Buying used products for remanufacturing: Negotiating or posted pricing

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Abstract: Product reclamation is a critical process in remanufacturing. It is generally assumed in the literature that customers simply want to get rid of their used products without expecting any compensation for them. Some authors have only recently started looking into firms that offer a posted (fixed) price for them. Following recent reports suggesting that customers are increasingly open to bargaining, we compare using a posted price and bargaining to obtain used products. In our analysis, we consider an original manufacturer acting as a monopolist as well as a manufacturer and an independent remanufacturer acting in a duopoly. We analytically show that bargaining is always beneficial to the monopoly manufacturer. In the duopoly case, we distinguish a Cournot competition and a market with the manufacturer as Stackelberg leader. The results of a numerical study show that both firms will use posted pricing in the Cournot competition, especially if bargaining is not costless. By contrast, the remanufacturer can significantly increase his profit by using negotiations if he is the Stackelberg follower.

Keywords: Remanufacturing, Closed-Loop Supply Chains, Bargaining

JEL Classification: M19, Q3

1 Introduction

In recent years, the efficient use of energy and raw materials has become increasingly important for ecological as well as economic and political reasons. In the past, this discussion has mainly centred on traditional raw materials and energy sources, such as metals, oil and gas, which are extracted in large quantities. Nowadays, however, public interest is increasingly shifting to the use of scarce materials, such as rare earth metals used, for example, in information technology products. Owing to their typically short life cycle, along with the absence of adequate recycling systems, the demand for these materials is widely expected to increase. Furthermore, toxic waste is generated during these products' production and end-of-life at which time they are disposed of, usually at overflowing landfills.

Both issues are addressed by creating recoverable product environments, in which products are reused rather than discarded. The most basic product recovery option is incineration, which retains some of the product's energy content. Recycling preserves the raw material along with the energy necessary to obtain it. However, it is most suitable for simple items, such as beverage containers, steel products, and paper goods. Recycling a more complex product, for example a mobile phone or a computer, results in a loss of almost all of the value-added content. In contrast, remanufacturing conserves not only the raw material content, but also much of the value added during the manufacturing process.[1]

Remanufacturing is "the process of restoring a non-functional, discarded or traded-in product to like-new condition" (Lund/Hauser 2010). It begins with the reclamation of used products, typically called "cores". These products are then disassembled into parts, which are cleaned and inspected. Subsequently, they are often combined with some new parts and reassembled into a remanufactured product. Remanufacturing has been reported for a number of industries, ranging from capital goods such as military weapon systems, manufacturing, mining and agricultural equipment or vending machines to consumer durable goods, such as automotive parts, computers, copiers and laser toner cartridges. Giuntini/Gaudette (2003) consider remanufacturing "the next great opportunity for boosting US productivity"; a point of view supported, for example, by Gray/Charter (2007) who look into remanufacturing in the UK. Firms engaging in remanufacturing often include both original manufacturers as well as independent remanufacturers; an example is the printer cartridge market.

Used product reclamation is a critical step in remanufacturing. For many years, the reasoning has been that customers want to dispose of used products and it is thus sufficient to provide the logistics to enable this reverse flow and to motivate the customers through adequate marketing to actually return their products. This assumption is perfectly suitable for low value items, such as printer cartridges. On the other hand, since leasing is used for many high value items and, thus, acquisition is not relevant (e.g. Agrawal et al. 2012). But many firms have recently started offering customers financial compensation for used goods of medium value. For example, ReCellular (www.recellular.com), one of the oldest and most well-known remanufacturing companies in the consumer electronics area, used to buy old devices in bulk from collectors, such as charities, but now also buys used phones directly from consumers (Hagerty 2011). Today, there are several similar companies, including BuyMyTronics (www.buymytronics.com) and reBuy (www.rebuy.de) that offer up to $350 for a used but working Apple iPad 4th Generation at the time of writing. Service providers like PowerOn (poweron.com) offer turnkey solutions to manufacturers who want to offer their customers trade-in programmes. These websites usually allow customers to indicate the model and condition of the product they want to sell before offering a provisional price for it. After accepting the offer, the device is mailed to the company, where it is tested. If customers' description of the product is accurate, they receive their money. Otherwise, the company usually offers a lower price. If this new offer is declined, the transaction fails and the device is returned to the seller, at some companies at the customer's expense. The San Diego-based ecoATM (www.ecoatm.com) allows customers to put their device in an "ecoATM" machine, where it is evaluated on the spot with the help of a remote operator. The transaction can thus be completed immediately.

However, all these companies offer a posted price for a device of a certain condition. To the best of our knowledge, bargaining over the acquisition of used products has not yet been considered in theory or in practice. This is astonishing, since customers are increasingly using bargaining to pay less for products. For example, Walker (2009) reports that 72 per cent of Americans bargained during the 2008 holiday season, compared to 56 per cent a year earlier, while Richtel (2008) observes that "a bargaining culture once confined largely to car showrooms and jewellery stores is taking root". Some stores have reported that a quarter of their customers try to bargain. Regarding the acquisition of used products, we think the bargaining process would most likely be performed with a human representative over the internet or via telephone. However, fully automated solutions have been proposed and tested as well (Chan et al. 2007).

In this paper, we examine whether it would be more beneficial for profit-maximising firms to use bargaining or posted pricing when acquiring used products for remanufacturing. Our setting consists of a more mature primary market in which used products are acquired for remanufacturing and a secondary market in which newly manufactured and remanufactured products are sold. In the primary market, customers owning used products sell them if they receive an amount that is at least equal to their heterogeneous valuation of the product. This acquisition can take place either through posted pricing or negotiations. In the secondary market, products are sold using posted pricing to customers with heterogeneous valuations. In a first step, we consider an original equipment manufacturer (OEM) that is a monopolist and produces new products and remanufactures used products. In a second step, we enhance the model to capture competition from an independent remanufacturer (IR), who also buys used products, remanufactures them and sells them. In this context, we consider two market types: a Cournot duopoly scenario and a Stackelberg scenario.

The remainder of the paper is organised as follows: Section 2 discusses relevant research from different fields, especially bargaining theory and remanufacturing. Our key assumptions and notation are outlined in Section 3. In Section 4, we analyse the OEM as a monopolist, before we turn to competition between OEM and IR in Section 5. Section 6 briefly summarises the results and concludes this paper.

2 Literature review

Our research draws on two separate literature streams: remanufacturing and bargaining. In this section, we briefly review the most prominent research in each stream. We begin with an overview of the relevant bargaining literature.

Bargaining theory has been studied extensively in economics, and there is a wealth of research that discusses the negotiation outcome under several negotiation processes and information structures. Two classic bargaining models are the Nash bargaining solution (Nash 1950) and Rubinstein's alternating offers game (Rubinstein 1982).

Nash (1950) describes the outcome of a negotiation based on four axioms. Under the Nash bargaining solution, two parties bargain over the division of a cake; the size of this cake is the difference between the total surplus and the parties' reservation utilities. Both parties conduct a cooperative game in which they maximise their individual surplus and split the cake equally. The classic Nash bargaining solution where the two players have identical bargaining power can be extended to the case in which the two parties have different bargaining powers. In this situation, which is referred to as the generalised (or asymmetric) Nash bargaining solution (GNBS), a larger portion of the total surplus goes to the more powerful party. We use the GNBS to model the outcome of the negotiation between the firm and customer.

Rubinstein's model explicitly considers the negotiation process. At the start of the game, one player offers a partition of the cake and the other chooses whether to accept the offer or to reject it and then makes a counter offer. There is a fixed time interval between two successive offers, and the cake will be split only after the players have reached an agreement. The players seek to maximise their utility, which is discounted over time by an individual discount rate, which can be interpreted as their respective negotiation costs. This bargaining process leads to a unique, subgame perfect equilibrium and the parties immediately agree in this equilibrium at the outset of the process. When the time interval between the offer and counter offer approaches zero, Rubinstein's model yields the GNBS and the players' shares depend on the ratio of their discount rates. Furthermore, a number of bargaining processes that can be modelled as variants of Rubinstein's model, such as including the risk of negotiation breakdown, lead to outcomes that are slight variations of the GNBS. In a textbook, Muthoo (1999) provides a detailed review of these bargaining processes.

A noncooperative game-theoretic solution could be used as an alternative for modelling the bargaining process/outcome. However, as Kuo et al. 2011b point out, a vast amount of experimental findings have suggested that such solutions are no better at predicting the outcomes of bargaining situations than the GNBS (e.g. Davis/Holt 1992, Chapter 5.2). Hagel/Roth (1995) provide a detailed description of experiments conducted.

The ultimatum game is a good example. In this game, Player A offers a share of a pot of money to Player B. If Player B agrees, the pot is divided accordingly. If B disagrees, neither gets anything. An obvious noncooperative solution would predict that Player A would offer Player B a very small amount of money and B would accept. However, in almost all ultimatum game experiments reported in the literature (e.g. Güth et al. 1982, Henrich et al. 2004), the outcome shows a much more balanced distribution of the money. This suggests that bargaining outcomes are less similar to those predicted by the noncooperative models and closer to those predicted by cooperative models like the GNBS. Similar observations have been made for variants of these models, such as the dictator game (e.g. Hoffmann et al. 1994). In addition to these simple games, the GNBS has received support from experiments in which two parties negotiate freely (e.g. Nydegger/Owen 1975) in more complicated settings, for example selling TV airtime for advertising (Neslin/Greenalgh 1983) and negotiations between spouses in a marriage (Hoddinott/Adam 1997).

The experimental support and the correspondence to a number of bargaining processes' equilibria, including Rubinstein's model and its variants, make the GNBS an attractive tool to model the negotiation outcome. Accordingly, the GNBS has been popular among researchers who study posted pricing versus bargaining. For example, Wang (1995), Arnold/Lippman (1998), Adachi (1999), Desai/Purohit (2004) as well as Roth et al. (2006) all use the GNBS. Moreover, the latter two papers consider negotiations between a retailer and an individual consumer. Several papers consider negotiation in forward supply chains (see, e.g., Dukes/Gal-Or 2003, Iyer/Villas-Boas 2003, Wu 2004, Terwiesch et al. 2005, Gurnani/Shi 2006, Kim/Kwark 2007, Lovejoy 2007, and Nagarajan/Bassok 2008).

In recent papers, Kuo et al. (2011a) investigate how the co-existence of bargainers and price-takers in the customer population affects pricing decisions. Kuo et al. (2012) analyse the interaction between a manufacturer and a reseller with regard to the pricing policy toward end customers. Nagarajan/Sosic (2008) provide a survey of some applications of cooperative bargaining in supply chains.

Furthermore, bargaining has recently been considered in the literature on dynamic pricing, where a firm disposes of a fixed inventory of a product that is sold during a finite selling horizon. By dynamically adjusting the posted price based on the inventory level and the remaining selling horizon, the firm seeks to maximise its revenues. [2] In this context, Kuo et al. (2011b) analyse a retailer that can simultaneously offer posted pricing and bargaining modelled via the GNBS. Using an infinite selling horizon, Bhandari/Secomandi (2011) compare four basic bargaining mechanisms.

There is a vast amount of research on remanufacturing and the closely related area of closed-loop supply chains. Several papers study competition in the markets for new and remanufactured products; they initially regarded the proportion of used products available for remanufacturing as exogenously given. For example, in Ferrer/Swaminathan (2006), the manufacturer collects a fraction of used products, and the rest are available to the remanufacturer, whereas Majumder/Groenevelt (2001) consider four scenarios that differ with regard to whether a company has access to another company's unused cores. Both papers focus on characterising the Nash equilibrium and investigating various parameters' impact thereon.

Recently, a number of authors have started exploring collection incentives. Guide/Van Wassenhove (2001) criticised prior studies' assumption that product returns are an exogenous process and that no published research had explicitly considered the problem of managing returns. They claim that actively acquiring used products may facilitate the management and profitability of the remanufacturing activities. Guide (2000) supports this claim by revealing that many remanufacturing firms actively control product returns. Moreover, with a strong focus on practice, Klausner/Hendrickson (2000) discuss the possibility of a buy-back program for Bosch's power tool devices.

Assuming exogenously given, linear acquisition costs, one group of authors analyses decisions about the quantity of used products to acquire. Galbreth/Blackburn (2006, 2010) consider a remanufacturer who buys unsorted used products that have a continuum of quality levels and derive optimal quantities and sorting policies. Whereas Galbreth/Blackburn (2006) assume that the quality distribution of an acquired lot is known with certainty, Galbreth/Blackburn (2010) drop this assumption and consider acquisition decisions when the quality of each acquired core is stochastic. Zikopoulos/Tagaras (2007, 2008) consider two discrete quality levels: good and bad. Zikopoulos/Tagaras (2007) analyse the quantity of cores to buy from two collection sites with quality following a joint probability distribution and uncertain demand. Focusing on a single collection site, which is prone to misclassification errors, Zikopoulos/Tagaras (2008) compare decisions with and without advanced sorting. Mukhopadhyay/Ma (2009) consider a system in which both used parts and new parts can serve as inputs in a production process with uncertain demand. Teunter/Flapper (2011) analyse how many cores should be acquired and how many cores of each quality level should be remanufactured after sorting in situations with multiple discrete quality classes and quality uncertainty.

Another group of authors explicitly considers a remanufacturer's decisions about acquisition and selling prices. Guide et al. (2003) develop a simple one-period framework for determining the optimal quality-dependent acquisition prices for used products. In a related work, Bakal/Akcali (2006) incorporate randomness in the supply process, in which the expected quality of returns depends on the acquisition price. Karakayali et al. (2007) consider the pricing problem in centralised as well as remanufacturer and collector-driven decentralised channels. Karakayali et al. (2010) study a problem in which multiple types of remanufactured products can be recovered from multiple used-product quality classes and develop practically implementable solution algorithms to characterise the optimal acquisition and selling prices. Vadde et al. (2007) analyse the acquisition price paid by a product recovery facility facing deterministic demand in a multi-period setting. Sun et al. (2013) analyse a periodic review inventory model with random price-sensitive returns. Some authors consider acquisition pricing with given selling prices. Liang et al. (2009) use an option pricing model to determine the acquisition price in situations with the selling price following a geometric Brownian motion. Xiong/Li (2013) propose a dynamic pricing policy to balance random, price-sensitive supply of cores with the random demand for remanufactured products with backlogs. Xiong et al. (2014) extend this analysis to lost sales and quality uncertainty. Hahler/Fleischmann (2013) focus on the value of acquiring used products of different quality levels at different prices in settings with centralised and decentralised quality grading.

Several authors analyse acquisition prices jointly with production and remanufacturing decisions. Ray et al. (2005) study the use of trade-in rebates to encourage the customer's replacement of a product and to provide the firm with additional profit through remanufacturing operations. Kaya (2010), Shi et al. (2011), and Tan/Yuan (2011) consider one-period settings in which the acquisition of used products does not depend on former (endogenous) sales. Minner/Kiesmüller (2012) also briefly analyse a static (one-period) model. Based on this, they develop a dynamic model with time-dependent demand. In addition to the acquisition price, supply also depends on time, but is independent of former sales. The firm may carry over inventory from periods with comparatively low acquisition costs to periods with higher expected costs. In a similar setting, Zhou/Yu (2011) study a periodic-review production-remanufacturing system with random demand and supply. Kleber et al. (2011) examine the impact of a buyback option on a spare parts supply chain where the repair shops can remanufacture replaced parts from the first to the second period. Xu et al. (2012) consider lead times. In a recent working paper, Lechner/Reimann (2013) analyse a two-period model with the quantity of new products sold in the first period and the acquisition price jointly determining the quantity of used products available for remanufacturing in the second period.

Especially relevant to our work are papers that consider both competition and acquisition pricing. In their investigation of pricing and remanufacturability level implications for an original manufacturer who only produces the new product, Debo et al. (2005) model several remanufacturers who are price-takers in perfectly competitive markets for used products as well as remanufactured products. Groenevelt/Majumder (2007) also consider acquisition and sales competition. Finally, a book chapter by Li/Li (2011) provides an overview of supply chain models with active acquisition and remanufacturing as well as a detailed presentation of six selected models and related key insights.

3 Key assumptions and notation

Before presenting our model in detail for a monopolist (Section 4) and for competition (Section 5), we state and discuss key assumptions specific to our remanufacturing environment and introduce some notation.

Assumption 1. *Key problem characteristics are captured by focusing on one time period.*

We first develop a model with an OEM producing new and remanufacturing used products. Later, we add competition from a remanufacturer. Used products are bought from a primary, more mature market in which the product is near the end of its life-cycle and remanufactured products are sold in a secondary market. The maximum quantity of available used products is exogenously given in our model. Our objective is to study used products acquisition through posted pricing and bargaining. Thus, a single-period model is sufficient and allows us to maintain tractability.

Assumption 2. *In the secondary market, customers do not distinguish between new and remanufactured products.*

We assume that the product is remanufactured to an "as new" condition and is therefore a perfect substitute for the new product. Often, a crucial element is that remanufactured products have the same warranty. Therefore, demand in the secondary market in which new and remanufactured products are sold can be satisfied by new products as well as by remanufactured products. Clearly, without this assumption, remanufacturing is less attractive. However, we explicitly do not focus on the advantageousness of remanufacturing, but on the advantage of bargaining if remanufacturing is beneficial. This assumption may be appropriate for one product but not for a very similar one, because, as Lebreton/Tuma (2006) demonstrate for the tyre industry, customer perceptions involve a lot of psychology.

Assumption 3. *In the secondary market, each customer's willingness-to-pay (WTP) for a product is heterogeneous and uniformly distributed in the interval* $[0, 1]$.

For product sales in the secondary market, we assume that a customer buys at most one unit in the period under consideration. He buys if and only if the price is not higher than his valuation (WTP), which is uniformly distributed in the interval $[0, 1]$. The utility he derives equals the difference of his valuation and the price paid.

The market size is normalised to 1 and we denote the selling price in the secondary market by p and the corresponding demand by q. Thus, we obtain the following linear inverse demand function:

$$p(q) = 1 - q \tag{1}$$

Assumption 4. *Only the OEM can manufacture new products at a cost of* $c_{OEM}^N \in [0,1]$ *per unit.*

We assume that only the OEM is capable of manufacturing new products, for example, because he possesses some proprietary technology. Manufacturing costs are linear and are denoted by $c_{OEM}^N \in [0,1]$. The customer's willingness-to-pay is limited to one, because manufacturing does not make sense if costs exceed the maximum willingness-to-pay.

Assumption 5. *In the primary market, each customer's willingness-to-sell (WTS)* ω *for his product is heterogeneous and uniformly distributed in the interval* $[\alpha p_p, p_p]$ *(*$p_p \in [0,1]$*).*

We assume that the product was sold in the primary market in which used products are acquired at a price of $p_p \in [0,1]$. For simplicity's sake, we furthermore assume that the quantity sold at p_p was $q_p(p_p) = 1 - p_p$, which is analogous to the demand function (1) for the secondary market. Each customer in possession of the product now has a certain valuation ω (WTS) for it. Customers sell their product if and only if they receive an amount for it that is not below their valuation, which is uniformly distributed in the interval $[\alpha p_p, p_p]$ with $\alpha \in [0,1]$. The utility that customers derive is calculated as the difference between the price paid and their valuation.

The assumption reflects the observation that many customers keep an old product, although they no longer actively use it, simply because they feel that it is still too valuable to be thrown away because it was once "so expensive". Accordingly, we let the distribution of the WTS depend on p_p, and use α to specify a lower bound below which no customer will return a product.

Assumption 6. *The variable cost to remanufacture a used product is* $c_{OEM}^R \in [0,1]$ *for the OEM and* $c_{IR}^R \in [0,1]$ *for the IR.*

We assume that after a used product is acquired, it is remanufactured by the OEM or the IR at a variable cost of $c_{OEM}^R \in [0,1]$ or $c_{IR}^R \in [0,1]$, respectively. Analogous to c_{OEM}^N (Assumption 4), the restriction to values smaller than or equal to one is reasonable since remanufacturing would not take place if costs exceed the maximum willingness-to-pay in the market. Note that the choice of one as the upper bound for these values is arbitrary but without loss of generality as it is only a matter of scale, that is, currency. Moreover, this assumption implies that the used products are of homogeneous quality regarding the remanufacturing process. Furthermore, in line with most of the literature on used product acquisition for remanufacturing, we do not consider any fixed costs, since these can easily be considered after the total profits have been computed, because they do not affect any price or quantity decision, but only influence the decision of whether or not to enter the market. It must be noted that constant variable costs are a common assumption, but that if acquisition costs are taken into account, the total per unit cost of remanufactured products increases in the quantity processed, thereby capturing a specific characteristic of remanufacturing environments.

Table 1 summarises the model parameters that have to be set to specify the setting. Table 2 contains additional notation used in this section to describe the setting. An overview of the notation used throughout the paper is given in Table A.1 in the appendix.

Table 1: Model parameters specifying the setting

Parameter	Description
α	Lower bound for customers' valuations
q_p	Quantity of used products in the market
c_{OEM}^N	OEM's manufacturing cost (per unit)
c_{OEM}^R	OEM's remanufacturing cost (per unit)
c_{IR}^R	IR's remanufacturing cost (per unit)

Table 2: Additional notation describing the setting

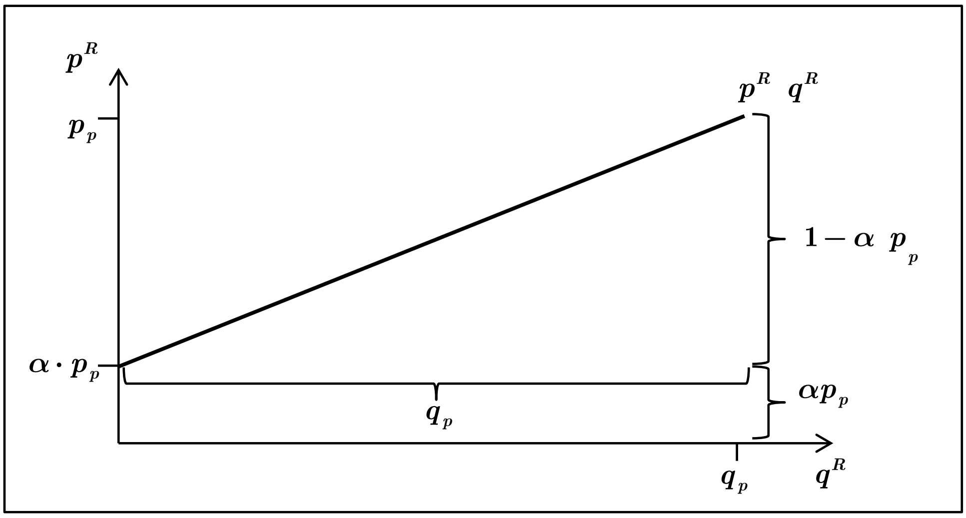
Variable	Description
$p_p(q_p) = 1 - q_p$	Selling price in the primary market
q	Quantity sold in the secondary market
$p(q) = 1 - q$	Selling price in the secondary market

4 OEM as a monopolist

In this section, we compare an OEM offering a posted price to acquire used products to an OEM bargaining with customers over the price of used products. Following the objective of studying an OEM producing new products and remanufacturing used products, we restrict the analysis to settings in which manufacturing as well as remanufacturing is profitable for at least a marginal unit. For the sake of simplicity and to ensure consistency with the subsequent analysis of competition (Section 5), we further restrict ourselves to settings without shortage in the used product market.

4.1 OEM using posted pricing

Fig. 1: Acquisition price p^R as a function of the quantity bought on the secondary market q^R



Using posted pricing, the OEM decides on the price p^R_{OEM} he offers for used products as well as the selling price p_{OEM} of his products. Given p_p (and q_p), the posted price p^R_{OEM} the OEM has to offer is a function of the quantity q^R_{OEM} of used products that the OEM acquires ($p^R_{OEM} = p^R(q^R_{OEM})$). Intuitively, this price must be chosen such that q^R_{OEM} customers have a valuation of p^R_{OEM} or lower. According to Assumption 5, customer valuations for used products are uniformly distributed in $[\alpha p_p, p_p]$. Customers will not sell at an acquisition price of below $\alpha \cdot p_p$ ($q^R = 0$). Moreover, an acquisition price of $p^R_{OEM} = p_p$ suffices to buy $q^R = q_p$, that is, to buy the products from all customers. Because of the uniform distribution of valuations, an intermediate quantity $0 < q^R < q_p$ is associated with a convex combination of the two extremes (see Fig. 1). Thus, p^R_{OEM} is given by the following equation, in which the first part is the minimum price necessary to buy a positive quantity and the second part reflects the linear increase as q^R increases from 0 to q_p:

$$p^R_{OEM} = p^R(q^R_{OEM}) = \alpha p_p + \frac{(1-\alpha)p_p}{q_p} \cdot q^R_{OEM}, \tag{2}$$

with $q^R_{OEM} \leq q_p$. As there is a one-to-one relationship between price and quantity in both the primary market, in which used products are bought (1) and the secondary market in which the products are sold (2), we can continue using the quantities q^R_{OEM} and q_{OEM} of remanufactured and total products sold, respectively, as the OEM's decision variables. Thus, the OEM's profit function is given by

$$
\begin{aligned}
\Pi_{OEM}^{PP}&(q_{OEM}^{R}, q_{OEM}) \\
&= p(q_{OEM}) \cdot q_{OEM} - q_{OEM}^{R} \cdot [p_{OEM}^{R}(q_{OEM}^{R}) + c_{OEM}^{R}] \\
&- [q_{OEM} - q_{OEM}^{R}] \cdot c_{OEM}^{N}
\end{aligned} \tag{3}
$$

where the first term is the revenue generated by selling products, the second term is the expenditures for buying used products and remanufacturing them and the last term accounts for the remaining quantity that has to be newly manufactured. The OEM's objective is to maximise (3), which is concave in both q_{OEM}^{R} and q_{OEM}. From the first-order conditions, we obtain the optimal quantities:

$$
q_{OEM}^{R,PP^*} = q_p \left[\frac{1}{2} \cdot \frac{c_{OEM}^{N} - c_{OEM}^{R} - \alpha p_p}{(1-\alpha)p_p}\right] \text{ and } q_{OEM}^{PP^*} = \frac{1}{2}[1 - c_{OEM}^{N}]. \tag{4}
$$

4.2 OEM using bargaining

Alternatively, the OEM can decide to negotiate the acquisition price with each customer. We do not focus on the negotiation process itself, but model the negotiation outcome using the GNBS, which captures the outcomes of several actual bargaining processes as discussed in the literature review. Under the GNBS, the total surplus resulting from a transaction is split between the two players according to their bargaining power. Let $\beta \in (0,1)$ denote the OEM's bargaining power, then the customer's bargaining power is $1 - \beta$. Furthermore, the outcome of the negotiation is determined by the customer's valuation ω and the maximum price $p_{OEM,max}^{R}$ the OEM is willing to pay for a used product (his cut-off point). If $\omega \le p_{OEM,max}^{R}$, a deal is always struck. According to the GNBS, they agree on the final price $p_{Barg}^{R}(p_{OEM,max}^{R}, \omega)$ given by (see, e.g., Muthoo 1999, Chapter 2.8)

$$
\begin{aligned}
p_{Barg}^{R}(p_{OEM,max}^{R}, \omega) &= \underset{p_{Barg}^{R}}{\operatorname{argmax}} \left(p_{OEM,max}^{R} - p_{Barg}^{R}\right)^{\beta} \left(p_{Barg}^{R} - \omega\right)^{1-\beta} \\
&= (1-\beta)p_{OEM,max}^{R} + \beta\omega.
\end{aligned}
$$

The OEM's decision variables are the total quantity to sell q_{OEM} and the maximum price $p_{OEM,max}^{R}$. Because – similar to posted pricing – the OEM buys the used product from every customer with a valuation not exceeding $p_{OEM,max}^{R}$, the relationship between $p_{OEM,max}^{R}$ and the quantity bought q_{OEM}^{R} still follows (2): $q_{OEM}^{R} = q^{R}(p_{OEM,max}^{R})$. Thus, the quantity bought using a maximum price $p_{OEM,max}^{R}$ is given by the inverse of (2), denoted by $q^{R}(\cdot)$. Note that the OEM can only choose $p_{OEM,max}^{R}$ once and it is the same for all customers. He cannot tailor $p_{OEM,max}^{R}$ to a specific customer and his valuation, which would allow him to arbitrarily manipulate the negotiation.

To calculate the total cost $C_{OEM}^{Barg}(p_{OEM,max}^{R})$ for buying and remanufacturing $q^{R}(p_{OEM,max}^{R})$ used products, we now integrate over the valuation of all customers with whom a transaction takes place, as the OEM agrees on a different price with each of them:

$$
\begin{aligned}
C_{OEM}^{Barg}(p_{OEM,max}^{R}) &= \int_{\alpha p_p}^{p_{OEM,max}^{R}} \left[p_{Barg}^{R}(p_{OEM,max}^{R}, \omega) + c_{OEM}^{R}\right] \cdot \frac{dq^{R}(\omega)}{d\omega} d\omega \\
&= q^{R}\left(p_{OEM,max}^{R}\right) \cdot \left[p_{OEM,max}^{R} - \frac{1}{2}\beta(p_{OEM,max}^{R} - \alpha p_p) + c_{OEM}^{R}\right].
\end{aligned} \tag{5}
$$

Again, the profit function is the revenue generated by selling products, minus the cost incurred from buying used products and remanufacturing them (now as given by (5)), and the cost of manufacturing.

$$\begin{aligned}\Pi_{OEM}^{Barg}\left(p_{OEM,max}^{R}, q_{OEM}\right) = p(q_{OEM}) \cdot q_{OEM} \\ -q^{R}\left(p_{OEM,max}^{R}\right) \cdot \left[p_{OEM,max}^{R} - \frac{1}{2}\beta(p_{OEM,max}^{R} - \alpha p_{p}) + c_{OEM}^{R}\right] \\ -\left[q_{OEM} - q^{R}\left(p_{OEM,max}^{R}\right)\right] \cdot c_{OEM}^{N}\end{aligned} \tag{6}$$

Checking again first-order conditions yields the profit-maximising values for the decision variables:

$$p_{OEM,max}^{R,Barg\ *} = \frac{c_{OEM}^{N} - c_{OEM}^{R} + (1-\beta)\alpha p_{p}}{(2-\beta)} \text{ and } q_{OEM}^{Barg*} = \frac{1}{2}[1 - c_{OEM}^{N}]. \tag{7}$$

This shows that the optimal maximum price $p_{OEM,max}^{R,Barg\ *}$ depends on both customers' minimum valuations in the primary market α and the OEM's bargaining power β. To gain further insight into this, we calculate the corresponding derivatives of $p_{OEM,max}^{R,Barg\ *}$ and obtain $\frac{dp_{OEM,max}^{R,Barg\ *}}{d\alpha} = \frac{1-\beta}{2-\beta} \cdot \alpha \geq 0$ as well as $\frac{dp_{OEM,max}^{R,Barg\ *}}{d\beta} = \frac{c_{OEM}^{N} - c_{OEM}^{R} - \alpha p_{p}}{(2-\beta)^{2}} \geq 0$ because remanufacturing is profitable for at least a small amount ($c_{OEM}^{N} \geq c_{OEM}^{R} + \alpha p_{p}$). Thus, the OEM's optimal maximum price increases in both α and β. This can be intuitively interpreted as follows: With a higher minimum valuation, all customers demand more money for their used product and, thus, the OEM has to pay more. On the other hand, a higher β allows him to buy more because, compared to a lower bargaining power, the surcharge paid to existing customers with low valuations is smaller.

Finally, we consider the influence of α and β on the optimal profit $\Pi_{OEM}^{Barg*}\left(p_{OEM,max}^{R,Barg\ *}, q_{OEM}^{Barg*}\right)$ calculated by substituting (7) into (6). The relevant derivatives are given by

$$\frac{d\Pi_{OEM}^{Barg*}}{d\alpha} = \frac{q_{p}}{2(2-\beta)}\left[-p_{p} + \frac{q_{p}\left(c_{OEM}^{R} - c_{OEM}^{N} + p_{p}\right)^{2}}{p_{p}(1-\alpha)^{2}}\right] \leq 0$$

and

$$\frac{d\Pi_{OEM}^{Barg*}}{d\beta} = \frac{q_{p}}{2p_{p}} \cdot \frac{\left(c_{OEM}^{R} - c_{OEM}^{N} + \alpha p_{p}\right)^{2}}{(1-\alpha)(2-\beta)^{2}} \geq 0,$$

where the inequalities again use ($c_{OEM}^{N} \geq c_{OEM}^{R} + \alpha p_{p}$) and the inequality regarding α follows after some rearrangements.[3] This shows that the profit under bargaining increases with the OEM's bargaining power and decreases with the customers' minimum valuation.

Table 3 provides an overview of the OEM's decision variables when posted pricing and bargaining are used.

Table 3: Decision variables for OEM as a monopolist

Variable	Description
	OEM using posted pricing (Section 4.1)
q^R_{OEM}	Quantity of used products bought and remanufactured
q_{OEM}	Quantity sold in the secondary market
	OEM using bargaining (Section 4.2)
$p^R_{OEM,max}$	Maximum price paid by the OEM for used products
q_{OEM}	Quantity sold in the secondary market

4.3 Comparison of posted pricing and bargaining

We first compare the OEM's profit under bargaining (6) to that of posted pricing (3). As expected, the difference

$$\Pi^{Barg}_{OEM}\left({q^R_{OEM}}^*, {q_{OEM}}^*\right) - \Pi^{PP}_{OEM}\left({q^R_{OEM}}^*, {q_{OEM}}^*\right)$$

$$= \frac{q_p \cdot \beta}{(2-\beta)} \cdot \frac{\left[c^N_{OEM} - c^R_{OEM} - \alpha p_p\right]^2}{4(1-\alpha)p_p}$$

is always nonnegative and bargaining is preferred over posted pricing with the advantage increasing in β. Since the quantity sold (and, thus, the selling price) is the same in both cases (see (4) and (7)), there are two possible explanations for the increase in profit under bargaining: the OEM (i) can buy used products at a lower average price, and/or (ii), if the sum of the average acquisition and remanufacturing costs is lower than the manufacturing costs, the OEM can remanufacture a larger quantity.

To check for lower average prices (i), we compare the optimal posted price $p^{R,PP^*}_{OEM} = \frac{1}{2}\left[c^N_{OEM} - c^R_{OEM} + \alpha p_p\right]$ obtained by substituting q^{R,PP^*}_{OEM} (4) into (2) with the optimal average acquisition price under bargaining, which is obtained by dividing the total acquisition and remanufacturing cost $C^{Barg}_{OEM}\left({p^{R,Barg}_{OEM,max}}^*\right)$ given by (5) by the quantity bought and subtracting remanufacturing cost:

$$C^{Barg}_{OEM}\left({p^{R,Barg}_{OEM,max}}^*\right) / q^R\left({p^{R,Barg}_{OEM,max}}^*\right) - c^R_{OEM} = \frac{1}{2}\left[c^N_{OEM} - c^R_{OEM} + \alpha p_p\right]. \qquad (8)$$

This shows that both the posted price and the average price paid when bargaining are equal and the OEM does not profit from a lower acquisition price.

Next (ii), we compare the quantities of remanufactured products under posted pricing and bargaining, respectively. While q^{R,PP^*}_{OEM} is already stated by (4), the quantity $q^R\left({p^{R,Barg}_{OEM,max}}^*\right) = q_p\left[\frac{1}{(2-\beta)} \cdot \frac{c^N_{OEM} - c^R_{OEM} - \alpha p_p}{(1-\alpha)p_p}\right]$ is obtained by substituting (7) into the inverse of (2). Since the structures of both terms are very similar, it is easy to see that $q^R\left({p^{R,Barg}_{OEM,max}}^*\right) \geq q^{R,PP^*}_{OEM}$. Hence, while the OEM pays the same average acquisition price, bargaining allows him to benefit from a larger quantity bought. Analogously to the profit functions, the difference of these quantities obviously increases in the bargaining power β. If, on the other hand, β approaches 0 in the limit, the OEM ends up paying the same price ${p_{OEM,max}^{R,Barg}}^*$ to every customer and the advantage of bargaining vanishes.

Fig. 2: Illustration of total and average acquisition costs depending on ${q_{OEM}^{R,PP}}^*$ and ${q_{OEM}^{R,Barg}}^*$ ($q_p = 0.5$, $\alpha = 0.1$, $c_{OEM}^N = 0.4$, and $c_{OEM}^R = 0.1$)

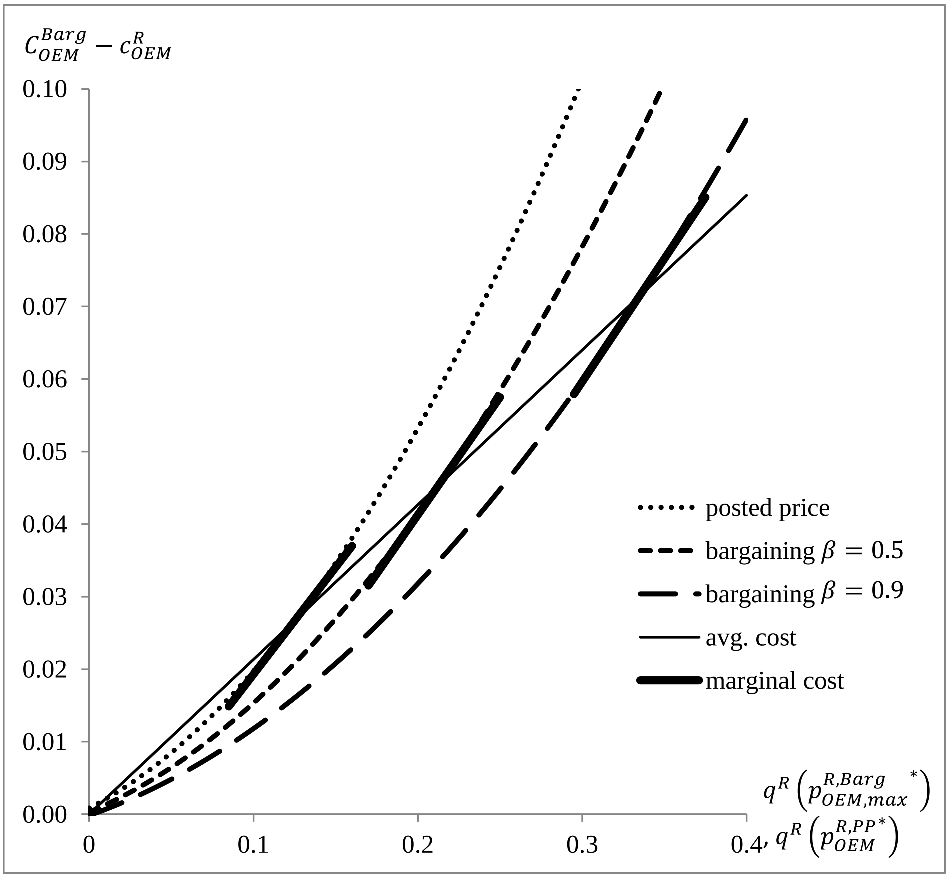


Fig. 2 illustrates the advantage of bargaining for $q_p = 0.5$, $\alpha = 0.1$, $c_{OEM}^N = 0.4$, and $c_{OEM}^R = 0.1$. It shows the total acquisition cost $C_{OEM}^{Barg}(p^R(q^R)) - c_{OEM}^R$ as a convex function[4] of the quantity of used products bought q^R for posted pricing and bargaining with $\beta = 0.5$ as well as $\beta = 0.9$. The bold lines are the tangents at the optimal quantities for posted pricing, bargaining with $\beta = 0.5$ and bargaining with $\beta = 0.9$ (from left to right). By connecting a point on a total acquisition cost curve with the origin, we obtain a line whose slope is the related average acquisition cost. Furthermore, it is important to note that all quantities have to be interpreted in the context of a market size that is normalised to one.

The figure shows that the quantity of used products acquired is the lowest for posted pricing and increases in the bargaining power β. Since the total cost is convex in the quantity remanufactured for all β, the marginal costs increase in the quantity acquired. The OEM should increase this quantity until the marginal acquisition costs equal the cost advantage of remanufacturing over manufacturing ($c_{OEM}^N - c_{OEM}^R$). Thus, the tangents (bold lines) in the optimal solutions all have this same slope. Furthermore, we see that the optimal points on the total acquisition cost curves all lie on a common line whose slope is the average acquisition cost that is independent of β (see (8)).

Fig. 3: Profit advantage of bargaining over posted pricing ($q_p = 0.5$, $\alpha = 0.1$, $c_{OEM}^N = 0.4$, and $c_{OEM}^R = 0.1$)

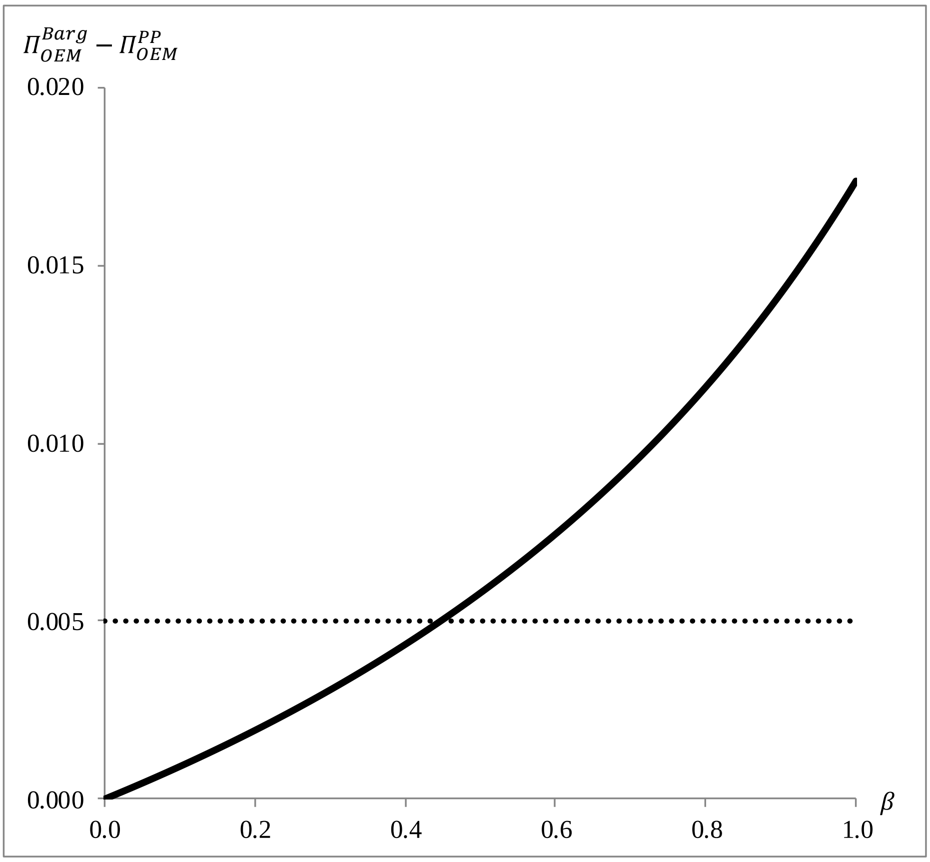


Fig. 3 shows the additional profit generated by bargaining for the same parameter values of $q_p = 0.5$, $\alpha = 0.1$, $c_{OEM}^N = 0.4$, and $c_{OEM}^R = 0.1$. Note that the values are small because we have normalised the market size to one. The solid line represents additional profit that can be generated, which is positive for all values of β.

So far, we have assumed that negotiation is costless and that the manufacturer always benefits from negotiations. However, the manufacturer might need to hire additional workers or train staff before offering negotiations, thus incurring a fixed cost F. If this is the case, the advantage will be smaller. Bargaining is preferred if and only if $F < \Pi_{OEM}^{Barg} - \Pi_{OEM}^{PP}$. If we consider, for example, a fixed cost of $F = 0.005$ (dotted line), the OEM in this example should choose bargaining only if $\beta > 0.45$.

5 OEM in competition with an independent remanufacturer

In our analysis so far, we have assumed that the OEM is a monopolist in both the market where he buys used products as well as when selling products. As discussed earlier, it is not uncommon for an independent firm to remanufacture another manufacturer's product. To investigate whether bargaining is still preferable in such an environment, we develop a model in which the OEM faces competition from an independent remanufacturer (IR). As in Section 4, the OEM still manufactures the product and remanufactures used products. Furthermore, we do not analyse the players' decision about whether or not to partake in the market (see, e.g., Ferguson/Toktay 2006). Instead, we restrict the analysis to settings in which manufacturing and remanufacturing are profitable for at least a marginal unit for both players.

We first introduce our extended model of posted pricing and bargaining. Thereafter, we discuss the OEM's and IR's profit and best response functions and, finally, analyse the equilibria in a Cournot duopoly and with the OEM as a Stackelberg leader.

Regarding the competition on the markets, we basically follow Debo et al. (2005). Accordingly, we assume that both firms buy used products from customers in a perfectly competitive market, that is, the used products' prices are such that the market clears. Let q_{OEM}^R and q_{IR}^R denote the quantities bought by the OEM and the IR, respectively. To ensure consistency and analytical tractability, we only consider settings in which such a price exists, that is, $q_{OEM}^R + q_{IR}^R \leq q_p$. If both firms use posted pricing, the OEM's decision variables are the total quantity of products to sell q_{OEM} and the quantity of products to remanufacture q_{OEM}^R; the IR decides on the quantity to remanufacture q_{IR}^R. Then, the market price is given by $p^R\,(q_{OEM}^R + q_{IR}^R)$. Selling their new and remanufactured products on the secondary market, both firms compete in quantities and obtain a price of $p(q_{OEM} + q_{IR}^R)$ per unit, where q_{OEM} is again the total quantity of new and remanufactured products sold by the OEM.

Alternatively, firm i can decide to use bargaining, while the other firm, j, posts a price (β always denotes the power of the firm that bargains, in this case i). Firm i decides on its cut-off price $p_{i,max}^R$ and we directly use the price posted $p_j^{R,Barg_i}$ as j's decision variable. Moreover, the OEM still decides on his total quantity to sell q_{OEM}. A customer with valuation ω can now either sell to i at the negotiated price $p_{Barg}^R\left(p_{i,max}^R, \omega\right)$ or turn to j and sell at $p_j^{R,Barg_i}$, whichever is more beneficial. Since we assume that remanufacturing is profitable for both firms, $p_{i,max}^R \geq p_j^{R,Barg_i}$, because, otherwise, i could not remanufacture. Thus, there exists a customer with valuation ω_{ind} who is indifferent between the two possibilities: $p_{Barg}^R\left(p_{i,max}^R, \omega_{ind}\right) = p_j^{R,Barg_i}$. Solving for ω_{ind}, we obtain

$$\omega_{ind} = \frac{1}{\beta} p_j^{R,Barg_i} + (1 - \frac{1}{\beta}) p_{i,max}^R. \tag{9}$$

All customers with $\omega < \omega_{ind}$ prefer the posted price and j buys $q^R(\omega_{ind})$ units at a price of $p_j^{R,Barg_i}$. Customers with higher valuations ($\omega_{ind} \leq \omega \leq p_{i,max}^R$) prefer the negotiated price and i's total buying and remanufacturing cost can be calculated analogously to (5):

$$\begin{aligned} C_i^{Barg}\left(p_{i,max}^R, \omega_{ind}\right) &= \int_{\omega_{ind}}^{p_{i,max}^R} \left[p_{Barg}^R\left(p_{i,max}^R, \omega\right) + c_{OEM}^R\right] \cdot \frac{dq^R\,(\omega)}{d\omega}\, d\omega \\ &= \frac{\left(p_{i,max}^R - p_j^{R,Barg_i}\right) q_p}{p_p(1-\alpha)2\beta^2} \cdot \left(p_{i,max}^R(5\beta - \beta^2 - 2) + (2-\beta) p_j^{R,Barg_i} + 2c_{OEM}^R \beta\right). \end{aligned} \tag{10}$$

5.1 Profit and response functions

In this subsection, we state the OEM's and IR's profit and best response functions. Regarding used product acquisition, we distinguish between three scenarios. We first consider both firms using posted pricing (denoted by PP_{both}), then consider negotiations by the OEM while the IR posts a price ($Barg_{OEM}$), and – finally – consider a situation in which the IR bargains and the OEM posts a price ($Barg_{IR}$).

5.1.1 *Both firms use posted pricing*

When both firms post a price, the OEM's profit depends on q_{OEM}^{R}, q_{OEM}, and q_{IR}^{R}:

$$\begin{aligned}\Pi_{OEM}^{PP_{both}}\left(q_{OEM}^{R}, q_{OEM}, q_{IR}^{R}\right) = p(q_{OEM} + q_{IR}^{R}) \cdot q_{OEM} - [q_{OEM} - q_{OEM}^{R}] \cdot c_{OEM}^{N} \\ -\left[p^{R}\left(q_{OEM}^{R} + q_{IR}^{R}\right) + c_{OEM}^{R}\right] \cdot q_{OEM}^{R}\end{aligned} \tag{11}$$

We obtain the following best response functions from first-order conditions, allowing us to maximise (11) subject to q_{IR}^{R}:

$$\begin{gathered} q_{OEM}^{R,PP_{both}^{*}}(q_{IR}^{R}) = \frac{1}{2} q_{p}\left[\frac{c_{OEM}^{N} - c_{OEM}^{R} - \alpha p_{p}}{(1-\alpha)p_{p}} - \frac{q_{IR}^{R}}{q_{p}}\right] \\ \text{and } q_{OEM}^{PP_{both}^{*}}(q_{IR}^{R}) = \tfrac{1}{2}[1 - c_{OEM}^{N} - q_{IR}^{R}]. \end{gathered} \tag{12}$$

Similarly, the IR's profit function,

$$\Pi_{IR}^{PP_{both}}\left(q_{OEM}^{R}, q_{OEM}, q_{IR}^{R}\right) = \left[p(q_{OEM} + q_{IR}^{R}) - p^{R}\left(q_{OEM}^{R} + q_{IR}^{R}\right) - c_{IR}^{R}\right] \cdot q_{IR}^{R}, \tag{13}$$

depends on his choice of q_{IR}^{R} as well as the OEM's quantities q_{OEM}^{R} and q_{OEM} and is maximised by

$$q_{IR}^{R,PP_{both}^{*}}\left(q_{OEM}^{R}, q_{OEM}\right) = \tfrac{1}{2}\left[q_{p} - \tfrac{(1-\alpha)p_{p}q_{OEM}^{R} + q_{p}\left(c_{IR}^{R} + q_{OEM}\right)}{1-\alpha p_{P}}\right]. \tag{14}$$

Note that the above functions state the quantities to choose for the OEM and the IR not only for the Nash solution, but they are also valid when the other player deviates from the optimal value. Equations (12) and (14) can be interpreted as follows: Under posted pricing, the optimal quantity the OEM sells ($q_{OEM}^{PP_{both}^{*}}$) decreases with the quantity remanufactured by the IR (q_{IR}^{R}) because higher overall quantities decrease the selling price. Similarly, the quantity remanufactured decreases with (q_{IR}^{R}) because they compete for the used products. The quantity processed by the IR ($q_{IR}^{R,PP_{both}^{*}}$) decreases in both the quantity remanufactured by the OEM (q_{OEM}^{R}) and the quantity sold by the OEM (q_{OEM}) due to increased competition when buying used and selling remanufactured producs.

5.1.2 *OEM bargains*

When negotiating with customers, the OEM must decide on a maximum acquisition price $p_{OEM,max}^{R}$ and the total quantity to sell q_{OEM}. His profit $\Pi_{OEM}^{Barg_{M}}$ also depends on the competitor's decision, on $p_{IR}^{R,Barg_{OEM}}$:

$$\begin{aligned} &\Pi_{OEM}^{Barg_{OEM}}\left(p_{OEM,max}^{R}, q_{OEM}, p_{IR}^{R,Barg_{OEM}}\right) \\ &= p\left(q_{OEM} + q^{R}(\omega_{ind})\right) \cdot q_{OEM} - \left[q_{OEM} - q^{R}\left(p_{OEM,max}^{R}\right) + q^{R}(\omega_{ind})\right] \cdot c_{OEM}^{N} \\ &- \frac{\left(p_{OEM,max}^{R} - p_{IR}^{R,Barg_{OEM}}\right)q_{p}}{p_{p}(1-\alpha)2\beta^{2}} \\ &\qquad \cdot \left(p_{OEM,max}^{R}(5\beta - \beta^{2} - 2) + (2-\beta)p_{IR}^{R,Barg_{OEM}} + 2c_{OEM}^{R}\beta\right). \end{aligned} \tag{15}$$

Again, we obtain the following response functions from first-order conditions, maximising (15) subject to $p_{IR}^{R,Barg_{OEM}}$:

$$p_{OEM,max}^{R,Barg_{OEM}*}(q_{OEM}^{Barg_{OEM}}) = c_{OEM}^{N} - c_{OEM}^{R} + (1-\beta)\cdot q_{OEM}^{Barg_{OEM}}$$
$$\text{and } q_{OEM}^{Barg_{OEM}*}\left(p_{IR}^{R,Barg_{OEM}}, p_{OEM,max}^{R}\right) = \tfrac{1}{2}\left[1 - c_{OEM}^{N} - q^{R}(\omega_{ind})\right], \tag{16}$$

where only the latter depends on the IR's choice of $p_{IR}^{R,Barg_{OEM}}$. Similarly, the IR's profit function

$$\begin{aligned}&\Pi_{IR}^{Barg_{OEM}}\left(p_{OEM,max}^{R}, q_{OEM}^{Barg_{OEM}}, p_{IR}^{R,Barg_{OEM}}\right)\\ &= \left[p\left(q_{OEM}^{R,Barg_{OEM}} + q^{R}(\omega_{ind})\right) - p_{IR}^{R,Barg_{OEM}} - c_{IR}^{R}\right]\cdot q^{R}(\omega_{ind})\end{aligned} \tag{17}$$

is maximised by

$$\begin{aligned}&p_{IR}^{R,Barg_{OEM}*}\left(p_{OEM,max}^{R}, q_{OEM}^{Barg_{OEM}}\right)\\ &= \frac{1}{2}\left[\frac{p_{OEM,max}^{R}(1-\beta)[2q_p+(1-\alpha)p_p\beta]}{q_p+(1-\alpha)p_p\beta} + \frac{p_p\beta\left[\left(1-c_{IR}^{R}-q_{OEM}^{Barg_{OEM}}\right)(1+\alpha)-\alpha\left((1-\alpha)p_p\beta\right)\right]}{q_p+(1-\alpha)p_p\beta}\right].\end{aligned} \tag{18}$$

Equations (16) show that when the OEM bargains, the optimal maximum price he is willing to offer ($p_{OEM,max}^{R,Barg_{OEM}*}$) increases in the total amount he sells ($q_{OEM}^{Barg_{OEM}}$). In turn, the optimal total selling quantity decreases in the price the IR is willing to offer through ω_{ind}. For the IR, Equation (18) shows that the optimal acquisition price $p_{IR}^{R,Barg_{OEM}*}$ increases in the OEM's maximum price and decreases in the total quantity sold by the OEM.

5.1.3 IR bargains

When the IR bargains, the bargaining power β refers to the IR, and $1-\beta$ is the customer's power. The OEM's profit depends on his decisions $p_{OEM}^{R,Barg_{IR}}$ and $q_{OEM}^{Barg_{OEM}}$, as well as the IR's $p_{IR,max}^{R,Barg_{OEM}}$:

$$\begin{aligned}&\Pi_{OEM}^{Barg_{IR}}\left(p_{OEM}^{R,Barg_{IR}}, q_{OEM}^{Barg_{IR}}, p_{IR,max}^{R,Barg_{OEM}}\right)\\ &\qquad = p\left(q_{OEM}^{Barg_{IR}} + q^{R}\left(p_{IR,max}^{R,Barg_{OEM}}\right) - q^{R}(\omega_{ind})\right)\cdot q_{OEM}^{Barg_{IR}}\\ &\qquad - \left[q_{OEM}^{Barg_{IR}} - q^{R}(\omega_{ind})\right]\cdot c_{OEM}^{N} - q^{R}(\omega_{ind})\cdot c_{OEM}^{R}\end{aligned} \tag{19}$$

The OEM maximises his profit by choosing

$$p_{OEM}^{R,Barg_{IR}*}\left(p_{IR,max}^{R,Barg_{IR}}\right) = \frac{1}{2}\left[c_{OEM}^{N} + q_{OEM}^{Barg_{IR}} + \alpha\beta p_p + (1-\beta)p_{IR,max}^{R,Barg_{IR}}\right]$$
$$\text{and } q_{OEM}^{Barg_{IR}*}\left(p_{IR,max}^{R,Barg_{IR}}\right) = \tfrac{1}{2}\left[1 - c_{OEM}^{N} - q^{R}\left(p_{IR,max}^{R,Barg_{IR}}\right) + q^{R}(\omega_{ind})\right]. \tag{20}$$

Finally, the IR's profit function

$$\begin{aligned}&\Pi_{IR}^{Barg_{IR}}\left(p_{OEM}^{R,Barg_{IR}}, q_{OEM}^{Barg_{IR}} p_{IR,max}^{R,Barg_{IR},}\right)\\ &\qquad = \left[p\left(q_{OEM}^{Barg_{IR}} + q_{IR}^{R,Barg_{IR}}\right) - p^{R}\left(q_{OEM}^{Barg_{IR}} + q_{IR}^{R,Barg_{IR}}\right) - c_{IR}^{R}\right]\\ &\qquad \cdot q_{IR}^{R,Barg_{IR}}\end{aligned} \tag{21}$$

is maximised by

$$p_{IR,max}^{R,Barg_{IR}*}\left(p_{OEM}^{R,Barg_{IR}}, q_{OEM}^{Barg_{IR}}\right) = \frac{2p_{OEM}^{R,Barg_{IR}} + (1-\alpha)p_p\beta\left[1-c_{IR}^{R}-q_{OEM}^{Barg_{IR}}\right]}{2q_p+(1-\alpha)p_p\beta}\ . \tag{22}$$

Equations (20) show that the OEM's optimal acquisition price $p_{OEM}^{R,Barg_{IR}*}$ increases in his total quantity sold and in the IR's maximum price. The OEM's optimal total quantity sold $q_{OEM}^{Barg_{IR}*}$ decreases in the IR's maximum price. Regarding the IR, (22) shows that his optimal maximum price $p_{IR,max}^{R}{}^{*}$ increases with the OEM's acquisition price and decreases with the OEM's total quantity sold. Again, the competition in the primary market simultaneously causes prices to rise, whereas a higher quantity sold on the secondary market decreases the selling price obtained and thus reduces the quantity of products bought and remanufactured.

Table 4 provides an overview of the IR's and OEM's decision variables with respect to using bargaining and posted pricing.

Table 4: Decision variables for OEM in competition with IR

Variable	Description
	Both use posted pricing (Section 5.1.1)
q_{OEM}^{R}	Quantity of used products bought and remanufactured by OEM
q_{IR}^{R}	Quantity of used products bought and remanufactured by IR
q_{OEM}	Quantity sold in the secondary market by OEM
	OEM bargains (Section 5.1.2)
$p_{OEM,max}^{R}$	Maximum price paid by the OEM for used products
q_{IR}^{R}	Quantity of used products bought and remanufactured by IR
q_{OEM}	Quantity sold in the secondary market by OEM
	IR bargains (Section 5.1.3)
q_{OEM}^{R}	Quantity of used products bought and remanufactured by OEM
$p_{IR,max}^{R}$	Maximum price paid by the IR for used products
q_{OEM}	Quantity sold in the secondary market by OEM

5.2 Cournot duopoly

In this subsection, we consider a Cournot competition in which both firms make simultaneous decisions and anticipate the other party's decision. Following Nash (1950), the resulting solution is such that no firm can do better by deviating from this equilibrium. We arrive at this Nash equilibrium by solving for the intersection of the OEM's best response functions ((12), (16), or (20)) with the IR's best response function ((14), (18), or (22), respectively). Table 5 illustrates the equilibrium values of the OEM's decision variables, which depend on only the six parameters of our model, for the three scenarios PP_{both}, $Barg_{OEM}$, and $Barg_{IR}$. Analogously, the IR's equilibrium values are given in Table 6. Now, equilibrium profits are straightforwardly calculated by substituting into the profit functions (11) and (13) for PP_{both}, (15) and (17) for $Barg_{OEM}$ as well as (19) and (21) for $Barg_{IR}$. To save space, the equations obtained for the equilibrium profits are not stated here because they are even more complex than the equilibrium decision variables.

Table 5: OEM's decision variables in equilibrium (Cournot duopoly)

	Total quantity sold	Quantity bought/acquisition price
Posted Pricing	$q_{OEM}^{PP_{both}*} = \frac{1}{2}\left[1 - c_{\mathrm{OEM}}^{\mathrm{N}} + \frac{1}{3}q_1\left[\frac{2c_{IR}^{R} - c_{OEM}^{R}}{1 - \alpha p_p} - 1\right]\right]$	$q_{OEM}^{R,PP_{both}*} = \frac{1}{2}q_p\left[\frac{2}{3} + \frac{1}{3}\cdot\frac{2c_{IR}^{R} - c_{OEM}^{R}}{1 - \alpha p_p} + \frac{c_{OEM}^{N} - c_{OEM}^{R} - p_p}{(1-\alpha)p_p}\right]$
Bargaining OEM	$q_{OEM}^{Barg_{OEM}*} = \frac{2(1 - c_{OEM}^{N})(1 - \alpha p_p)\beta + q_p\left(1 - c_{OEM}^{N} - \beta + p_p\alpha\beta + c_{IR}^{R}(1+\beta)\right)}{q_p(2-\beta) + 4(1 - p_p\alpha)\beta}$	$p_{OEM,max}^{R,Barg_{OEM}*} = \frac{2(1 + c_{OEM}^{N} - 2c_{IR}^{R})(1-\alpha)p_p\beta + q_p(1 + c_{OEM}^{N} + c_{IR}^{R} + 3p_p\alpha\beta)}{q_p(2-\beta) + 4(1 - p_p\alpha)\beta}$
Bargaining IR	$q_{OEM}^{Barg_{IR}*} = \frac{2(1 - c_{OEM}^{N})(1 - p_p\alpha)\beta + q_p(1 + c_{IR}^{R} - (c_{OEM}^{N} + c_{OEM}^{R})(1-\beta) - 2\beta + p_p\alpha\beta)}{4(1-\alpha)\beta + q_p(2 - \beta(2 - 4\alpha + \beta))}$	$p_{OEM}^{R,Barg_{IR}*} = $ A)

A) $\frac{1}{8(1-\alpha)\beta+2q_p(2-(2-4\alpha)\beta-\beta^2)}\cdot\left[{q_p}^2\alpha\beta((3-2\alpha)\beta-4) + (1-\alpha)\beta\left(4 - 2c_{IR}^{R} - 2c_{OEM}^{R}(3-\beta) - 4\beta + 2\alpha\beta + \beta^2 + c_{OEM}^{N}(4 + 2\beta - \beta^2)\right) + q_p\left(2 + 2c_{IR}^{R} - 7\beta - c_{IR}^{R}\beta + 8\alpha\beta - 2c_{IR}^{R}\alpha\beta + 5\beta^2 + c_{IR}^{R}\beta^2 - 9\alpha\beta^2 + 4\alpha^2\beta^2 - \beta^3 + \alpha\beta^3 - c_{OEM}^{R}((9-6\alpha)\beta - 2(1-\alpha)\beta^2 - 6) + c_{OEM}^{N}(2 - \beta + 4\alpha\beta - 2(2-\alpha)\beta^2 + (1-\alpha)\beta^3)\right)\right]$

Given the complexity of these solutions, it is unfortunately not tractable to analytically compare the profits and to derive conditions for when to choose posted pricing and when to choose bargaining. Instead, we resort to a numerical comparison of the analytically derived profit functions. We use a full factorial design to evaluate every combination of 11 values for the six parameters of our model, that is, $c_{OEM}^{N}, c_{OEM}^{R}, c_{IR}^{R}, q_p, \alpha, \beta \in \{0.01, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.99\}$. However, we restrict these to parameterisations that satisfy our assumptions outlined in Sections 4 and 5, such as that manufacturing and remanufacturing are both profitable for a marginal unit.

Table 6: IR's decision variables in equilibrium (Cournot duopoly)

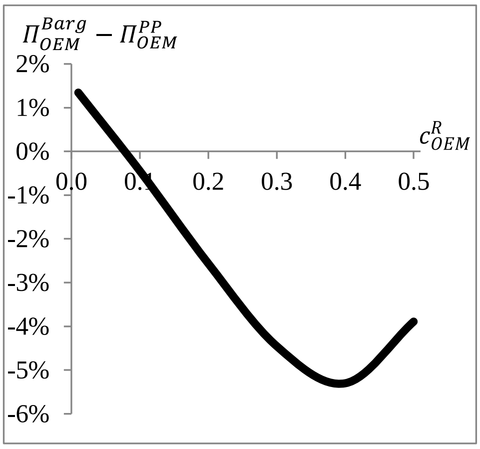
	Quantity bought/acquisition price
Posted Pricing	$q_{IR}^{R,PP_{both}*} = \frac{1}{3} q_p \cdot \left[\frac{1 + c_{OEM}^R - 2c_{IR}^R - p_p\alpha}{1 - p_p\alpha} \right]$
Bargaining OEM	$p_{IR}^{R,Barg_{OEM}*} = \frac{1}{-8(-1+\alpha)\beta + q_p(4 + (-2+8\alpha)\beta)} \cdot \left[-2q_p^2\alpha\beta(3 + (-1+\alpha)\beta) + (-1+\alpha)\beta(-4 + c_{OEM}^N(-4+\beta) - 2c_{IR}^R(-3+\beta) + \beta - 2\alpha\beta) + q_p\left(2 - 4\beta + 10\alpha\beta + \beta^2 - 5\alpha\beta^2 + 4\alpha^2\beta^2 + c_{OEM}^N(2 + 4(-1+\alpha)\beta - (-1+\alpha)\beta^2) + 2c_{IR}^R(1 - 3(-1+\alpha)\beta + (-1+\alpha)\beta^2)\right)\right]$
Bargaining IR	$p_{OEM}^{R,Barg_{IR}*} = \frac{\left(2 + 2c_{OEM}^N - 4c_{OEM}^R - 3q_p + 4c_{OEM}^R q_p - c_{IR}^R q_p - p_p\left(2 + 2c_{OEM}^N - 4c_{OEM}^R - q_1\right)\alpha\right)\beta}{4(1-\alpha)\beta + q_p\left(2 - \beta(2 - 4\alpha + \beta)\right)} + \frac{(1 + c_{OEM}^N - 3c_{OEM}^R + c_{IR}^R)q_p - p_p(2 + 2c_{OEM}^N(-1+\alpha) + (-2+q_p)\alpha)\beta^2}{4(1-\alpha)\beta + q_p(2 - \beta(2 - 4\alpha + \beta))}$

Table 7: Settings with OEM's advantage from bargaining exceeding 2% (Cournot duopoly)

c_{OEM}^N	c_{OEM}^R	c_{IR}^R	q_p	α	β	OEM's profit Π_{OEM}			IR's profit Π_{IR}			OEM's advantage from bargaining	
						PP_{both}	$Barg_{IR}$	$Barg_{OEM}$	PP_{both}	$Barg_{IR}$	$Barg_{OEM}$		
0.7	0.01	0.2	0.2	0.01	0.99	0.03403	0.04559	0.03475	0.00812	0.00527	0.02275	0.00072	2.11%
0.7	0.01	0.3	0.2	0.01	0.99	0.03950	0.04806	0.04062	0.00362	0.00155	0.01615	0.00111	2.82%
0.7	0.01	0.3	0.2	0.1	0.99	0.03812	0.04517	0.03900	0.00263	0.00082	0.01319	0.00088	2.32%
0.7	0.01	0.4	0.2	0.01	0.99	0.04543	0.05071	0.04699	0.00091	0.00004	0.01068	0.00157	3.45%
0.8	0.01	0.2	0.1	0.01	0.99	0.01821	0.02496	0.01866	0.00405	0.00313	0.01251	0.00045	2.45%
0.8	0.01	0.3	0.1	0.01	0.99	0.02095	0.02587	0.02161	0.00180	0.00109	0.00912	0.00066	3.15%
0.8	0.01	0.3	0.1	0.1	0.99	0.02016	0.02414	0.02070	0.00125	0.00061	0.00742	0.00054	2.69%
0.8	0.01	0.3	0.1	0.2	0.99	0.01931	0.02230	0.01972	0.00072	0.00022	0.00561	0.00041	2.12%
0.8	0.01	0.4	0.1	0.01	0.99	0.02391	0.02682	0.02481	0.00045	0.00010	0.00626	0.00090	3.78%
0.8	0.01	0.4	0.1	0.1	0.99	0.02319	0.02519	0.02397	0.00018	0.00000	0.00476	0.00078	3.37%
0.8	0.1	0.4	0.1	0.01	0.99	0.01927	0.02682	0.01968	0.00095	0.00010	0.00628	0.00040	2.09%
0.9	0.01	0.3	0.01	0.01	0.99	0.00386	0.00442	0.00395	0.00018	0.00014	0.00102	0.00009	2.21%
0.9	0.01	0.4	0.01	0.01	0.99	0.00416	0.00448	0.00427	0.00004	0.00002	0.00072	0.00011	2.70%
0.9	0.01	0.4	0.01	0.1	0.99	0.00408	0.00428	0.00418	0.00002	0.00000	0.00055	0.00010	2.45%

For every parameterisation, we calculate six profit functions: one for the OEM and one for the IR for each of the three scenarios PP_{both}, $Barg_{IR}$, and $Barg_{OEM}$. Subsequently, the profits obtained are numerically compared. This evaluation shows that, for the IR, bargaining ($Barg_{IR}$) is always the worst of the three scenarios. Thus, the IR will always decide not to bargain, independent of the OEM's decision and it remains for the OEM to decide whether to use bargaining ($Barg_{OEM}$) or for both to post a price (PP_{both}). A comparison of the relevant profits $\Pi_{OEM}^{PP_{both}}$ and $\Pi_{OEM}^{Barg_{OEM}}$ shows that there are only very few settings (approximately 1%) in which the OEM prefers bargaining. Table 7 shows the parameterisations of the settings with the OEM's advantage from bargaining exceeding 2%. It is immediately obvious from the table that the OEM only profits from bargaining when he has extraordinarily high bargaining power. In all 14 scenarios $\beta = 0.99$. We never observed advantages exceeding 1.4% for values of $\beta \leq 0.9$. For example, Fig. 4 shows the OEM's profit advantage of bargaining over posted pricing depending on c_{OEM}^N. It shows that bargaining is only superior for very low values of the remanufacturing cost in the setting depicted. Moreover, these results are obtained without considering any cost incurred by bargaining. Thus, we conclude that bargaining is not beneficial for either type of firm in practice and that both choose posted pricing in a Cournot duopoly scenario.

Fig. 4: The OEM's profit advantage of bargaining over posted pricing depending on c_{OEM}^{R} ($q_p = 0.1$, $\alpha = 0.01$, $\beta = 0.9$, $c_{OEM}^{N} = 0.8$, and $c_{IR}^{R} = 0.4$)



5.3 Stackelberg competition

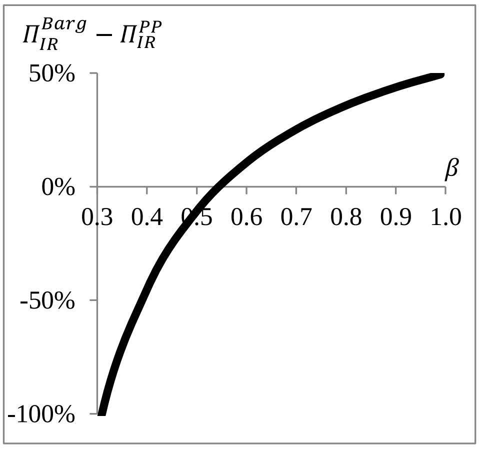
Finally, we consider a situation in which the OEM moves first and the IR follows. As a Stackelberg leader, the OEM knows how the IR will respond to his decision, that is, he maximises his profit given the IR's best response function. This will lead to a greater or equal profit than the profit he obtained in the Cournot duopoly, because the OEM is not constrained to the intersection of their best response functions but can freely choose a point on the IR's response function. We derive this subgame-perfect equilibrium by first substituting the IR's response function ((14), (18), or (22)) into the OEM's profit function ((11), (15), or (19), respectively) and maximising with regard to his decision variables. In a second step, the IR's decision and profit are determined using his best response and profit function ((13), (17), or (21)). Again, we numerically compare the profits using 11 values for each parameter.

The results differ quite significantly from the Cournot duopoly scenario. Being the Stackelberg leader, bargaining is almost always the worst alternative for the OEM. The exceptions are a few combinations of parameter values, where the OEM slightly prefers bargaining over having the IR bargain. However, both using a posted price still generates the highest revenue for the OEM. Since, in these instances, the IR attains the highest profit in PP_{both}, both decide for posted pricing. In contrast, bargaining is now often attractive for the IR. In approximately 17% of the settings considered, the IR now prefers bargaining ($Barg_{IR}$); otherwise, both the IR and OEM use posted pricing (PP_{both}). Table 8 shows settings in which bargaining is very attractive for the IR. For this table, we only included settings in which the advantage of bargaining exceeds 10% and an absolute value of 0.001. Moreover, we restricted the bargaining power to intermediate values ($\beta \in \{0.6, 0.7\}$); there are many more similar settings with higher bargaining power. In this context, Fig. 5 shows further examples where bargaining is beneficial for the IR. In the setting considered ($q_p = 0.1$, $\alpha = 0.01$, $c_{OEM}^{N} = 0.8$, $c_{OEM}^{R} = 0.01$, and $c_{IR}^{R} = 0.4$), bargaining is preferred if the bargaining power exceeds a value of about 0.5.

Table 8: Settings with IR's advantage from bargaining exceeding 10% and 0.001 and $\beta \in \{0.6, 0.7\}$ (Stackelberg competition)

c_{OEM}^N	c_{OEM}^R	c_{IR}^R	q_p	α	β	OEM's profit Π_{OEM}			IR's profit Π_{IR}			IR's advantage from bargaining	
						PP_{both}	$Barg_{IR}$	$Barg_{OEM}$	PP_{both}	$Barg_{IR}$	$Barg_{OEM}$		
0.7	0.01	0.01	0.2	0.01	0.6	0.02756	0.02973	0.02010	0.01215	0.01352	0.02598	0.00136475	10.10%
0.7	0.01	0.01	0.2	0.01	0.7	0.02756	0.03272	0.02148	0.01215	0.01485	0.02848	0.00270151	18.19%
0.7	0.01	0.01	0.2	0.1	0.7	0.02584	0.03032	0.02026	0.01125	0.01357	0.02585	0.00231545	17.07%
0.7	0.01	0.01	0.2	0.2	0.7	0.02394	0.02769	0.01893	0.01025	0.01214	0.02294	0.00188508	15.53%
0.7	0.01	0.01	0.2	0.3	0.7	0.02208	0.02509	0.01763	0.00925	0.01071	0.02003	0.00145368	13.58%
0.7	0.01	0.01	0.2	0.4	0.7	0.02026	0.02256	0.01638	0.00825	0.00927	0.01713	0.00102228	11.02%
0.7	0.01	0.1	0.2	0.01	0.7	0.03222	0.03655	0.02627	0.00639	0.00830	0.02061	0.00191452	23.06%
0.7	0.01	0.1	0.2	0.1	0.7	0.03051	0.03424	0.02506	0.00557	0.00713	0.01809	0.00156851	21.99%
0.7	0.01	0.1	0.2	0.2	0.7	0.02863	0.03173	0.02374	0.00467	0.00586	0.01532	0.00119499	20.39%
0.8	0.01	0.01	0.1	0.01	0.7	0.01498	0.01807	0.01148	0.00607	0.00750	0.01540	0.00142617	19.03%
0.8	0.01	0.01	0.1	0.1	0.7	0.01400	0.01670	0.01080	0.00556	0.00678	0.01392	0.00122123	18.00%
0.8	0.01	0.1	0.1	0.01	0.7	0.01731	0.01990	0.01386	0.00319	0.00426	0.01142	0.00107498	25.22%

Fig. 5: The IR's profit advantage of bargaining over posted pricing depending on β ($q_p = 0.1$, $\alpha = 0.01$, $c_{OEM}^N = 0.8$, $c_{OEM}^R = 0.01$, and $c_{IR}^R = 0.4$)



6 Summary and conclusion

In this paper, we considered used products' acquisition for remanufacturing. Whereas the literature generally assumes that customers must simply be motivated to return their used products and a few authors consider fixed prices for these "cores", we followed recent reports suggesting that customers are becoming increasingly open to bargaining and we compared using a posted price and bargaining to obtain used products. We considered a primary market in which used products are bought from customers with heterogeneous valuations and a secondary market in which products are sold and new products and remanufactured products are equally valued. In our first model, we considered an OEM acting as a monopolist. Then, we analysed competition from an independent remanufacturing company, in which one of the two firms can choose bargaining.

Our results show that bargaining's advantage over using a posted price strongly depends on the market type. We analytically showed that, as a monopolist, the OEM will always bargain over the acquisition price, because this allows for discriminating among customers with heterogeneous valuations for a used product. In contrast, our numerical study suggests that, in a Cournot duopoly, neither the OEM nor IR partake in bargaining. It is completely unattractive for the remanufacturer. For the OEM, there are rare combinations of model parameters with extraordinarily high bargaining power for which he obtains a slightly higher profit from negotiations. However, this will probably be offset by the additional cost incurred in reality. Nevertheless, when the OEM acts as a Stackelberg leader and the remanufacturer follows, the picture is completely different. Now, the remanufacturer obtains considerably higher profits in almost a fifth of the parameterisations, whereas the OEM always prefers to post a price. Of course, we obtained these results under several assumptions, for instance that new and remanufactured products are perfect substitutes, valuations are uniformly distributed (linear demand) and that the generalised Nash bargaining solution describes the negotiation outcome.

We feel that these results show that the use of bargaining in used product acquisition is well worth considering and that it provides ample room for further research. Possible future topics could include the consideration of other market types or distributions of valuations. While we focus on the negotiation outcome on a rather abstract level, future research could consider specific products or industries and, thus, model the negotiation process in more detail, for example using a variant of Rubinstein's approach. Furthermore, the impact of various aspects already considered in the literature on remanufacturing could be explored. These include multiple quality levels of used products, customers differentiating between the products with regard to quality and brand, and customers being strategic in the sense of considering the total cost of ownership (TCO), to name a few.

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Remarks

[1]There is no doubt that the benefits from remanufacturing go well beyond energy conservation, materials and value added. Giuntini/Gaudette (2003) show in detail how enterprises (e.g. through increased profits), the workforce (remanufacturing requires higher skills and is usually on-shore), consumers (greater variety, more competition and lower cost) and society benefit from remanufacturing. Lund/Hauser (2010) add that remanufacturing is less dependent on subsidies than recycling and is probably less cyclical than manufacturing. A nice anecdote in this context is that, in the 1930s, when the Great Depression brought new car sales to a standstill, Henry Ford began remanufacturing automobile engines.

[2]For an overview of dynamic pricing, see, for example, the surveys by Chan et al. (2004) and Gönsch et al. (2009, 2013).

[3] $\frac{d\Pi_{OEM}^{Barg^*}}{d\alpha} = \frac{q_p}{2(2-\beta)}\left[-p_p + \frac{\left(c_{OEM}^R - c_{OEM}^N + p_p\right)^2}{p_p(1-\alpha)^2}\right] \leq 0 \Leftrightarrow -p_p + \frac{\left(c_{OEM}^R - c_{OEM}^N + p_p\right)^2}{p_p(1-\alpha)^2} \leq 0 \Leftrightarrow \frac{c_{OEM}^R - c_{OEM}^N + p_p}{1-\alpha} \leq p_p \Leftrightarrow c_{OEM}^R - c_{OEM}^N + \alpha p_p \leq 0$

[4] The quadratic function $C_{OEM}^{Barg}(p^R(q^R))$ is convex in q^R.

Appendix

Table A.1: Notation and indices used

Symbol	Description
	Notation
α	Lower bound for customers' valuations
β	Firm's bargaining power
c	Cost (per unit)
C	Total cost of buying and remanufacturing
ω	Customer's valuation/willingness-to-sell for his used product
p	Price
Π	Profit
q	Quantity
	Indices
$Barg$	Bargaining
ind	Indifferent
IR	Independent remanufacturer
max	Maximum
N	New
OEM	Original equipment manufacturer
P	Primary market
PP	Posted pricing
R	Return/remanufacture

Table A.2: OEM's decision and key variables (Cournot duopoly)

	Posted Pricing	Bargaining OEM	Bargaining IR
qty. remanufactured [i)]	$\frac{1}{2}q_p\left[\frac{2}{3}+\frac{1}{3}\cdot\frac{2c_{IR}^R-c_{OEM}^R}{1-\alpha p_p}+\frac{c_{OEM}^N-c_{OEM}^R-p_p}{(1-\alpha)p_p}\right]$	$q_p\cdot\frac{\left(1+c_{OEM}^N-2\alpha p_p\right)\left[q_p\left(1-\beta(1+\alpha)\right)+\beta(1-\alpha)\right]}{(1-\alpha)p_p\left[4(1-\alpha)\beta+q_p(2-(1-4\alpha)\beta)\right]}$ $+c_{IR}^R\cdot\frac{q_p(2\alpha(1-\beta)+2\beta-1)+2(1-\alpha-\beta+\alpha\beta)}{(1-\alpha)p_p\left[4(1-\alpha)\beta+q_p(2-(1-4\alpha)\beta)\right]}$	*A)*
avg. price [ii)]	$\frac{1}{2}\left[c_{OEM}^N-\frac{2}{3}(c_{OEM}^R-c_{IR}^R)+\frac{1}{3}(1+2\alpha)p_p\right.$ $\left.-\frac{1}{3}\cdot\frac{(c_{OEM}^R-2c_{IR}^R)\cdot q_p}{(1-\alpha)p_p}\right]$	$p_p(1-\alpha)\beta\cdot\frac{2+c_{OEM}^N(2-\beta)-2c_{IR}^R(1-\beta)-\beta+2p_p\alpha\beta}{q_p(2-\beta)+4\left(1-p_p\alpha\right)\beta}$ $+q_p\cdot\frac{\left(1+c_{OEM}^N+c_{IR}^R+3p_p\alpha\beta\right)}{q_p(2-\beta)+4\left(1-p_p\alpha\right)\beta}$	*B)*
cut-off price $p_{OEM,max}^R$	-	$\frac{2(1+c_{OEM}^N-2c_{IR}^R)(1-\alpha)p_p\beta+q_p\left(1+c_{OEM}^N+c_{IR}^R+3p_p\alpha\beta\right)}{q_p(2-\beta)+4\left(1-p_p\alpha\right)\beta}$	-
total quantity	$\frac{1}{2}\left[1-c_{\mathrm{OEM}}^{\mathrm{N}}+\frac{1}{3}q_p\left[\frac{2c_{IR}^R-c_{OEM}^R}{1-\alpha p_p}-1\right]\right]$	$\frac{2(1-c_{OEM}^N)(1-\alpha p_p)\beta+q_p\left(1-c_{OEM}^N-\beta+p_p\alpha\beta+c_{IR}^R(1+\beta)\right)}{q_p(2-\beta)+4\left(1-p_p\alpha\right)\beta}$	$\frac{2(1-c_{OEM}^N)\left(1-p_p\alpha\right)\beta+q_p\left(1+c_{IR}^R-(c_{OEM}^N+c_{OEM}^R)(1-\beta)-2\beta+p_p\alpha\beta\right)}{4(1-\alpha)\beta+q_p\left(2-\beta(2-4\alpha+\beta)\right)}$
selling price [iii)]	$\frac{1}{2}\left[c_{OEM}^N+\frac{1-\alpha}{1-\alpha p_p}\right.$ $\left.-\frac{q_p\left[1+c_{OEM}^R-2c_{IR}^R-\alpha\left(4-\frac{1}{3}q_p\right)\right]}{1-\alpha p_p}\right]$	$\frac{2(1+c_{OEM}^N)(1-\alpha)\beta-{q_p}^2\alpha\beta}{4(1-\alpha)\beta+q_p(2-(1-4\alpha)\beta)}$ $+q_p\cdot\frac{1+c_{OEM}^N+c_{IR}^R-\beta(1+c_{OEM}^N-c_{IR}^R-3\alpha-2c_{OEM}^N\alpha)}{4(1-\alpha)\beta+q_p(2-(1-4\alpha)\beta)}$	$\frac{2(1+c_{OEM}^N)(1-\alpha)\beta-{q_p}^2\alpha\beta}{4(1-\alpha)\beta+q_p(2-(2-4\alpha)\beta-\beta^2)}$ $+q_p\cdot\frac{\left(1+c_{IR}^R-c_{OEM}^R(1-\beta)-2\beta+3\alpha\beta+c_{OEM}^N(1-\beta+2\alpha\beta-\beta^2)\right)}{4(1-\alpha)\beta+q_p(2-(2-4\alpha)\beta-\beta^2)}$

i) posted pricing: ${q_{OEM}^{R,PP_{both}}}^*$; bargaining OEM: $q^R\left({p_{OEM,max}^R}^*\right)-q^R(\omega_{ind})$; bargaining IR: $q^R(\omega_{ind})$.

ii): posted pricing: $p^R\left({q_{OEM}^{R,PP_{both}}}^*+{q_{IR}^{R,PP_{both}}}^*\right)$; bargaining OEM: $C_{OEM}^{Barg}\left({p_{OEM,max}^R}^*,\omega_{ind}\right)/\left(q^R\left({p_{OEM,max}^R}^*\right)-q^R(\omega_{ind})\right)$; bargaining IR: ${p_{OEM}^{R,Barg_{IR}}}^*$.

iii): posted pricing: $p\left({q_{OEM}^{PP_{both}}}^*+{q_{IR}^{R,PP_{both}}}^*\right)$; bargaining OEM: $p\left(q_{OEM}^{Barg_{OEM}}+\mathrm{q}^{\mathrm{R}}(\omega_{ind})\right)$; bargaining IR: $p\left(q_{OEM}^{Barg_{IR}}+q^R\left({p_{IR,max}^R}^*\right)-q^R(\omega_{ind})\right)$.

A): $$\frac{q_p\left(q_p+c_{OEM}^Nq_p-2q_p\alpha+2{q_p}^2\alpha+c_{IR}^R\left(2-2\alpha-q_p(1-2\alpha+\beta)\right)+2c_{OEM}^N\beta-q_p\beta-2\alpha\beta-2c_{OEM}^N\alpha\beta+3q_p\alpha\beta+2c_{OEM}^Nq_p\alpha\beta-{q_p}^2\alpha\beta+2\alpha^2-4q_p\alpha^2\beta+2{q_p}^2\alpha^2\beta-\beta^2+c_{OEM}^N\beta^2+q_p\beta^2-c_{OEM}^Nq_p\beta^2+\alpha\beta^2-c_{OEM}^N\alpha\beta^2-q_p\alpha\beta^2+c_{OEM}^Nq_p\alpha\beta^2-c_{OEM}^R\left(2(1-\alpha)(1+\beta)+q_p\left(1-2\beta+2\alpha(1+\beta)\right)\right)\right)}{p_p(1-\alpha)\left(4(1-\alpha)\beta+q_p(2-(2-4\alpha)-\beta^2)\right)}$$

B): $$\frac{{q_p}^2\alpha\beta((3-2\alpha)\beta-4)+(1-\alpha)\beta\left(4-2c_{IR}^R-2c_{OEM}^R(3-\beta)-4\beta+2\alpha\beta+\beta^2+c_{OEM}^N(4+2\beta-\beta^2)\right)+q_p\left(2+2c_{IR}^R-7\beta-c_{IR}^R\beta+8\alpha\beta-2c_{IR}^R\alpha\beta+5\beta^2+c_{IR}^R\beta^2-9\alpha\beta^2+4\alpha^2\beta^2-\beta^3+\alpha\beta^3-c_{OEM}^R\left((9-6\alpha)\beta-2(1-\alpha)\beta^2-6\right)+c_{OEM}^N\left(2-\beta+4\alpha\beta-2(2-\alpha)\beta^2+(1-\alpha)\beta^3\right)\right)}{8(1-\alpha)\beta+2q_p(2-(2-4\alpha)\beta-\beta^2)}$$

Table A.3: IR's decision and key variables (Cournot duopoly)

	Posted Pricing	Bargaining OEM	Bargaining IR
qty. re-manufactured *i)*	$\frac{1}{3}q_p \cdot \left[\frac{1+c^R_{OEM}-2c^R_{IR}-p_p\alpha}{1-p_p\alpha}\right]$	$q_p \cdot \frac{\left(1+c^N_{OEM}-2p_p\alpha\right)\beta-2c^R_{IR}(1+\beta)}{4(1-\alpha)\beta+q_p(2-(1-4\alpha)\beta)}$	$q_p \cdot \frac{2c^R_{OEM}(1-\beta)-2c^R_{IR}+\beta\left(2-2\alpha+2q_p\alpha-\beta+c^N_{OEM}\beta\right)}{4(1-\alpha)\beta+q_p\left(2-\beta(2-4\alpha+\beta)\right)}$
avg. price *ii)*	$\frac{1}{2}\left[c^N_{OEM}-\frac{2}{3}(c^R_{OEM}-c^R_{IR})+\frac{1}{3}(1+2\alpha)p_p - \frac{1}{3}\cdot\frac{(c^R_{OEM}-2c^R_{IR})\cdot q_p}{(1-\alpha)p_p}\right]$	*A)*	*B)*
cut-off price $p^{R}_{IR,max}{}^{*}$	-	-	$\frac{\left(2+2c^N_{OEM}-4c^R_{OEM}-3q_p+4c^R_{OEM}q_p-c^R_{IR}q_p-p_p(2+2c^N_{OEM}-4c^R_{OEM}-q_1)\alpha\right)\beta}{4(1-\alpha)\beta+q_p\left(2-\beta(2-4\alpha+\beta)\right)} + \frac{(1+c^N_{OEM}-3c^R_{OEM}+c^R_{IR})q_p-p_p\left(2+2c^N_{OEM}(-1+\alpha)+\left(-2+q_p\right)\alpha\right)\beta^2}{4(1-\alpha)\beta+q_p\left(2-\beta(2-4\alpha+\beta)\right)}$
selling price *iii)*	$\frac{1}{2}\left[c^N_{OEM}+\frac{1-\alpha}{1-\alpha p_p} - \frac{q_p\left[1+c^R_{OEM}-2c^R_{IR}-\alpha\left(4-\frac{1}{3}q_p\right)\right]}{1-\alpha p_p}\right]$	$\frac{2(1+c^N_{OEM})(1-\alpha)\beta-q_p{}^2\alpha\beta}{4(1-\alpha)\beta+q_p(2-(1-4\alpha)\beta)} + q_p\cdot\frac{1+c^N_{OEM}+c^R_{IR}-\beta(1+c^N_{OEM}-c^R_{IR}-3\alpha-2c^N_{OEM}\alpha)}{4(1-\alpha)\beta+q_p(2-(1-4\alpha)\beta)}$	$\frac{2(1+c^N_{OEM})(1-\alpha)\beta-q_p{}^2\alpha\beta}{4(1-\alpha)\beta+q_p(2-(2-4\alpha)\beta-\beta^2)} + q_p\cdot\frac{\left(1+c^R_{IR}-c^R_{OEM}(1-\beta)-2\beta+3\alpha\beta+c^N_{OEM}(1-\beta+2\alpha\beta-\beta^2)\right)}{4(1-\alpha)\beta+q_p(2-(2-4\alpha)\beta-\beta^2)}$

i) posted pricing: $q^{R,PP_{both}*}_{IR}$; bargaining OEM: $q^R\,(\omega_{ind})$; bargaining IR: $q^R\left(p^R_{IR,max}{}^*\right)-q^R\,(\omega_{ind})$.

ii) Fixed-Price: $p^R\left(q^{R,PP_{both}*}_{OEM}+q^{R,PP_{both}*}_{IR}\right)$; bargaining OEM: $p^{R,Barg_{IR}*}_{OEM}$; bargaining IR: $C^{Barg}_{IR}\left(p^R_{IR,max}{}^*,\omega_{ind}\right)/\left(q^R\left(p^R_{IR,max}{}^*\right)-q^R\,(\omega_{ind})\right)$.

iii) posted pricing: $p\left(q^{PP_{both}*}_{OEM}+q^{R,PP_{both}*}_{IR}\right)$; bargaining OEM: $p\left(q^{Barg_{OEM}}_{OEM}+q^R\,(\omega_{ind})\right)$; bargaining IR: $p\left(q^{Barg_{IR}}_{OEM}+q^R\left(p^R_{IR,max}{}^*\right)-q^R\,(\omega_{ind})\right)$, see OEM.

A): $\frac{-2q_p{}^2\alpha\beta(3+(-1+\alpha)\beta)+(-1+\alpha)\beta\left(-4+c^N_{OEM}(-4+\beta)-2c^R_{IR}(-3+\beta)+\beta-2\alpha\beta\right)+q_p\left(2-4\beta+10\alpha\beta+\beta^2-5\alpha\beta^2+4\alpha^2\beta^2+c^N_{OEM}\left(2+4(-1+\alpha)\beta-(-1+\alpha)\beta^2\right)+2c^R_{IR}\left(1-3(-1+\alpha)\beta+(-1+\alpha)\beta^2\right)\right)}{-8(-1+\alpha)\beta+q_p(4+(-2+8\alpha)\beta)}$

B): $\frac{(1+c^N_{OEM}-3c^R_{OEM}+c^R_{IR})q_p+\left(2+2c^N_{OEM}-2c^R_{OEM}-2c^R_{IR}-4q_p-c^N_{OEM}q_p+5c^R_{OEM}q_p-p_p\left(2c^N_{OEM}-2\left(-1+c^R_{OEM}+c^R_{IR}\right)-3q_p\right)\alpha\right)\beta+\left(-2+\left(3-2c^N_{OEM}+c^R_{IR}\right)q_p-2c^R_{OEM}p_p(-1+\alpha)+4\alpha+2\left(-3+q_p\right)q_p\alpha-2p_p{}^2\alpha^2\right)\beta^2+\left(-1+c^N_{OEM}\right)p_p(-1+\alpha)\beta^3}{4(1-\alpha)\beta+q_p\left(2-\beta(2-4\alpha+\beta)\right)}$

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