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*Verantwortlich für diese Ausgabe:*
Rainer Kleber
Otto-von-Guericke-Universität Magdeburg
Fakultät für Wirtschaftswissenschaft
Postfach 4120
39016 Magdeburg
Germany

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# Two-sided competition with vertical differentiation in both acquisition and sales in remanufacturing

Rainer Kleber[a,*], Marc Reimann[b,d], Gilvan C. Souza[c,b], Weihua Zhang[d]

[a]*Faculty of Economics and Management, Otto-von-Guericke University Magdeburg, Universitätsplatz 2, 39106 Magdeburg, Germany*
[b]*Department of Production and Operations Management, University of Graz, Universitätsstrasse 15/E3, 8010 Graz, Austria*
[c]*Kelley School of Business, Indiana University, Bloomington, IN 47405, USA*
[d]*Newcastle Business School, Northumbria University, Newcastle-upon-Tyne NE1 8ST, UK*

**Abstract**

We study the competition between two remanufacturers in the acquisition of used products and the sales of remanufactured products. One firm has a market advantage; we consider two separate cases where either firm could have an acquisition advantage. The problem is formulated as a simultaneous game on a market that is vertically differentiated in both acquisition and sales, where both firms decide on their respective acquisition prices for used products, and selling prices for remanufactured products. A key finding is that a market advantage is significantly more powerful than an acquisition advantage. The firm with a market advantage can preempt the entry of the other firm, even if that firm has a significant acquisition advantage, but not the other way around. This is accomplished through an aggressive acquisition strategy, where the firm with a market advantage sets significantly higher acquisition prices.
*Keywords:* Supply chain management, closed-loop supply chains, remanufacturing, used product acquisition, price competition

## 1. Introduction

In this paper, we analytically study two-sided competition between two remanufacturers. They compete on the sales of remanufactured products, and also on the acquisition of used products, which are the input for remanufacturing, by setting their respective acquisition and selling prices. The novelty here, as we elaborate on later, is that the two firms are vertically differentiated, on both sales of remanufactured products (i.e., all consumers prefer firm 1 over firm 2 at the same selling price), as well as on acquisition (i.e., all consumers prefer selling their used product to one firm over the other, at the same acquisition price). This problem is motivated

[*]Corresponding author
*Email addresses:* rainer.kleber@ovgu.de (Rainer Kleber), marc.reimann@uni-graz.at (Marc Reimann), gsouza@indiana.edu (Gilvan C. Souza), weihua.zhang@northumbria.ac.uk (Weihua Zhang)

by the electronics remanufacturing industry, such as cell phones and tablets, as we elaborate on below, but its insights might apply to other industries where firms compete for sales of remanufactured products and acquisition of used products, such as automotive parts. We analytically provide a key insight: for a firm, having an advantage in sales is much more important than having an advantage in the acquisition. That is, the firm with a market advantage can preempt the firm with an acquisition advantage, but not the other way around.

Consider cell phone remanufacturing as a motivating example. Remanufacturing (or refurbishing) of used cell phones, not of the most current generation, is performed by different independent remanufacturers (IRs) and even some original equipment manufacturers (OEMs). In this paper, we use the terms remanufacturing and refurbishing interchangeably. Firms acquire used phones from sellers (existing consumers) through direct purchasing via online and other channels (e.g., `www.gazelle.com`), or through a trade-in program, and acquisition prices for a specific model vary depending on the buying firm and channel; hence consumers have choices when selling their used phone, with some being more convenient than others. Likewise, a more price-sensitive consumer interested in buying a refurbished phone has access to different sellers (e.g., Gazelle, third-party sellers on sites such as Best Buy, Amazon, and eBay), some of which could be authorized by the OEM, and possibly have a market advantage (Subramanian & Subramanyam, 2012), that is, they are able to command a higher selling price.

In our model, firm 1, without loss of generality, has a market advantage—consumers have a higher willingness-to-pay for firm 1's remanufactured product than for firm 2's product. On the acquisition side, we consider both cases: where firm 2 has an advantage or a disadvantage on acquisition—sellers prefer selling to one firm over the other at the same acquisition price. Given this setting, how should the two firms compete with one another in such two-sided competition? In particular, our research question is:

*How should two vertically differentiated remanufacturers compete in both product acquisition and sales of remanufactured products, in terms of acquisition and sales prices? Can remanufacturer 1, with a market advantage, preempt a remanufacturer with an acquisition advantage, when they also compete on the acquisition of used products? If so, under which conditions?*

Two key findings in our paper are as follows. First, a market demand advantage is necessary to preempt the other player, that is, the remanufacturer with an acquisition advantage cannot preempt the remanufacturer with a market advantage, even if the acquisition advantage is very significant. Second, the firm with a market advantage can preempt the remanufacturer with an acquisition advantage. This occurs when remanufacturing is most attractive: when unit remanufacturing costs (excluding product acquisition costs) are low, and consumers have low residual values for their used products (which implies used product acquisition cost is low). Under those conditions, the remanufacturer with a market advantage employs a strategy we refer to as *aggressive acquisition*, whereby it offers significantly higher acquisition prices than the other firm, thus acquiring all available used products. With its market advantage and the low remanufacturing cost, it can charge a price for the remanufactured product such that it can still make a positive profit on each unit sold, whereas the other firm cannot compete profitably. These findings are also highlighted in a comprehensive numerical study, designed to be symmetrical concerning the relative advantage of each player. In this study, the remanufacturer with a market advantage can preempt the other firm in 65% of instances, and in the cases where the other remanufacturer is able to compete, the profit of the remanufacturer with a market advantage is more than double, on average, than the other firm's profit.

## 2. Literature Review

Within the vast CLSC literature (see, e.g. Souza, 2013, for a review), we review here four streams of literature more closely related to this research: differentiated competition in remanufacturing, product acquisition, competition in acquisition, and competition in both product acquisition and remanufacturing sales.

Differentiated competition in remanufacturing: Such competition is analyzed in Majumder & Groenevelt (2001), Ferguson & Toktay (2006), Ferrer & Swaminathan (2006), Örsdemir et al. (2014), Agrawal et al. (2016), Yenipazarli (2016), and Pazoki & Zaccour (2019), among others. In Ferguson & Toktay (2006), Örsdemir et al. (2014), and Agrawal et al. (2016), the competition is strictly between the OEM's new product and the IR's remanufactured product. Each work focuses on different aspects such as convex collection and remanufacturing costs (Ferguson & Toktay, 2006), the quality of the new product set by the OEM (Örsdemir et al., 2014), a trade-in program run by the OEM to recover some used products from the market (Agrawal et al., 2016), or environmental regulations (Yenipazarli, 2016; Pazoki & Zaccour, 2019). In Majumder & Groenevelt (2001) and Ferrer & Swaminathan (2006), the OEM offers a remanufactured product that is a perfect substitute for the new product, however, the IR's remanufactured product is valued less; the OEM collects a fixed fraction of the used products whereas the IR collects the rest. In this stream, there is no competition in acquisition; a key research question in our paper.

Competition in product acquisition: A large portion of the product acquisition literature in CLSCs focuses on the trade-off between the number of products acquired, and the total remanufacturing cost, as used products have different quality levels. Different qualities imply different remanufacturing cost, with alternative disposition options (e.g., recycling, or disassembly for spare parts). This stream of research finds the optimal acquisition quantities (e.g., Ferrer, 2003; Guide et al., 2003; Bakal & Akcali, 2006; Zikopoulos & Tagaras, 2007; Galbreth & Blackburn, 2006, 2010; Mutha et al., 2016, 2019). There is also research that considers used product acquisition when remanufactured and new products are perfect substitutes, but remanufacturing is cheaper than new production on a per unit basis. Here, the fraction of demand met with remanufactured products is a function of a collection effort, and collection may occur through dual collection channels such as retailer, and manufacturer or third-party (e.g., Savaskan et al., 2004; Savaskan & Wassenhove, 2006; Wei et al., 2015; Han et al., 2016; Giri et al., 2017; Liu et al., 2017; Xie et al., 2017; Zhao et al., 2017; Wan & Hong, 2019; Wei et al., 2019). These studies do not consider differentiation in either acquisition or sales of remanufactured products, which are key aspects of our model. There is, however, research on dual collection channels that examine the differentiated competition in acquisition of e-waste between an OEM and a third party (Liu et al., 2016; Li et al., 2017; Esenduran et al., 2019). Unlike our case, however, these papers do not consider differentiated competition in sales of remanufactured products.

Competition in both product acquisition and remanufacturing sales: The most related paper to ours is Bulmus et al. (2014a), who analyze the competition between an OEM and an IR. In their model, the OEM offers both a new and a remanufactured product, whereas the IR offers a remanufactured version of the OEM's product. The OEM and IR set their respective acquisition price for used products; the OEM sets the selling prices for new and remanufactured products, whereas the IR sets the selling price for its remanufactured product. *In their setting, unlike ours, the remanufactured products offered by the OEM and the IR are identical and thus perfect substitutes in the eyes of consumers.* In addition, all of their analytical results are derived for the case where new and remanufactured products are also perfect substitutes. Hong et al. (2017) consider a setting similar to Bulmus et al. (2014a), but analyze the case where the IR requires permission from the OEM to apply remanufacturing technology, and analyze different licensing agreements. In Wu (2015) and Wu & Wu (2016), the OEM's and IR's remanufactured products are vertically differentiated, *but there is no vertical differentiation in the acquisition.* In our simplified setting, by focusing solely on the competition between two remanufacturers (one of which could be an OEM or OEM-authorized), we analytically derive a key new insight: that a market advantage can be used to preempt the other player, even if the other player has a pronounced acquisition advantage, but not the other way around. Thus, our paper makes a significant theoretical contribution to the literature, by analyzing the important case of two-sided vertically differentiated competition in product acquisition and sales.

## 3. Model

We consider a market where two firms, which we refer to as independent remanufacturers (IRs), compete, each with their own remanufactured version of an OEM's product. We do not explicitly model the OEM's original new product, and instead focus solely on the competition between the two IRs, to ensure a tractable model and for parsimony. In other words, we consider the case where the OEM's new product does not directly compete with the remanufactured products by the two IRs, perhaps because they belong to different technological generations. For example, the price of a new iPhone is set by Apple at a fixed level upon its introduction in the market, and that price is maintained until the introduction of the next generation of iPhones, regardless of the presence of remanufactured offerings of previous generations of iPhones. We emphasize that our paper is not meant to capture the exact reality of such markets, but it is rather a tractable abstraction that allows us to derive a significant theoretical insight. We use the term *consumers* for potential buyers of remanufactured products on the secondary market. Consumers from which both firms can acquire used products are referred to as *sellers*.

The two IRs, IR1 and IR2, compete on both acquisition of used products, as well as sales of remanufactured products in a vertically differentiated market. We focus on a single period of an infinite planning horizon, where the decisions are identical across periods. This setting is an abstraction of reality, but it is standard in the CLSC literature (see, e.g., Ray et al., 2005; Atasu et al., 2008; Souza, 2013; Örsdemir et al., 2014; Agrawal et al., 2016; Abbey et al., 2017).

We first describe the competition on the demand side of the market. Without loss of generality, IR1 has a market advantage as follows. The market size for remanufactured products is normalized to one. Consumers are differentiated in their willingness-to-pay (WTP) for the remanufactured product by IR1, denoted by $\theta$, where $\theta \sim U[0,1]$. In addition, a consumer of type $\theta$ has a WTP $\gamma\theta$ for the remanufactured unit by IR2, where $\gamma < 1$ is the *discount factor*, and it is assumed *constant* across consumers. Such consumer preference model is common in the CLSC literature, and in fact, it is identical to that of Majumder & Groenevelt (2001) and Ferrer & Swaminathan (2006).

As a result of this assumption, a consumer of type $\theta$ has net utility $\theta - p_{r1}$ for IR1's product, and $\gamma\theta - p_{r2}$ for IR2's product. Setting the two utilities to equality yields the consumer $\theta_{12} = \frac{p_{r1}-p_{r2}}{1-\gamma}$ that is indifferent between the two products. In addition, the consumer of type $\frac{p_{r2}}{\gamma}$ is indifferent between buying IR2's product and buying nothing. This market segmentation is shown in Figure 1, top. Considering the uniform distribution for $\theta$, the demand for IR1's product is then $q_{r1} = 1{\cdot}\Pr\{\theta \geq \theta_{12}\} = 1 - \frac{p_{r1}-p_{r2}}{1-\gamma}$, whereas the demand for IR2's product is $q_{r2} = 1{\cdot}\Pr\{\frac{p_{r2}}{\gamma} \leq$

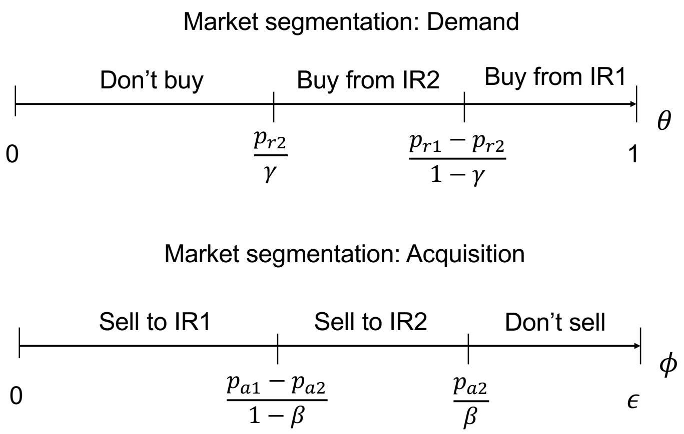



Figure 1: Market segmentation: demand (top) and supply acquisition (bottom)

$\theta \leq \theta_{12}\} = \frac{p_{r1}-p_{r2}}{1-\gamma} - \frac{p_{r2}}{\gamma}$. The respective inverse demand functions are $p_{r1} = 1-q_{r1}-\gamma q_{r2}$ and $p_{r2}=\gamma(1-q_{r1}-q_{r2})$ (e.g., Debo et al., 2005; Bulmus et al., 2014b; Abbey et al., 2017).

We now describe the competition on the supply side, for the acquisition of used products. Each seller has his/her own idiosyncratic valuation for his/her used product, or willingness-to-sell (WTS) for the used product. Sellers can sell their used products to either IR2 or IR1, but one is perceived to be more convenient than the other. For example, IR2 may have a strength in the collection, and offers quicker cash payments; similarly for a situation where IR1 has strength in the collection. To model this situation, denote by $\phi$ a seller's WTS to IR1 for his/her product, where $\phi \sim U[0,\epsilon]$. It is reasonable to set $\epsilon < 1$, since the maximum WTP for IR1's product is 1. We then assume that such seller of type $\phi$ has a WTS to IR2 for his/her used product equal to $\beta\phi$, where $\beta$ is assumed to be constant across sellers. If $\beta < 1$, then IR2 has an advantage in the collection—the seller is happy to be paid less for his/her used product, as IR2 makes it more convenient for him/her to sell the used product. Conversely, if $\beta > 1$, then IR1 has an advantage in the collection. We first present the analysis for the more interesting case where $\beta < 1$, when IR1 has a market advantage, whereas IR2 has an acquisition advantage. The case $\beta > 1$, when IR1 has both market and acquisition advantages, is presented in Section 5.

The total number of used products for acquisition in each period is exogenous and given by $a$. Because the market for remanufactured products is equal to one, we assume $a < 1$ to consider the interesting case where there is competition for the acquisition of used products. A seller of type $\phi$ has net utility $p_{a1} - \phi$ for selling the used product to IR1, and $p_{a2} - \beta\phi$ for selling to IR2. Setting the two utilities to equality yields the seller $\phi_{oi} = \frac{p_{a1}-p_{a2}}{1-\beta}$ that is indifferent between the two firms. Also, the seller of type $\frac{p_{a2}}{\beta}$ is indifferent between selling to IR2 and keeping the product. In the absence of other considerations, IR2 would not need to set its acquisition price higher than the maximum WTS of a seller to IR2, $\beta\epsilon$. Consider this possibility first, $p_{a2} \le \beta\epsilon$, as illustrated in Figure 1, bottom, so that the acquisition quantities are:

$$q_{a1} = a \cdot \Pr\{0 \le \phi \le \frac{p_{a1} - p_{a2}}{1-\beta}\} = \frac{a}{\epsilon}\left(\frac{p_{a1} - p_{a2}}{1-\beta}\right), \tag{1}$$

$$q_{a2} = a \cdot \Pr\{\frac{p_{a1} - p_{a2}}{1-\beta} \le \phi \le \frac{p_{a2}}{\beta}\} = \frac{a}{\epsilon}\left(\frac{p_{a2} - \beta p_{a1}}{\beta(1-\beta)}\right). \tag{2}$$

Similar acquisition quantity expressions are found in Liu et al. (2016) and Li et al. (2017), who also consider differentiated acquisition. These relationships hold for $p_{a1} \ge p_{a2} \ge \beta p_{a1}$, ensuring non-negative quantities. If $p_{a1} < p_{a2}$, a seller's net utility is always lower when selling to IR1 than when selling to IR2, so that the resulting quantities are $(q_{a1}, q_{a2}) = (0, \frac{a}{\epsilon}\frac{p_{a2}}{\beta})$. Such quantities are independent of $p_{a1}$, and are the same as their respective functional values in (1)-(2) when $p_{a1} = p_{a2}$. Thus, both players are indifferent among all solutions where $p_{a1} \le p_{a2}$ for any given $p_{a2}$, as they have the same collection cost and quantities; such solutions are thus subsumed by the solution where $p_{a1} = p_{a2}$, which is allowed in (1)-(2). In other words, all solutions where $p_{a1} < p_{a2}$ can be excluded from the analysis. Similarly, if $\beta p_{a1} > p_{a2}$, the quantities are $(q_{a1}, q_{a2}) = (\frac{a}{\epsilon}p_{a1}, 0)$, which are independent of $p_{a2}$ and are the same as their respective functional values when $\beta p_{a1} = p_{a2}$. Hence, all solutions where $\beta p_{a1} > p_{a2}$ can also be excluded from the analysis because they result in the same profits as the solution where $\beta p_{a1} = p_{a2}$, which is allowed in (1)-(2). Note that this formulation (1)-(2), valid when $p_{a2} \le \beta\epsilon$, implies that the acquisition quantities are linearly related to acquisition prices, as in Bakal & Akcali (2006), Esenduran et al. (2019), Guide et al. (2003), Li et al. (2017) and Pazoki & Zaccour (2019).

Given its advantage on the acquisition side when $\beta < 1$, however, IR2 may find it beneficial to increase its price $p_{a2}$ beyond $\beta\epsilon$ to provide a more hostile environment for IR1, who has the demand side advantage. This outcome can indeed occur if such possibility is allowed, as we show below. We refer to this strategy, when $p_{a2} > \beta\epsilon$, as *excessive acquisition price*, because all used products are collected but at an even higher than needed price to convince all sellers to return their product. Similarly, it could also be possible for IR1 to offer an excessive acquisition price to keep IR2 out, that is, $p_{a1} > \epsilon$. As a result, $q_{a2} = \min[\frac{a}{\epsilon}\left(\frac{p_{a2}-\beta p_{a1}}{\beta(1-\beta)}\right), a - q_{a1}]$, where the second term reflects the possibility that $p_{a2} > \beta\epsilon$. These quantities are valid for $p_{a1} \ge p_{a2} \ge \max[\beta p_{a1}, p_{a1} - \epsilon(1-\beta)]$, and in the same way as before, solutions outside this interval can be excluded. Our notation is summarized in Table 1.

In terms of costs, IR1 and IR2 only incur the acquisition cost, and a remanufacturing cost that is linear in the acquisition quantities, that is, the unit remanufacturing cost $c_r$ is constant. For tractability, we assume $c_r$ to be the same across firms. In practice, this is justified in

Table 1: Notation

| | |
|---|---|
| **Parameters** | |
| $a$ | total number of available used products, $0 < a < 1$ |
| $c_r$ | unit cost of the remanufactured product $0 \leq c_r < 1$ |
| $\beta$ | hassle factor for returning cores to IR1 relative to IR2, $0 < \beta < 1$ or $\beta > 1$ |
| $\gamma$ | discount factor for WTP for the remanufactured product by IR2 relative to IR1, $0 < \gamma < 1$ |
| $\epsilon$ | maximum WTS, or used product valuation for a seller, $0 < \epsilon < 1$ |
| **Decision variables** | |
| $p_{ri}$ | selling price of the product remanufactured by IR$i$, $i \in \{1, 2\}$ |
| $p_{ai}$ | acquisition price for a used product by IR$i$, $i \in \{1, 2\}$ |
| **Auxiliary variables** | |
| $q_{ri}$ | quantity of remanufactured products sold by IR$i$, $i \in \{1, 2\}$ |
| $q_{ai}$ | quantity of used products acquired by IR$i$, $i \in \{1, 2\}$ |

some industries, for example, cell phone remanufacturing consists mostly of cosmetic repairs, software updates, or replacement of standard parts such as batteries. In these cases, it is unlikely that firms have significantly different remanufacturing costs. A constant $c_r$ implicitly assumes that the used products have similar qualities. When used products have different qualities, the firm remanufactures higher quality items first, resulting in an increasing unit remanufacturing cost. In other words, the total remanufacturing cost would be convex in the total quantity of remanufactured products. To test the robustness of our results, we consider a convex remanufacturing cost curve in the appendix and confirm the assumption's robustness: our insights hold. Thus, for parsimony, in our model below, we assume that the used products have similar qualities so that $c_r$ is interpreted as the average remanufacturing cost per unit.

IR1 and IR2 play a simultaneous game, which is defined by the following equations:

$$\max_{p_{r1}, p_{a1}} \quad \pi_1(p_{r1}, p_{a1}) = (p_{r1} - c_r) \cdot q_{r1} - p_{a1} \cdot q_{a1}, \tag{3}$$

$$s.t. \quad 0 \leq q_{r1} \leq q_{a1} \leq a, \tag{4}$$

$$\max_{p_{r2}, p_{a2}} \quad \pi_2(p_{r2}, p_{a2}) = (p_{r2} - c_r) \cdot q_{r2} - p_{a2} \cdot q_{a2}, \tag{5}$$

$$s.t. \quad 0 \leq q_{r2} \leq q_{a2} \leq a. \tag{6}$$

Additionally for both, $q_{a1} + q_{a2} \leq a$ must hold. The solution procedure to find the Nash equilibrium in this simultaneous game is standard: the Karush-Kuhn-Tucker (KKT) conditions for both players are solved simultaneously. All proofs are available upon request.

## 4. Analysis: IR2 has collection advantage ($\beta < 1$)

### *4.1. Characterization of equilibria*

We find that neither firm ever acquires excessive cores, i.e., $q_{aj} = q_{rj}, j \in \{1, 2\}$ always holds. This result is mostly driven by the assumption that there is no salvage value for products that are collected but not remanufactured. We relax this assumption in Appendix C, where we show that the key insights of our paper (Proposition 1 and Observation 1 below) hold under a positive salvage value for non-remanufactured returns, despite the fact that the equilibrium structure is much more complex. The equilibrium can be described along two dimensions: whether the collection of cores is full ($q_{a1} + q_{a2} = a$) or partial ($q_{a1} + q_{a2} < a$), and whether only IR1 participates in the markets (IR2 is preempted), or both firms compete. When both compete under full collection, we differentiate between the cases where IR1 offers an excessive acquisition price or not. We use the following naming convention: "P" means partial collection, "F" means full collection, "1" means only IR1 remanufactures, "b" means both IRs remanufacture, and "e" means excessive acquisition price. There are five equilibrium regions: F-1-e, F-b-e, F-b, P-1, and P-b. The full characterization of the equilibrium is indicated in the lemma below.

**Lemma 1.** *The equilibrium solution is described in Table A.4 in Appendix A, where in all regions, IR1's and IR2's profits are computed through* (3) *and* (5), *respectively. The conditions of occurrence in each of the regions are as follows (threshold values are given in Table A.4):*

1. *If* $\epsilon < \frac{(1-\gamma)(1-2a)}{2(1-\beta)}$, *then*
    - $c_r \leq A$: *full collection by IR1 only; IR1 offers excessive acquisition price (F-1-e),*
    - $c_r > A$: *partial collection by IR1 only (P-1).*
2. *If* $\frac{(1-\gamma)(1-2a)}{2(1-\beta)} \leq \epsilon$, *then*
    - $c_r \leq B$: *full collection by both; IR2 offers excessive acquisition price (F-b-e),*
    - $B < c_r \leq C$: *full collection by both (F-b),*
    - $C < c_r \leq D$: *partial collection by both (P-b),*
    - $c_r > D$: *partial collection by IR1 only (P-1).*

The five regions described in Lemma 1 immediately lead to the following proposition, which is a key insight in this paper.

**Proposition 1.** *An advantage on the market for remanufactured products is necessary to preempt the other player. In particular, the remanufacturer with a market advantage IR1 cannot be preempted by the remanufacturer with an acquisition advantage IR2. However, IR2 can be preempted by IR1.*

The solution is graphically illustrated in Figure 2 for two values of $\beta$. When $c_r < c_{r1}(a, \beta, \gamma, \epsilon)$, then there is full collection; otherwise, there is partial collection. According to Lemma 1, the threshold is given by $c_{r1}(a, \beta, \gamma, \epsilon) = A$ for small $\epsilon$ or $c_{r1}(a, \beta, \gamma, \epsilon) = C$ for larger values of $\epsilon$. Note from Figure 2 that $c_{r1}(a, \beta, \gamma, \epsilon)$ decreases in $\epsilon$: easier acquisition (lower values of $\epsilon$) implies that full collection and remanufacturing takes place at higher remanufacturing cost $c_r$. This is intuitive because product acquisition is a potentially costly aspect of remanufacturing.

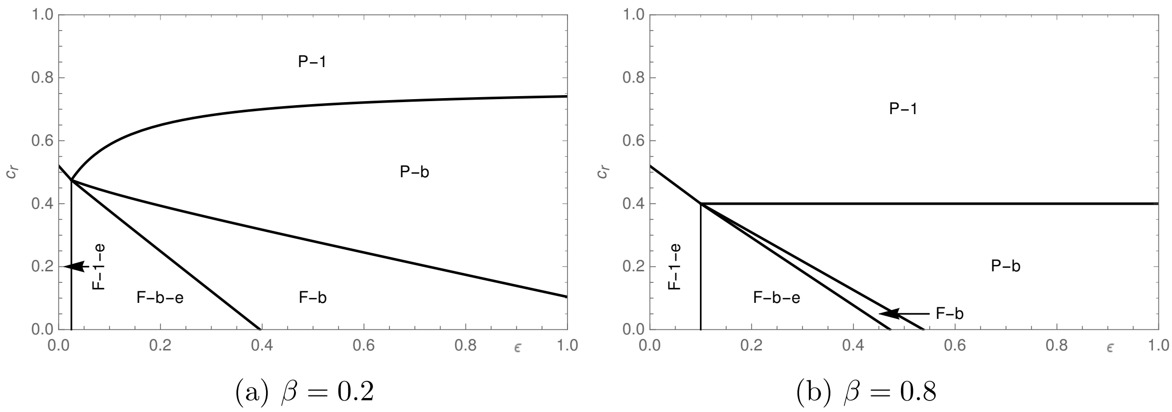


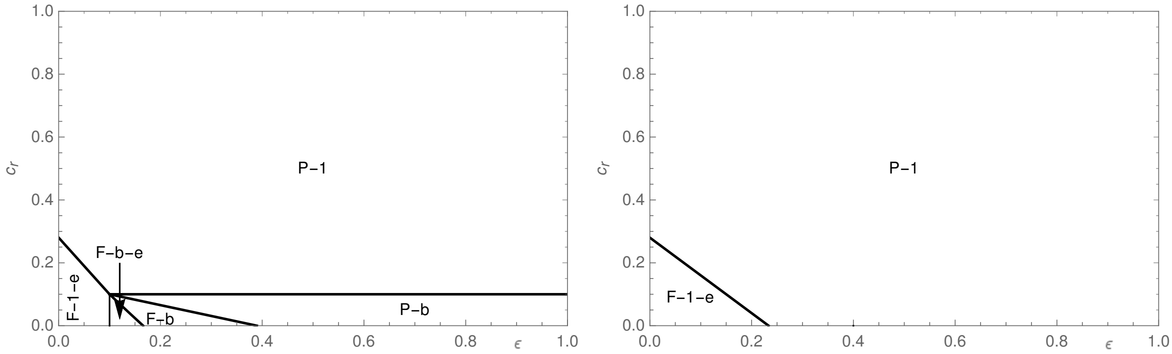

Figure 2: Illustration of solution regions for $a = 0.4$ and $\gamma = 0.8$

Now, note that when $\beta$ increases, as one moves from Figure 2(a) to (b), IR2's advantage in collection decreases, and hence the regions where both firms compete (F-b-e, F-b, and P-b) shrink. If IR1, with a market advantage, can also narrow the collection gap with IR2, then IR1 can drive IR2 out of the market in a broader range of scenarios.

With partial collection, only IR1 remanufactures if the unit remanufacturing cost $c_r$ is sufficiently high (region P-1 in the top part of Figure 2), as in that case IR2, given its market disadvantage $\gamma$, cannot compete with IR1, who can set a higher price for its remanufactured products to compensate for the high remanufacturing cost. For lower values of $c_r$ (region P-b in Figure 2), IR2 competes with IR1: remanufacturing is more attractive, including for IR2.

Under full collection, we have three regions: only IR1 remanufactures (F-1-e), and both firms compete (F-b-e and F-b). When $c_r$ is small and $\epsilon$ is relatively large, both IR1 and IR2 compete in regions F-b-e and F-b, although IR1 needs to offer a higher acquisition price due to its collection disadvantage. IR2's remanufactured product price is also lower, to allow it to successfully compete with IR1 given IR1's market advantage.

Note, however, that when both $c_r$ and $\epsilon$ are small, in region F-1-e, IR2 does not enter. This is interesting, as these are the most favorable conditions for remanufacturing: acquisition is easy, as sellers have lower valuations for their used products, and the unit remanufacturing cost is low. The reason for such result is because in this region IR2 cannot overcome IR1's dominant market position: given the low seller valuations (WTS), IR1 collects all cores through an excessive acquisition price $p_{a1} > \epsilon$, which is higher than needed for a full collection. At the same time, IR1 is able to price its remanufactured products low, due to the low remanufacturing cost, and relatively low acquisition cost (as $\epsilon$ is low), in a way that IR2 cannot profitably compete in the sales of remanufactured products given that it would need to charge an even lower price. Hence, when conditions are very favorable for remanufacturing, IR1 can preempt IR2 through




(a) $\beta = 0.2$ (b) $\beta = 0.8$

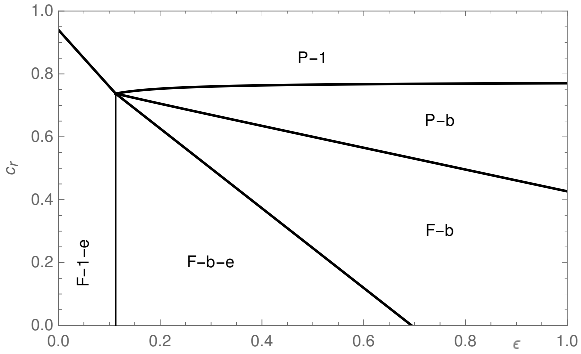
Figure 3: Illustration of solution regions for $a = 0.4$ and $\gamma = 0.2$

*aggressive acquisition.* In sum:

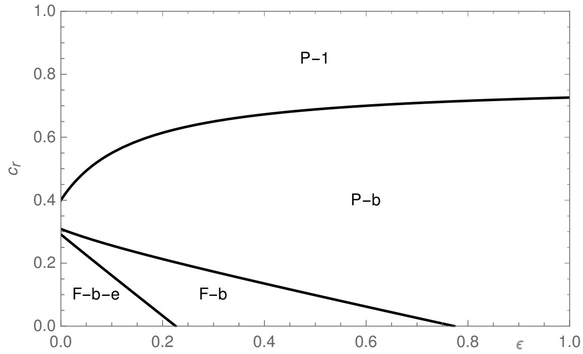
**Observation 1.** *When conditions for remanufacturing are most attractive (both in acquisition and remanufacturing costs), IR1 uses an aggressive acquisition strategy to counter IR2's acquisition advantage: it sets an excessive acquisition price, and uses its market advantage to price its remanufactured product at such a low level such that IR2 is not able to profitably compete.*

We now consider the impact of $\gamma$, which is the discount factor for IR2's remanufactured products. Intuitively, one would expect that for a lower value of $\gamma$, the region where IR2 also remanufactures is smaller. Indeed, Figure 3, where $\gamma = 0.2$, confirms this intuition; this figure can be directly compared with the previously discussed Figure 2, where $\gamma = 0.8$. Interestingly, when $\beta$ increases, as one moves from Figure 3(a) to (b), IR1's disadvantage in collection decreases, and hence the regions where both IR1 and IR2 compete (F-b-e, F-b, and P-b) disappear in this case, in which IR1's market advantage is very pronounced.

Finally, we now comment on the impact of $a$, the size of the pool of used products. As $a$ increases, the area of the regions with partial collection (P-1 and P-b) increases, since more used products become available for collection, and hence firms compete less on the acquisition. This is illustrated in Figure 4, where $a = 0.05$ in the left panel (a) and $a = 0.6$ in the right panel (b); this figure can directly be also compared with Figure 2(a), which has the same parameter values except that $a = 0.4$. Besides, a rising $a$ increases the partial collection region where both compete, hence favoring more heavily IR2, which has an advantage in the acquisition. As we show in the next subsection, IR2's acquisition price $p_{a2}$ decreases in $a$ in region P-b. Hence, an increase in $a$ decreases IR2's acquisition costs and makes remanufacturing more attractive for IR2, more so than for IR1, and thus widening the P-b region in Figure 4.




(a) $a = 0.05$




(b) $a = 0.6$

Figure 4: Impact of $a$ on solution regions ($\beta = 0.2$ and $\gamma = 0.8$)

*4.2. Comparative statics*

Now, we present some comparative statics, indicating how equilibrium prices and quantities behave with respect to changes in the key parameter values, one at a time. We offer the results formally below and then comment on the more interesting relationships.

**Proposition 2 (Comparative Statics).** *Table 2 indicates whether a row variable ($q_{a1}$, $q_{a2}$, $p_{a1}$, $p_{a2}$, $p_{r1}$ or $p_{r2}$) increases (↑) decreases (↓), or stays constant (=), as the column parameter ($a$, $c_r$, $\beta$, $\gamma$ or $\epsilon$) increases, within each of the five regions.*

From Proposition 2, we offer the following observation and then elaborate on it:

**Observation 2.** *An increase in $\beta$ or $\gamma$ reduces the competitive gap between the two firms, in acquisition and market, respectively. An increase in a firm's capability relative to the competitor (acquisition or market) generally prompts a relative increase in the respective price (acquisition or selling price), with a compensating adjustment on the other price to match supply and demand.*

To illustrate, consider what happens to IR1 when its acquisition disadvantage gap shrinks, in regions P-1 and F-b. As $\beta$ increases, IR1's acquisition price $p_{a1}$ increases, resulting in a larger acquisition quantity $q_{a1}$. To match the more abundant supply with demand, IR1 lowers its remanufactured product price $p_{r1}$ to increase demand. Now, an increase in IR2's market acceptance $\gamma$ in region F-b, for example, prompts IR2 to increase its selling price $p_{r2}$ (reducing demand) and reduce the acquisition price (and hence quantity) $p_{a2}$ to match supply and demand. We refer to this as a high-margin strategy. IR1, on the other hand, with a reduced market advantage, goes for a volume strategy: it lowers $p_{r1}$ (increasing demand) and increases $p_{a1}$ to match acquisition with increased demand.

Table 2: Comparative statics

| | $a$ | $c_r$ | $\beta$ | $\gamma$ | $\epsilon$ |
|---|---|---|---|---|---|
| $q_{a1}$ | $\uparrow$ | $=$ | $=$ | $=$ | $=$ |
| $p_{a1}$ | $\downarrow$ | $\downarrow$ | $\uparrow$ | $\uparrow$ | $\downarrow$ |
| $p_{r1}$ | $\downarrow$ | $=$ | $=$ | $=$ | $=$ |

(a) Full collection by IR1 only, IR1 offers excessive acquisition price (region F-1-e)

| | $a$ | $c_r$ | $\beta$ | $\gamma$ | $\epsilon$ |
|---|---|---|---|---|---|
| $q_{a1}$ | $\uparrow$ | $\downarrow$ | $\uparrow$ | $\uparrow$ | $\downarrow$ |
| $p_{a1}$ | $\downarrow$ | $\downarrow$ | $\uparrow$ | $\uparrow$ | $\uparrow$ |
| $p_{r1}$ | $\downarrow$ | $\uparrow$ | $\downarrow$ | $\downarrow$ | $\uparrow$ |

(b) Partial collection by IR1 only (region P-1)

| | $a$ | $c_r$ | $\beta$ | $\gamma$ | $\epsilon$ |
|---|---|---|---|---|---|
| $q_{a1}$ | $\uparrow\downarrow$ | $\downarrow$ | $\uparrow (\downarrow)$ | $\uparrow (\downarrow)$ | $\downarrow$ |
| $q_{a2}$ | $\uparrow$ | $\uparrow$ | $\downarrow (\uparrow)$ | $\downarrow (\uparrow)$ | $\uparrow$ |
| $p_{a1}$ | $\downarrow$ | $\downarrow$ | $\uparrow$ | $\uparrow (\downarrow)$ | $\uparrow$ |
| $p_{a2}$ | $=$ | $=$ | $\uparrow$ | $=$ | $\uparrow$ |
| $p_{r1}$ | $\downarrow$ | $\uparrow$ | $\downarrow (\uparrow)$ | $\downarrow$ | $\uparrow$ |
| $p_{r2}$ | $\downarrow$ | $=$ | $=$ | $\uparrow$ | $=$ |

(c) Full collection by both (region F-b).

| | $a$ | $c_r$ | $\beta$ | $\gamma$ | $\epsilon$ |
|---|---|---|---|---|---|
| $q_{a1}$ | $\uparrow$ | $=$ | $\uparrow$ | $\downarrow (\uparrow)$ | $\downarrow$ |
| $q_{a2}$ | $\uparrow$ | $=$ | $\downarrow$ | $\uparrow (\downarrow)$ | $\uparrow$ |
| $p_{a1}$ | $\downarrow$ | $\downarrow$ | $\downarrow (\uparrow)$ | $\uparrow (\downarrow)$ | $\uparrow (\downarrow)$ |
| $p_{a2}$ | $\downarrow$ | $\downarrow$ | $\uparrow$ | $\uparrow (\downarrow)$ | $\downarrow$ |
| $p_{r1}$ | $\downarrow$ | $=$ | $\downarrow$ | $\uparrow (\downarrow)$ | $\uparrow$ |
| $p_{r2}$ | $\downarrow$ | $=$ | $=$ | $\uparrow$ | $=$ |

(d) Full collection by both, IR2 offers excessive acquisition price (region F-b-e)

Here, $\uparrow\downarrow$ indicates that $q_{a1}$ first increases and then decreases as $a$ increases. Also, $\uparrow (\downarrow)$ indicates that the row variable increases with the column parameter for small to moderate values of $a$, but may decrease for larger values of $a$.

| | $a$ | $c_r$ | $\beta$ | $\gamma$ | $\epsilon$ |
|---|---|---|---|---|---|
| $q_{a1}$ | $\uparrow$ | $\downarrow$ | $\uparrow_n$ | $\downarrow_n$ | $\downarrow$ |
| $q_{a2}$ | $\uparrow_n$ | $\downarrow$ | $\downarrow_n$ | $\uparrow_n$ | $\downarrow_n$ |
| $p_{a1}$ | $\downarrow$ | $\downarrow$ | $\uparrow_n$ | $-$ | $\uparrow$ |
| $p_{a2}$ | $\downarrow_n$ | $\downarrow$ | $\uparrow_n$ | $\uparrow_n$ | $\uparrow_n$ |
| $p_{r1}$ | $\downarrow$ | $\uparrow$ | $\uparrow_n$ | $\downarrow_n$ | $\uparrow$ |
| $p_{r2}$ | $\downarrow$ | $\uparrow$ | $\uparrow_n$ | $\uparrow_n$ | $\uparrow$ |

(e) Partial collection by both (region P-b).

Here, a subscript $n$ indicates a relationship determined numerically.

The observations above focus on the firms' responses within an equilibrium region. As parameter values change in a broader range, however, the equilibrium may shift to another region, and we may encounter non-monotonic responses. For example, consider IR2's acquisition response to an increase in $c_r$ when $\epsilon = 0.4$ and $c_r = 0.2$ in Figure 2(a), when the equilibrium is F-b. As $c_r$ increases from 0.2 to 0.65, the equilibrium shifts from F-b to P-b, and hence, from Table 2(b) to (e), IR2 acquisition quantity $q_{a2}$ first increases (in region F-b) but then decreases (in region P-b). The latter response is what one expects without competition in the acquisition, as a higher remanufacturing cost would lead the firm to increase its sale price, but that does not occur when the equilibrium is in region F-b, where firms compete fiercely in the acquisition.

**Observation 3.** *Due to a possible shift in the equilibrium, firms may turn from a volume strategy (increase the acquisition and reduce sales prices) to a high-margin strategy (decrease the acquisition and increase sales prices) in response to an increase in remanufacturing costs, $c_r$. For example, IR2's acquisition quantity may first increase and then decrease with rising $c_r$.*

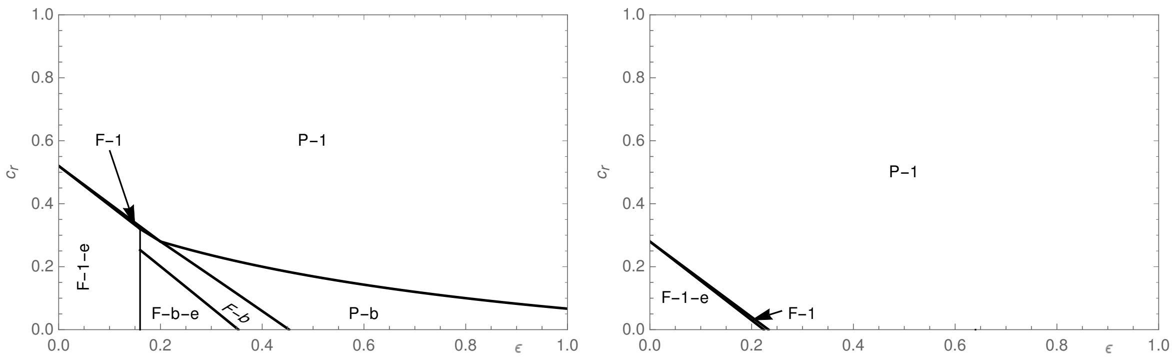
## 5. Analysis: IR1 also has a collection advantage ($\beta > 1$)

We now consider the case where IR1 also has a collection advantage ($\beta > 1$), in addition to its market advantage. In this case, a seller of type $\phi$, that is, one with WTS $\phi$ to IR1, has WTS $\beta\phi$ to IR2, where $\beta > 1$. This collection advantage enables IR1 to set an acquisition price lower than IR2, and so $p_{a1} \le p_{a2}$. Referring back to the market segmentation in the acquisition of Figure 1, the segmentation changes in that sellers with WTS $\phi$ between 0 and $\frac{p_{a2}-p_{a1}}{\beta-1}$ now sell to IR2, and hence the number of products acquired by IR2 is $q_{a2} = \frac{a}{\epsilon}\left(\frac{p_{a2}-p_{a1}}{\beta-1}\right)$. In addition, sellers with WTS between $\frac{p_{a2}-p_{a1}}{\beta-1}$ and $p_{a1}$ now sell to IR1, which would imply, in a derivation similar to that of Section 3, that the number of products acquired by IR1 would be $\frac{a}{\epsilon}\left(\frac{\beta p_{a1}-p_{a2}}{\beta-1}\right)$, as long as $p_{a1} < \epsilon$. Similarly to the case $\beta < 1$ discussed above, when $\beta > 1$ IR1 could offer an acquisition price higher than $\epsilon$, because with both market and collection advantages, this strategy could be used to reduce the number of used products acquired by IR2, and indeed this outcome is possible, as we show below. We again refer to this strategy — when $p_{a1} > \epsilon$ — as excessive acquisition price, because all used products are collected but at a higher than needed price to achieve full collection. As a result, $q_{a1} = \min\left[\frac{a}{\epsilon}\left(\frac{\beta p_{a1}-p_{a2}}{\beta-1}\right), a - q_{a2}\right]$, where the second term reflects the possibility where $p_{a1} > \epsilon$. The relationships hold for $p_{a1} \le p_{a2} \le \min[\beta p_{a1}, p_{a1} + \epsilon(\beta - 1)]$.

As before, we find that neither firm ever acquires excessive cores, i.e., $q_{aj} = q_{rj}, j \in \{1, 2\}$ always holds. We use the same naming convention as before, and now we have six different equilibrium regions: F-1, F-1-e, F-b-e, F-b, P-1, and P-b; the region F-1 is in addition to the scenario where $\beta < 1$. We formally state the solution of this game and comment on it below.

**Lemma 2.** *The equilibrium is described in Table A.5 in Appendix A, where in all regions, IR1's and IR2's profits are computed through* (3) *and* (5)*, respectively. The conditions of occurrence in each of the regions are described as follows (threshold values are given in Table A.5):*

1. *If* $\epsilon < \frac{(1-\gamma)(1-2a)}{\beta-1}$*, then*
   - $c_r \le E$*: full collection by IR1 only; IR1 offers excessive acquisition price (F-1-e),*
   - $E < c_r \le F$*: full collection by IR1 only (F-1),*
   - $F < c_r$*: partial collection by IR1 only (P-1).*
2. *If* $\frac{(1-\gamma)(1-2a)}{\beta-1} \le \epsilon < \frac{\beta(1-\gamma)(1-2a)}{\beta-1}$*, then*
   - $c_r \le G$*: full collection by both; IR1 offers excessive acquisition price (F-b-e),*
   - $G < c_r \le H$*: full collection by both (F-b),*
   - $H < c_r \le F$*: full collection by IR1 only (F-1),*
   - $F < c_r$*: partial collection by IR1 only (P-1).*
3. *If* $\epsilon \ge \frac{\beta(1-\gamma)(1-2a)}{\beta-1}$ *then*




(a) $\gamma = 0.8$ (b) $\gamma = 0.2$

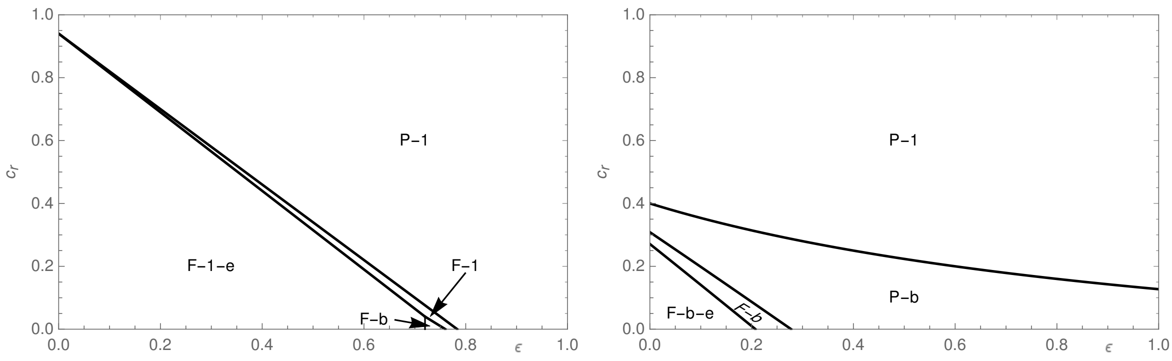
Figure 5: Illustration of solution regions for $a = 0.4$ and $\beta = 1.25$

- *$c_r \leq G$: full collection by both; IR1 offers excessive acquisition price (F-b-e),*
- *$G < c_r \leq I$: full collection by both (F-b),*
- *$I < c_r \leq J$: partial collection by both (P-b),*
- *$J < c_r$: partial collection by IR1 only (P-1),*

Similar to the case of $\beta < 1$, the regions where there is an excessive acquisition price reflect inefficiencies arising from the supply-side competition because the maximum of $a$ cores is already collected when $p_{a1} = \epsilon$. Increasing $p_{a1}$ above $\epsilon$ only increases acquisition costs without changing total supply; however, IR1's share of acquired products increases, because the quantity acquired by IR2 $q_{a2}$ decreases linearly in $p_{a1}$. IR1 can even drive IR2 out of the market if $p_{a1}$ is high enough. Note that, from Lemma 2, IR1 uses this strategy when both $\epsilon$ and $c_r$ are low, implying that conditions for buying and remanufacturing cores are highly attractive (to any player).

The solution is graphically illustrated in Figure 5, where the parameter values are similar to those of Figure 2, for two values of IR1's market advantage $\gamma$: (a) low ($\gamma = 0.8$), and (b) high ($\gamma = 0.2$). In general, the solution is consistent with the case $\beta < 1$. The new region F-1 is very small; instead, IR1 uses an excessive acquisition price strategy under a wider set of conditions to leverage its collection advantage, such that the region F-1-e is larger, as we see more clearly in other plots below. With a substantial advantage by IR1, both in the market and in the collection, conditions where IR2 competes with IR1, are significantly fewer, with a consequent increase in the region P-1, where there is partial collection by only IR1. These patterns are magnified for lower values of $\gamma$ when IR1's market advantage is more pronounced. The observation below summarizes this insight, which is parallel to Observation 1:

**Observation 4.** *When conditions for remanufacturing are most attractive (both in the acquisition and remanufacturing costs), and IR1 also has a collection advantage, it uses an excessive*




(a) $a = 0.05$

(b) $a = 0.6$

Figure 6: Impact of $a$ on solution regions ($\beta = 1.25$ and $\gamma = 0.8$)

*acquisition price to significantly restrict IR2's market share, and in many cases drive IR2 out of the market entirely. An excessive acquisition price is used less when IR1's market advantage is higher (i.e., $\gamma$ is lower).*

Figure 6 shows the impact of the size of the pool of used products $a$ on the structure of the solution, for the same values of $\gamma$ and $\beta$ as in Figure 5(a). When the used product pool size is very small at $a = 0.05$ (Figure 6(a)), the two firms compete fiercely for scarce cores, and hence IR1 uses an excessive acquisition price to keep IR2 out in a wide range of $c_r$ and $\epsilon$ values, that is, the region F-1-e is significantly larger. In addition, IR2 is only able to compete with IR1 in region F-b, under a very narrow set of scenarios: for middle values of $\epsilon$, which prevents IR1 from using excessive acquisition price, as it would hurt its profitability significantly, and when $c_r$ is very small so that IR2 can price its products at a correspondingly low level to be able to compete. At a large value of $a = 0.6$, as shown in Figure 6(b), cores are more abundant, and competition in the acquisition is not as fierce, so that IR1 chooses excessive acquisition pricing in a much smaller set of circumstances, but it is not able to keep IR2 out, region F-b-e. Besides, IR2 can compete with IR1 under a wide range of scenarios for $\epsilon$, the maximum WTS, as long as the unit remanufacturing cost $c_r$ is not too high. Finally, in most equilibria, there is partial collection. This can be summarized as follows:

**Observation 5.** *When IR1 also has a collection advantage, IR2 can compete with IR1 in a much broader set of conditions when the pool of used products $a$ is large, that is, when competition in the acquisition is not as fierce, and hence partial collection occurs often.*

We close this section by analyzing the impact of the acquisition advantage $\beta$ on the solution regions. To that end, we plot the regions as a function of $\beta$ and $c_r$, for both cases $\beta > 1$ and $\beta < 1$, which also illustrates the consistency of the two equilibrium solutions, particularly for $\beta$

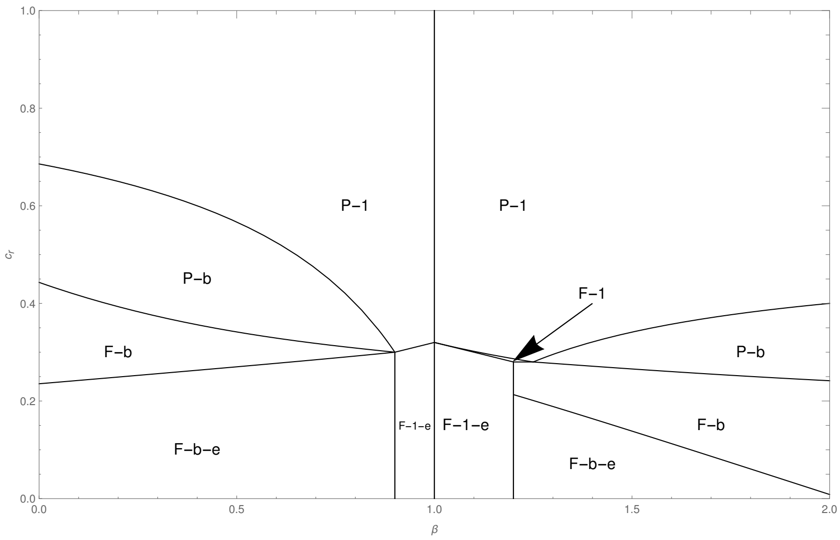



Figure 7: Impact of $\beta$ and $c_r$ on solution regions ($a = 0.4$, $\gamma = 0.8$, and $\epsilon = 0.2$)

values near one. This is shown in Figure 7 for $\gamma = 0.8$, $a = 0.4$, and $\epsilon = 0.2$. The middle line in the figure corresponds to the line $\beta = 1$, which divides the plot area into the two scenarios analyzed in the paper. When $\beta$ approaches one, neither player has a significant acquisition advantage, and that is when IR1 preempts IR2, with either an excessive acquisition price under full collection (when $c_r$ is low, F-1-e), or through its market advantage under partial collection (when $c_r$ is high, P-1). Further, excessive acquisition prices only occur for low values of $c_r$, as this allows firms to still provide a competitive selling price despite the increased acquisition costs associated with excessive acquisition prices. Finally, as $\beta$ moves further from one, there is less of a need for the firms to use an excessive acquisition price, as their respective acquisition advantage becomes more pronounced.

## 6. Numerical study

In this section, we provide the results of a numerical study, whose main objective is to show the impact of the key parameters $a$, $\epsilon$, $c_r$, $\beta$, and $\gamma$ on the magnitude of profits for the two players. This allows us to highlight the most critical parameters, and hence provide insights into where firms should invest their resources. For example, would an improvement in relative WTP $\gamma$ for IR2 result in higher gains relative to a corresponding increase in relative WTS $\beta$? Is reducing $c_r$ more important than expanding marketing efforts to improve relative WTP $\gamma$? We focus our study on the more interesting case where $\beta < 1$, so that IR2 has an advantage in the acquisition, but IR1 has a market advantage.

As all the key parameters are normalized between 0 and 1, we conduct a full factorial experimental design, where we vary all parameters $a$, $\epsilon$, $c_r$, $\beta$, and $\gamma$ in the general levels

Table 3: Number of equilibria observed as a function of $\gamma$ and $\beta$

| $\gamma$ levels | Equilibria F-b | F-b-e | F-1-e | P-b | P-1 | $\beta$ levels | Equilibria F-b | F-b-e | F-1-e | P-b | P-1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.2 | 0 | 0 | 8 | 0 | 312 | 0.2 | 16 | 21 | 2 | 120 | 161 |
| 0.4 | 1 | 0 | 10 | 29 | 280 | 0.4 | 5 | 19 | 2 | 127 | 167 |
| 0.6 | 3 | 11 | 9 | 62 | 235 | 0.6 | 0 | 16 | 5 | 99 | 200 |
| 0.8 | 7 | 17 | 6 | 137 | 153 | 0.8 | 0 | 13 | 10 | 85 | 212 |
| 0.99 | 10 | 43 | 2 | 233 | 32 | 0.99 | 0 | 2 | 16 | 30 | 272 |
| All | 21 | 71 | 35 | 461 | 1012 | All | 21 | 71 | 35 | 461 | 1012 |

$\{0.2, 0.4, 0.6, 0.8\}$. For the parameters $\beta$ and $\gamma$, we also add the level 0.99 to simulate conditions where IR1 and IR2 have little differentiation in acquisition and market, respectively. Note that the study is "symmetric" regarding the relative advantage of the two players. Specifically, the market parameters $a$ and $\epsilon$ and the unit remanufacturing cost $c_r$ are common to both players. However, the relative IR1 market and IR2 acquisition advantage parameters $\gamma$ and $\beta$ are varied at the same levels, thus resulting in a symmetrical study. This setting yields an experimental design with $4^3 \cdot 5^2 = 1600$ experimental cells, covering a wide variety of conditions. As all of our results are given in closed-form according to Lemma 1, we conduct all calculations using Excel and use R to analyze the results.

We first provide an overview of the frequency of equilibria observed, as well as the profitability of IR1 and IR2 in each of them, on average. As $\gamma$ and $\beta$ are two critical parameters that differentiate the two players, Table 3 tabulates the number of observed equilibrium types as a function of the various levels of $\gamma$ and $\beta$. From the table, we make a few observations. First, most of the equilibria consist of partial collection: P-1 and P-b, with 1012 (63%) and 461 (29%) of observations, respectively; the full collection cases F-b, F-b-e, and F-1-e consist of only 8% of observations. Full collection when both players compete F-b and F-b-e are observed at higher levels of $\gamma$ and lower values of $\beta$, when IR2 is more competitive. Second, IR2 does not compete when $\gamma = 0.2$: there are no observed equilibria F-b, F-b-e, or P-b. Hence, when IR2 has a severe market disadvantage, it cannot compete even if it has a similar relative strength of advantage on acquisition ($\beta = 0.2$). In general, IR2 can compete in 553 out of the 1600 cases, or 35%, when the resulting equilibrium is either F-b, F-b-e, or P-b. Hence, in 65% of the cases, IR1 preempts IR2 with its market advantage, even when it has a significant collection disadvantage. These results also illustrate Proposition 1.

Figure 8 presents the average profit for each player for each type of equilibrium outcome. From the figure, average IR1 profit across all 1600 instances ("Overall") is more than double that of IR2 in the 553 instances when IR2 can compete (the average profit for IR2 does not

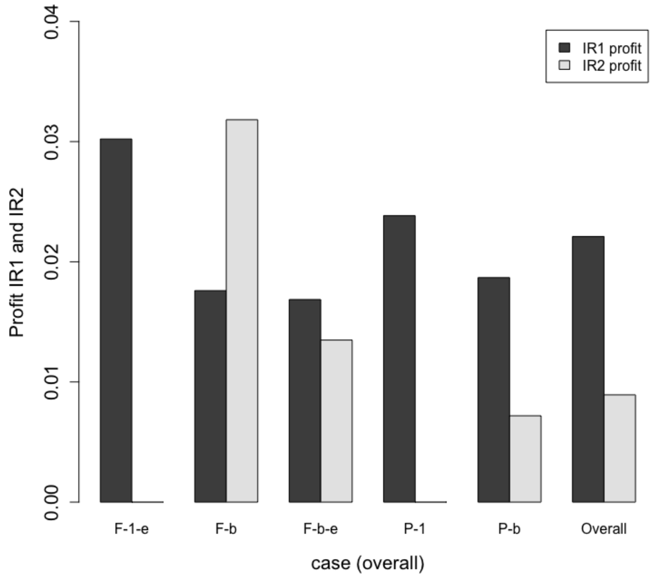
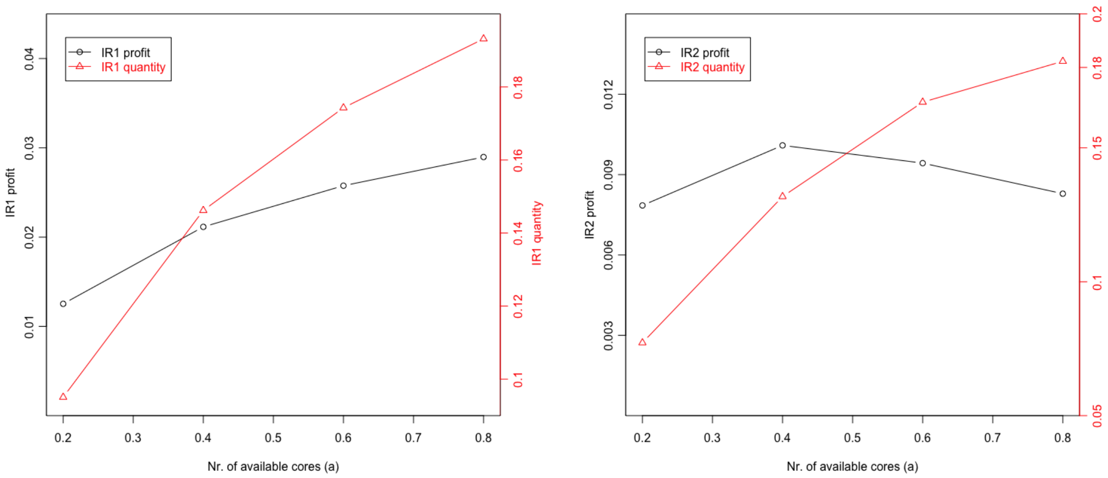



Figure 8: Average profit for IR1 and IR2 in each equilibrium type

include the instances where only IR1 remanufactures). This again confirms the insight that IR1's market advantage results in higher profits than IR2's acquisition advantage. It is also clear that IR1 has a higher average profit in the cases where it preempts IR2: F-1-e and P-1, and it has slightly lower than average profit when it competes with IR2. Interestingly, there is one type of equilibrium where IR2's average profit is significantly higher than IR1: F-b. As shown in Table 3, however, instances where the equilibrium F-b is observed correspond to only 21 out of 1600 instances or 1.3%. And these instances are precisely the ones where IR2's acquisition advantage is very pronounced while it's market handicap is not as severe: the average values of $\beta$ and $\gamma$ are 0.25 and 0.84, respectively, across the 21 instances. This can also be seen in Table 3, which shows the distribution of F-b occurrences for the different levels of $\gamma$ (mostly at 0.99 and 0.8) and $\beta$ (either 0.2 or 0.4).

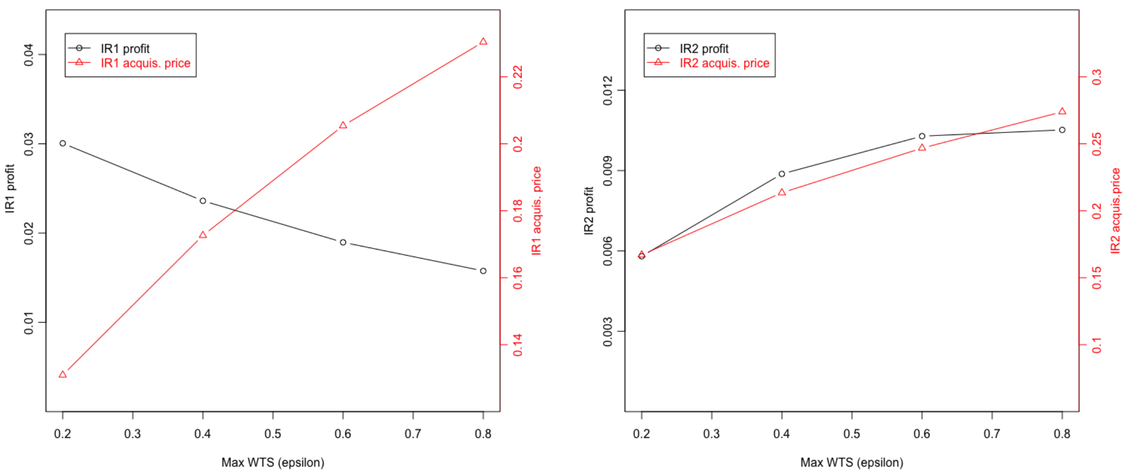
We now provide insights into the magnitude of the impact of the parameters on each player's profit. For each parameter, we plot the average profit for IR1 and IR2 as a function of the parameter level, and we also plot the key decision variable that explains this profit variation. We note that all variables in all figures are plotted in the same scale for each player, that is, the scale of profits for IR1 is always the same in all figures, as are the scales for other variables such as IR1 acquisition prices. This allows an easy visual comparison into the strength of each parameter in impacting profit.

First, consider $a$, the number of available cores. For a given level of $a$, for example, 0.2, we plotted the average of the 400 occurrences where $a = 0.2$ occurs. As $a$ increases, one would expect the acquisition (and remanufacturing) quantity to increase for both players, given




(a) IR1 (b) IR2

Figure 9: Impact of $a$ on IR1 and IR2 profit and acquisition quantities

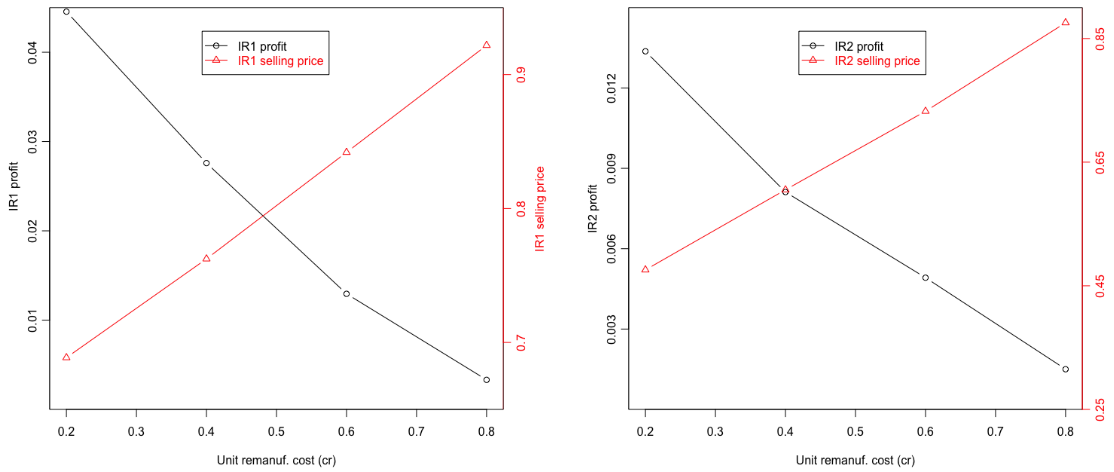



(a) IR1 (b) IR2

Figure 10: Impact of $\epsilon$ on IR1 and IR2 profit and acquisition prices

the higher availability of cores, and Figure 9 confirms this. The increase in acquisition and remanufacturing quantities means lower selling prices $p_{r1}$ and $p_{r2}$. In fact, as $a$ increases from 0.2 to 0.8, $p_{r1}$ decreases from 0.85 to 0.64, whereas $p_{r2}$ decreases from 0.72 to 0.53. As competition in acquisition becomes less intense as $a$ increases, IR1 leverages its market advantage to increase its profits, as shown in Figure 9(a). IR2's profit has an inverted-U relationship with $a$, as shown in Figure 9(b): at low levels of $a$, an increase in acquisition quantity increases IR2's profit as it results in larger sales despite the lower selling price; further increases in $a$ result in a decline in IR2's profit because the effect of the resulting price decrease to compete with IR1 outweighs the positive impact of the sales quantity increase.

Next, we consider the impact of the maximum consumer WTS $\epsilon$, shown in Figure 10. As one would expect, as $\epsilon$ increases, acquisition prices for both players should increase, as consumers




(a) IR1 (b) IR2

Figure 11: Impact of $c_r$ on IR1 and IR2 profit and selling prices

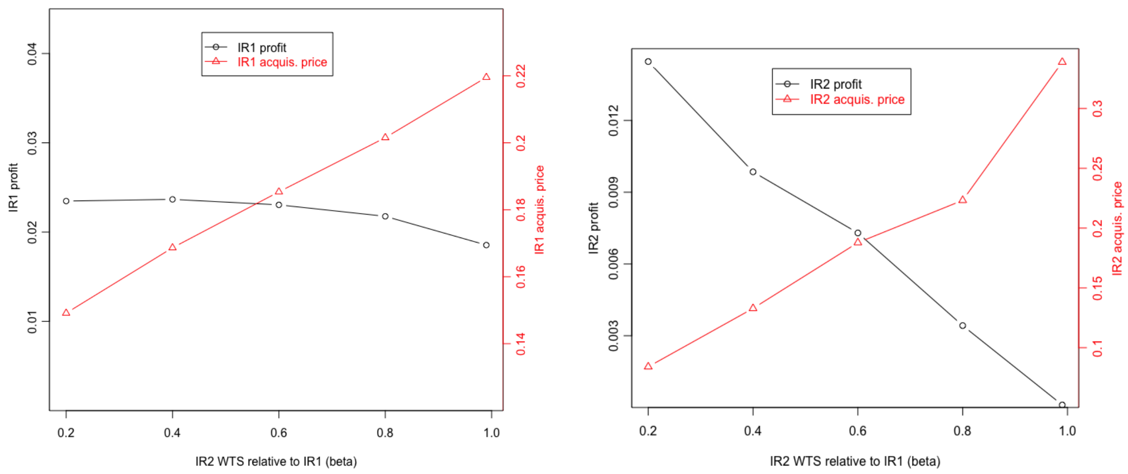
have higher reservation prices for their used products, and Figure 10 confirms this. Note that this higher acquisition price impacts IR1 negatively whereas it impacts IR2 positively, as IR2 has an acquisition advantage: IR1's profit decreases in $\epsilon$, while IR2's profit increases in $\epsilon$.

Figure 11 shows that an increase in the unit remanufacturing cost $c_r$ has a significant negative impact on both players' profitability: it requires them to increase their selling prices to reflect the higher costs, which lowers the selling quantities. Thus, an increase in $c_r$ results in a double negative impact: a decrease in the unit margin, as well as a decrease in the overall sales quantity.

Now, consider the impact of IR2 WTS relative to IR1 $\beta$. As $\beta$ increases, IR2's acquisition advantage decreases; as a result, IR2's profit decreases, which is shown in Figure 12(b). Interestingly, IR1's profit also decreases, as shown in Figure 12(a). This surprising result is because as $\beta$ increases, acquisition becomes more expensive for both players, since a larger reservation price for consumers results in higher acquisition prices.

Finally, consider the impact of IR2 WTP relative to IR1, $\gamma$. As $\gamma$ increases, IR1's market advantage decreases, and hence, its profit should decrease while IR2's profit should increase; Figure 13 confirms that. The underlying mechanism is that a higher $\gamma$ means IR2 can charge higher selling prices, while IR1 must reduce its selling price to be competitive. At $\beta = 0.99$, the players have similar market strength. However, IR2 still holds an acquisition advantage overall, and therefore, IR1's average profit is 0.0023, which is significantly smaller than that of IR2 at 0.01.

Because the figures were plotted on the same vertical scale for each player, a simple scan of Figures 9-13 allows one to quickly see which are the parameters of the most impact on each player's profit. For IR1, it is clear that $c_r$ and $\gamma$ have the most impact on its profit, followed




(a) IR1 (b) IR2

Figure 12: Impact of $\beta$ on IR1 and IR2 profit and acquisition prices

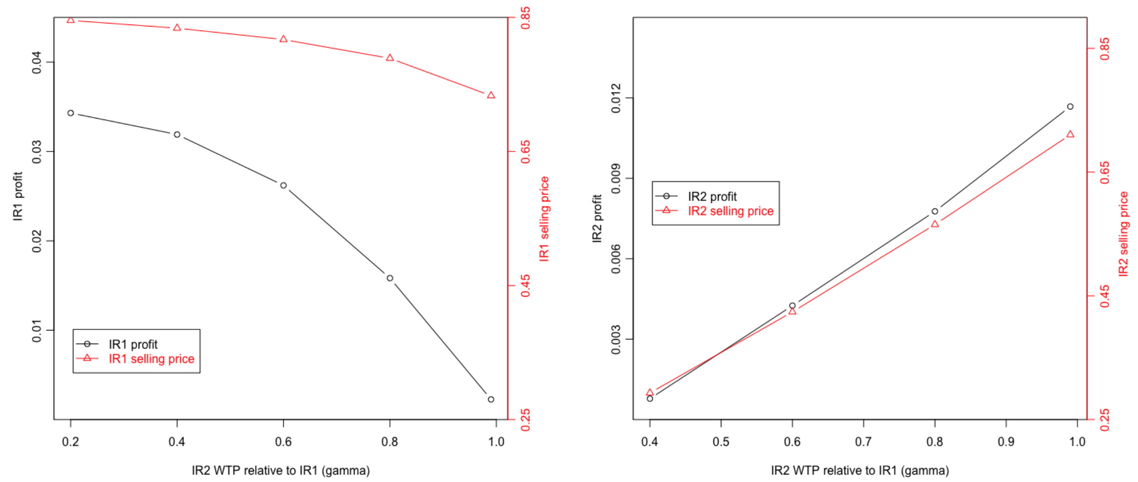
by the market parameters $a$ and $\epsilon$, which have a similar effect, and then to a lesser extent $\beta$. For IR2, $\beta$, $\gamma$,and $c_r$ all have significant impacts on its profitability, followed by the market parameters $a$ and $\epsilon$. The same conclusion can be reached by running two multiple regressions, one for each player, where the independent variable is profit, and the dependent variables are the parameters; we omit the results for briefness. This leads to another observation:

**Observation 6.** *To increase their profitability, both players should actively pursue opportunities to decrease their remanufacturing cost (e.g., through process improvement or automation). Besides, IR1 should focus its resources on highlighting its brand advantage over IR2, since reducing its acquisition disadvantage has a much lower impact on IR1's profitability. For IR2, improving its brand advantage in both market and acquisition are necessary.*

## 7. Conclusion

In this paper, we have studied the two-sided competition between two differentiated firms in both the acquisition of used products and sales of remanufactured products. This problem is common in several industries, in particular in the mobile phone industry. In our model, we denote the player with a market advantage as IR1. On the acquisition side, we consider the cases where either player has an advantage.

The key finding in our paper is that a market advantage is much more critical than an acquisition advantage. Specifically, IR1 can preempt IR2 from competing even when IR1 has an acquisition disadvantage, whereas there is no equilibrium where IR2 preempts IR1. Also, IR1 preempts IR2 precisely when the conditions for remanufacturing are the most attractive: consumers have lower reservation prices for their used products, implying less expensive acquisition




(a) IR1 (b) IR2

Figure 13: Impact of $\gamma$ on IR1 and IR2 profit and selling prices

costs, and unit remanufacturing costs are low. In a comprehensive numerical study designed to be symmetrical to the relative advantage of each player, we find that IR2 is only able to compete in 35% of the instances, and so IR1 can preempt IR2 in 65% of the instances. In addition, IR1's profit is more than double, on average, IR2's profit in the circumstances where IR2 is able to compete. An exception is the case where there is full collection of all used products, but that corresponds to only 1.3% of the numerical observations, corresponding to cases where IR2's relative acquisition advantage is much higher than IR1's comparative market advantage.

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## Appendix A. Description of the equilibrium solutions and threshold values

The equilibrium solutions are shown in Tables A.4 and A.5.

## Appendix B. The case of quadratic remanufacturing cost

In this section, we revisit our model with $\beta < 1$ under a quadratic remanufacturing cost function, to more accurately reflect the difference in conditions of used products. With all else equal, we now assume that total remanufacturing cost is given by $c_r q_r + \delta q_r^2$, where $\delta$ is a shape parameter that models the magnitude of these differences in used product qualities. When $\delta = 0$, we have our original model with linear remanufacturing cost. The following lemma presents the main analytical result, and the proof is available from the authors.

**Lemma 3.** *The equilibrium regions under quadratic remanufacturing cost are characterized by the following conditions of occurrence:*

1. *If* $\epsilon < \frac{(1-\gamma)(1-2a)-2a\delta}{2(1-\beta)}$*, then*
   - $c_r \leq A'$*: full collection by IR1 only, IR1 offers excessive acquisition price (F-1-e),*
   - $c_r > A'$*: partial collection by IR1 only (P-1).*
2. *If* $\frac{(1-\gamma)(1-2a)-2a\delta}{2(1-\beta)} \leq \epsilon$*, then*
   - $c_r \leq B'$*: full collection by the both, IR2 offers excessive acquisition price (F-b-e),*
   - $B' < c_r \leq C'$*: full collection by the both (F-b),*
   - $C < c_r \leq D'$*: partial collection by the both (P-b),*
   - $c_r > D'$*: partial collection by IR1 only (P-1).*

*where* $A' = 1 - a(2-\gamma) - \epsilon(2-\beta) - 2a\delta$,
$B' = \frac{2\left(-2a^2(\delta(\delta-2\gamma+6)-3\gamma+3)+a(\delta(4(\beta-1)\epsilon-\gamma+5)-2(\beta-1)\epsilon(2\gamma-5)-3\gamma+3)+(\beta-1)\epsilon(-2(\beta-1)\epsilon+\gamma-4)\right)}{4a\delta-a(\gamma-1)(\gamma+2)-3(\beta-1)\epsilon} + \frac{\delta(a(2a-3)\delta+2(\beta-1)\epsilon)}{2(a(3\delta-2\gamma+2)-2(\beta-1)\epsilon)} + \frac{1}{2}(-2a\delta+8a-2\beta\epsilon+\delta-4)-(a-1)\gamma$, $C' = \frac{3a(1-\gamma)\gamma-a^2(4-\gamma)(1-\gamma)\gamma-a(\beta(2-\gamma)+2\gamma)(2-\beta-\gamma)\epsilon+(1-\beta)\epsilon(\beta+2\gamma-(4-\beta)\beta\epsilon)}{a(2-\gamma-\gamma^2)+(2-\beta-\beta^2)\epsilon+4a\delta} + \frac{a(2\delta-2(2-\beta)(\delta(1+\beta))\epsilon+2\delta\gamma)-a^2(4\delta(1+\delta)+2\delta\gamma-2\delta\gamma^2)}{a(2-\gamma-\gamma^2)+(2-\beta-\beta^2)\epsilon+4a\delta}$*, and* $D' = \frac{a(1-\gamma)\gamma-(\beta-(2-\beta)\gamma)\epsilon+2a\gamma\delta}{2a(1-\gamma)+2(1-\beta)\epsilon+2a\delta}$.

In sum, the solution is structurally very similar to the solution under linear remanufacturing cost. This can also be seen numerically, through Figures B.14 and B.15, which compare the solutions of our original model (where $\delta = 0$, already shown in Figure 2 but repeated here for ease of comparison), with the solution under quadratic remanufacturing cost with various levels of $\delta$: 0.01, 0.02, and 0.1. As perhaps one would expect, an increase in $\delta$ shifts all thresholds down and left in the figures, thus reducing the regions with full collection.

Table A.4: Acquisition and remanufacturing quantities and prices in the different solution regions when $\beta < 1$

| | **Full collection** | **Full collection with excessive acquisition price** | |
|---|---|---|---|
| | IR1 and IR2 (F-b) | IR1 only (F-1-e) | IR1 and IR2 (F-b-e) |
| $q_{a1}$ | $\frac{a(1-c_r-a\gamma-\beta\epsilon)}{2a(1-\gamma)+2(1-\beta)\epsilon}$ | $a$ | $\frac{a((1-\beta)\epsilon+(1-\gamma)(1+a\gamma))}{3(1-\beta)\epsilon+a(2-\gamma-\gamma^2)}$ |
| $q_{a2}$ | $q_{a1}-\frac{a(1-c_r-a-\epsilon)}{a(1-\gamma)+(1-\beta)\epsilon}$ | n.a. | $\frac{a(2(1-\beta)\epsilon+2a(1-\gamma)+\gamma-1)}{3(1-\beta)\epsilon+a(2-\gamma-\gamma^2)}$ |
| $p_{a1}$ | $\beta\epsilon+\frac{\epsilon(1-\beta)(1-c_r-a\gamma-\beta\epsilon)}{2a(1-\gamma)+2(1-\beta)\epsilon}$ | $1-c_r-\epsilon(1-\beta)-a(2-\gamma)$ | $\frac{(1-\beta)\epsilon(2-3c_r-(1-\beta)\epsilon+\gamma)-a^2(4-\gamma)(1-\gamma)\gamma+a(3(1-\gamma)\gamma-(1-\beta)\epsilon(2+(2-\gamma)\gamma)-c_r(2-\gamma-\gamma^2))}{3(1-\beta)\epsilon+a(2-\gamma-\gamma^2)}$ |
| $p_{a2}$ | $\beta\epsilon$ | n.a. | $\frac{(1-\beta)\epsilon(1-3c_r-2(1-\beta)\epsilon+2\gamma)-a^2(4-\gamma)(1-\gamma)\gamma+a(3(1-\gamma)\gamma-(1-\beta)\epsilon(2+(3-2\gamma)\gamma)-c_r(2-\gamma-\gamma^2))}{3(1-\beta)\epsilon+a(2-\gamma-\gamma^2)}$ |
| $p_{r1}$ | $p_{a1}+c_r+\frac{1-c_r-a\gamma-\beta\epsilon}{2}$ | $1-q_{a1}$ | $\frac{3(1-\beta)\epsilon-3a^2(1-\gamma)\gamma+a(1-(1-\beta)\epsilon-\gamma)(1+2\gamma)}{3(1-\beta)\epsilon+a(2-\gamma-\gamma^2)}$ |
| $p_{r2}$ | $\gamma(1-(q_{a1}+q_{a2}))=\gamma(1-a)$ | n.a. | $\gamma(1-a)$ |

| | **Partial collection** | |
|---|---|---|
| | IR1 only (P-1) | IR1 and IR2 (P-b) |
| $q_{a1}$ | $\frac{a(1-c_r)}{a(2-\gamma)+(2-\beta)\epsilon}$ | $\frac{a(a(2-c_r)(1-\gamma)\gamma+2\beta\epsilon-\beta(c_r+\beta-c_r\beta+\gamma)\epsilon)}{a^2(4-\gamma)(1-\gamma)\gamma+a(\beta(2-\gamma)+2\gamma)(2-\beta-\gamma)\epsilon+(4-\beta)(1-\beta)\beta\epsilon^2}$ |
| $q_{a2}$ | n.a. | $\frac{a(-a(2c_r-\gamma)(1-\gamma)-(2c_r(1-\beta)-2\gamma+\beta(1+\gamma))\epsilon)}{a^2(4-\gamma)(1-\gamma)\gamma+a(\beta(2-\gamma)+2\gamma)(2-\beta-\gamma)\epsilon+(4-\beta)(1-\beta)\beta\epsilon^2}$ |
| $p_{a1}$ | $\frac{\epsilon}{a}q_{a1}$ | $\frac{\epsilon(a(-1+\gamma)(-(2+\beta)\gamma+c_r(2\beta+\gamma))-(-1+\beta)\beta(2-3c_r+\gamma)\epsilon)}{a^2(4-\gamma)(1-\gamma)\gamma+a(\beta(2-\gamma)+2\gamma)(2-\beta-\gamma)\epsilon+(4-\beta)(1-\beta)\beta\epsilon^2}$ |
| $p_{a2}$ | n.a. | $\frac{\beta\epsilon(a(-1+\gamma)(-3\gamma+c_r(2+\gamma))+(-1+\beta)(-\beta+c_r(2+\beta)-2\gamma)\epsilon)}{a^2(4-\gamma)(1-\gamma)\gamma+a(\beta(2-\gamma)+2\gamma)(2-\beta-\gamma)\epsilon+(4-\beta)(1-\beta)\beta\epsilon^2}$ |
| $p_{r1}$ | $1-q_{a1}$ | $\frac{a^2(2(1-\gamma)+3c_r)(1-\gamma)\gamma+a(c_r(1-\beta)+(2-\beta)(1-\gamma))(\beta+2\gamma)\epsilon+(4-\beta)(1-\beta)\beta\epsilon^2}{a^2(4-\gamma)(1-\gamma)\gamma+a(\beta(2-\gamma)+2\gamma)(2-\beta-\gamma)\epsilon+(4-\beta)(1-\beta)\beta\epsilon^2}$ |
| $p_{r2}$ | n.a. | $\frac{\gamma(a^2(1-\gamma)(\gamma-\gamma^2+c_r(2+\gamma))+a(c_r(2-\beta-\beta^2)+(1-\gamma)(\gamma(2-\beta)+\beta(3-\beta)))\epsilon+(4-\beta)(1-\beta)\beta\epsilon^2)}{a^2(4-\gamma)(1-\gamma)\gamma+a(\beta(2-\gamma)+2\gamma)(2-\beta-\gamma)\epsilon+(4-\beta)(1-\beta)\beta\epsilon^2}$ |

$$A = 1-a(2-\gamma)-\epsilon(2-\beta),\ B = \frac{(1-\beta)\epsilon(2-(4-\beta)\epsilon+\gamma)-a^2(1-\gamma)(4-(2-\gamma)\gamma)+a(1-\gamma)(2+\gamma^2)-a\epsilon(8-5\gamma-\beta(6-(4-\gamma)\gamma))}{3(1-\beta)\epsilon+a(2-\gamma-\gamma^2)},$$
$$C = \frac{3a(1-\gamma)\gamma-a^2(4-\gamma)(1-\gamma)\gamma-a(\beta(2-\gamma)+2\gamma)(2-\beta-\gamma)\epsilon+(1-\beta)\epsilon(\beta+2\gamma-(4-\beta)\beta\epsilon)}{a(2-\gamma-\gamma^2)+(2-\beta-\beta^2)\epsilon},\ D = \frac{a(1-\gamma)\gamma-(\beta-(2-\beta)\gamma)\epsilon}{2a(1-\gamma)+2(1-\beta)\epsilon}$$

Table A.5: Acquisition and remanufacturing quantities and prices in the different equilibrium regions when $\beta > 1$

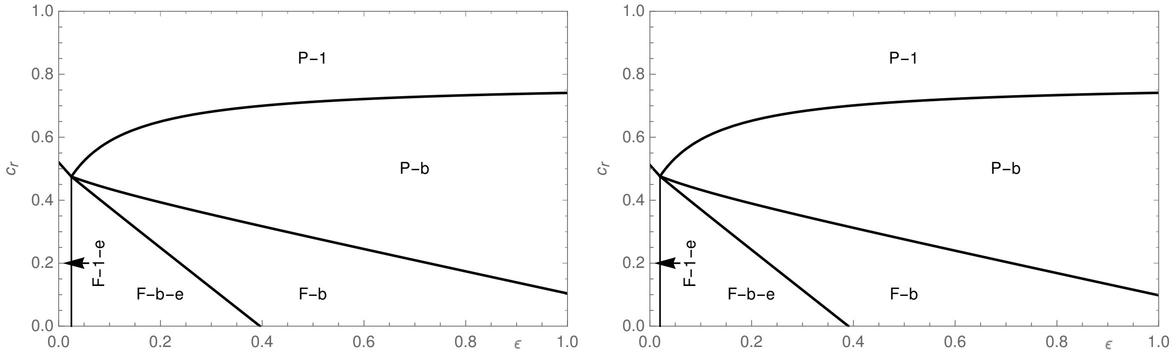
| | **Full collection** | | **Full collection, IR1 offers excessive acquisition price** | |
|---|---|---|---|---|
| | IR1 only (F-1) | IR1 and IR2 (F-b) | IR1 only (F-1-e) | IR1 and IR2 (F-b-e) |
| $q_{a1}$ | $a$ | $a - q_{a2}$ | $a$ | $a - q_{a2}$ |
| $q_{a2}$ | n.a. | $\frac{a(\gamma - c_r - a\gamma - \epsilon)}{a(1-\gamma)\gamma + 2(\beta-1)\epsilon}$ | n.a. | $\frac{a(\epsilon(\beta-1)+(2a-1)(1-\gamma))}{3(\beta-1)\epsilon + a(2-\gamma-\gamma^2)}$ |
| $p_{a1}$ | $\epsilon$ | $\epsilon$ | $\epsilon + (1 - c_r - \epsilon\beta - a(2-\gamma))$ | $\epsilon + \frac{(\beta-1)\epsilon(2-\epsilon-2\beta\epsilon+\gamma) - a^2(4-\gamma)(1-\gamma)\gamma + a(3(1-\gamma)\gamma + \epsilon(2+\gamma-\beta(4-\gamma^2)))}{3(\beta-1)\epsilon + a(2-\gamma-\gamma^2)} - c_r$ |
| $p_{a2}$ | n.a. | $p_{a1} + \frac{(\beta-1)\epsilon((1-a)\gamma - c_r - \epsilon)}{2(\beta-1)\epsilon + a(1-\gamma)\gamma}$ | n.a. | $p_{a1} + \frac{(\beta-1)\epsilon(\epsilon(\beta-1)+(2a-1)(1-\gamma))}{3(\beta-1)\epsilon + a(2-\gamma-\gamma^2)}$ |
| $p_{r1}$ | $1 - q_{a1}$ | $\frac{2(\beta-1)\epsilon - 2a^2(1-\gamma)\gamma - a(c_r + \epsilon(2\beta-1) - (2+c_r+\epsilon)\gamma + 2\gamma^2)}{a(1-\gamma)\gamma + 2(\beta-1)\epsilon}$ | $1 - q_{a1}$ | $\frac{3(\beta-1)\epsilon - 3a^2(1-\gamma)\gamma + a(1+\gamma-2\gamma^2-(\beta-1)\epsilon(2+\gamma))}{3(\beta-1)\epsilon + a(2-\gamma-\gamma^2)}$ |
| $p_{r2}$ | n.a. | $\gamma(1-a)$ | n.a. | $\gamma(1-a)$ |

| | **Partial collection** | |
|---|---|---|
| | IR1 only (P-1) | IR1 and IR2 (P-b) |
| $q_{a1}$ | $\frac{a\beta(1-c_r)}{a\beta(2-\gamma)+(2\beta-1)\epsilon}$ | $\frac{a\beta(a(2-c_r)(1-\gamma)\gamma - \epsilon(1-2\beta(1-c_r)-2c_r+\gamma))}{(\beta-1)(4\beta-1)\epsilon^2 + a^2\beta(4-\gamma)(1-\gamma)\gamma + a\epsilon((2-\gamma)(\beta+\gamma)(2\beta-1)-2\beta\gamma)}$ |
| $q_{a2}$ | n.a. | $\frac{a(\epsilon(c_r - \beta(1+c_r-2\gamma)-\gamma) - a\beta(2c_r-\gamma)(1-\gamma))}{(\beta-1)(4\beta-1)\epsilon^2 + a^2\beta(4-\gamma)(1-\gamma)\gamma + a\epsilon((2-\gamma)(\beta+\gamma)(2\beta-1)-2\beta\gamma)}$ |
| $p_{a1}$ | $\frac{\epsilon}{a} q_{a1}$ | $\frac{\epsilon((\beta-1)\epsilon(2\beta(1-c_r)-c_r+\gamma) + a\beta(1-\gamma)(3\gamma - c_r(2+\gamma)))}{(\beta-1)(4\beta-1)\epsilon^2 + a^2\beta(4-\gamma)(1-\gamma)\gamma + a\epsilon((2-\gamma)(\beta+\gamma)(2\beta-1)-2\beta\gamma)}$ |
| $p_{a2}$ | n.a. | $\frac{\beta\epsilon((\beta-1)\epsilon(1-3c_r+2\gamma) - a(1-\gamma)(2\beta c_r - (2+\beta-c_r)\gamma))}{(\beta-1)(4\beta-1)\epsilon^2 + a^2\beta(4-\gamma)(1-\gamma)\gamma + a\epsilon((2-\gamma)(\beta+\gamma)(2\beta-1)-2\beta\gamma)}$ |
| $p_{r1}$ | $1 - q_{a1}$ | $\frac{(\beta-1)(4\beta-1)\epsilon^2 + a^2\beta(2+3c_r-2\gamma)(1-\gamma)\gamma + a\epsilon(2\beta^2(1+c_r-\gamma) - \gamma(2+c_r-2\gamma) - \beta(1+c_r(2-\gamma)-(5-4\gamma)\gamma))}{(\beta-1)(4\beta-1)\epsilon^2 + a^2\beta(4-\gamma)(1-\gamma)\gamma + a\epsilon((2-\gamma)(\beta+\gamma)(2\beta-1)-2\beta\gamma)}$ |
| $p_{r2}$ | n.a. | $\frac{\gamma((\beta-1)(4\beta-1)\epsilon^2 + a^2\beta(1-\gamma)(\gamma-\gamma^2+c_r(2+\gamma)) - a\epsilon(c_r - 2\beta^2(1+c_r-\gamma) + (1-\gamma)\gamma + \beta(c_r - 2(1-\gamma)\gamma)))}{(\beta-1)(4\beta-1)\epsilon^2 + a^2\beta(4-\gamma)(1-\gamma)\gamma + a\epsilon((2-\gamma)(\beta+\gamma)(2\beta-1)-2\beta\gamma)}$ |

$E = 1 - \beta\epsilon - a(2-\gamma)$, $F = \frac{\beta(1-a(2-\gamma)) - \epsilon(2\beta-1)}{\beta}$,

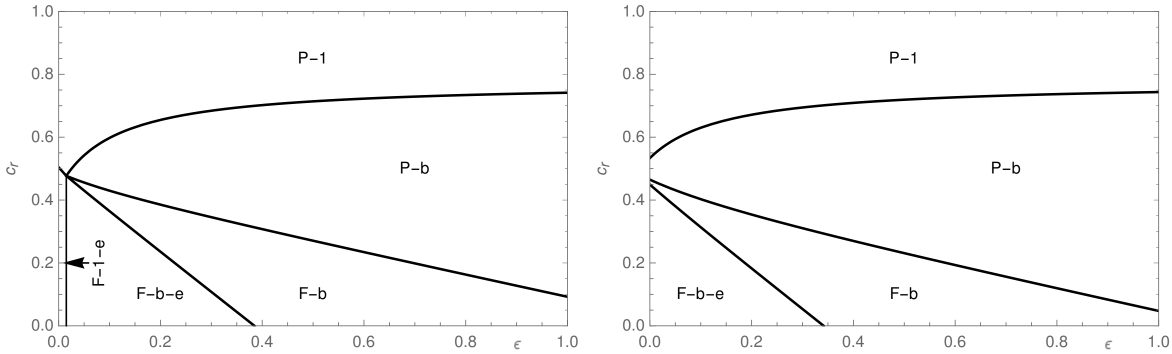
$G = -1 + 4a - \beta\epsilon + \gamma - 3a\gamma + a\gamma^2 - \frac{2(1-a)(\epsilon(\beta-1)+a(1-\gamma))}{2(\beta-1)\epsilon + a(1-\gamma^2)} - \frac{4a(\beta-1)\epsilon(4-\gamma) - 6a(1-\gamma) + 12a^2(1-\gamma) - (\beta-1)\epsilon(7-(\beta-1)\epsilon-\gamma)}{3(\beta-1)\epsilon + a(2-\gamma-\gamma^2)}$,

$H = \gamma(1-a) - \epsilon$, $I = \frac{2\beta^2\epsilon(-1+2\epsilon-a(-2+\gamma)) + \epsilon(\epsilon+\gamma+a(-2+\gamma)\gamma) + \beta(-5\epsilon^2 + a(3+a(-4+\gamma))(-1+\gamma)\gamma - \epsilon(-2+\gamma+a(2+\gamma(-3+2\gamma))))}{\epsilon + \beta(\epsilon - 2\beta\epsilon + a(-2+\gamma+\gamma^2))}$, $J = \frac{(\epsilon\gamma + \beta(\epsilon - 2\epsilon\gamma - a(1-\gamma)\gamma)}{\epsilon - \beta\epsilon - 2a\beta(1-\gamma)}$




(a) $\delta = 0$ (b) $\delta = 0.01$

Figure B.14: Impact of $\delta$ on solution regions ($a = 0.4$, $\beta = 0.2$ and $\gamma = 0.8$)




(a) $\delta = 0.02$ (b) $\delta = 0.1$

Figure B.15: Impact of $\delta$ on solution regions ($a = 0.4$, $\beta = 0.2$ and $\gamma = 0.8$)

## Appendix C. The case with a salvaging option

In introducing the option to salvage acquired cores (as opposed to remanufacturing and reselling them), the problems solved by the two players are modified as follows:

$$\max_{p_{r1},p_{a1}} \quad \pi_1(p_{r1}, p_{a1}) = (p_{r1} - c_r) \cdot q_{r1} - p_{a1} \cdot q_{a1} + p_s(q_{a1} - q_{r1}), \tag{C.1}$$
$$s.t. \quad 0 \leq q_{r1} \leq q_{a1} \leq a, \tag{C.2}$$
$$\max_{p_{r2},p_{a2}} \quad \pi_2(p_{r2}, p_{a2}) = (p_{r2} - c_r) \cdot q_{r2} - p_{a2} \cdot q_{a2} + p_s(q_{a2} - q_{r2}), \tag{C.3}$$
$$s.t. \quad 0 \leq q_{r2} \leq q_{a2} \leq a. \tag{C.4}$$

Note that we assume that salvaging yields the same per-unit profit of $p_s > 0$ for both firms. Apart from the extra term in both objective functions the model is unchanged. The key insight of our paper (Proposition 1) also holds when there is a salvaging option for non-remanufactured cores, confirming the robustness of our insights:

**Proposition 3.** *In the presence of a salvaging option, an advantage on the market for remanufactured products is necessary to preempt the other player. In particular, the remanufacturer* *with a market advantage IR1 cannot be preempted by the remanufacturer with an acquisition advantage IR2. However, IR2 can be preempted by IR1.*

The numerical example below indicates that there are equilibria where firms may use an excessive acquisition price, another key insight of our paper. Hence, our results are robust. In the figure below, the notation used for the regions is as before, except that the last letters identify the market strategy of the active player(s): r means remanufacturing only, s means salvaging only, and d means the dual strategy of partly remanufacturing and partly salvaging.

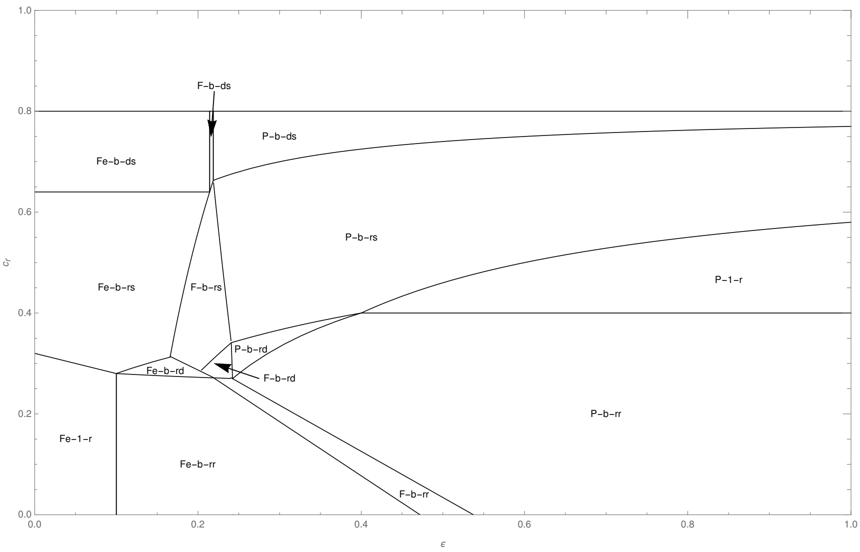



Figure C.16: Illustration of solution regions ($a = 0.4$, $\beta = \gamma = 0.8$, and $p_s = 0.2$)

**Otto von Guericke University Magdeburg**
Faculty of Economics and Management
P.O. Box 4120 | 39016 Magdeburg | Germany

Tel.: +49 (0) 3 91 / 67-1 85 84
Fax: +49 (0) 3 91 / 67-1 21 20

**www.fww.ovgu.de/femm**

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