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Proprietary Parts as a Secondary Market Strategy

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Abstract

Introducing proprietary parts to gain a competitive edge is a well-known, yet poorly understood strategy original equipment manufacturers (OEMs) adopt. In this paper, we consider an OEM which sells new products and competes with an independent remanufacturer (IR) selling remanufactured products. The OEM considers using proprietary parts to manage the secondary market for remanufactured products. Thereby, the OEM designs its product to balance the trade-off between the cost of proprietariness and the extra income from selling the proprietary parts to the IR. We observe that the OEM always chooses the smallest possible proportion of proprietary parts. This allows it to control the secondary market without the need to overly adjust the price charged for new products. Deterring market entry by the IR by pricing the proprietary parts prohibitively, an OEM strategy observed in several industries, is only optimal when the willingness-to-pay for remanufactured products is low. Otherwise, the OEM benefits more from sharing the secondary market profits with the IR through the use of proprietary parts. Finally, we find that the OEM can also use proprietary parts to strategically deter entry by the IR and discourage it from collecting the cores. This can support the OEM's decision to engage in remanufacturing even in the case of a collection cost disadvantage. We show that – counterintuitively – the OEM may take up remanufacturing in situations where the IR would not. While the introduction of proprietary parts is detrimental to both IRs and consumers, OEM remanufacturing softens this loss for the consumers.

Keywords: Proprietary parts, product remanufacturing, closed-loop supply chains.

1 Introduction

Remanufacturing is the process whereby used products are collected and brought back to their original cosmetic and functional conditions (Thierry et al. 1995). The remanufacturing business is worth billions of dollars worldwide and is relevant to a considerable number of industrial sectors (Hagerty and Glader 2011, Sundin and Dunbäck 2013, Stindt et al. 2017). Remanufacturing is carried out by either the original equipment manufacturer that also builds the new product (henceforth referred to as the OEM or 'he') or by independent remanufacturers (IR or 'she').

OEMs frequently see the existence of IRs as a menace, due to the widely accepted belief that remanufactured products are in direct competition with their new counterparts (Guide Jr. and Li 2010, Ferguson and Toktay 2006).

> "I think that they see us as another competitor, that customers who buy refurbished items, they will not buy new ones" (Independent remanufacturer A, on the relationships between OEMs and IRs).[1]

OEMs also believe that poorly remanufactured products can lead to brand damage (Guide Jr. et al. 2003), and see little benefit in collaborating with IRs.

> " [...] if a customer chooses non-AirFlight[2] parts, we will probably write to the customer and say that we cannot take responsibility for the quality [of the product]" (aerospace OEM engaged in B2B).

As a result, some OEMs, either deliberately or not, hinder the secondary market by increasing the prices of proprietary spare parts to a point where remanufacturing becomes economically infeasible. A part is said to be proprietary if the manufacturer holds the design rights, and therefore exerts greater control over the marketing and sales of spare parts, and consequently, inordinate power over the supply chain of remanufactured products. In some cases, OEMs refuse to supply parts to non-authorized repair shops or seek legal action against anyone modifying and repairing their products (Brandom 2015, Matchar 2016). Take Apple, for instance. In 2013, its flagship personal computer contained proprietary hard drives, cables and even unique pentalobe screws (McAllistair 2013). Such practices are not only applied in the electronics industry with its short life cycles but also in automotive manufacturing (Solon 2017) and the white goods industry as the following quote suggests:

[1]Unless otherwise stated, all quotes in this paper are from interviews and personal communications with the company representatives. Further evidence on the importance of the topic is presented in Appendix B.

[2]fictitious name

> "I would guess over 90% of frost-free [fridges] fail because of electronics. [...] New boards are simply too expensive as they have to be bought from the manufacturer. The fridges are still collected and are in demand because they look modern. Who on a low income wouldn't want one? The vast majority go for scrap recycling" (Independent remanufacturer B).

This quote also highlights two other aspects. First, it suggests that the use of proprietary parts affects society in general. It limits consumer choice and contributes to the escalating volume of products discarded every year, which could otherwise be diverted from the landfill to the secondary market. This problem is particularly acute for certain types of waste, such as electrical and electronic waste, which contains numerous substances that, if released to the environment, can seriously contaminate soil and water streams, e.g., lead, cadmium, and mercury (BBC 2002, European Comission 2018).

Second, it implies that the way proprietary parts are used may not be optimal from an OEM's point of view either. Specifically, it may actually reduce the profit accrued from the sale of spare parts. There is also the possibility that it may force remanufacturers to consider other strategies for sourcing spare parts.[3] To prevent the IR from doing so, the OEM makes such parts proprietary, which show a high failure rate.

In summary, introducing proprietary parts is a strategy OEMs can use to control the market of used products and generate revenue from the sale of spare parts. However, it is less obvious how it should be implemented. Thus, our first research question is:

- What is the OEM's optimal product design and market strategy when introducing proprietary parts?

Besides the question of which proportion of the product to make proprietary, the aforementioned research question also captures whether the OEM should use proprietary parts to preempt the secondary market or to extract extra profits from it.

Since the control over the secondary market through the use of proprietary parts comes at a price, our second research question is:

- Under what conditions does the introduction of proprietary parts pay off for the OEM?

[3] A commonly applied approach is to scavenge parts from used units. Note, however, that, because extra cores need to be collected and on some occasions purchased, and labor must be employed, scavenged parts are not free. Besides this, scavenging for parts creates additional complexities and even delays in the remanufacturing process, as remanufacturers might need to wait for similar products to the one being remanufactured to become available.

Clearly, without proprietary parts, the OEM accepts the potential entry of an IR and consequently the possible decrease in profits due to competition between the new and remanufactured products. The OEM also foregoes revenues accrued from the sale of spare parts. Yet, these aspects are traded off against the design and (re-)manufacturing cost of proprietary parts.

Using proprietary parts also generates a side-effect that may be used by the OEM. Large, multinational, OEMs often find it difficult to compete with local IRs in collecting cores. Even without the fear of demand cannibalization, this serves as a barrier to OEM remanufacturing. In such a context, the OEM can use proprietary parts to obtain exclusive access to the cores, by making the secondary market unprofitable for the IR. Having removed the collection barrier, the OEM may then find it optimal to engage in remanufacturing. This leads to our third research question:

- Under what conditions should the OEM prefer in-house remanufacturing over IR remanufacturing after introducing proprietary parts?

To answer our research questions, we use a stylized model combining the new product and proprietary parts pricing decisions of the OEM with the remanufactured product pricing decisions of the IR. We model the proprietariness decision of the OEM by considering the product design as well as (re-)manufacturing cost implications of introducing proprietary parts.

A first key insight of our analysis is that it is always optimal for the OEM to choose the smallest possible proportion of proprietary parts for his product. This keeps the cost of proprietariness down without compromising the control the OEM can exert over the secondary market. This result also reflects and explains the observations from practice, e.g., the use of pentalobe screws (arguably among the smallest and least expensive parts) by Apple.

A second key insight is that using proprietary parts to preempt the secondary market should only be the preferred option when consumers' willingness-to-pay for remanufactured products is low. Otherwise, sales revenues from proprietary parts will outweigh the profit reduction in the primary market due to demand cannibalization. This insight complements the existing literature, which argues that demand cannibalization of new by remanufactured products may be less of an issue for OEMs, by showing how extra value can be generated from the secondary market (Atasu et al. 2010, Guide Jr. and Li 2010).

Our third key insight is that, counter to the findings from the extant literature, the OEM may engage in remanufacturing in situations where the IR would not. Previous work has found that the IR, which does not have a stake in the primary market, faces lower hurdles when seeking to enter the secondary market than the OEM. The results of this paper suggest that, despite a collection cost disadvantage due to having less local involvement than the IR, the OEM can benefit from easier access to cores if it discourages the IR from collecting used products by pricing spare parts prohibitively.

The remainder of this paper is organized as follows. In Section 2 we place our work within and highlight our contributions to the existing literature. Section 3 captures our base model and analysis of the non-remanufacturing OEM, while Section 4 presents the extension focusing on OEM remanufacturing. Finally, Section 5 concludes our paper.

2 Literature review

Remanufacturing and closed-loop supply chain (CLSC) management have been extensively studied in the past decades. Comprehensive literature reviews can be found in Souza (2013) and Govindan et al. (2015). Atasu (2016) integrated the latest and most influential research in an edited book. Our study builds on two specific streams within the CLSC literature: first, market segmentation and competition between new and remanufactured products, and second, product design.

2.1 Market segmentation and competition in CLSCs

Market segmentation and competition have been recognized as essential strands of research on CLSCs. Majumder and Groenevelt (2001) and Ferrer and Swaminathan (2010) addressed the competition between an OEM and an IR and considered the volume of returns as, respectively, a fraction of the products sold (and therefore an exogenous variable) and as having a linear relationship with effort. Atasu et al. (2008) proposed an alternative approach to modeling competition, and contributed to prior research by incorporating green segments, incorporating OEM competition, and examining product life-cycle effects, while Örsdemir et al. (2014) considered the impact that quality has on the competition between the OEM and the IR. Heese et al. (2005) studied the case of an OEM both manufacturing and remanufacturing products (i.e., hospital beds) and competing with another OEM.

More recently, others have examined the competition in the primary market, and how it affects the collection strategy. Jena and Sarmah (2014) considered the case of two OEMs competing in both the primary and secondary markets. Wu and Zhou (2017) extended the work of Savaskan et al. (2004) by examining the effect of competition in the primary market (the market for new products) on product recovery decisions.

Some papers have explicitly addressed the strategies OEMs use to control the secondary market. For example, Ferguson and Toktay (2006) studied an OEM preemptively collecting cores without actually remanufacturing them. Oraiopoulos et al. (2012) studied relicensing of software in the IT sector as a means to benefit from the secondary market, as consumers buying refurbished hardware from an IR have to buy a license from the OEM in addition. Finally, Hong et al. (2017) considered competitive settings in which the IR had to buy the remanufacturing license from the OEM. They analyzed different types of licensing agreements between the OEM and IR.

Essentially, this stream of literature examines how OEMs compete with IRs and other OEMs and focuses mostly on pricing decisions. Moreover, it is usually assumed that technology and product design are exogenously given and do not change during the decision horizon. The last two papers, Oraiopoulos et al. (2012) and Hong et al. (2017), come closest to our setting in studying a mechanism through which the OEM can benefit from the secondary market. However, in both papers, it is assumed that the product design is fixed and the licensing does not incur any cost for the OEM. Moreover, in Oraiopoulos et al. (2012) the licensing interaction takes place between the OEM and the consumer directly, while in our model, like in Hong et al. (2017), the proprietary parts (license) have to be bought by the IR.

2.2 Product design

Product design has different dimensions, and several of them have been studied in the past in the context of CLSCs. A stream of literature focuses on demand-inducing product design and its interaction with used-product recovery. Atasu and Souza (2013) investigated how product reuse impacts product quality choice and found that recovery may lead to higher product quality. They also showed how the form of product recovery, recovery cost structure and product take-back legislation affects a firm's quality choice. Örsdemir et al. (2014) extended Atasu and Souza (2013) to the oligopoly setting and studied the competitive quality choice in the presence of remanufacturing. They found that, when an OEM competes with an IR, remanufacturing may reduce quality and increase environmental impact.

Another sub-field of research examines design choices affecting remanufacturability and cost of remanufacturing. Debo et al. (2005) studied the joint pricing and remanufacturability decision faced by a manufacturer introducing a remanufacturable product. If a firm can decide on product quality and remanufacturability levels, it will couple increased remanufacturing with higher product quality, as shown in Gu et al. (2015). Wu (2012) studied the design-for-disassembly problem in a supply chain formed by an OEM producing only new products and an IR. Using a two-period model, the author finds that the optimal level of disassemblability crucially depends on the recovery costs of the used products. When recovery costs are low, the OEM chooses low levels of disassemblability to discourage competition from the IR. These papers are related to our setting in that the introduction of proprietary parts by the OEM also affects the remanufacturing cost for the IR. However, in none of these papers does the design decision yield direct benefits for the OEM in the secondary market.

2.3 Summary of our work's contributions to this literature

Our paper builds on and contributes to these two streams of research within the CLSC field in two ways. First, by considering the use of proprietary parts which – unlike software licenses – impose a cost on the OEM both in their design and their embedding in new (and remanufactured) products, we model different market environments (e.g., white goods, cell phones, heavy machinery). We also contribute to the understanding of an OEM's optimal decision under the presence of such a costly action being required to control the secondary market. Both OEM and IR, in this case, adopt a coopetition strategy, where the IR is managed as both competitor and buyer. Second, we enrich the product design literature by introducing the optimal decision regarding the proportion of proprietary parts to include in a new product. This decision essentially complements our understanding of the mechanisms manipulating the remanufacturing cost. Unlike the papers focusing on remanufacturability or design-for-disassembly, we model a setting where the design choice, the proportion of proprietary parts, is used by the OEM in such a way that it benefits directly from IR remanufacturing.

3 The case of a non-remanufacturing OEM

To study the questions posed in the introduction we use a stylized model of an OEM offering new products only and an IR which may compete with the OEM by remanufacturing used products. The environment in which both competitors operate is described in Section 3.1. Then, we reconsider the pure price competition solution (as in, e.g., Ferguson and Toktay 2006) in Section 3.2. In Section 3.3, we show how the OEM competes with the IR when he also gets to choose the proprietary fraction of the new product, and compare this solution with the pure price competition case. Finally, in a numerical study put forth in Section 3.4, we quantify the economic impact of using proprietary parts for a broad set of possible scenarios.

3.1 Model description

Setting. Since our focus is on the competition between the OEM and the IR, we assume – in line with prior research – a monopolist OEM in the market for new products (Savaskan et al. 2004, Atasu et al. 2013, De Giovanni and Zaccour 2014). We assume a mature market and thus consider a single period in a steady-state setting, where a period corresponds to the usage period of the product (Agrawal et al. 2015). At the end of the period, a fraction γ of the new units sold at a per-unit price p_n becomes available for collection and subsequent remanufacturing, as in Esenduran et al. (2017) and Ferrer and Swaminathan (2006).

We also assume, as a starting point, that the OEM is currently not engaged in remanufacturing his end-of-use products. Reasons for that could be resource-based, such as the absence of a logistical collection network (Stindt et al. 2017), or demand-based, such as fear of cannibalization of new product sales (Guide Jr. and Li 2010). While the OEM does not collect and remanufacture himself, he recognizes the threat of an IR entering the secondary market.

In light of that threat, the OEM considers (re-)designing his products using proprietary parts. Being proprietary, these parts can only be purchased from the OEM, which sells them at a markup. To become a competitive lever, the OEM chooses such parts to be proprietary which show a high failure rate (see quote from IR B in the introduction). In order to focus on the OEM's spare-parts decision, we assume the failure rate to be one. Thus, the IR cannot scavenge collected cores for those parts. There is no such restriction for non-proprietary parts, which are procured from the market. The OEM, therefore, exerts control over the profitability of the secondary market.

OEM decision and cost. The OEM decides on the optimal proprietary content β of his product's unit cost, where $\beta_{\min} \leq \beta \leq 1$. The minimum fraction $\beta_{\min}$ of the product that needs to be made proprietary is an industry-specific parameter. Introducing proprietary parts causes a fixed design cost and, depending on the proprietary content, it increases the marginal cost of both producing new products and proprietary spare parts. Regarding design cost, we assume the general form $\xi\beta^{\nu}$, where ξ denotes the design cost factor for making proprietary content and ν relates to design efficiency. A value of $\nu = 0$ would model a fixed design cost independent of the proportion of proprietary content and $\nu > 0$ would mimic variable design cost, with increasing ν implying a less efficient design.

Unit production cost, c_n, linearly increases in the proprietary content, i.e.

$$c_n = \beta(1+\psi)c + (1-\beta)c = (1+\beta\psi)c, \tag{1}$$

where c is the unit cost of a completely non-proprietary product, and ψ is the percentage cost increase for a fully proprietary product. Analogously, the unit production cost of proprietary spare parts, c_p, is

$$c_p = \beta(1+\psi)c. \tag{2}$$

IR decision and cost. The OEM sets a per-unit wholesale price $w_s \geq c_p$ that he charges the IR for the proprietary portion β of the product provided as a spare part. For the remaining portion of the product, $1-\beta$, we assume that there is a cost advantage of remanufacturing over new production, $0 < \phi < 1$. Consequently, the unit remanufacturing cost for the IR, c_r, becomes

$$c_r = w_s + (1-\beta)\phi c, \tag{3}$$

being larger than the *effective remanufacturing cost* (without a markup), $\tilde{c}$, which would be

$$\tilde{c} = \beta(1+\psi)c + (1-\beta)\phi c. \tag{4}$$

In line with Atasu et al. (2013), the IR faces convex collection cost $c_c q_r^2$ for the used products, where q_r is the collection quantity. Note that the IR would never collect more than she wished to remanufacture. Thus, q_r is also the number of remanufactured units offered to the secondary market at price p_r.

Consumer behavior. To finalize the description of our model, we need to characterize how the prices for new and remanufactured products, p_n and p_r, respectively, will shape the demand in the primary and secondary markets. Here, we follow the utility-based approach (see, e.g., Debo et al. 2005, Oraiopoulos et al. 2012, Souza 2013), which assumes that the willingness-to-pay for the new product is distributed uniformly in the interval $[0,1]$, and that all consumers show a lower willingness-to-pay for the remanufactured product, reflected by a commonly applied discount factor $\delta < 1$ (WTP discount factor). Normalizing the market size to one, this yields linear demand functions as follows:

$$q_n(p_n,p_r) = 1 - \frac{p_n - p_r}{1-\delta} \quad \text{and} \quad q_r(p_n,p_r) = \frac{\delta p_n - p_r}{\delta(1-\delta)}. \tag{5}$$

Figure 1 illustrates the basic structure of our model. For ease of reference, Table 1 summarizes our notation.

In the considered Stackelberg setting with the OEM as a leader, the timeline of the decisions is given by the following steps[4]:

[4]To test the robustness of our results with respect to the competitive setting we also considered two alternative

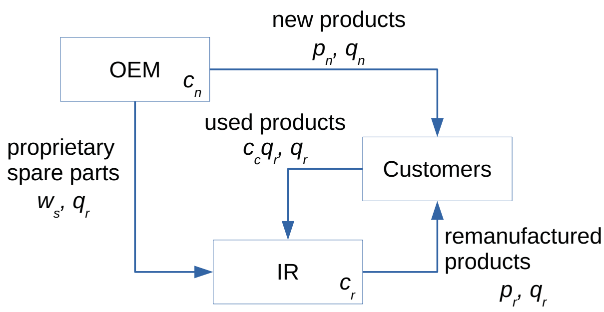

Figure 1: Model structure with proprietary parts

Table 1: Summary of model notation

Parameters:	
$0 < \beta_{\min} \leq 1$	Minimum proprietary content of product's unit cost
$0 < c < 1$	Marginal cost of a new product without proprietary content ($\beta = 0$)
$0 \leq \psi$	Marginal cost increase induced by a fully proprietary product ($\beta = 1$)
$0 < \phi < 1$	Cost advantage due to remanufacturing
$0 < c_c$	IR's cost of collecting a used product
$0 < \delta < 1$	WTP discount factor for remanufactured products
$0 < \gamma \leq 1$	Core collection yield factor, fraction of used products that is collectable
$0 < \xi$	OEM's design cost factor for making proprietary content
$0 < \nu$	OEM's design efficiency
Decision variables:	
β	Proportion of product's unit cost that is proprietary (OEM)
w_s	Wholesale price of (proprietary content) spare parts (OEM)
p_n	Sales price of new products (OEM)
p_r	Sales price of remanufactured products (IR)
Auxiliary variables:	
q_n	Sales quantity of new products
q_r	Sales quantity of remanufactured products
$\tilde{c}$	Effective remanufacturing cost

1. Initially, the OEM decides on the proprietary content β of the product.

2. Then the OEM decides on the wholesale price for proprietary spare parts w_s as well as on the price for the new product p_n.

3. Finally, the IR decides on the price of the remanufactured product p_r.

model variants. The first one kept the Stackelberg structure and replaced the market price competition with quantity competition, i.e. the OEM sets q_n while the IR sets q_r. The second one assumed that market prices were determined simultaneously by the OEM and the IR. We modeled this as a Nash game. It turned out that the main structural insights were unchanged. The results are provided in Appendix D.

The equilibrium of this model and all considered variants are derived through backward induction.

3.2 Benchmark: Selling the product with generic parts

Before we look at the proprietariness decision of the OEM, let us first consider a situation without proprietary parts. In that case, the production cost is $c_n = c$ and the remanufacturing cost becomes $c_r = \phi c$ due to the fully generic content of the product. The profit functions of the OEM and the IR in the considered Stackelberg game with the OEM as leader are

$$\max_{p_n} \Pi_{gen}^{OEM}(p_n|p_r) = (p_n - c)q_n \quad \text{s.t.} \quad 0 \leq q_n, \tag{6}$$

$$\max_{p_r} \Pi_{gen}^{IR}(p_r|p_n) = (p_r - \phi c - c_c q_r)q_r \quad \text{s.t.} \quad 0 \leq q_r \leq \gamma q_n. \tag{7}$$

Besides non-negativity constraints on all quantities, the IR faces the core availability constraint $q_r \leq \gamma q_n$. The following lemma characterizes the different equilibrium strategy regions when there are no proprietary parts.

Lemma 1. *For the case in which proprietary parts are not used, the characteristics of the equilibrium regions are provided in Table 2. There exists a threshold value for the core collection yield factor, $\hat{\gamma}$, and two threshold values for the marginal cost of a new product $\hat{c}_1$ and $\hat{c}_2$ (for functional forms see the proof in Appendix A). The equilibrium regions can be described as follows:*

No remanufacturing *If $\delta \leq \phi$ and $c \geq \hat{c}_1$, the IR does not enter the market, i.e., $q_r = 0$.*

Partial remanufacturing *If ($\delta \leq \phi$ and $\hat{c}_1 > c > \hat{c}_2$) OR ($\delta > \phi$ and $\gamma \geq \hat{\gamma}$ and $c < \hat{c}_2$), the IR enters the market but does not remanufacture all available cores, i.e., $0 < q_r < \gamma q_n$.*

Full remanufacturing *If ($\delta \leq \phi$ and $\hat{c}_2 \geq c$) OR ($\delta > \phi$ and $\gamma \geq \hat{\gamma}$ and $c \geq \hat{c}_2$) OR ($\delta > \phi$ and $\gamma < \hat{\gamma}$), the IR enters the market and remanufactures all available cores, i.e., $q_r = \gamma q_n$.*

Figure 2 illustrates the strategy space for the two cases in which the core collection yield factor, γ, is larger and respectively smaller than the threshold $\hat{\gamma}$. In the case of pure price competition, the OEM reacts to the entry threat – even if the IR does not enter the market – by reducing the price of new products (compared with a monopoly market price $p_n = \frac{1+c}{2}$, see Atasu et al. 2008) and giving up some profit.

3.3 Selling the product with proprietary parts

Above we have seen that – despite deviating from the monopoly market price – the OEM can deter entry by the IR for a limited range of situations in which the attractiveness of remanu-

Table 2: Equilibrium prices and quantities when there are no proprietary parts

Strategy region	**No remanufacturing**	**Partial remanufacturing**	**Full remanufacturing**
p_n	$\frac{1+c}{2} - \frac{\delta^2(1-c)}{8c_c+8\delta-6\delta^2}$	$\frac{1+c}{2} - \frac{\delta(\delta-c\phi)}{4c_c+4\delta-2\delta^2}$	$\frac{1+c}{2} - \frac{\delta(\delta+\gamma(\delta(2-\delta)+2c_c))(1-c)}{8c_c+8\delta-6\delta^2+\gamma\delta(4c_c+4\delta-2\delta^2)}$
p_r	n.a.	$\delta\frac{1+c}{2} - \frac{\delta(\delta-c\phi)}{4c_c+4\delta-2\delta^2} - \frac{\delta(1-\delta)(\delta-\phi)c}{4c_c+4\delta-4\delta^2}$	$\delta p_n - \frac{2\delta(1-\delta)\gamma(\delta(2-\delta)+2c_c)(1-c)}{8c_c+8\delta-6\delta^2+\gamma\delta(4c_c+4\delta-2\delta^2)}$
q_n	$\frac{1-c}{2} + \frac{\delta^2(1-c)}{8c_c+8\delta-6\delta^2}$	$\frac{1-c}{2} - \frac{\delta(\delta-\phi)c}{4c_c+4\delta-4\delta^2}$	$\frac{1-c}{2} + \frac{\delta(\delta-\gamma(\delta(2-\delta)+2c_c))(1-c)}{8c_c+8\delta-6\delta^2+\gamma\delta(4c_c+4\delta-2\delta^2)}$
q_r	0	$\frac{\delta-c\phi}{4c_c+4\delta-2\delta^2} + \frac{(\delta-\phi)c}{4c_c+4\delta-4\delta^2}$	γq_n

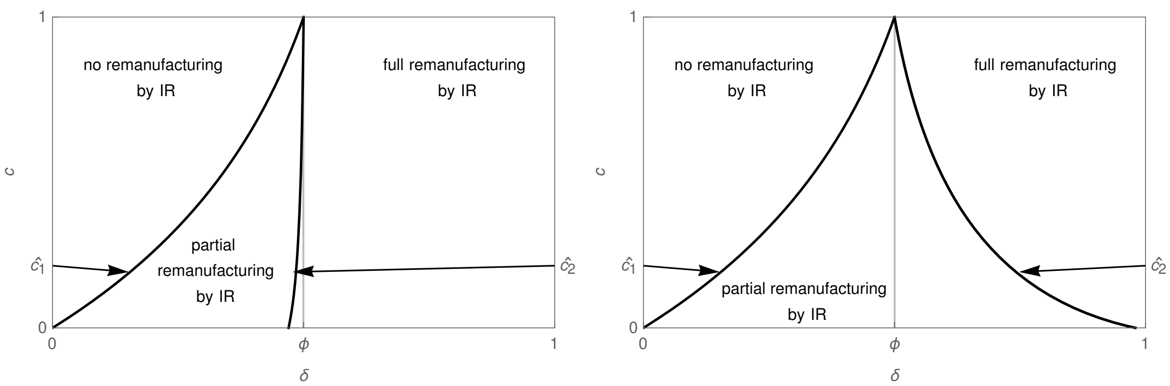

Figure 2: Characterization of the strategy regions when the OEM does not use proprietary parts for $\gamma < \hat{\gamma}$ (left) and $\gamma \geq \hat{\gamma}$ (right)

factured products is low (δ is small) and production costs c are high. Thus, we now study how introducing proprietary parts affects the competitive environment.

Given a proprietary content β, the manufacturer and the IR solve a price game as follows:

$$\max_{p_n, w_s} \Pi_{prop}^{OEM}(p_n, w_s | p_r) = (p_n - c_n)q_n + (w_s - c_p)q_r - \xi\beta^\nu \quad \text{s.t.} \quad 0 \leq q_n, \tag{8}$$

$$\max_{p_r} \Pi_{prop}^{IR}(p_r | p_n, w_s) = (p_r - c_r - c_c q_r)q_r \quad \text{s.t.} \quad 0 \leq q_r \leq \gamma q_n. \tag{9}$$

In the next step, the OEM decides on the optimal proprietariness fraction β^* by solving

$$\max_{\beta} \Pi_{prop}^{OEM}(\beta | p_n^*, w_s^*, p_r^*) \quad s.t. \quad \beta \geq \beta_{\min}. \tag{10}$$

Note that, by model design, the unit production cost of a new product must not exceed an upper bound, $c_{\max}$, which corresponds to the proprietary content β, i.e., $c < c_{\max} = \frac{1}{1+\beta\psi}$. Otherwise, introducing proprietary content at level β would render new production non-profitable.

The following lemma characterizes the different strategy regions in the equilibrium.

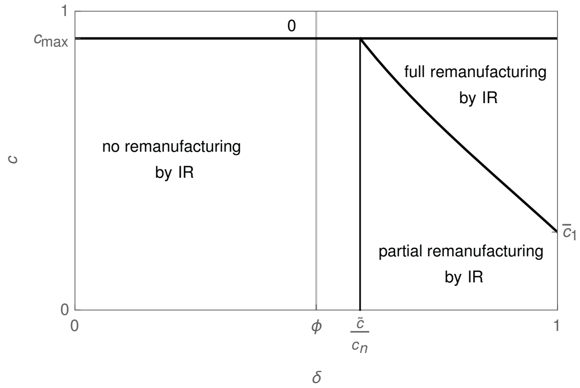

Figure 3: Characterization of the strategy regions in the case of an OEM using proprietary parts

Lemma 2. *Characteristics of the equilibrium regions for a fixed value of β are given in Table 3. Given new production is profitable using proprietary parts ($c < c_{\max}$), there exists a threshold value for the marginal production cost of a new product, $\bar{c}_1$ (for the functional form see the proof in Appendix A), and the equilibrium regions can be described as follows:*

No remanufacturing *If $\delta < \frac{\tilde{c}}{c_n}$, the IR does not enter the market and the OEM acts as a monopolist, i.e., $q_r = 0$.*

Partial remanufacturing *If $\delta \geq \frac{\tilde{c}}{c_n}$ and $c < \bar{c}_1$, the IR enters the market but does not remanufacture all available cores, i.e., $0 < q_r < \gamma q_n$.*

Full remanufacturing *If $\delta \geq \frac{\tilde{c}}{c_n}$ and $c \geq \bar{c}_1$, the IR enters the market and remanufactures all available cores, i.e., $q_r = \gamma q_n$.*

Table 3: Equilibrium prices and quantities in all three strategy regions

Strategy region	**No remanufacturing**	**Partial remanufacturing**	**Full remanufacturing**
w_s	$\geq c_p + \frac{\delta(1-c_n)}{2}$	$c_p + \frac{\delta-\tilde{c}}{2}$	$c_p + \frac{(\delta+2c_c\gamma+(2-\delta)\delta\gamma)(1-c_n)}{2(1+\delta\gamma)}$
p_n	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2}$
p_r	n.a.	$\delta p_n - \frac{\delta(1-\delta)(\delta c_n-\tilde{c})}{4(c_c+\delta(1-\delta))}$	$\delta p_n - \frac{\gamma\delta(1-\delta)(1-c_n)}{2(1+\delta\gamma)}$
q_n	$\frac{1-c_n}{2}$	$\frac{1-c_n}{2} - \frac{\delta(\delta c_n-\tilde{c})}{4(c_c+\delta(1-\delta))}$	$\frac{1-c_n}{2} - \frac{\gamma\delta(1-c_n)}{2(1+\delta\gamma)}$
q_r	0	$\frac{\delta c_n-\tilde{c}}{4(c_c+\delta(1-\delta))}$	γq_n

Figure 3 shows the strategy space for given proprietary content β. Note that region 0 depicts the disregarded case where new production is not viable. Using the results from Lemma 2, we can now turn to the optimal level of β.

Proposition 1. *When designing a product with the use of proprietary parts, the OEM will always choose minimum proprietary content, i.e.* $\beta^* = \beta_{\min}$. *The OEM will deter market entry by the IR, setting the spare parts price* w_s *such that* $\delta c_n < \tilde{c}$, *if* $\beta_{\min} > \frac{\delta-\phi}{1-\phi+(1-\delta)\psi}$.

This result is in line with empirical and anecdotal evidence (e.g. the pentalobe screws from Apple (McAllistair 2013), for more on which see Appendix B). Making a small (the smallest possible) portion of the product proprietary minimizes the associated design and (re-)manufacturing cost and suffices to give the OEM control over the secondary market. Specifically, when the attractiveness of the secondary market is sufficiently high (i.e. δ is large), it is optimal for the OEM to let the IR enter. Under the optimal choice of the wholesale price w_s (as shown in Table 3), the OEM's extra profits due to spare parts sales outweigh the reduced profits on the primary market caused by a reduction in the sales of new products. Thus, although the OEM could deter entry by the IR, it is only optimal for him to do so when the secondary market is not very profitable or the required minimum proprietary fraction is too large.

Moreover, comparing Table 3 with Table 2 reveals another interesting result. Without proprietary parts, the OEM lowers its price p_n – taking the market conditions into account – to establish a more hostile environment for the IR. Conversely, when introducing proprietary parts, the OEM controls competition without the need to change the market price for new products p_n.[5] Thus, the OEM asserts control over the secondary market entirely via the wholesale price charged for the proprietary parts.

The decision of whether or not to introduce proprietary parts, and thereby how best to deter market entry by the IR, crucially depends on the design cost of introducing proprietary parts. From Lemma 1 and Figure 2 we observe that the IR does not enter the secondary market when there are no proprietary parts for small WTP discount factor, δ, and high new product unit cost, c. In that case, it would seem that introducing proprietary parts cannot make sense. However, Proposition 2 provides a condition under which the OEM is better off by introducing proprietary parts.

Proposition 2. *Assume that under zero proprietariness it is optimal for the IR not to enter the market. In that case, the OEM still prefers to introduce proprietary parts when*

$$\xi \beta_{\min}^{\nu} < \frac{1}{4}\left[\frac{\delta^4(1-c)^2}{(4c_c+4\delta-3\delta^2)^2} - 2(1-c)c\psi\beta_{\min} + c^2\psi^2\beta_{\min}^2\right]. \tag{11}$$

Thus, the OEM may benefit from introducing proprietary parts and pricing them prohibitively high in order not to sell them to the IR. Thereby, the OEM deters entry without experiencing

[5] Note that, if a monopoly were guaranteed, the OEM would always choose $\beta = 0$ and consequently unit cost $c_n = c$.

a loss in profit due to the strategic reduction in the price for the new product, p_n.

As already discussed above, the price p_n is always larger – and quantity q_n is smaller – under the use of proprietary parts than without proprietary parts. The condition given in Proposition 2 provides an upper bound on the fixed design cost $\xi\beta_{\min}^{\nu}$ that guarantees that the associated extra primary market profit outweighs the cost of introducing proprietariness.

3.4 Numerical analysis

To explicitly quantify the economic differences between the use and lack of use of proprietary parts by the OEM, we now present the results of a comprehensive numerical analysis. After introducing the experimental design, we focus on the OEM's profitability and decision making but also briefly highlight the implications for the IR and the consumers.

3.4.1 Experimental design

To capture the widest possible set of industry scenarios, we employ a full-factorial experimental design. For each relevant parameter, we consider two values, a high one and a low one. These values are shown in Table 4 and were chosen in line with previous work on remanufacturing (Subramanian and Subramanyam 2012, Guide Jr. et al. 2006, Ferguson et al. 2006, 2011). The values of $\beta_{\min}$ and ψ were estimated on the basis of interviews with company representatives from both computer and white-goods OEMs. For design efficiency, controlled by ν, we consider two special but realistic cases. The first one ($\nu = 0$) reflects a fixed design cost which is independent of the proportion of proprietary content in the final product. The second one ($\nu = 2$) represents quadratic cost, which models the increasing difficulty of making a larger proportion of the product proprietary. Finally, the values of ξ have been chosen such that all strategy regions are relevant. Overall, we obtain 512 instances (9 parameters with 2 realizations each, i.e. $2^9 = 512$).

Table 4: Experimental design

Parameter	$\beta_{\min}$	c	ψ	ϕ	c_c	δ	γ	ξ	ν
Low	0.1	0.2	0	0.3	0.1	0.5	0.3	0.0001	0
High	0.3	0.6	0.25	0.7	0.3	0.85	0.7	0.001	2

The full set of results can be obtained from the authors. Here, for the sake of brevity, we focus on the most relevant, aggregated results.

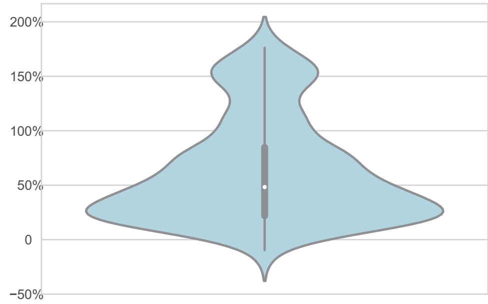

Figure 4: Violin plot of relative OEM profit changes $(\Pi_{prop}^{OEM} - \Pi_{gen}^{OEM})/\Pi_{gen}^{OEM}$

Table 5: Distribution of instances (left panel) and average relative OEM profit changes $(\Pi_{prop}^{OEM} - \Pi_{gen}^{OEM})/\Pi_{gen}^{OEM}$ (right panel)

# of instances		**Model *gen*** no reman	**Model *gen*** reman	$\frac{\Pi_{prop}^{OEM}-\Pi_{gen}^{OEM}}{\Pi_{gen}^{OEM}}$		**Model *gen*** no reman	**Model *gen*** reman
Model	no reman	64	128	**Model**	no reman	-6%	21%
prop	reman	0	320	***prop***	reman	–	81%

3.4.2 Profit and decision making impact on the OEM

We first consider the profit impact on the OEM of using proprietary parts. On average, over all the 512 instances, the OEM gains 55% (computed as $\frac{\Pi_{prop}^{OEM}-\Pi_{gen}^{OEM}}{\Pi_{gen}^{OEM}}$) by using proprietary parts. The violin plot in Figure 4 presents the distribution of percentage changes in OEM profit when introducing proprietary parts.

This result supports the widespread use of proprietary parts in practice. To get a deeper insight, we take a more granular look at our results. Specifically, for each model we distinguish between the cases with ($q_r > 0$) and without ($q_r = 0$) remanufacturing. Tables 5 and 6 provide the results for each of the resulting four strategy combinations.

The left panel of Table 5, showing the prevalence of each combination, confirms that we can never have a situation where there is remanufacturing under the use of proprietary parts but no remanufacturing without proprietary parts. In 25% of the cases, the OEM deters entry by the IR through using proprietary parts when otherwise the IR would enter and sell remanufactured cores. However, in the majority of cases, it is optimal to let the IR enter regardless of whether or not proprietary parts are used.

The right panel of Table 5 provides the profit implications of using proprietary parts (compared to not using them) for these different strategy combinations. Clearly, profit differences

Table 6: Average relative price changes (left panel) and quantity changes (right panel)

$\frac{p_{n,prop}-p_{n,gen}}{p_{n,gen}}$ $(\frac{p_{r,prop}-p_{r,gen}}{p_{r,gen}})$		**Model *gen*** no reman	reman	$\frac{q_{n,prop}-q_{n,gen}}{q_{n,gen}}$ $(\frac{q_{r,prop}-q_{r,gen}}{q_{r,gen}})$		**Model *gen*** no reman	reman
Model	no reman	4% (–)	14% (–)	**Model**	no reman	-15% (–)	-4% (-100%)
prop	reman	– (–)	30% (37%)	***prop***	reman	– (–)	-19% (-64%)

are more pronounced when it is optimal for the OEM, which introduces proprietary parts, to let the IR enter the secondary market. Here the OEM capitalizes on profitably selling proprietary parts and thereby sharing the revenues in the secondary market with the IR. This is also shown by the results in Table 6, where we present the average price and quantity changes in both the primary and the secondary market (where applicable). Clearly, in the scenarios where the IR enters regardless of the OEM's strategy, the introduction of proprietary parts allows the OEM to charge a 30% higher price for new products while only facing a 19% reduction in quantity. Thus, the OEM not only benefits from the secondary market but also observes increased primary market profits.

We also observe that, on average, the OEM is worse off if he introduces proprietary parts in the environment underlying Proposition 2. In those cases, the average profit change is -6% as shown in the right panel of Table 5. Disaggregating the results reveals a small number of cases supporting the finding from Proposition 2 with a maximum profit change of 2%. However, particularly when c is large and δ is small, the profit decrease associated with introducing proprietary parts can be as large as 23%. A high c implies that the primary market and the associated profits are small, while a small δ implies that the secondary market is not very attractive. Jointly, these market characteristics make the investment in proprietary parts costly (regarding primary market profits) but scarcely effective (in terms of gains from preempting the secondary market).

Summarizing, our results suggest that using proprietary parts to preempt the secondary market is the preferred option for the OEM only in a minority of possible environments. In most of the considered scenarios, the OEM benefits more from strategically using these proprietary parts to skim some profits from the secondary market without getting directly involved in the reverse supply chain. Yet, our empirical and anecdotal evidence from various IRs suggests that, currently, OEMs often fail to tap that potential, hurting both the IR and also themselves.

Table 7: Average relative IR profit changes $(\Pi^{IR}_{prop} - \Pi^{IR}_{gen})/\Pi^{IR}_{gen}$ and consumer surplus changes $(\Upsilon_{prop} - \Upsilon_{gen})/\Upsilon_{gen}$ (in brackets)

		Model *gen*	
		no reman	reman
Model	no reman	– (-27%)	-100% (-36%)
prop	reman	–	-93% (-54%)

3.4.3 Impact on the IR and consumer surplus

To conclude this section let us briefly highlight and discuss the effect of the strategy adopted by the OEM on the IR's profit as well as on consumer surplus. In line with the assumptions made for deriving demand functions (5), we define the consumer surplus Υ to be the cumulative difference between a consumer's willingness to pay for the chosen product (new or remanufactured) and the corresponding price, which calculates as follows (for a derivation see Appendix C)

$$\Upsilon = q_n\left(1 - p_n - \frac{q_n}{2}\right) + \frac{\delta q_r^2}{2} \tag{12}$$

Table 7 shows the average relative changes in IR profits and consumer surplus (in brackets). As expected, both IR and consumers are worse off when the OEM introduces proprietary parts. Interestingly, the OEM can essentially extract all the extra profits from the secondary market when introducing proprietary parts and letting the IR enter. Also, consumer surplus takes the largest dip in those cases. The reason for this is the significant price increase on both the primary and secondary markets and the associated massive drop in remanufactured product sales (compare Table 6).

4 Remanufacturing by the OEM

Above we have considered the case of a non-remanufacturing OEM. As mentioned in Section 3.1, the reasons for not remanufacturing come from two categories, namely, demand-based and resource-based issues. On the demand side, cannibalization of new product sales critically impacts the OEM's decision not to sell remanufactured products. However, this opens the door for IRs, which are not worried about primary market profits. In our analysis so far, we have seen how the non-remanufacturing OEM combines proprietary parts and an appropriate pricing strategy to counter the entry threat from an IR. We have found that, although the OEM could always deter market entry by the IR through prohibitive pricing, this is only optimal when

$\delta c_n < \tilde{c}$. Otherwise, the OEM benefits more from letting the IR enter and sharing the secondary market profits. In those cases, a market expansion effect outweighs the cannibalization, and demand-side drivers for not remanufacturing do not seem to be prevalent.

Yet, there may still be resource-based obstacles, including the lack of remanufacturing capabilities as well as the difficulty of accessing cores. While the former hurdle is internal to the OEM, the latter relates to competition with a more locally operating IR that may be able to collect cores more efficiently. In this case, the OEM may be reluctant to develop its internal remanufacturing skills. However, if the OEM could more easily access the cores, he might consider remanufacturing more favorably. Proprietary parts can play a role in solving this issue, since pricing these parts to deter market entry also removes the IR's incentive to collect cores. Thus, the OEM may gain exclusive access to used products and might decide to perform remanufacturing himself. In what follows, we analyze this scenario in more detail.

For parsimony (w.l.o.g.), we consider the same demand functions (5) as in the IR remanufacturing case by assuming that the valuation of the products does not depend on whether the OEM or the IR remanufactures. Keeping the basic cost structure from the case of a non-remanufacturing OEM (see Section 3.3), the OEM's cost of remanufacturing a product with β proprietary content is proportional to the production cost and given by

$$c_r^{OEM} = \phi[\beta c(1+\psi) + (1-\beta)c] = \phi c(1+\beta\psi) = \phi c_n. \tag{13}$$

Since OEMs are typically large multinational companies, having to collect across long distances, and IRs are (relatively) small local firms, we assume that the OEM faces a higher collection effort. This is modeled by applying a factor $\alpha > 1$ to the collection cost, which represents the collection cost disadvantage.

Under these conditions, the OEM's objective function becomes

$$\Pi_{prop+rem}^{OEM}(p_n) = (p_n - c_n)q_n + (p_r - c_r^{OEM} - \alpha c_c q_r)q_r - \xi\beta^{\nu}. \tag{14}$$

Again, the core availability constraint $q_r \leq \gamma q_n$ as well as $\beta \geq \beta_{\min}$ have to hold. Analogously to the result in Proposition 1, it is easy to observe that, in the optimal solution, $\beta = \beta_{\min}$ holds.

Lemma 3. *Characteristics of the equilibrium regions in the case of OEM remanufacturing are given in Table 8. Given new production is profitable using proprietary parts, there exists a threshold value for the marginal production cost of a new product, $\bar{c}_2$, and the equilibrium regions can be described as follows:*

No OEM remanufacturing *If $\delta \leq \phi$, the OEM does not remanufacture, i.e., $q_r = 0$.*

Table 8: Structure of optimal solution in case of OEM remanufacturing

Strategy region	**No OEM remanufacturing**	**Partial OEM remanufacturing**	**Full OEM remanufacturing**
p_n	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2} - \frac{\gamma((\delta-\phi)c_n+\gamma(\alpha c_c+(1-\phi)\delta)c_n-\gamma(\alpha c_c+\delta(1-\delta)))}{2(1+2\delta\gamma+(\alpha c_c+\delta)\gamma^2)}$
p_r	n.a.	$\delta p_n - \frac{\delta(1-\delta)(\delta-\phi)c_n}{2(\alpha c_c+\delta(1-\delta))}$	$\delta p_n - \frac{\delta(1-\delta)\gamma(1-c_n+\gamma(\delta-\phi c_n))}{2(1+2\delta\gamma+(\alpha c_c+\delta)\gamma^2)}$
q_n	$\frac{1-c_n}{2}$	$\frac{1-c_n}{2} - \frac{\delta(\delta-\phi)c_n}{2(\alpha c_c+\delta(1-\delta))}$	$\frac{1-c_n+\gamma(\delta-\phi c_n)}{2(1+2\delta\gamma+(\alpha c_c+\delta)\gamma^2)}$
q_r	0	$\frac{(\delta-\phi)c_n}{2(\alpha c_c+\delta(1-\delta))}$	γq_n

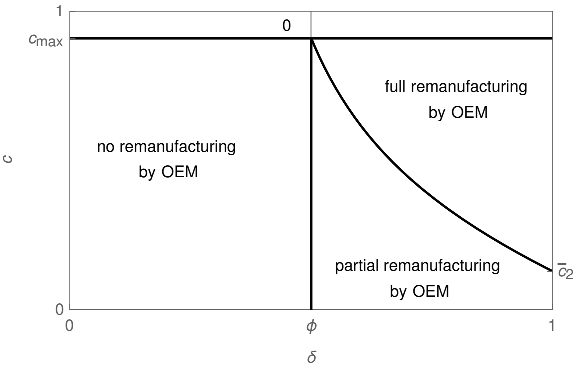

Figure 5: Strategy space in case of OEM remanufacturing

Partial OEM remanufacturing *If $\delta > \phi$ and $c < \bar{c}_2$, the OEM remanufactures some cores, i.e., $0 < q_r < \gamma q_n$.*
Full OEM remanufacturing *If $\delta > \phi$ and $c \geq \bar{c}_2$, the OEM remanufactures all available cores, i.e., $q_r = \gamma q_n$.*

Figure 5 illustrates the structural properties of the optimal solution. Comparing Figures 3 and 5 we can observe an interesting result which is summarized in Proposition 3.

Proposition 3. *When the OEM decides to introduce proprietary parts and consequently sets $\beta^* = \beta_{\min}$, his optimal secondary market policy is to deter entry by the IR but to remanufacture himself when $\phi < \delta \leq \bar{\delta} = \frac{\tilde{c}}{c_n}$.*

Note that this result is counter to the extant finding in the literature (see, e.g., Ferguson and Toktay 2006), according to which the OEM has less inclination to remanufacture than an IR, since he takes into account not only the potential extra profit in the secondary market but also the profit decline in the primary market. Thus, the IR that just needs to consider the

Table 9: Distribution of instances (left panel) and average relative OEM profit changes $(\Pi^{OEM}_{prop+rem} - \Pi^{OEM}_{prop})/\Pi^{OEM}_{prop}$ (right panel)

# of instances		Model ***prop+rem*** no reman	Model ***prop+rem*** reman
Model ***prop***	no reman	128	64
	reman	0	320

$\frac{\Pi^{OEM}_{prop+rem} - \Pi^{OEM}_{prop}}{\Pi^{OEM}_{prop}}$		Model ***prop+rem*** no reman	Model ***prop+rem*** reman
Model ***prop***	no reman	0%	8%
	reman	–	13%

secondary market effect, which is strictly positive for her, will enter the market under conditions in which the OEM prefers to sell only new products. Proposition 3 reveals conditions under which – despite the IR collection cost advantage – the OEM remanufactures even though the IR is deterred from entering the market. This result is driven by the cost advantage of the OEM, induced by being the only one able to remanufacture the proprietary parts. Thus, here, the proprietary parts serve an additional purpose. Using those parts, the OEM discourages the IR from collecting cores, thereby gaining exclusive access to the cores. Then, the OEM remanufactures these cores, capitalizing on a market expansion effect that outweighs the demand cannibalization effect.

Using the same experimental setup as in the previous section, we now present insights from our numerical analysis to show the emergence and magnitude of the profit increase due to the OEM's own remanufacturing compared to the IR's remanufacturing, in the case of entry deterrence through prohibitive pricing of the proprietary parts. Regarding the collection cost disadvantage of the OEM, we assume that $\alpha = 2$, i.e., the costs are twice as high as those the IR would face. The aggregated results are shown in Tables 9 and 10. We observe that, despite the significant collection cost disadvantage, the OEM on average receives an extra profit of more than 10% when strategically using proprietary parts to gain exclusive access to the cores as well as remanufacturing and selling them himself in comparison to the case where he lets the IR remanufacture. We also find that the setting described in Proposition 3 occurs in more than 12% of the cases and the average profit increase in those cases is still 8%.

As the OEM's remanufacturing removes the double marginalization problem arising when the IR remanufactures, this also makes the consumers better off by roughly the same percentage as shown in Table 10. However, these benefits do not outweigh the losses faced by the consumers due to the introduction of proprietary parts (compare Table 7). Thus, overall, the OEM benefits from using proprietary spare parts (and remanufacturing them himself), while both the IR and the consumers lose.

Table 10: Average relative consumer surplus change $(\Upsilon_{prop+rem} - \Upsilon_{prop})/\Upsilon_{prop}$

		Model *prop+rem*	
		no reman	reman
Model	no reman	0%	5%
prop	reman	–	12%

5 Conclusions

In this paper, we examine the competition between an OEM and an IR, where the OEM strategically adopts proprietary parts as a means to obtain a competitive edge over the IR, and to exert greater control over the secondary market for remanufactured products. This study was inspired by various first-hand accounts and cases reported in the media of such a strategy.

We contribute to the existing literature by developing a framework for strategic decision making concerning pricing (i.e., pricing of new and remanufactured products) and the use of proprietary parts. Our findings imply that it is always optimal for the OEM to choose the smallest possible fraction of proprietariness. This enables the OEM to control the secondary market sufficiently, while keeping the design and (re-)manufacturing costs low. Moreover, by appropriately pricing the proprietary parts, governance of the secondary market is possible for the OEM without the need to manipulate the price of the new products. Another insight is that the use of proprietary parts as a strategy to starve the secondary market is only suitable for the OEM when the willingness-to-pay for remanufactured products is low. This helps to explain the prevalence of such a strategy in the white-goods industry, particularly for washing machines, as indicated by the accounts we obtained from IRs in that industry.

Further, we find that the OEM benefits from easier access to cores. Global OEMs may find it difficult to compete with local IRs in collecting cores. Here, the use of proprietary parts and a prohibitive pricing strategy not only deters remanufacturing by the IR but also discourages collection of cores, giving the OEM exclusive access. This effect can lead to situations where – counter to findings in the existing literature – the OEM may find it optimal to remanufacture when the IR will not do so. While this result depends on the relative collection cost of the OEM compared to the IR, we find that, even under a twofold increase in the collection cost, the OEM can extract a significant extra profit with this strategy.

The insights of this paper are also relevant to IRs and policymakers. We demonstrate that even small changes in product design in the direction of making the product more proprietary can lead to the collapse of the secondary market, and have severe consequences for the IR and the consumers. We observe that IRs might even be pushed out of the secondary market completely. Moreover, consumer surplus decreases when proprietary parts are adopted. Yet, OEM remanufacturing softens this loss, at least for consumers. Thus, any initiatives targeting standardization should be scrutinized by policymakers to ensure an overall benefit to the various stakeholders.

For future research, we encourage the examination of the scenario in which cores can be scavenged for parts by the IR. Since parts scavenged from cores by the IR reduce the volume of spare parts the OEM can sell, it should be interesting to study the OEM's durability/quality decision regarding his (proprietary) parts used in the products under such a threat.

Finally, we have assumed that the OEM is a monopolist in the primary market. While this is a reasonable proxy for modeling particular market niches, there are many situations where competition with other OEMs will decidedly shape an OEM's decision. Regarding the optimal proprietary content in the new product, such a case could arise when the IR can remanufacture cores from different OEMs. In such a context, OEMs may even consider exclusivity clauses, where an IR is authorized to remanufacture the OEM's cores only if it does not remanufacture any other OEM's cores. A more detailed treatment of the effect of these complicating factors on the OEM's profitability presents another promising avenue for further research that could provide additional insights into the optimal proprietariness decisions of the OEM.

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A Proofs

A.1 Proof of Lemma 1

We omit details of the proof here since it follows along the same lines as the proof for our main model in Lemma 2 given below. Yet, the detailed exposition of the proof can of course be obtained from the authors upon request.

A.2 Proof of Lemma 2

We first show that the IR's profit is concave in her decision variable p_r. The profit function of the IR is given by $\Pi^{IR}_{prop}(p_r|p_n, w_s) = (p_r - c_r - c_c q_r)q_r$. The second derivative of this function with respect to p_r is $\frac{\partial^2 \Pi^{IR}_{prop}(p_r|p_n,w_s)}{\partial^2 p_r} = -\frac{2(c_c+\delta(1-\delta))}{(1-\delta)^2\delta^2} < 0$. Thus, the optimal response of the IR to the OEM's decisions is given by the unique maximizer of the IR's Lagrangean function, which is given by $\mathcal{L}^{IR}(p_r, \lambda, \lambda_2) = \Pi^{IR}_{prop}(p_r|p_n, w_s) - \lambda(q_r - \gamma q_n) + \lambda_2 q_r$. Thus we get $p_r = \frac{\delta((1-\delta)(1+\delta\gamma)\lambda-(1-\delta)\lambda_2+2c_c p_n+(1-\delta)(c\phi-\beta c\phi+\delta p_n)+w_s-\delta w_s)}{2(c_c+\delta(1-\delta))}$.

Next, we insert this result into the OEM profit function $\Pi^{OEM}_{prop}(p_n, w_s|p_r) = (p_n - c_n)q_n + (w_s - c_p)q_r - \xi\beta^\nu$. To check the concavity of the OEM's profit with respect to his decision variables p_n and w_s we compute the Hessian matrix as $\mathcal{H} = \begin{bmatrix} -1 - \frac{c_c+\delta}{c_c+\delta(1-\delta)} & \frac{\delta}{c_c+\delta(1-\delta)} \\ \frac{\delta}{c_c+\delta(1-\delta)} & -\frac{1}{c_c+\delta(1-\delta)} \end{bmatrix}$. The determinant of the matrix is given by $\det[\mathcal{H}] = \frac{2}{c_c+\delta(1-\delta)} > 0$, while the first leading minor is negative. Thus, the OEM's profit is jointly concave in his decision variables. Consequently, the OEM's optimal decisions are given by the unique maximizers of his profit function. We get $p_n = \frac{1+c_n}{2}$ and $w_s = \frac{\delta-\lambda-\delta\gamma\lambda+\lambda_2-c\phi+\beta c\phi+c_p}{2} = c_p + \frac{\delta-\tilde{c}}{2} + \frac{\lambda_2-\lambda-\delta\gamma\lambda}{2}$. Now we only have to consider the four possible cases resulting from the two constraints. The case where both constraints are binding, i.e., $q_r = \gamma$ and $q_n = 0$, can be excluded since it is not interesting when there is no production at all. Moreover, this can only happen when $c_n \geq 1$, which we have ruled out by assumption. Then we are left with the three described cases. Observe, first, that the price p_n is independent of the constraints. Thus we already have the proposed result. Now, let us start out with the partial remanufacturing case, i.e., the case where neither constraint is binding ($\lambda = \lambda_2 = 0$). For this case w_s simplifies to $w_s = c_p + \frac{\delta - \tilde{c}}{2}$, i.e., we have the proposed result. From the condition that, in this case $0 < q_r < \gamma q_n$, we can readily obtain the two conditions $\delta \geq \frac{\tilde{c}}{c_n}$ and $c < \bar{c}_1$, where $\bar{c}_1 = \frac{2\gamma(c_c+\delta-\delta^2)}{\gamma[(2c_c+\delta-\delta^2)(1+\beta\psi)+\delta(1-\phi)(1-\beta)]+(1+\beta\psi)\delta-(1-\beta)\phi-\beta(1+\psi)}$. The remaining prices and quantities can readily be obtained by plugging in the values of p_n and w_s. Now let us move to the case of no remanufacturing, i.e., $0 = q_r < \gamma q_n$. In this case, $\lambda = 0$ and $\lambda_2 > 0$. Plugging these λs into w_s, then p_n and w_s into p_r, and finally everything into q_r and solving for $q_r = 0$, we obtain $\lambda_2 = c(\beta(1-\phi+\psi-\delta\psi)-\delta+\phi) = \tilde{c}-\delta c_n$. Since $\lambda_2 > 0$ this yields $\delta < \frac{\tilde{c}}{c_n}$. The remaining prices and quantities can again readily be obtained by plugging in the values of λ_2 and p_n. Finally, the third case, full remanufacturing, implies that $0 < q_r = \gamma q_n$, and consequently $\lambda > 0$ and $\lambda_2 = 0$. Using the same logic as in the no remanufacturing scenario, i.e., inserting these λs into w_s, then w_s and p_n into p_r, and finally everything into q_r and q_n and solving the equation $q_r = \gamma q_n$, we obtain $\lambda = \frac{c(2c_c\gamma-\phi+\delta(1+\gamma(2-\delta-\phi)))-\beta c((1+\delta\gamma)(1-\phi)+(1-2c_c\gamma-\delta(1+\gamma-\delta\gamma))\psi)-2(c_c+\delta(1-\delta))\gamma}{(1+\delta\gamma)^2}$. Inserting λ into q_r and rearranging the condition $q_r > 0$, straightforward algebra yields the two bounds $\delta \geq \frac{\tilde{c}}{c_n}$ and $c \geq \bar{c}_1$. Similarly, all the remaining prices and quantities can be computed. This concludes the proof of Lemma 2.

A.3 Proof of Proposition 1

The OEM's profits in the three cases derived in Lemma 2 are given by

- Case 1 (no remanufacturing): $\Pi^{OEM}_{prop} = \frac{(1-c_n)^2}{4} - \xi\beta^{\nu}$
- Case 2 (partial remanufacturing): $\Pi^{OEM}_{prop} = \frac{(1-c_n)^2}{4} - \xi\beta^{\nu} + \frac{(\delta c_n - \tilde{c})^2}{8(c_c+\delta(1-\delta))}$
- Case 3 (full remanufacturing): $\Pi^{OEM}_{prop} = \frac{(1-c_n)^2}{4} - \xi\beta^{\nu} + \frac{\gamma^2(c_c+\delta(1-\delta))(1-c_n)^2}{2(1+\delta\gamma)^2}$.

Note that c_n is strictly increasing in β. Thus, the first term is strictly decreasing in β in all three cases. The second term, representing the design cost, is strictly increasing in β since $\nu \geq 0$. Under partial remanufacturing, the first derivative of the third term $\frac{(\delta c_n - \tilde{c})^2}{8(c_c+\delta(1-\delta))}$ with respect to β is given by $\frac{-c^2(1-\phi+(1-\delta)\psi)(\delta-\phi-\beta(1-\phi+(1-\delta)\psi))}{4(c_c+\delta(1-\delta))}$. This term may be increasing in β. However, it is straightforward to verify that, under the conditions required for partial remanufacturing, it is in absolute terms always smaller than the first derivative of the first term $\frac{(1-c_n)^2}{4}$. Under full remanufacturing, the third term is again strictly decreasing in β.

Consequently, in each case, the profit is strictly decreasing in β such that the optimal choice for the OEM is always $\beta^* = \beta_{\min}$.

From Lemma 2 we know that the OEM deters entry by the IR when $\delta c_n < \tilde{c}$. Rewriting this in terms of β we get $\beta > \frac{\delta-\phi}{1-\phi+(1-\delta)\psi}$. Together with $\beta^* = \beta_{\min}$, this implies that entry deterrence is only optimal if $\beta_{\min} > \frac{\delta-\phi}{1-\phi+(1-\delta)\psi}$.

A.4 Proof of Proposition 2

From Lemmas 2 and 1 we know that the region in which the OEM deters entry by the IR is always larger when there is proprietary content in the product. Thus, we now only need to compare the profits for the *no remanufacturing* cases with and without proprietary parts. In the model with proprietary parts, the OEM's associated profit is given by $\Pi_{prop}^{OEM} = \frac{(1-c_n)^2}{4} - \xi\beta^\nu$. Conversely, in the model without proprietary parts, the OEM's profit is given by $\Pi_{gen}^{OEM} = \frac{(1-c)^2}{4} - \frac{\delta^4(1-c)^2}{(8c_c+8\delta-6\delta^2)^2}$. The OEM prefers introducing proprietary parts when $\Pi_{prop}^{OEM} > \Pi_{gen}^{OEM}$. Inserting the profit functions, rearranging for $\xi\beta^\nu$ and then performing straightforward computations yield the proposed result.

A.5 Proof of Lemma 3

The logic of the proof follows along exactly the same lines as Lemma 2. The detailed exposition can be obtained from the authors upon request.

A.6 Proof of Proposition 3

From Lemma 2 we know that the OEM deters entry when $\delta c_n < \tilde{c}$. Lemma 3 shows that the OEM remanufactures when $\delta > \phi$. Putting these two results together we directly obtain that the OEM will deter entry by the IR but remanufacture himself when $\phi < \delta < \frac{\tilde{c}}{c_n}$.

B Empirical evidence on the importance of the topic

In this session, we outline the evidence we collected through interviews carried out for a previous project and from publicly available information. The issue of using proprietary parts spans entire industries, such as those of personal computers, mobile phones, tractors, and washing machines.

> "Surprising no one, the laptop is not very easy to open up and work on, and few components will be easy for end users to replace. The battery is still glued in, and the one system component that users can actually remove and replace – the SSD – is a proprietary module that's much different from the proprietary modules in MacBook Airs and Pros from years past." Source: Arstechnica, iFixit: New MacBook Pros

are unsurprisingly difficult to repair and upgrade, URL: https://arstechnica.com/gadgets/2016/11/ifixit-new-macbook-pros-are-unsurprisingly-difficult-to-repair-and-upgrade/

“Lastly the use of proprietary screws and fixings, requiring specialised tools, poses a great problem for disassembly if these are only available to the after sales service providers of the manufacturers.” Source: Investigation into the repairability of Domestic Washing Machines, Dishwashers and Fridges, URL: http://www.rreuse.org/wp-content/uploads/RREUSE_Case_Studies_on_reparability_-_Final.pdf

“Fifty years ago, if your television broke you could bring it to the local electronics shop to be repaired. These days, a broken TV likely means a trip to Best Buy for a new one. [...] A growing number of people, seeing this as an unreasonable state of affairs, are fighting back. In a so-called “right to repair” movement, this loose coalition of consumer advocates, repair professionals and ordinary individuals are working to create legislation that would make it harder for companies to keep repair information proprietary.” Source: The Smithsonianmag, URL: https://www.smithsonianmag.com/innovation/fight-right-repair-180959764/$#$dOdDZUJEcjR8P0WB.99

“Do you know where I can find further information on washing machine diagnosis systems? [...] The manufacturers will not share!” Source: Personal communication with the CEO of a large IR, 21 December 2012.

“The plan is to hook the laptop up to a gigantic John Deere combine, which, like all farm equipment, has become increasingly difficult to repair as companies have introduced new sensors and software into nearly every component.” Source: Tractor-Hacking Farmers Are Leading a Revolt Against Big Tech’s Repair Monopolies, The Motherboard, Vice, URL: https://motherboard.vice.com/en$_$us/article/kzp7ny/tractor-hacking-right-to-repair.

“AS DEVICES go, smartphones and tractors are on the opposite ends of the spectrum. And an owner of a chain of mobile-device repair shops and a farmer of corn and soyabeans do not usually have much in common. But Jason DeWater and Guy Mills are upset for the same reason. ‘Even we can no longer fix the home button of an iPhone,’ [...] Messrs DeWater and Mills have more and more company. It includes not just fellow repairmen and farmers, but owners of all kinds of gear, including washing machines, coffee makers and even toys.” Source: A “right to repair” movement tools up, The Economist, URL: `https://www.economist.com/business/2017/09/30/a-right-to-repair-movement-tools-up`

“ Your shiny new iPad Pro is on the fritz. The touchscreen is cracked and isn’t working properly. [...] Frustrated, you turn to Apple’s official support system. If you didn’t purchase the company’s AppleCare+ warranty plan when you bought the device, you find that replacing the screen will cost a whopping $599, plus shipping. Or, you could buy an entirely new replacement from an Amazon vendor for $674.88.” Source: Apple Is Fighting A Secret War To Keep You From Repairing Your Phone, The Huffington Post, URL: `https://www.huffingtonpost.co.uk/entry/apple-right-to-repair$_$us$_$5755a6b4e4b0ed593f14fdea`

“That made it far more difficult for home tinkerers to fix a laptop, a television, or smartphone – let alone a car or farm tractor – making independent repair outfits essential. Then manufacturers started using copyright laws to keep their repair manuals offline, proprietary fasteners to seal their products, and in some cases, digital rights management to protect their software.” Source: You bought that gadget, and dammit, you should be able to fix it. Wired, URL: `https://www.wired.com/2017/03/right-to-repair-laws/`

“On Monday, January 16th, Nikon Inc. sent a letter to independent camera repair technicians in the US to say that ‘it will no longer make repair parts available for purchase by repair facilities that have not been authorized by Nikon Inc. to perform camera repairs.’ So after July 13, 2012, all Nikon repairs will be pushed through Nikon’s own repair service or one of 22 Nikon authorized repair stations. Local, independent camera repair shops will no longer be able to repair Nikon cameras with manufacturer-approved parts. [...] Eliminating the supply of parts will devastate many local repair shops – Nikon repairs make up a significant portion of their business – and will make it significantly more difficult for photographers to get their Nikon equipment fixed.” Source: How Nikon is killing camera repair. iFixit, URL: `https://ifixit.org/blog/1349/`

“The RAM, which even Apple usually concedes as a necessarily user-replaceable part, is soldered to the MacBook Air’s logic board. This makes the online order decision to upgrade from 2GB to 4GB a do-or-die moment.

Overall, iFixit rated the Air a 4 out of 10 for serviceability. Many parts, like the flash drive, fan, and WiFi chip, are held in by only a couple of screws. However, *all parts are proprietary*, not to mention barricaded by the five-point Security Torx." Source: iFixit finds MacBook Air full of pesky screws, proprietary parts, Arstechnica, URL: `https://arstechnica.com/gadgets/2010/10/ifixit-finds-macbook-air-full-of-pesky-screws-proprietary-parts/`.

C Consumer surplus derivation

In line with the assumptions made when deriving the demand functions (5), we define the consumer surplus to be the cumulative difference between a consumer's willingness-to-pay for the chosen product (new or remanufactured) and the corresponding price. The assumptions are as follows (see, e.g., Debo et al. 2005, Oraiopoulos et al. 2012, Souza 2013): The willingness-to-pay for new products θ is uniformly distributed among the consumers with support $U[0,1]$. The willingness-to-pay for a remanufactured product is a constant fraction δ of that for a new product, i.e., $\delta\theta$. Thus, for any customer, the net utilities for buying a new, remanufactured, or no product are $U_n = \theta - p_n$, $U_r = \delta\theta - p_r$, $U_z = 0$, respectively, and consumer surplus (for a standardized market size of 1) becomes

$$\Upsilon = \int_0^1 \max\{U_n, U_r, U_z\}\, d\theta$$

.Switching points for θ between not buying and buying remanufactured and between buying remanufactured and new items, $0 \leq \theta_{zr} < \theta_{rn} < 1$ are given by $\theta_{zr} = \frac{p_r}{\delta}$ and $\theta_{rn} = \frac{p_n - p_r}{1-\delta}$ (Abbey et al. 2017), and therefore consumer surplus becomes

$$\begin{aligned} \Upsilon &= \int_{\theta_{rn}}^1 (\theta - p_n)\, d\theta + \int_{\theta_{zr}}^{\theta_{rn}} (\delta\theta - p_r)\, d\theta = \left[\frac{1}{2}\theta^2 - p_n\theta\right]_{\theta_{rn}}^1 + \left[\frac{\delta}{2}\theta^2 - p_r\theta\right]_{\theta_{zr}}^{\theta_{rn}} \\ &= q_n\left(1 - p_n - \frac{q_n}{2}\right) + \frac{\delta q_r^2}{2}. \end{aligned} \tag{15}$$

D Alternative competitive settings

D.1 Quantity competition

In this model variant, we keep the sequence of events but replace the price decisions with quantity decisions, i.e.

1. Initially, the OEM decides on the proprietary content β of the product.

2. Then, the OEM decides on the wholesale price for proprietary spare parts w_s as well as on the quantity of new products q_n to sell.

3. Finally, the IR decides on the quantity of remanufactured products q_r.

Solving the quantity competition, we obtain the following results, structured analogously to Lemma 2.

Lemma 4. *Characteristics of the equilibrium regions for a fixed value of β are given in Table 11. Given new production is profitable using proprietary parts, there exists a threshold value for the marginal production cost of a new product, $\bar{c}_1^Q$, and the equilibrium regions can be described as follows:*

R1 *If $\delta c_n < \tilde{c}$, the IR does not enter the market and the OEM acts as a monopolist (no remanufacturing).*

R2 *If $\delta c_n \geq \tilde{c}$ and $c < \bar{c}_1^Q$, the IR enters the market but does not remanufacture all available cores (partial remanufacturing).*

R3 *If $\delta c_n \geq \tilde{c}$ and $c \geq \bar{c}_1^Q$, the IR enters the market and remanufactures all available cores (full remanufacturing).*

Table 11: Equilibrium prices and quantities in all three strategy regions

Strategy region	R1 no remanufacturing	R2 partial remanufacturing	R3 full remanufacturing
w_s	$\geq c_p + \frac{\delta(1-c_n)}{2}$	$c_p + \frac{\delta-\tilde{c}}{2}$	$c_p + \frac{(\delta+2c_c\gamma+2\delta\gamma)(1-c_n)}{2(1+\delta\gamma)}$
p_n	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2}$
p_r	n.a.	$\delta p_n - \frac{\delta(1-\delta)(\delta c_n-\tilde{c})}{2(2c_c+2\delta-\delta^2)}$	$\delta p_n - \frac{\gamma\delta(1-\delta)(1-c_n)}{2(1+\delta\gamma)}$
q_n	$\frac{1-c_n}{2}$	$\frac{1-c_n}{2} - \frac{\delta(\delta c_n-\tilde{c})}{2(2c_c+2\delta-\delta^2)}$	$\frac{1-c_n}{2} - \frac{\gamma\delta(1-c_n)}{2(1+\delta\gamma)}$
q_r	0	$\frac{\delta c_n-\tilde{c}}{4(c_c+\delta(1-\delta))}$	γq_n

$$\bar{c}_1^Q = \frac{(2c_c+(2-\delta)\delta)\gamma}{\delta+2c_c\gamma+2\delta\gamma-\beta(1+\delta\gamma)(1-\phi)-(1+\delta\gamma)\phi-\beta(1-\delta-2c_c\gamma-\delta\gamma)\psi}$$

The proof of Lemma 4 follows along the same lines as the proof of Lemma 2 and is omitted here. It can be obtained from the authors upon request.

These results confirm the structural similarity of the price and quantity competition models. The bound for R1 (no remanufacturing) is identical to the bound in our original setting (see Lemma 2). Comparing the thresholds $\bar{c}_1^Q$ and $\bar{c}_1$ we find that $\bar{c}_1^Q > \bar{c}_1$. Thus, under quantity competition, the region in which partial remanufacturing is optimal is larger.

D.2 Simultaneous market price decisions

In this model variant, we move away from the Stackelberg setting and consider a situation where the OEM and the IR set their market prices p_n and p_r simultaneously. The associated sequence of events is as follows:

1. Initially, the OEM decides on the proprietary content β of the product.
2. Then, the OEM decides on the wholesale price for proprietary spare parts w_s.
3. Finally, the OEM decides on the price for the new product p_n, and the IR decides on the price of remanufactured products p_r.

Solving the third stage as a Nash game, we obtain the following results, structured analogously to Lemma 2.

Lemma 5. *Characteristics of the equilibrium regions for a fixed value of β are given in Table 12. Given new production is profitable using proprietary parts, there exists a threshold value for the marginal production cost of a new product, $\bar{c}_1^N$, and the equilibrium regions can be described as follows:*

R1 *If $\delta c_n < \tilde{c}$, the IR does not enter the market and the OEM acts as a monopolist (no remanufacturing).*

R2 *If $\delta c_n \geq \tilde{c}$ and $c < \bar{c}_1^N$, the IR enters the market but does not remanufacture all available cores (partial remanufacturing).*

R3 *If $\delta c_n \geq \tilde{c}$ and $c \geq \bar{c}_1^N$, the IR enters the market and remanufactures all available cores (full remanufacturing).*

Table 12: Equilibrium prices and quantities in all three strategy regions

Strategy region	R1 no remanufacturing	R2 partial remanufacturing	R3 full remanufacturing
w_s	$\geq c_p + \frac{\delta(1-c_n)}{2}$	$c_p + \frac{\delta-\tilde{c}}{2} - \frac{(\delta c_n-\tilde{c})(2c_c+\delta(1-\delta))^2}{2[(2c_c+2-\delta-\delta^2)^2-4(1-\delta^2)(1-3\delta)]}$	$c_p + \frac{\delta(1-c_n)}{2} + \frac{2(1-c_n)(1-\delta)(c_c+\delta(1-\delta))\gamma}{2c_c(1+\gamma)+(1-\delta)(2+\delta+3\delta\gamma)}$
p_n	$\frac{1+c_n}{2}$	$\frac{1+c_n}{2} + \frac{(\delta c_n-\tilde{c})(1-\delta)(2c_c+\delta(1-\delta))}{(2c_c+2-\delta-\delta^2)^2-4(1-\delta^2)(1-3\delta)}$	$\frac{1+c_n}{2} + \frac{(1-c_n)(1-\delta)(2c_c+\delta(1-\delta))\gamma}{2[2c_c(1+\gamma)+(1-\delta)(2+\delta+3\delta\gamma)]}$
p_r	n.a.	$\delta\frac{1+c_n}{2} - \frac{2\delta(1-\delta)^2(\delta c_n-\tilde{c})}{(2c_c+2-\delta-\delta^2)^2-4(1-\delta^2)(1-3\delta)}$	$\delta\frac{1+c_n}{2} - \frac{(1-c_n)(1-\delta)^2\delta\gamma}{2c_c(1+\gamma)+(1-\delta)(2+\delta+3\delta\gamma)}$
q_n	$\frac{1-c_n}{2}$	$\frac{1-c_n}{2} - \frac{(\delta c_n-\tilde{c})(2c_c+3\delta(1-\delta))}{(2c_c+2-\delta-\delta^2)^2-4(1-\delta^2)(1-3\delta)}$	$\frac{1-c_n}{2} - \frac{(1-c_n)(2c_c+3\delta(1-\delta))\gamma}{2[2c_c(1+\gamma)+(1-\delta)(2+\delta+3\delta\gamma)]}$
q_r	0	$\frac{(\delta c_n-\tilde{c})(2c_c+2-\delta-\delta^2)}{(2c_c+2-\delta-\delta^2)^2-4(1-\delta^2)(1-3\delta)}$	γq_n

$$\bar{c}_1^N = \frac{(4c_c^2+(1-\delta)^2\delta(8+\delta)+4c_c(2-\delta(1+\delta)))\gamma}{(4c_c^2+(1-\delta)^2\delta(8+\delta)+4c_c(2-\delta(1+\delta)))\gamma+2(2c_c(1+\gamma)+(1-\delta)(2+\delta+3\delta\gamma))(\delta-\beta(1-\phi)-\phi)-\beta(2c_c+(1-\delta)(2+\delta))(2-2c_c\gamma-\delta(2+\gamma-\delta\gamma))\psi}$$

The proof of Lemma 5 follows along the same lines as the proof of Lemma 2 and is omitted here. It can be obtained from the authors upon request.

These results confirm the structural similarity of the price and quantity competition models. The bound for R1 (no remanufacturing) is identical to the bound in our original setting (see Lemma 2). Comparing the thresholds $\bar{c}_1^N$ and $\bar{c}_1$ we find that $\bar{c}_1^N < \bar{c}_1$. Thus, under simultaneous market pricing decisions, the region in which partial remanufacturing is optimal is smaller.

To conclude, Figure 6 illustrates the variations in the strategy space implied by the different types of competition, clearly highlighting the structural similarity of the results.

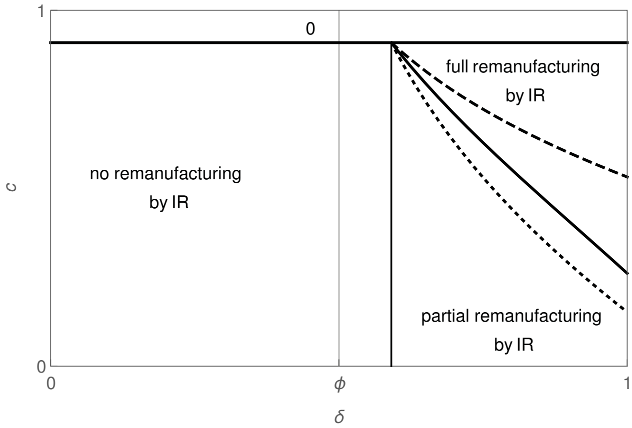

Figure 6: Strategy regions in the case of an OEM using proprietary parts, under different types of competition: Stackelberg price competition (bold), Stackelberg quantity competition (dashed), Nash price competition (dotted)

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