectively. If we assume that Apple priced the products optimally for the forward chain, we have $p_l^{FC} = 499$ and $p_h^{FC} = 699$. Using the expressions for p_l^{FC} and p_h^{FC} from Proposition 2 and solving for q_h and q_l yields $q_h = 1180.15$ and $q_l = 768.65$. While a broader numerical study could be carried out using different s and Δ values, for illustration purposes, we take these as given and use the resulting quality values in the analysis that follows.

Implications of Ignoring Third-Party Remanufacturing

With a third-party remanufacturer in the fray, our purpose is to compare the OEM's (Apple's) profit with commonality against that in the hypothetical situation where the OEM did not choose commonality in the first place. To fully specify our model, we need to provide base values for the parameters λ , c_r , η , and α , noting to the best of our experience that OEMs and third-party remanufacturers do not always track these parameters. From eBay data on purchases of iPads in late 2010, we found that the purchase prices of remanufactured iPads were 82-85% that of corresponding new iPads. We therefore set the base value of λ to be 0.85. As mentioned earlier, the costs of replacement parts can be quite high for third parties that remanufacture Apple's products. Consequently, we set the base value of c_r for the third party to be $0.85c_h$. Due to the high level of commonality between the 16GB and 64GB models, we assume the following base values: [i.] $\eta = 1.5$, i.e., a 50% increase in the cost of the low-end product when moving from the hypothetical No Commonality scenario to the observed Commonality scenario; and [ii.] $\alpha = 0.85$, i.e., a 15% reduction in the cost of remanufacturing attributable to commonality.

Using the specified parameter values and the derived q_h and q_l values, we obtain the equilibrium profits for the third-party remanufacturing scenario under Commonality and under No Commonality. We vary the parameters locally from their base values to understand under what circumstances and to what extent commonality would be suboptimal when third-party remanufacturers have access to used product cores and their common components. For ease of exposition, we change each parameter from its base value (by 5%) in the direction that benefits the third-party remanufacturer. The results are summarized in Table 7.

In all cases in Table 7, commonality is optimal in the manufacturing only scenario (i.e., $\gamma_F = \frac{\Pi_M^{FC} - \Pi_M^{FN}}{\Pi_M^{FN}}$ is always > 0). This is consistent with Apple's choice to adopt commonality. However, commonality ceases to be optimal when competition from a third-party remanufacturer is also considered

Parameter change (by 5%)	Profit improvement from commonality for manufacturing only $\gamma_F = \frac{\Pi_M^{FC} - \Pi_M^{FN}}{\Pi_M^{TC}} \times 100$	Profit impact of ignoring remanufacturing ($C \rightarrow NC$ reversal) $\gamma_R = \frac{\Pi_M^{TN} - \Pi_M^{TC}}{\Pi_M^{TC}} \times 100$
None (base values)	2.79%	6.88%
α ; from 0.85 to 0.8075	2.79%	20.65%
c_r ; from $0.85c_h$ to $0.8925c_h$	2.79%	8.24%
η ; from 1.5 to 1.575	2.29%	9.40%
λ ; from 0.85 to 0.8075	2.79%	9.74%

Table 7: Profit Impact of Ignoring Remanufacturing: Illustration Using the Example of iPads

(i.e., $\gamma_R = \frac{\Pi_M^{TN} - \Pi_M^{TC}}{\Pi_M^{TC}}$ is always > 0). Consistent with the third managerial insight presented in Section 5.1, we see that the profit improvement (γ_F) obtained from adopting commonality but without considering third-party remanufacturing, is dominated by the opportunity cost (γ_R) of this decision not being optimal should third-party remanufacturing emerge. This is a first-order effect that is present for all the parameters considered. As explained previously, the reason is that the negative competitive effects of the remanufacturing cost-reduction potential provided by component commonality dominate the positive manufacturing cost-reduction effect. In this example, the opportunity cost is most sensitive to α followed by λ and η . The high sensitivity to α and η was also documented in Table 4 that was based on a broad numerical set, while the high sensitivity to λ is specific to the iPad example (but note that here we do not change s).

In concluding this illustration, we would like to note some caveats. First, since many parameters had to be estimated, the actual numbers in Table 7 may change if more accurate data becomes available. Nevertheless, the first-order effects recorded in the γ_R column and the relative sensitivities to the different parameters are expected to hold. Second, since ours is a representative-period model, the profit impacts of ignoring remanufacturing estimated by our model may be regarded as an upper bound on the actual profit impact over the life cycle of the product because there would be a period of time when product returns would be sporadic (barring warranty or “grace-period” returns) and before enough cores become available for a third-party remanufacturer. However, component commonality could speed the third-party remanufacturer’s entry into the market because of greater volumes across components for remanufacturing. Third, the illustration assumed full access to cores by the third-party remanufacturer and no remanufacturing by Apple; the opportunity cost of ignoring remanufacturing

can be expected to be lower when these conditions are relaxed. Nevertheless, this example demonstrates how an OEM could combine our model with market intelligence to provide input into her commonality strategy in the face of potential remanufacturing competition.

7 Discussion of Model Extensions

We briefly discuss certain extensions to our main model. *First*, we examine the situation where *a portion of the market would never consider buying a remanufactured product*, a phenomenon discussed in Guide and Li (2010). By modeling a parameter $\xi \in (0, 1]$ such that a fraction ξ of the market would only consider new products while the remaining fraction $1 - \xi$ would consider remanufactured products as well, we obtain optimal (or equilibrium) segment sizes and prices in closed form and observe the following: [i] Under both OEM and third-party remanufacturing, the likelihood and profit impacts of commonality decision reversals decrease as ξ increases because of the shrinking remanufactured product segment; [ii.] Over the entire range of ξ values, the profit impact under third-party remanufacturing is substantially higher than that under OEM remanufacturing; and [iii.] Under third-party remanufacturing, as ξ increases, the OEM prefers commonality for a greater level of benefit to remanufacturing (e.g., lower α for the same s) or lower benefit to new production (e.g., lower s for the same α).

Second, to see how our results are affected *if the consumer type θ is non-uniformly distributed*, we use a distribution of the form $F(\theta) = 1 - (1 - \theta)^k$ as in Debo et al. (2005). With this specification, as k increases, the mass of customers shifts towards lower consumer types. We obtain optimal (or equilibrium) segment sizes and prices in closed form for the OEM remanufacturing scenario but have to resort to numerical insights for the third-party remanufacturing scenario due to intractability. We observe the following: [i.] As k increases, the OEM generally finds commonality more attractive. This is due to the complementary effects of commonality increasing the perceived quality of the low-end product and the larger k shifting the mass of customers towards the low-end product; [ii.] Over the entire range of k values, the profit impact of commonality decision reversals under third-party remanufacturing is substantially higher than that under OEM remanufacturing; [iii.] The profit impact of ignoring remanufacturing increases as k increases. This is because as k increases, the total number of products sold to the market decreases, resulting in a greater sensitivity of profit to a commonality decision that ignores remanufacturing.

Third, our main analysis focused on settings where at optimality (or in equilibrium), remanufactured product sales are not constrained by supply (i.e., $n_r < \rho n_h$ holds). The analysis of the case when *remanufacturing is constrained by supply* is similar except that at optimality (or in equilibrium), the prices are coupled via the supply constraint $n_r = \rho n_h$. In the OEM remanufacturing scenario,

we solve for p_r as a function of p_h and p_l using the equality $n_r = \rho n_h$. In the third-party remanufacturing scenario, the third party's best response under the supply constraint is to price so as to use all available supply, i.e., to choose p_r such that $n_r = \rho n_h$ given the OEM's choice of p_h and p_l . We obtain optimal (or equilibrium) segment sizes and prices in closed form. We find the following: [i.] The profit impact of ignoring remanufacturing decreases in ρ , but the observation of significantly higher profit impact under third-party remanufacturing still holds; [ii.] As long as it is optimal for the third party to remanufacture all available products, the level of α is not relevant to his pricing decision and does not come into play in the OEM-third party equilibrium; [iii.] As supply becomes more constrained (ρ decreases), the third-party remanufacturer becomes a weaker competitor and the OEM's profit increases; [iv.] At the same time, the OEM's benefit from a reduction in ρ is lower with commonality than without because of savings in the remanufacturing cost (i.e., α) that accrue to the third party from commonality. Thus, for a given s , η , or Δ , as ρ decreases, the profit increase to the OEM under no commonality is greater than the profit increase under commonality, leading to a $C \rightarrow NC$ type reversal below a threshold level of ρ .

8 Conclusion

Firms seek to add new products to their existing portfolios in order to meet diverse market niches, but product line expansions often increase operational costs. One of the methods commonly employed to keep the cost of product line expansion under control is redesigning existing products to utilize common components. While the benefits and trade-offs involved in the decision to incorporate common components have been well studied in the new product environment, little is known about how the optimal commonality decision is affected when there is a market for remanufactured versions of the firm's products.

In this paper, we extend the classic component commonality decision to consider end-product remanufacturing by either the OEM or a third-party firm. Our benchmark is an OEM that bases her commonality decision on the manufacturing and sales of new products alone. Our analysis determines the conditions – in terms of the savings in unit production costs from commonality, the effect of commonality on the production cost of the low-end product, the effect of commonality on perceived product quality, and the effect of commonality on the unit remanufacturing cost – under which the commonality decision may be reversed if remanufacturing is taken into account. Our analytical and numerical results provide guidance on the existence, prevalence, and profit impacts of different types of reversals of the commonality strategy, i.e., commonality in the no remanufacturing scenario to no commonality in the remanufacturing scenario, or vice-versa. We also identify the parameters that are

the most influential in driving reversals of the commonality decision.

Our analysis yields a number of interesting managerial insights pertaining to the research questions posed in the Introduction. First and foremost, it matters significantly as to who does the remanufacturing. In our numerical study, not only was the likelihood of a commonality decision reversal greater, but the median profit impact under third-party remanufacturing was 18.20% as compared to 0.33% under OEM remanufacturing. While this difference is less dramatic when the supply of remanufacturable products is limited, we can clearly conclude that an OEM should pay special attention to incorporating remanufacturing considerations in her commonality strategy if her products are remanufactured by third parties. Second, when third-party remanufacturing is prevalent, it is particularly important to review an “Implement Commonality” decision if it was made without consideration of remanufacturing: Since commonality benefits the third party at the remanufacturing stage, we observe the majority of commonality decision reversals to be from commonality to no commonality when third-party remanufacturing is taken into account.

Certain product types are more prone to commonality decision reversals and significant profit impacts when remanufacturing is taken into account: Under third-party remanufacturing, the decision to implement commonality is important to review for products that promise larger savings from commonality to the third-party remanufacturer or whose production cost savings to the OEM from commonality are low. In such a situation, the OEM has much to lose from handing a cost advantage to the third party and it is therefore desirable for her to not implement commonality. Conversely, the decision to not implement commonality is important to review if the low-end product’s cost does not increase significantly with commonality but its perceived quality (and, therefore, competitiveness vis-à-vis the remanufactured product) does.

The commonality decision could be used by the OEM as a tactic to deter a third party from remanufacturing. On the one hand, not implementing commonality could be a way for the OEM to discourage a third-party remanufacturer by limiting his potential competitiveness. On the other hand, implementing commonality may deter entry if the effect of commonality on perceived quality is large enough and/or the perceived quality of the remanufactured product is low enough that the OEM’s low-end product cannibalizes sales of the remanufactured product – more so if the savings from commonality are substantial in manufacturing, but not so in remanufacturing.

Finally, we apply our model to the example of Apple iPads to illustrate its potential applicability. We find that while it may be beneficial for Apple to adopt component commonality if third-party remanufacturing is ignored, the commonality strategy could cease to be optimal if third-party remanufacturing emerges, leading to significant opportunity costs.

A limitation of our work is that, for tractability, we abstracted from the costs of collecting end-of-life products and did not explicitly model uncertainties in the qualities and quantities of returning products. We expect that component commonality would be favored with increasing collection costs and uncertainties in returns. Further, for tractability and clarity, we did not analyze the situation where both the OEM and a third party are active in the remanufactured product market (e.g., Atasu et al. 2008). Based on our findings for the two separate scenarios, we anticipate that as the third party's share of the remanufactured product market increases, the opportunity costs of ignoring remanufacturing will increase. Additionally, we did not consider the possibility of a market for individual product modules. Intuitively, we expect that the likelihood and profit impacts of commonality decision reversals would increase as the market for individual modules becomes more sizeable. Finally, we did not consider potential intricacies related to pricing and demand. For example, Ovchinnikov (2011) provides some evidence that high-end customers may view pricing as a signal of product quality and may prefer to not switch from a new product to the remanufactured version if the price difference between them is too large. While the specific relationship of the relative willingness to pay for remanufactured and new products as a function of this price difference is currently an open research question, it will be worthwhile to revisit our modeling assumptions and analysis as further research in this area becomes available.

We conclude by noting that the importance of proactively considering remanufacturing holds true for several strategic decisions other than component commonality. An increasing number of firms conduct reverse supply chain activities in addition to those in the traditional forward supply chain. We therefore believe that it would be useful to extend other seminal operations and marketing models to account for the different cost and market effects of remanufacturing.

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Appendix A: Proofs

Proof of Proposition 1: Given the net utilities for the products, the segment sizes (when they are positive) are derived as follows: Let $\theta'' := \theta|_{u_h(\theta)=u_l(\theta)}$ and $\theta' := \theta|_{u_l(\theta)=0}$. Then, $n_h = 1 - \theta''$ and $n_l = \theta'' - \theta'$, or, $n_h = \frac{(q_h - p_h) - (q_l - p_l)}{q_h - q_l}$ and $n_l = \frac{q_l p_h - q_h p_l}{q_l (q_h - q_l)}$. Substituting these segment sizes into (1), we have:

$$\begin{aligned} \frac{\partial^2 \Pi_M^{FN}}{\partial p_h^2} &= -\frac{2}{q_h - q_l} < 0, \\ \frac{\partial^2 \Pi_M^{FN}}{\partial p_l^2} &= -\frac{2q_h}{q_l (q_h - q_l)} < 0, \end{aligned}$$

and the determinant of the Hessian matrix of Π_M^{FN} w.r.t. p_h and p_l is $\frac{4}{q_l (q_h - q_l)} > 0$, implying that Π_M^{FN} is jointly concave in prices p_h and p_l . Equating the first-order derivatives of Π_M^{FN} w.r.t. p_h and p_l to 0 and solving simultaneously, yields the result. ■

Proof of Proposition 2: Similar to the proof of Proposition 1. ■

Proof of Proposition 3: Given the net utilities for the products, the segment sizes (when they are positive) are derived as follows: Let $\tilde{\theta}''' := \theta|_{u_h(\theta)=u_r(\theta)}$, $\tilde{\theta}'' := \theta|_{u_r(\theta)=u_l(\theta)}$, and $\tilde{\theta}' := \theta|_{u_l(\theta)=0}$. Then, $n_h = 1 - \tilde{\theta}'''$, $n_r = \tilde{\theta}''' - \tilde{\theta}''$, and $n_l = \tilde{\theta}'' - \tilde{\theta}'$, or, $n_h = \frac{(q_h - p_h) - (q_r - p_r)}{q_h - q_r}$, $n_r = \frac{q_r (p_h - p_l) - q_h (p_r - p_l) - q_l (p_h - p_r)}{(q_h - q_r)(q_r - q_l)}$, and $n_l = \frac{q_l p_r - q_r p_l}{q_l (q_r - q_l)}$. Substituting the segment sizes into (3), we have:

$$\begin{aligned} \frac{\partial^2 \Pi_M^{MN}}{\partial p_h^2} &= -\frac{2}{q_h - q_r} < 0, \\ \frac{\partial^2 \Pi_M^{MN}}{\partial p_r^2} &= -\frac{2(q_h - q_l)}{(q_h - q_r)(q_r - q_l)} < 0, \text{ and} \end{aligned}$$

$$\frac{\partial^2 \Pi_M^{MN}}{\partial p_l^2} = -\frac{2q_r}{q_l(q_r - q_l)} < 0.$$

The determinant of the principal minor (2×2) of the Hessian matrix of Π_M^{MN} w.r.t. p_h , p_r , and p_l is $\frac{4\lambda}{(1-\lambda)q_l(q_r - q_l)} > 0$, while the determinant of the Hessian matrix itself (3×3) is $-\frac{8}{q_l(q_h - q_r)(q_r - q_l)} < 0$. The alternating signs imply that Π_M^{MN} is jointly concave in prices p_h , p_r , and p_l . Equating the first-order derivatives of Π_M^{MN} w.r.t. p_h , p_r , and p_l to 0 and solving simultaneously, yields the result. ■

Proof of Proposition 4: Similar to the proof of Proposition 3. ■

Proof of Proposition 5: We solve for the equilibrium values by backward induction. Given net utilities for the products, the segment sizes (when they are positive) are as derived in Proposition 3; i.e., $n_h = \frac{(q_h - p_h) - (q_r - p_r)}{q_h - q_r}$, $n_r = \frac{q_r(p_h - p_l) - q_h(p_r - p_l) - q_l(p_h - p_r)}{(q_h - q_r)(q_r - q_l)}$, and $n_l = \frac{q_l p_r - q_r p_l}{q_l(q_r - q_l)}$. Substituting for n_r in (6), we have:

$$\frac{\partial^2 \Pi_T^{TN}}{\partial p_r^2} = -\frac{2(q_h - q_l)}{(q_h - q_r)(q_r - q_l)} < 0,$$

implying that the third-party remanufacturer's profit is concave in price p_r . Equating the first-order derivative of Π_T^{TN} w.r.t. p_r to 0 gives us:

$$p_r^{TN}(p_h, p_l) = \frac{p_h(q_r - q_l) + c_r(q_h - q_l) + p_l(q_h - q_r)}{2(q_h - q_l)} \quad (\text{A1})$$

Also, we have:

$$\begin{aligned} \frac{\partial^2 \Pi_M^{TN}}{\partial p_h^2} &= -\frac{2}{q_h - q_r} < 0, \\ \frac{\partial^2 \Pi_M^{TN}}{\partial p_l^2} &= -\frac{2q_r}{q_l(q_r - q_l)} < 0, \end{aligned}$$

and the determinant of the Hessian matrix of Π_M^{TN} w.r.t. p_h and $p_l = \frac{4q_r}{q_l(q_h - q_r)(q_r - q_l)} > 0$. Thus, the OEM's profit Π_M^{TN} is jointly concave in prices p_h and p_l . Equating the first-order derivatives of Π_M^{TN} w.r.t. p_h and p_l , respectively, to 0 and solving simultaneously for p_h , p_r , and p_l using (A1), yields the result. ■

Proof of Proposition 6: Similar to the proof of Proposition 5. ■

Proof of Proposition 7:

- i. We know Π_M^{FD} is independent of α . Using the envelope theorem, we have

$$\frac{\partial \Pi_M^{TD}}{\partial \alpha} = \frac{1}{2} \frac{c_r [(1 - \lambda)q'_h(p_l^{TC} - c'_l) + (\lambda q'_h - q'_l)(p_h^{TC} - c'_h)]}{(1 - \lambda)q'_h(\lambda q'_h - q'_l)}.$$

Under our assumption that the ordering of the perceived qualities is maintained, we have $\lambda q'_h - q'_l > 0$. At optimality, the OEM would price above cost, therefore $p_l^{TC} - c'_l > 0$ and $p_h^{TC} - c'_h > 0$. Consequently, Π_M^{TD} increases in α . When Π_M^{FD} is positive and Π_M^{TD} crosses zero in the feasible range of the parameter space, the $C \rightarrow NC$ reversal occurs below this crossover point.

ii. Using the envelope theorem and the positivity of segment sizes, we have $\frac{\partial \Pi_M^{FD}}{\partial s} = n_h^{FC} + n_l^{FC} > 0 \neq \frac{\partial \Pi_M^{TD}}{\partial s} = n_h^{TC} + n_l^{TC} > 0$. Thus, these functions increase monotonically. Let s^{FD} be the solution, if any, to $\Pi_M^{FD}(s) = 0$, and s^{TD} be the solution, if any, to $\Pi_M^{TD}(s) = 0$. If $s^{FD} < s^{TD}$, the case $\Pi_M^{FD} > 0$ but $\Pi_M^{TD} < 0$, or $C \rightarrow NC$ reversals, occur on the segment (s^{FD}, s^{TD}) , i.e., below the threshold s^{TD} .

iii. Solving for s^{TD} using $\Pi_M^{TD}(s) = 0$, and taking the first derivative with respect to α , we obtain $\frac{\partial s^{TD}}{\partial \alpha} = -\frac{\lambda q_h c_r (1-\lambda) + c_r (\lambda q_h - q_l)}{\lambda (q_h - q_l)} < 0$.

■

Proof of Proposition 8:

i. Using the envelope theorem and the non-negativity of segment sizes, we have $\frac{\partial \Pi_M^{FD}}{\partial \eta} = -c_l n_l^{FC} < 0 \neq \frac{\partial \Pi_M^{TD}}{\partial \eta} = -c_l n_l^{TC} < 0$. Thus, these functions decrease monotonically. Let η^{FD} be the solution, if any, to $\Pi_M^{FD}(\eta) = 0$, and η^{TD} be the solution, if any, to $\Pi_M^{TD}(\eta) = 0$. If $\eta^{TD} < \eta^{FD}$, the case $\Pi_M^{FD} > 0$ but $\Pi_M^{TD} < 0$, or $C \rightarrow NC$ reversals, occur on the segment (η^{TD}, η^{FD}) , i.e., above the threshold η^{TD} .

ii. Solving for η^{TD} using $\Pi_M^{TD}(\eta) = 0$, and taking the first derivative with respect to α , we obtain $\frac{\partial \eta^{TD}}{\partial \alpha} = \frac{\lambda q_h c_r (1-\lambda) + c_r (\lambda q_h - q_l)}{\lambda q_h c_l (1-\lambda)} > 0$.

■

Appendix B: GSA Results for Third-Party Remanufacturing

Table B1: Parameters that explain Indicator of $C \rightarrow NC$ Reversals

	<i>Coefficient</i>	<i>Standard Error</i>	<i>t-Statistic</i>
Intercept	117.5776	7.1553	16.4323
η	41.0847	1.3512	30.4062
λ	28.9637	7.8067	3.7101
q_h	-0.4346	0.0999	-4.3492
Δ	-3.2474	0.2311	-14.0543
c_l	4.3045	0.5279	8.1541
c_r	1.0303	0.3882	2.6539
c_h	0.6645	0.2958	2.2467
α	-204.8514	5.0178	-40.8247
s	-20.8246	0.7008	-29.7168

Table B2: Parameters that explain Profit Impacts of $C \rightarrow NC$ Reversals

	<i>Coefficient</i>	<i>Standard Error</i>	<i>t-Statistic</i>
Intercept	162.7454	11.3047	14.3962
η	59.1946	2.6246	22.5541
λ	35.4172	12.7167	2.7851
q_h	-1.4977	0.1527	-9.8058
Δ	-1.8123	0.4531	-4.0002
c_l	7.7182	0.8807	8.7639
c_r	3.5904	0.6740	5.3270
c_h	0.7888	0.4933	1.5992
α	-284.8346	9.3317	-30.5235
s	-34.1948	1.4602	-23.4179

Table B3: Parameters that explain Indicator of $NC \rightarrow C$ Reversals

	<i>Coefficient</i>	<i>Standard Error</i>	<i>t-Statistic</i>
Intercept	-24.4995	6.8199	-3.5923
η	-12.4570	1.1209	-11.1134
λ	16.0163	7.6756	2.0866
q_h	-0.3809	0.0953	-3.9963
Δ	3.1937	0.1927	16.5757
c_l	-3.7632	0.5345	-7.0407
c_r	0.0174	0.4139	0.0420
c_h	0.5032	0.2977	1.6900
α	44.6797	4.6522	9.6040
s	5.4720	0.6257	8.7458

Table B4: Parameters that explain Profit Impacts of $NC \rightarrow C$ Reversals

	<i>Coefficient</i>	<i>Standard Error</i>	<i>t-Statistic</i>
Intercept	-499.4145	66.5704	-7.5020
η	-104.5896	7.8291	-13.3591
λ	370.1503	57.5510	6.4317
q_h	-7.7009	0.7654	-10.0612
Δ	24.2022	1.3955	17.3427
c_l	-28.9978	3.7594	-7.7133
c_r	-14.0434	3.0504	-4.6037
c_h	19.1346	2.5930	7.3794
α	497.1949	54.0905	9.1919
s	49.1705	4.0841	12.0394