The Value of Competition in Remanufacturing

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July 14, 2015

Abstract

In line with the general perception among practitioners, the extant literature on remanufacturing shows that an OEM’s profit suffers when a third-party remanufacturer competes with the OEM’s remanufacturing operations. Accordingly, the literature recommends ways to deter third-party competition. However, competition for acquisition of used products (or product cores) can influence the price of new products because strategic (forward-looking) consumers consider the resale value of new products when making their purchase decisions. In our model, an OEM offers a new product that depreciates over time. The OEM has an opportunity to acquire and remanufacture depreciated used products and remarket the remanufactured products. A third-party remanufacturer also competes with the OEM for acquisition and remanufacturing of the used products. We investigate the impact of competition from the third-party remanufacturer on the OEM’s profit in the presence of strategic consumers. Of specific interest is whether competition from the third-party remanufacturer is always undesirable for the OEM when they face strategic consumers.

Keywords: closed-loop supply chain; remanufacturing; competition; product returns; strategic consumers; secondhand markets
1. Introduction

According to a Gartner research report (Gartner 2015), consumers in mature markets upgrade their smartphones every 18 to 20 months. Consequently, as the report forecasts, the worldwide market for refurbished phones that are sold to end users is set to grow to 120 million units by 2017, with an equivalent wholesale revenue of around $14 billion. This is up from 56 million units in 2014, with an equivalent wholesale revenue of $7 billion. While only seven percent of smartphones end up in official recycling programs, 64 percent get a second lease of life with 41 percent being traded in or sold privately.

The report also reckons that the growing number of privately sold phones will stir up competition in the take-back market and drive refurbishers to engage in more aggressive marketing campaigns and new incentives. Therefore, original equipment manufacturers (OEMs) often try to deter the entry of independent third-party remanufacturers by various means. Such efforts begin at the design phase of new products. OEMs design their products such that acquisition and remanufacturing of used products by third-party remanufacturers becomes expensive and difficult. For example, the MacBook Pro with Retina Display 13” consists of proprietary pentalobe screws (making opening the device unnecessarily difficult), the battery assembly is entirely, and very solidly, glued into the case (complicating replacement), the screws and cable holding the trackpad are buried under battery (making it impossible to replace the trackpad without first removing the battery), the Retina display is a fused unit (requiring the entire assembly to be replaced) with no protective glass (making it susceptible to break), the proprietary SSD isn’t a standard drive, and the RAM is soldered to the motherboard (making it much harder to extract and replace) (iFixit 2013). Similarly, OEMs selling smartphones and tablets too solder/glue components such as battery and memory card to logic board, fuse the display with the front glass, and use proprietary screws, making disassembly and repair difficult. Moreover, OEMs such as Apple do not share repair manuals with consumers and third-party remanufacturers. Finally, OEMs try to be proactive in acquiring the used products from consumers.

Moreover, consumers are increasingly becoming more informed and sophisticated (Li et al. 2014, Su 2007). When consumers buy products, they consider not only the products (among new, used and remanufactured products) and their selling prices but also future resale value of these products (Reardon 2015).
In this paper we show that an OEM who remanufactures used products can be better off with competition in remanufacturing from an independent third-party remanufacturer. The reason is that competition in acquisition of the used products for remanufacturing increases the resale value of the new products. As a result, the OEM can charge a higher price for the new products, thereby earning a higher overall profit.

2. Literature Review

Our paper spans two streams of research: (a) secondhand (used-product) markets, and (b) remanufacturing of used products.

The durable goods literature studies the behavior of a firm selling products that depreciate over time. A firm selling new products has an incentive to induce consumers to replace their used products with the new products. In the presence of a well-functioning secondhand market, consumers holding used products can sell their used products to other consumers. Products are traded from high-valuation consumers to low-valuation consumers in a competitive secondary market, allowing consumers to update to their preferred quality. This stream of literature mainly investigates whether and when a firm benefits from the secondhand market, and whether and when a firm has incentives to eliminate the secondhand market, that is, to behave in a fashion such that there are no old products available to serve as potential substitutes for the new products. The effect of a secondhand market on the demand for the new products can be decomposed into two components: a positive resale value effect due to the option value of selling new units as they become old; and a negative substitution effect due to the (imperfect) substitutability of new and used products (Hendel and Lizzeri 1999, Waldman 1996a, Waldman 1996b, Waldman 1997). The literature is equivocal in answering whether a firm benefits from the secondhand market. While Levinthal and Purohit (1989) and Waldman (1996a) show that the presence of a secondhand market can cause a reduction in the profitability of a monopolist firm, Hendel and Lizzeri (1999) show, to the contrary, that a firm benefits from a smoothly functioning secondhand market. The literature also identifies various ways firms try to eliminate the secondhand markets such as leasing (Bulow 1982, Waldman 1997), planned obsolescence (Bulow 1986, Levinthal and Purohit 1989, Waldman 1993, Waldman 1996a, Waldman 1996b), restricting a consumer’s ability to maintain the good (Hendel and Lizzeri 1999) and trade-ins (Fudenberg and Tirole 1998). However,
this stream of research ignores the remanufacturing of used products and the effect of competition in remanufacturing on resale value of products and resulting impact on firm profit.

Existing research in the remanufacturing literature has largely investigated whether and when the OEMs should remanufacture the used products (also called “cores”), and whether and when the OEMs allow third-party players to remanufacturer the used products (Atasu et al. 2008, Debo et al. 2005, Ferguson and Toktay 2006, Majumder and Groenevelt 2001). To make sound decisions, the OEMs must take into account the following: first, the presence of remanufactured products may cannibalize the demand of an OEM’s new products since remanufactured products may act as low-end substitutes for the new product. Second, if the OEM chooses not to remanufacture, third-party players may collect and remanufacture the used products, creating a competition for the OEM’s new products.

Literature in remanufacturing models price of used products either zero (Atasu et al. 2008, Ferguson and Toktay 2006, Majumder and Groenevelt 2001), or as a function of quantity of used products available (Debo et al. 2005) or both quantity and quality of used products (Oraiopoulos et al. 2012). Majumder and Groenevelt (2001) consider core allocation mechanism between the OEM and local remanufacturers as exogenously given and do not consider the competition for used items. However, the literature in remanufacturing implicitly assumes that the competition in remanufacturing does not influence the resale (residual) value of the new product. In our model, the price of used products depends not only on quantity and quality of used products but also on competitive environment in remanufacturing.

The literature in remanufacturing concludes that the entry of a third-party remanufacturer is detrimental for the OEM and that it is profitable for the OEM to remanufacture or collect cores to preempt third parties (Atasu et al. 2008, Debo et al. 2005, Ferguson and Toktay 2006). Majumder and Groenevelt (2001) show that OEM’s profits are higher in monopoly than in competition from a local remanufacturer. Therefore, OEM has the incentive to restrict competition from local remanufacturer by making cost of remanufacturing high and is willing to forego some of the benefits of remanufacturing in order to restrict the local remanufacturer. Ferrer and Swaminathan (2006) show that a low cost of remanufacturing causes higher participation by the OEM in the secondary market. Ferguson and Toktay (2006) find that as the third party remanufacturer becomes more competitive and the cannibalization threat increases, the OEM increases her efforts to deter the entry of independent remanufacturers through collection of cores even if remanufacturing is not profitable for the OEM.
Debo et al. (2005) show that when independent firms remanufacture the cores, the OEM incorporates lower remanufacturability (defined by the number of cores available for remanufacturing) to reduce the number of cores independent remanufacturers can collect, effectively deterring the competition. They show that keeping all else equal, a manufacturer is better off without competition in the market for remanufactured products. Atasu et al. (2008) show that under competition (either from another firm offering the new product or from a local remanufacturer) remanufacturing can become an effective marketing strategy, allowing the OEM to defend its market share via price discrimination. They show that remanufacturing is more beneficial under competition than in a monopoly setting; the tougher the competition, the more profitable is remanufacturing. This is so because remanufactured products help the OEM compete for the low-valuation consumer, who would otherwise be lost to competitors.

Oraiopoulos et al. (2012) consider resale value as an endogenous decision (dependent on quantity and quality of used products and competition from the OEM’s new products), they also show that as the number of third-party remanufacturers increases, the OEM profit increases. However, they show this result in a situation where the OEM does not participate in remanufacturing and charges a relicensing fee – an additional lever through which the OEM extracts profits from remanufacturing – to the third-party remanufacturer.

In contrast, we show that an OEM, who also remanufactures used products, can be better off with encouraging competition in remanufacturing from third-party (independent) remanufacturers. Competition can affect the OEM’s profit in two ways: the profit from remanufacturing decreases; the profit from the new product may increase due to an increase in resale value of the new products.

3. Model

Consider a discrete time, two-period world inhabited by an OEM, a third-party remanufacturer (3PR) and consumers.

**Consumers:** Market consists of two consumer segments. We henceforth refer to these segments by “high segment” and “low segment” respectively. These segments differ in their preferences for product quality. We denote this characteristics of the high and low segments by \( \theta_h \) and \( \theta_l \), respectively, where \( \theta_h > \theta_l \). In particular, the high and low segments get per period utility \( \theta_h q \) and \( \theta_l q \), respectively, from a product of quality \( q \). Moreover, we denote the size of the high and low segments by \( n_h \) and \( n_l \),
respectively, and assume that the size of each segment remains constant over time. In each period, a consumer uses either zero or one unit of the products (out of new, used and remanufactured products). Consumers are strategic in the sense that they make purchase decisions in order to maximize their intertemporal net utility.

In the first period, the OEM offers a new product of quality $q$ at price $p_1$ and consumers, taking into account second period options, decide whether to buy the new product. The new product can be used for two periods. However, the product depreciates over time and the units of the new product sold in the first period become “used products” in the second period. We denote the quality of the used product by $\delta q$, where $\delta$ can be interpreted as durability of the new product. If a consumer of type $\theta$ keeps the used product, he derives utility $\theta \delta q$ from using it in the second period.

However, in the second period, a consumer holding a used product can buy a new product and sell his used product to either the OEM or the 3PR, who, in turn, can remanufacture the acquired used products and sell the remanufactured products to consumers. For exposition, we assume that consumers cannot trade the used products among themselves and that the OEM and the 3PR need to remanufacture the used products in order to resell them to consumers. We model the second period interactions among the OEM, the 3PR and consumers by a two stage game.

In the first stage, the OEM offers the new product at price $p_2$ to consumers including those who hold the used products, and consumers, taking into account expected prices of the used and the remanufactured products, decide whether to buy the new product. The cost and quality of the new product remains the same in both the periods. We denote the marginal cost of producing the new product by $c_n$.

In the second stage, the OEM and the 3PR acquire the used products from consumers and offer remanufactured products of quality $\delta_r q$ and $\tilde{\delta}_r q$, respectively. In line with empirical findings, we assume that (a) the remanufactured products are of lower quality than the new product but of higher quality than the used product, and (b) the remanufactured products offered by the 3PR are not of higher quality than those offered by the OEM. In particular, we assume $1 > \delta_r \geq \tilde{\delta}_r > \delta \geq 0$. The cost of remanufacturing a used product for the OEM and the 3PR are $c_r$ and $\tilde{c}_r$, respectively. The OEM and the 3PR compete to acquire the used products by setting prices $p_u$ and $\tilde{p}_u$, respectively. A consumer sells his used product to the player (between the OEM or the 3PR) who pays a higher price. We assume that if both the OEM and the 3PR set the same price, the consumer sells the
product to the OEM. This assumption is reasonable because OEMs, in practice, have greater access to used products due to their established relationships with consumers. Let the quantities of the used products acquired by the OEM and the 3PR be $Q_u$ and $\tilde{Q}_u$, respectively. The OEM and the 3PR offer the remanufactured products at prices $p_r$ and $\tilde{p}_r$, respectively. Let the quantities of remanufactured products offered by the OEM and the 3PR be $Q_r$ and $\tilde{Q}_r$, respectively.

The OEM and the 3PR discount their profits and consumers their net utilities by a common discount factor $\rho$. We denote total profits of the OEM by $\Pi_t$, and the first and second period profits of the OEM by $\Pi_1$ and $\Pi_2$, respectively. Finally, we denote profits of the OEM and the 3PR from acquisition and remanufacturing of the used products by $\Pi_r$ and $\tilde{\Pi}_r$, respectively.

To focus on the remanufacturing of the used products, we consider parameter settings in which the OEM has an incentive to offer the new product to the consumers holding the used products, and the OEM and the 3PR have incentives to acquire and remanufacture the used products. In particular, we restrict our attention to parameter settings in which it is optimal for the OEM to offer the new product to the high segment in each period but not optimal to offer the new product to the low segment in either of the periods. Moreover, we assume $\theta_h (1 - \delta) q + \theta_l \delta_r q > c_n + c_r$ to ensure that, in the second period, the OEM has an incentive to offer the new product to the high segment and the remanufactured product to the low segment. Finally, we also assume $\theta_l \delta_r q > c_r$ and $\theta_l \tilde{\delta}_r q > \tilde{c}_r$ to ensure that the OEM and the 3PR have incentives to acquire and remanufacture the used products, and sell the remanufactured products to the low segment in the second period.

4. Analysis

We first solve for acquisition and remanufacturing of the used products in the absence of competition from the 3PR (monopoly) and presence of competition from the 3PR (competition). Subsequently, we analyze the offering of the new products by the OEM in each period.

4.1 Second Period: Acquisition and Remanufacturing

4.1.1 Monopoly

In the second stage, the OEM (in the absence of competition from the 3PR) sets price and quantity of the used products to be acquired, and price and quantity of the remanufactured products to be sold
in the consumer market. Thus, the OEM solves

\[
\max_{p_u, Q_u, p_r, Q_r} \Pi_r = \max_{p_u, Q_u, p_r, Q_r} Q_r (p_r - c_r) - Q_u p_u
\]

\[\text{s.t.} \quad Q_r \leq Q_u \leq n_h, \tag{4.1}\]

where the constraint implies that the OEM cannot remanufacture more than the number of used products acquired by her and that the OEM cannot acquire more than the number of used products available in the market. Proposition 1 outlines the optimal solution of the OEM’s problem (4.1). We denote the optimal solution by superscript \(m\).

**Proposition 1.** In the monopoly, the following is the optimal solution:

(a) acquisition price of used products \(p_u^m = 0\);

(b) acquired quantity of used products \(Q_u^m = \min \{n_h, n_l\}\);

(c) price of remanufactured products \(p_r^m = \theta_l \delta_r q\);

(d) sales quantity of remanufactured products \(Q_r^m = \min \{n_h, n_l\}\);

(e) the OEM profit: \(\Pi_r^m = \min \{n_h, n_l\} (\theta_l \delta_r q - c_r)\).

Proposition 1 highlights two main points. First, the number of used products the OEM acquires is just equal to the number of remanufactured products she offers. In other words, the OEM does not have any incentive to acquire the used products more than she requires for the remanufacturing. Second, when the OEM is a monopoly, the price at which the OEM buys the used products is zero.

### 4.1.2 Competition

In the second stage of the second period, the OEM and the 3PR set prices and quantities of the used products to be acquired, and prices and quantities of the remanufactured products to be sold in the consumer market. Thus, the OEM and the 3PR solve

\[
\max_{p_u, Q_u, p_r, Q_r} \Pi_r = \max_{p_u, Q_u, p_r, Q_r} Q_r (p_r - c_r) - Q_u p_u
\]

\[\text{s.t.} \quad Q_r \leq Q_u \leq n_h, \tag{4.2}\]

\[Q_u + \tilde{Q}_u \leq n_h\]
and

\[
\max_{\tilde{p}_u, Q_u, \tilde{p}_r, Q_r} \bar{\Pi}_r = \max_{\tilde{p}_u, Q_u, \tilde{p}_r, Q_r} \tilde{Q}_r (\tilde{p}_r - \tilde{c}_r) - \tilde{Q}_r \tilde{p}_u \\
\text{s.t.} \quad \tilde{Q}_r \leq \tilde{Q}_u \\
Q_u + Q_u \leq n_h, 
\]

(4.3)

respectively. The constraints in (4.2) imply that the OEM cannot remanufacture more than the number of used products acquired by her and that the number of used products acquired by her cannot exceed the number of used products available in the market minus the number of used products acquired by the 3PR. Similarly, the constraints in (4.3) imply that the 3PR cannot remanufacture more than the number of used products acquired by him (the 3PR) and that the number of used products acquired him cannot exceed the number of used products available in the market minus the number of used products acquired by the OEM.

Proposition 2 outlines the equilibrium solution of the OEM’s problem (4.2) and the 3PR’s problems (4.3). We denote the optimal solution by superscript c.

**Proposition 2.** In the competition, the following is the equilibrium solution:

(a) acquisition price of used products \( p_u^c = \min \left\{ \frac{\min \{n_h, n_l\}}{n_h} \left( \theta_l \delta_r q - c_r \right), \frac{\min \{n_h, n_l\}}{n_h} \left( \theta_l \delta_r q - c_r \right) \right\}; \)

(b) quantity of used products acquired by the OEM: \( Q_u^c = n_h \) if \( \theta_l \delta_r q - c_r \geq \theta_l \delta_r q - c_r \); else \( Q_u^c = 0 \);

(c) quantity of used products acquired by the 3PR: \( \tilde{Q}_u^c = 0 \) if \( \theta_l \delta_r q - c_r \geq \theta_l \delta_r q - c_r \); else \( \tilde{Q}_u^c = n_h \);

(d) quantity of remanufactured products sold by the OEM: \( Q_r^c = \min \{ n_h, n_l \} \) if \( \theta_l \delta_r q - c_r \geq \theta_l \delta_r q - c_r \); else \( Q_r^c = 0 \);

(e) quantity of remanufactured products sold by the 3PR: \( \tilde{Q}_r^c = 0 \) if \( \theta_l \delta_r q - c_r \geq \theta_l \delta_r q - c_r \); else \( \tilde{Q}_r^c = \min \{ n_h, n_l \} \);

(f) price of remanufactured products offered by the OEM: \( p_r^c = \theta_l \delta_r q \);

(g) price of remanufactured products offered by the 3PR: \( \tilde{p}_r^c = \theta_l \delta_r q \);

(h) the OEM profit: \( \Pi_r^c = \min \{ n_h, n_l \} \left[ \theta_l \delta_r q - c_r - \left( \theta_l \delta_r q - c_r \right) \right] \) if \( \theta_l \delta_r q - c_r > \theta_l \delta_r q - c_r \); else \( \Pi_r^c = 0 \);

(i) the 3PR profit: \( \tilde{\Pi}_r^c = \min \{ n_h, n_l \} \left[ \theta_l \delta_r q - \tilde{c}_r - (\theta_l \delta_r q - c_r) \right] \) if \( \theta_l \delta_r q - c_r < \theta_l \delta_r q - c_r \); else \( \tilde{\Pi}_r^c = 0 \).

Note that when the OEM is a monopoly, the OEM sets the price of the used product \( p_u^m = 0 \). In contrast, when the OEM faces competition from the 3PR, the price of the used product is \( p_u^c > 0 \). Thus, competition for acquisition of the used products raises the price of the used product \( (p_u^c > p_u^m) \).
Moreover, in the presence of competition, each player has the incentive to deter the competition in remanufacturing by acquiring all the used products even if the player does not remanufacture all the used products. Finally, competition in acquisition of the used products reduces the profit of the OEM from remanufacturing, that is, $\Pi_c^r < \Pi_m^r$. In particular, when $\theta_l \delta_r q - c_r > \theta_l \tilde{\delta}_r q - \tilde{c}_r$, the OEM’s profit from remanufacturing is positive but decreases as the 3PR becomes more competitive\textsuperscript{1}. Similarly, when $\theta_l \delta_r q - c_r < \theta_l \tilde{\delta}_r q - \tilde{c}_r$, the 3PR’s profit from remanufacturing is positive but decreases as the OEM becomes more competitive. When $\theta_l \delta_r q - c_r = \theta_l \tilde{\delta}_r q - \tilde{c}_r$, competition between the OEM and the 3PR intensifies, and none of the player makes profit from remanufacturing.

4.2 Second Period: New Product

4.2.1 Monopoly

In the first stage of the second period, the OEM sets price of the new product and sells it to the high segment, which already owns the used product. In the beginning of the second period, a high segment consumer has three options. First, he can keep the used product and receive a second-period net utility $\theta_h \delta q$ from using it. Second, he can buy a new product at price $p_2$ and sell the used product at a price $p_u^m$ to the OEM, thereby receiving a second-period net utility $\theta_h q - p_2 + p_u^m$. Third, he can buy a remanufactured product offered by the OEM at price $p_r^m$ and sell the used product at a price $p_u^m$, thereby receiving a second-period net utility either $\theta_h \delta_r q - p_r^m + p_u^m$.

To induce a high-segment consumer to buy the new product again in the second period, the OEM must set price of the new product in the second period such that the consumer is not worse off buying the new product in the second period; that is, $\theta_h q - p_2 + p_u^m \geq \max \{\theta_h \delta q, \theta_h \delta_r q - p_r^m + p_u^m\}$. Thus, the OEM solves

$$\max_{p_2} \Pi_2 = \max_{p_2} Q_2 (p_2 - c_n) + \Pi_r^m$$

s.t. $\theta_h q - p_2 + p_u^m \geq \max \{\theta_h \delta q, \theta_h \delta_r q - p_r^m + p_u^m\}$

(4.4)

Note that in the monopoly $p_u^m = 0$ and $p_r^m = \theta_l \delta_r q$ (Proposition 1). Proposition 3 outlines the equilibrium solution of the OEM’s problem (4.4).

\textsuperscript{1}We define competitiveness of a player by difference between the perceived quality of the remanufactured product offered by the player minus her cost of remanufacturing.
Proposition 3. In the monopoly, the following is the equilibrium solution for the new product offered in the second period:

(a) price of the new product: \( p_2^m = \theta_h q - \max \{ \theta_h \delta q, (\theta_h - \theta_l) \delta_r q \} \);
(b) the OEM profit: \( \Pi_2^m = n_h (\theta_h q - \max \{ \theta_h \delta q, (\theta_h - \theta_l) \delta_r q \} - c_n) + \min \{ n_h, n_l \} (\theta_l \delta_r q - c_r) \).

4.2.2 Competition

In the first stage of the second period, the OEM sets price of the new product and sells it to the high segment, which already owns the used product. In the beginning of the second period, a high segment consumer has three options. First, he can keep the used product and receive a second-period net utility \( \theta_h \delta q \) from using it. Second, he can buy a new product at price \( p_2 \) and sell the used product at a price \( p_u^c \) (to whoever pays a higher price between the OEM and the 3PR), thereby receiving a second-period net utility \( \theta_h q - p_2 + p_u^c \). Third, he can sell the used product at a price \( p_u^c \) (i.e. to whoever pays a higher price) and buy a remanufactured product offered by either the OEM at price \( p_r^c \) or the 3PR at price \( \tilde{p}_r^c \), thereby receiving a second-period net utility either \( \theta_h \delta_r q - p_r^c + p_u^c \) (when buying from the OEM) or \( \theta_h \delta_r q - \tilde{p}_r^c + p_u^c \) (when buying from the 3PR).

To induce a high-segment consumer to buy the new product again in the second period, the OEM must set price of the new product in the second period such that the consumer is not worse off buying the new product in the second period; that is, \( \theta_h q - p_2 + p_u^c \geq \max \{ \theta_h \delta q, \theta_h \delta_r q - p_r^c + p_u^c \} \) if \( \theta_l \delta_r q - c_r \geq \theta_l \tilde{\delta}_r q - \tilde{c}_r \) and \( \theta_h q - p_2 + p_u^c \geq \max \{ \theta_h \delta q, \theta_l \tilde{\delta}_r q - \tilde{p}_r^c + p_u^c \} \) if \( \theta_l \delta_r q - c_r < \theta_l \tilde{\delta}_r q - \tilde{c}_r \), where \( p_r^c = \theta_l \delta_r q \) and \( \tilde{p}_r^c = \theta_l \tilde{\delta}_r q \). Thus, the OEM solves

\[
\max_{p_2} \Pi_2 = \max_{p_2} Q_2 (p_2 - c_n) + \Pi_r
\]
\[
\text{s.t.} \quad \theta_h q - p_2 + p_u^c \geq \max \{ \theta_h \delta q, \theta_h \delta_r q - p_r^c + p_u^c \} \quad \text{for} \quad \theta_l \delta_r q - c_r \geq \theta_l \tilde{\delta}_r q - \tilde{c}_r \tag{4.5}
\]
\[
\theta_h q - p_2 + p_u^c \geq \max \{ \theta_h \delta q, \theta_l \tilde{\delta}_r q - \tilde{p}_r^c + p_u^c \} \quad \text{for} \quad \theta_l \delta_r q - c_r < \theta_l \tilde{\delta}_r q - \tilde{c}_r.
\]

Proposition 4 outlines the equilibrium solution of the OEM’s problem (4.5).

Proposition 4. In the competition, the following is the equilibrium price of the new product offered in the second period:

(a) \( p_2^c = \theta_h q - \max \{ \theta_h \delta q - p_u^c, (\theta_h - \theta_l) \delta_r q \} \) if \( \theta_l \delta_r q - c_r \geq \theta_l \tilde{\delta}_r q - \tilde{c}_r \);
(b) \( p_2^c = \theta_h q - \max \{ \theta_h \delta q - p_u^c, (\theta_h - \theta_l) \tilde{\delta}_r q \} \) if \( \theta_l \delta_r q - c_r < \theta_l \tilde{\delta}_r q - \tilde{c}_r \).
Proposition 5 outlines the optimal profit of the OEM in the second period under competition.

**Proposition 5.** In the competition, the following is the OEM profit in the second period,

(a) $\Pi^*_2 = n_h (\theta_h q - \theta_h \delta q - c_n) + \min \{n_h, n_l\} \left(\theta_l \delta_r q - c_r\right)$ if $\frac{\min \{n_h, n_l\}}{n_h} \left(\theta_l \tilde{\delta}_r q - \tilde{c}_r\right) \leq \theta_h \delta q - (\theta_h - \theta_l) \delta_r q$ and $\theta_l \delta_r q - c_r \geq \theta_l \tilde{\delta}_r q - \tilde{c}_r$ or $\frac{\min \{n_h, n_l\}}{n_h} \left(\theta_l \delta_r q - c_r\right) \leq \theta_h \delta q - (\theta_h - \theta_l) \delta_r q$ and $\theta_l \delta_r q - c_r < \theta_l \tilde{\delta}_r q - \tilde{c}_r$;

(b) $\Pi^*_2 = n_h (\theta_h q - (\theta_h - \theta_l) \delta_r q - c_n) + \min \{n_h, n_l\} \left(\theta_l \delta_r q - c_r - \left(\theta_l \tilde{\delta}_r q - \tilde{c}_r\right)\right)$ if $\frac{\min \{n_h, n_l\}}{n_h} \left(\theta_l \tilde{\delta}_r q - \tilde{c}_r\right) > \theta_h \delta q - (\theta_h - \theta_l) \delta_r q$ and $\theta_l \delta_r q - c_r \geq \theta_l \tilde{\delta}_r q - \tilde{c}_r$;

(c) $\Pi^*_2 = n_h \left(\theta_h q - (\theta_h - \theta_l) \tilde{\delta}_r q - c_n\right)$ if $\frac{\min \{n_h, n_l\}}{n_h} \left(\theta_l \tilde{\delta}_r q - \tilde{c}_r\right) > \theta_h \delta q - (\theta_h - \theta_l) \tilde{\delta}_r q$ and $\theta_l \tilde{\delta}_r q - c_r < \theta_l \tilde{\delta}_r q - \tilde{c}_r$.

4.3 First Period

In the first period, the OEM sets price of the new product and sells it to the high segment. If a high-segment consumer buys the new product in the first period, the consumer again buys the new product in the second period at price $p^*_2$ and sells the used product at price $p^*_u$; as a result, the consumer gets a net utility $(1 + \rho) \theta_h q - p_1 - \rho (p^*_2 - p^*_u)$, where $p^*_2 = p^*_2$ and $p^*_u = p^*_u$ in the monopoly and $p^*_2 = p^*_2$ and $p^*_u = p^*_u$ in the competition. On the other hand, if the consumer does not buy the new product in the first period, he buys the new product at price $p^*_2$; as a result, the consumer gets a net utility $\rho (\theta_h q - p^*_2)$.

To induce the consumer to buy in the first period, the OEM must set price of the new product in the first period such that the consumer is not worse off buying the new product in the first period; that is, $(1 + \rho) \theta_h q - p_1 - \rho (p^*_2 - p^*_u) \geq \rho (\theta_h q - p^*_2)$, which yields $\theta_h q - p_1 + \rho p^*_u \geq 0$. Thus, the maximum price the OEM can charge for the new product in the first period is consumer’s utility from using the new product in the first period plus the present value of the used product price (i.e. resale price of the new product offered in the first period). Thus, the OEM solves

$$\max_{p_1} \Pi_t = \max_{p_1} Q_1 (p_1 - c_n) + \rho \Pi^*_2$$
$$\text{s.t. } \theta_h q - p_1 + \rho p^*_u \geq 0. \quad (4.6)$$

Proposition 6 outlines the equilibrium solution of the OEM’s problem (4.6).

**Proposition 6.** The following is the equilibrium solution in the first period:

(a) the optimal price of the new product: $p^*_1 = \theta_h q + \rho p^*_u$;
(b) the optimal total profit of the OEM: \( \Pi_t = n_h (\theta_h q + \rho p_u^* - c_n) + \rho \Pi_t^p \),
where \( p_u^* = p_u^m \) and \( \Pi_t^m = \Pi_t^2 \) in the monopoly, and \( p_u^* = p_u^c \) and \( \Pi_t^c = \Pi_t^2 \) in the competition.

Since in the monopoly \( p_u^* = p_u^m \), the optimal new product price in the first period is \( p_1^m = \theta_h q \) and the OEM profit \( \Pi_1^m = n_h (\theta_h q - c_n) + \rho [n_h (\theta_h q - \max \{\theta_h \delta q, (\theta_h - \theta_t) \delta_r q\} - c_n) + \min \{n_h, n_t\} (\theta_t \delta_r q - c_r)] \).

Similarly, in the competition \( p_u^* = p_u^c \) and the optimal new product price in the first period is \( p_1^c = \theta_h q + \rho p_u^c \) and the OEM profit \( \Pi_1^c = n_h (\theta_h q + \rho p_u^c - c_n) + \rho [n_h (p_2^c - c_n) + \min \{n_h, n_t\} (\theta_t \delta_r q - c_r)] - \rho m_h p_u^c \), where \( p_2^c \) is the optimal price of the new product in the second period (refer Proposition 4) and \( p_u^c \) is optimal price of the used product (refer Proposition 2).

Proposition 7 outlines the effect of competition on overall profit of the OEM.

**Proposition 7.** Effect of competition from the 3PR on the OEM profit:

(a) \( \Pi_t^c > \Pi_t^m \) if \( \theta_1 \delta_r q - c_r > \theta_1 \delta_r q - c_r \) and \( \theta_2 \delta q > (\theta_h - \theta_t) \delta_r q \) or if \( \theta_1 \delta_r q - c_r < \theta_1 \delta_r q - c_r \), \( \theta_2 \delta q > (\theta_h - \theta_t) \delta_r q \);

(b) else \( \Pi_t^c = \Pi_t^m \).

The Proposition 7 states that the OEM is strictly better off (i.e. \( \Pi_t^c > \Pi_t^m \)) with competition from the 3PR if either \( \theta_2 \delta q > (\theta_h - \theta_t) \delta_r q \) and the OEM succeeds in acquiring and remanufacturing the used products or \( \theta_2 \delta q > (\theta_h - \theta_t) \delta_r q \) and the 3PR succeeds in acquiring and remanufacturing the used products. This implies that as long as keeping the used product gives a higher utility than buying the remanufactured product, the OEM is better off with competition; in that case, the OEM needs to price the new product in the second period keeping in mind only the used product, not the remanufactured product.

The following example illustrates the situation in which competition from a third-party remanufacturer benefits the OEM.

**Example 1.** Let \( \theta_h = 0.8, \theta_t = 0.5, n_h = 1, n_t = 1, q = 10, \delta = 0.4, \delta_r = 0.7, \tilde{\delta}_r = 0.6, c_n = 5.0, c_r = 2, \tilde{c}_r = 2 \) and \( \rho = 0.5 \).

**Monopoly:** The OEM optimally sets price of the used product at \( p_u^m = 0 \) and price of the remanufactured product at \( p_r^m = 3.5 \), resulting in \( \Pi_t^m = 1.5 \). In the second period, a high segment consumer has the following options: keep his used product, thereby getting a net utility \( 3.2 \); buy the new product at price \( p_2^m \) and sell the used product at price \( p_u^m \), thereby getting a net utility \( 8.0 - p_2^m + p_u^m = 8.0 - p_2^m \);
The remanufactured product at price $p_{rr}$ and sell the used product at price $p_{ru}$, thereby getting a net utility $5.6 - p_{ru} + p_{rr} = 2.1$. To incentivize the high segment consumer to buy the new product again in the second period, the OEM optimally sets $p_{rr} = 4.8$ and, thus, earns a second-period profit $\Pi_r^2 = 1.3$. In the first period, a high segment consumer’s willingness to pay for the new product is sum of the utility he gets from using it in the first period and the discounted used product price he gets in the second period. Thus, the OEM optimally sets $p_{ru} = 8.0$ and, thus, earns a total profit $\Pi_r^r = 3.65$.

**Competition:** The OEM and the 3PR would earn $1.0 - p_u$ and $1.5 - \tilde{p}_u$ respectively if they acquire the used products at price $p_u$ and $\tilde{p}_u$ respectively. In the equilibrium, the OEM succeeds in acquiring and remanufacturing the used products. The OEM optimally sets price of the used product at $p_{ru} = 1.0$ and price of the remanufactured product at $p_{rr} = 3.5$, resulting in $\Pi_r^c = 0.5$ and $\tilde{\Pi}_r^c = 0$. In the second period, a high segment consumer has the following options: keep his used product, thereby getting a net utility $3.2$; buy the new product at price $p_{r2}$ and sell the used product at price $p_{ru}$, thereby getting a net utility $8.0 - p_{r2} + p_{ru} = 9.0 - p_{r2}$; buy the remanufactured product at price $p_{rr}$ and sell the used product at price $p_{ru}$, thereby getting a net utility $5.6 - p_{rr} + p_{ru} = 3.1$. To incentivize the high segment consumer to buy the new product again in the second period, the OEM optimally sets $p_{r2} = 5.8$ and, thus, earns a second-period profit $\Pi_r^2 = 1.3$. In the first period, a high segment consumer’s willingness to pay for the new product is sum of the utility he get from using it in the first period and the discounted value of used product price he get in the second period. Thus, the OEM optimally sets $p_{r1} = 8.0 + pp_{ru} = 8.5$ and, thus, earns a total profit $\Pi_r^r = 4.15$.

A higher price of the used product enables the OEM charge a higher price for the new product in the first period. Moreover, under certain conditions, a higher price of the used product also enables the OEM charge a higher price for the new product in the second period. However, the reasons are different. In the first period, consumers are willing to pay a higher price for the new product because they expect a higher resale price of the product in the second period. In the second period, consumers are sometime willing to pay a higher price for the new products because in the second period the higher price of the used products makes selling the used products more attractive than keeping them.

If the OEM does not allow the entry of the third-party remanufacturer, the OEM cannot credibly commit to future resale value of the new product (i.e. $p_u$). If strategic consumers anticipate lower resale value (or no resale value, to be specific) of the new product, they lower their willingness to pay...
for the new product in the first period and sometimes in the second period as well.

However, by allowing the entry of the third-party remanufacturer, the OEM subjects herself to a competitive pressure from the third-party remanufacturer for acquisition of the used products. The competition from the 3PR plays a crucial role: it increases price of the used product and reassures consumers about the future resale value of the new product (when the new product becomes a used product). This assurance of a higher resale value of the new products increases consumers’ willingness to pay for the new products. In fact, the competition may have a positive spillover effect on the prices of the new product in both the periods, increasing the profits from the new product sales. Though competition from the 3PR decreases the OEM’s profits from the remanufacturing, the benefits for the OEM in the form of a higher price of the new product can more than offset the losses in the remanufacturing. Thus, overall, the competition from the 3PR may benefit the OEM.

The OEMs often consider third-party remanufacturers as a threat and try to deter the entry of the third-party remanufacturers by various means such as designing their products in such a way that it makes remanufacturing difficult and expensive for the third-party remanufacturers. On the contrary, keeping the cost of remanufacturing for the third-party remanufacturers low can actually benefit the OEM if it intensifies the competition in acquisition of the used products. In conclusion, an OEM who remanufactures used products can be better off with competition in remanufacturing from an independent third-party remanufacturer.
References


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A. Proofs

A.1 Proof of Proposition 1

Since, the OEM is a monopoly both in the acquisition of the used products and in the selling of the remanufactured products, she extracts whole consumer surplus from both the high-segment consumers, who sell the used products, and the low-segment consumers, who buy the remanufactured products. Thus, the OEM optimally sets \( p_u^m = 0 \) and \( p_r^m = \theta_l \delta_r q \).

Since \( \theta_l \delta_r q - c_r > p_u^m \), the OEM has an incentive to sell as many remanufactured products as she can. The number of remanufactured products the OEM can sell is constrained by either the quantity of the used products (i.e. supply constraint) available or the size of the low-segment market (i.e. demand constraint) or both. Thus, \( Q_r^m = \min \{ n_h, n_l \} \). Moreover, the OEM has no incentive to acquire more than the number of used products she is going to remanufacture, that is, \( Q_u^m = Q_r^m \). Substituting the optimal solution in the OEM’s profit function \( \Pi_r = Q_r (p_r - c_r) - Q_u p_u \) yields optimal profit as shown in Proposition 1(e).

A.2 Proof of Proposition 2

Suppose \( n_h \leq n_l \). Since \( n_h \leq n_l \), the OEM and the 3PR have sufficient number of low-segment consumers available to sell their remanufactured products and, thus, can extract whole surplus from the low segment. Therefore, the OEM and the 3PR optimally set \( \tilde{p}_r = \theta_l \delta_r q \) and \( \tilde{p}_r^c = \theta_l \tilde{\delta}_r q \), respectively, for their remanufactured products. As long as \( \theta_l \delta_r q - c_r > p_u \) and \( \theta_l \tilde{\delta}_r q - \tilde{c}_r > \tilde{p}_u \), the OEM and the 3PR have incentives to sell as many remanufactured products as they can. Since \( n_h \leq n_l \), the number of remanufactured products a player can sell is constrained by the quantity of the used products (supply constraint) she acquires. Thus, the OEM and the 3PR optimally set \( Q_r^c = Q_u \) and \( \tilde{Q}_r^c = \tilde{Q}_u \).

Since \( n_h \leq n_l \), the supply of the used products is constrained and each player competes to acquire as many used products as she can by setting acquisition price of the used products. Consumers sell their used products to a player who pays a higher price. When both the players set the same price, we assume that consumers sell their used products to the OEM. This is a reasonable assumption since OEMs usually have a greater access to used products. Thus,
\[ Q_u = \begin{cases} n_h & \text{if } p_u \geq \tilde{p}_u \\ 0 & \text{if } p_u < \tilde{p}_u \end{cases} \]  \hspace{1cm} (A.7)

and

\[ \hat{Q}_u = \begin{cases} 0 & \text{if } p_u \geq \tilde{p}_u \\ n_h & \text{if } p_u < \tilde{p}_u \end{cases} \]  \hspace{1cm} (A.8)

Each player has an incentive to set lowest price but high enough to acquire all the used products as long as the player makes nonnegative profit. Thus, the OEM’s objective is to minimize \( p_u \) such that \( p_u \geq \tilde{p}_u \) and \( p_u \leq \theta_l \tilde{\delta}_r q - c_r \). Similarly, the 3PR’s objective is to minimize \( \tilde{p}_u \) such that \( \tilde{p}_u > p_u \) and \( \tilde{p}_u \leq \theta_l \tilde{\delta}_r q - \tilde{c}_r \).

We can easily show that when \( \theta_l \delta_r q - c_r \geq \theta_l \tilde{\delta}_r q - \tilde{c}_r \), the equilibrium price of the used product is \( p_u^c = \theta_l \delta_r q - \tilde{c}_r \), and the corresponding number of used products acquired and remanufactured by the OEM and the 3PR are \( Q_u^c = Q_r^c = n_h \) and \( \hat{Q}_u^c = \hat{Q}_r^c = 0 \) respectively. Similarly, when \( \theta_l \delta_r q - c_r < \theta_l \tilde{\delta}_r q - \tilde{c}_r \), the equilibrium price of the used product is \( p_u^c = \theta_l \delta_r q - c_r \), and the corresponding number of used products acquired and remanufactured by the OEM and the 3PR are \( Q_u^c = Q_r^c = 0 \) and \( \hat{Q}_u^c = \hat{Q}_r^c = n_h \) respectively.

\textbf{Suppose } \( n_h > n_l \). \textbf{ If the total number of remanufactured products offered by the OEM and the 3PR combined is more than the number of low-segment consumers available, the equilibrium price of the remanufactured products are } \( p_r^c = 0 \) \textbf{ and } \( \tilde{p}_r^c = 0 \), \textbf{ respectively, and each player makes negative profit. Therefore, in the equilibrium, the total number of the remanufactured products by the OEM and the 3PR combined is } \( Q_r^c + \hat{Q}_r^c = n_l \) \textbf{ and, thus, the OEM and the 3PR set } \( p_r^c = \theta_l \delta_r q \) \textbf{ and } \( \tilde{p}_r^c = \theta_l \tilde{\delta}_r q \), \textbf{ respectively. As long as } \( \theta_l \delta_r q - c_r > p_u \) \textbf{ and } \( \theta_l \tilde{\delta}_r q - \tilde{c}_r > \tilde{p}_u \), \textbf{ the OEM and the 3PR have incentives to sell as many remanufactured products as they can. Since } \( n_h > n_l \), \textbf{ the number of remanufactured products a player can sell is either constrained by the number of used products (supply constraint) she acquires or the remaining market size (} \( n_l - \hat{Q}_r \) \textbf{ for the OEM and } \( n_l - Q_r \) \textbf{ for the 3PR). Thus, the OEM’s and the 3PR’s best responses are to remanufacture } \( Q_r = \min \left\{ Q_u, n_l - \hat{Q}_r \right\} \) \textbf{ and } \( \hat{Q}_r = \min \left\{ \hat{Q}_u, n_l - Q_r \right\} \) \textbf{ respectively. Note that the optimal solution may have multiple Nash equilibria if } \( Q_u > 0, \hat{Q}_u > 0 \) \textbf{ and } \( Q_u + \hat{Q}_u > n_l \).
Since consumers sell their used products to a player who pays a higher price (along with the assumption that consumers sell their used products to the OEM when \( p_u = \hat{p}_u \)), either \( Q_u = 0 \) & \( Q_u = 0 \), and, thus, we get unique Nash equilibria. Thus, expressions (A.7) and (A.8) also apply when \( n_h > n_I \). Each player has an incentive to set lowest price but high enough to acquire all the used products as long as the player makes nonnegative profit. Thus, the OEM’s objective is to minimize \( p_u \) such that \( p_u \geq \hat{p}_u \) and \( n_h p_u \leq n_I (\theta_l \delta_r q - c_r) \). Similarly, the 3PR’s objective is to minimize \( \hat{p}_u \) such that \( \hat{p}_u > p_u \) and \( n_h \hat{p}_u \leq n_I (\theta_l \delta_r q - c_r) \).

We can easily show that when \( \theta_l \delta_r q - c_r \geq \theta_l \delta_r q - \hat{c}_r \), the equilibrium price of the used product is \( p_u^c = \frac{n_h}{n_l} (\theta_l \delta_r q - \hat{c}_r) \); the corresponding number of used products acquired and remanufactured by the OEM are \( Q_u^c = n_h \) and \( Q_r^c = n_l \) respectively, and by the 3PR are \( \hat{Q}_u^c = 0 \) and \( \hat{Q}_r^c = 0 \) respectively. Similarly, when \( \theta_l \delta_r q - c_r < \theta_l \delta_r q - \hat{c}_r \), the equilibrium price of the used product is \( p_u^c = \frac{n_l}{n_h} (\theta_l \delta_r q - c_r) \); the corresponding number of used products acquired and remanufactured by the OEM are \( Q_u^c = 0 \) and \( Q_r^c = 0 \) respectively, and by the 3PR are \( \hat{Q}_u^c = n_h \) and \( \hat{Q}_r^c = n_l \) respectively.

Thus, \( p_u^c = \min \left\{ \frac{\min \{n_h, n_l\}}{n_h} (\theta_l \delta_r q - \hat{c}_r), \frac{\min \{n_h, n_l\}}{n_l} (\theta_l \delta_r q - c_r) \right\} \). Substituting the optimal solution in the OEM’s profit function \( \Pi_r = Q_r (p_r - c_r) - Q_u p_u \) yields optimal profit as shown in Proposition 2(h). Similarly, substituting the optimal solution in the 3PR’s profit function \( \hat{\Pi}_r = \hat{Q}_r (\hat{p}_r - \hat{c}_r) - \hat{Q}_u \hat{p}_u \) yields optimal profit as shown in Proposition 2(i).

Table 2 summarizes outcome of the acquisition and remanufacturing of the used products under competition.

### A.3 Proof of Proposition 3

If the high segment consumer keeps the used product, he receives a second-period net utility \( \theta_h \delta q \) from using it. If the consumer buys the new product at price \( p_2 \) and sells the used product at price \( p_u^m \), he receives a second-period net utility \( \theta_h q - p_2 + p_u^m \). If the consumer sells the used product at price \( p_u^m \) and buys the OEM’s remanufactured product at price \( p_u^m \), he receives a second-period net utility \( \theta_h \delta_r q - p_u^m + p_u^m \). To induce the consumer to buy the new product again in the second period, the OEM must set the price of the new product in the second period such that the consumer is not worse off buying the new product in the second period; that is, \( \theta_l \delta q - p_2 + p_u^m \geq \max \{\theta_h \delta q, \theta_h \delta_r q - p_r^m + p_u^m\} \). Thus, the OEM solves (4.4).

We know that in the monopoly \( p_u^m = 0 \) and \( p_u^m = \theta_l \delta_r q \) (Proposition 1). Moreover, the OEM would
like to set price of the new product as high as possible given the constraint. Thus, the OEM optimally sets $p_2^\ast = q - q \delta_q$ if $q \delta_q \geq (q - q) \delta_q$ and $p_2^\ast = q - (q - q) \delta_q q$ if $q \delta_q < (q - q) \delta_q$. Thus, $p_2^\ast = q - \max \{ q \delta_q, (q - q) \delta_q \}$. Moreover, optimal sales quantity is $Q_2^\ast = n_h$. Thus, the optimal profit of the OEM is $\Pi_2^\ast = n_h (q - \max \{ q \delta_q, (q - q) \delta_q \} - c_n) + \min \{ n_h, n_l \} (q \delta_q - c_r)$, as shown in Proposition 3(b).

A.4 Proof of Proposition 4

If the high segment consumer keeps the used product, he receives a second-period net utility $q \delta_q$ from using it. If the consumer buys the new product at price $p_2$ and sells the used product at price $p_u^c$, he receives a second-period net utility $q - p_2 + p_u^c$. If the consumer sells the used product at price $p_u^c$ and buys the OEM’s remanufactured product at price $p_u^c$, he receives a second-period net utility $q \delta_q - p_u^c + p_u^c$. If the consumer sells the used product at price $p_u^c$ and buys the 3PR’s remanufactured product at price $p_u^c$, he receives a second-period net utility $q \delta_q - p_u^c + p_u^c$. To induce the consumer to buy the new product again in the second period, the OEM must set the price of the new product in the second period such that the consumer is not worse off buying the new product in the second period; that is, $q - p_2 + p_u^c \geq \max \{ q \delta_q, q \delta_q - p_u^c + p_u^c \}$ if $q \delta_q - c_r \geq q \delta_q - c_r$, and $q - p_2 + p_u^c \geq \max \{ q \delta_q, q \delta_q - p_u^c + p_u^c \}$ if $q \delta_q - c_r < q \delta_q - c_r$, where $p_u^c = q \delta_q$ and $\tilde{p}_u = q \delta_q$. Thus, the OEM solves (4.5).

Note that the OEM would like to set price of the new product as high as possible given the constraints. Thus, the OEM optimally sets $p_2^\ast = q - \max \{ q \delta_q, (q - q) \delta_q \} = \min \{ n_h, n_l \} (q \delta_q - c_r)$. If $q \delta_q - c_r \geq q \delta_q - c_r$, and $p_2^\ast = q - \max \{ q \delta_q, q \delta_q - \tilde{p}_u^c + \tilde{p}_u^c \}$ if $q \delta_q - c_r < q \delta_q - c_r$, where $p_u^c$ is the optimal price of the used product in the competition (refer Proposition 2).

A.5 Proof of Proposition 5

Note that optimal sales quantity is $Q_2^\ast = n_h$. Therefore, the OEM profit is $\Pi_2^\ast = n_h (p_2^\ast - c_n) + \min \{ n_h, n_l \} (q \delta_q - c_r) - n_h p_u^c$, where $p_u^c$ is the optimal price of the used product in the competition (refer Proposition 2) and $p_2^\ast$ is the optimal price of the new product of the second period in the competition (refer Proposition 4).

Note that if $q \delta_q - c_r \geq q \delta_q - c_r$, then $p_2^\ast = q - \max \{ q \delta_q - p_u^c, (q - q) \delta_q \}$. Where $p_u^c = \min \{ n_h, n_l \} (q \delta_q - c_r)$.
min \{n_h, n_l\} \left( \theta_q \tilde{q} - c_r \right) (4(a)).

If \( \theta_q \tilde{q} - c_r \geq \theta_q \tilde{q} - \tilde{c}_r \) and \( \theta_q q - \min \{n_h, n_l\} \left( \theta_q \tilde{q} - \tilde{c}_r \right) \geq (\theta_q - \theta_q) \tilde{q} - q \), then \( p^*_2 = \theta_q q - (\theta_q - \theta_q) \tilde{q} - q \) and \( \Pi^*_2 = n_h (\theta_q q - \theta_q \tilde{q} - c) + \min \{n_h, n_l\} (\theta_q \tilde{q} - c_r).

If \( \theta_q \tilde{q} - c_r \geq \theta_q \tilde{q} - \tilde{c}_r \) and \( \theta_q q - \min \{n_h, n_l\} \left( \theta_q \tilde{q} - \tilde{c}_r \right) < (\theta_q - \theta_q) \tilde{q} - q \), then \( p^*_2 = \theta_q q - (\theta_q - \theta_q) \tilde{q} - q \) and \( \Pi^*_2 = n_h (\theta_q q - (\theta_q - \theta_q) \tilde{q} - q) + \min \{n_h, n_l\} (\theta_q \tilde{q} - c_r).

If \( \theta_q \tilde{q} - c_r < \theta_q \tilde{q} - \tilde{c}_r \) and \( \theta_q q - \min \{n_h, n_l\} \left( \theta_q \tilde{q} - \tilde{c}_r \right) \geq (\theta_q - \theta_q) \tilde{q} - q \), then \( p^*_2 = \theta_q q - (\theta_q - \theta_q) \tilde{q} - q \) and \( \Pi^*_2 = n_h \left( \theta_q q - (\theta_q - \theta_q) \tilde{q} - q \right) + \min \{n_h, n_l\} (\theta_q \tilde{q} - c_r).

Note that if \( \theta_q \tilde{q} - c_r < \theta_q \tilde{q} - \tilde{c}_r \), then \( p^*_2 = \theta_q q - \max \{\theta_q q - p^*_u, (\theta_q - \theta_q) \tilde{q} - q\} \), where \( p^*_u = \min \{n_h, n_l\} (\theta_q \tilde{q} - c_r) (4(b)). \)

A.6 Proof of Proposition 6

If a high-segment consumer buys the new product in the first period, the consumer again buys the new product in the second period at price \( p^*_2 \) and sells the used product at price \( p^*_u \); as a result, the consumer gets a net utility \((1 + \rho) \theta_q q - p_1 - \rho (p^*_2 - p^*_u)\). If the consumer does not buy the new product in the first period, he has the following four options in the second period: (i) buy the new product at price \( p^*_2 \) and thereby get a net utility \( \rho (\theta_q q - p^*_2) \); (ii) buy the remanufactured product offered by the OEM (if \( \theta_q \tilde{q} - c_r \geq \theta_q \tilde{q} - \tilde{c}_r \)) at price \( p^*_r \) and thereby get a net utility \( \rho (\theta_q \tilde{q} - p^*_r) \); (iii) buy the remanufactured product offered by the 3PR (if \( \theta_q \tilde{q} - c_r < \theta_q \tilde{q} - \tilde{c}_r \)) at price \( \tilde{p}^*_r \) and thereby get a net utility \( \rho (\theta_q \tilde{q} - \tilde{p}^*_r) \); (iv) buy none and thereby get zero utility.

From the second period analysis, we already know that at optimality \( \theta_q q - p^*_2 + p^*_u = \max \{\theta_q \tilde{q}, \theta_q \tilde{q} - p^*_2 + p^*_u\} \), if \( \theta_q \tilde{q} - c_r \geq \theta_q \tilde{q} - \tilde{c}_r \) and \( \theta_q q - p^*_2 + p^*_u = \max \{\theta_q \tilde{q}, \theta_q \tilde{q} - \tilde{p}^*_2 + p^*_u\} \), if \( \theta_q \tilde{q} - c_r < \theta_q \tilde{q} - \tilde{c}_r \); that is, \( \theta_q q - p^*_2 \geq \theta_q \tilde{q} - p^*_2 \) if \( \theta_q \tilde{q} - c_r \geq \theta_q \tilde{q} - \tilde{c}_r \) and \( \theta_q q - p^*_2 \geq \tilde{p}^*_r \) if \( \theta_q \tilde{q} - c_r < \theta_q \tilde{q} - \tilde{c}_r \).

To induce the consumer to buy the new product in the first period, the OEM must set price of the new product in the first period such that the consumer is not worse off buying the new product in the first period; that is, \((1 + \rho) \theta_q q - p_1 - \rho p^*_2 + \rho p^*_u \geq \rho (\theta_q q - p^*_2) \) or \( \theta_q q - p_1 - \rho p^*_u \geq 0 \). Thus, the OEM solves (4.6).
Since, the OEM would like to set price of the new product as high as possible given the constraint \( \theta_h q - p_1 + \rho p_u^* \geq 0 \), the OEM optimally sets \( p_1^* = \theta_h q + \rho p_u^* \). Moreover, optimal sales quantity is \( Q_1^* = n_h \). Substituting the optimal solution in \( \Pi_1 = Q_1 (p_1 - c_n) + \rho \Pi_2^* \) yields optimal profit of the OEM as shown in Proposition 6(b).

A.7 Proof of Proposition 7

In the monopoly, the optimal first period price of the new product is \( p_1^m = \theta_h q \) and the OEM profit \( \Pi_t^m = n_h (\theta_h q - c_n) + \rho [n_h (\theta_h q - \max \{ \theta_h \delta q, (\theta_h - \theta_l) \delta r q \} - c_n) + \min \{ n_h, n_l \} (\theta_l \delta_r q - c_r)] \). Let

\[
\Delta^m = \max \{ \theta_h \delta q, (\theta_h - \theta_l) \delta_r q \}.
\]

Moreover, let \( K = n_h (\theta_h q - c_n) + \rho (n_h (\theta_h q - c_n) + \min \{ n_h, n_l \} (\theta_l \delta_r q - c_r)) \). Then \( \Pi^m_t = K - \rho n_h \Delta^m \).

Similarly, in the competition, the optimal first period price of the new product is \( p_1^c = \theta_h q + \rho p_u^c \) and the OEM profit \( \Pi_t^c = n_h (\theta_h q + \rho p_u^c - c_n) + \rho [n_h (p_2^c - c_n) + \min \{ n_h, n_l \} (\theta_l \delta_r q - c_r)] - \rho n_h p_u^c \). Let \( \Delta^c = p_2^c - \theta_h q \), where \( p_2^c \) is optimal second period price of the new product in the competition (refer Proposition 4). Thus,

\[
\Delta^c = \begin{cases} 
\max \left\{ \theta_h \delta q - \min \left\{ n_h, n_l \right\} \left( \theta_l \tilde{\delta}_r q - \tilde{c}_r \right), (\theta_h - \theta_l) \delta_r q \right\} & \text{if } \theta_l \tilde{\delta}_r q - c_r \geq \theta_l \tilde{\delta}_r q - \tilde{c}_r, \\
\max \left\{ \theta_h \delta q - \min \left\{ n_h, n_l \right\} \left( \theta_l \delta_r q - c_r \right), (\theta_h - \theta_l) \tilde{\delta}_r q \right\} & \text{if } \theta_l \tilde{\delta}_r q - c_r < \theta_l \tilde{\delta}_r q - \tilde{c}_r.
\end{cases}
\]

Then \( \Pi^c_t = K - \rho n_h \Delta^c \).

Thus, \( \Pi^c_t = \Pi^m_t + \rho n_h (\Delta^m - \Delta^c) \). Therefore \( \Pi^c_t \geq \Pi^m_t \) if and only if \( \Delta^m \geq \Delta^c \). Assuming \( \delta_r \geq \tilde{\delta}_r \), we establish relationship between \( \Pi^c_t \) and \( \Pi^m_t \) for each parameter setting as follows:

- If \( \theta_l \delta_r q - c_r \geq \theta_l \tilde{\delta}_r q - \tilde{c}_r \) and \( \theta_h \delta q - \min \left\{ n_h, n_l \right\} \left( \theta_l \tilde{\delta}_r q - \tilde{c}_r \right) \geq (\theta_h - \theta_l) \delta_r q \), then \( \Delta^c = \theta_h \delta q - \min \left\{ n_h, n_l \right\} \left( \theta_l \tilde{\delta}_r q - \tilde{c}_r \right) \) and \( \Delta^m = \theta_h \delta q \). Thus, \( \Pi^c_t = \Pi^m_t + \rho n_h \left( \min \left\{ n_h, n_l \right\} \left( \theta_l \tilde{\delta}_r q - \tilde{c}_r \right) \right) > \Pi^m_t \).

- If \( \theta_l \delta_r q - c_r \geq \theta_l \tilde{\delta}_r q - \tilde{c}_r \) and \( (\theta_h - \theta_l) \delta_r q > \theta_h \delta q - \min \left\{ n_h, n_l \right\} \left( \theta_l \tilde{\delta}_r q - \tilde{c}_r \right) \), then \( \Delta^c = (\theta_h - \theta_l) \delta_r q \) and \( \Delta^m = \theta_h \delta q \). Thus, \( \Pi^c_t = \Pi^m_t + \rho n_h (\theta_h \delta q - (\theta_h - \theta_l) \delta_r q) > \Pi^m_t \).

Thus, \( \Pi^c_t = \Pi^m_t \).
If \( \theta \delta_r\varphi - c_\varphi < \theta \delta_r\varphi - \tilde{c}_r, \theta_h\delta q - \min \frac{\{n_h, m_l\}}{n_h} (\theta_l\delta_r\varphi - c_\varphi) \geq (\theta_h - \theta_l) \tilde{\delta}_r\varphi, \) and \( \theta_h\delta q > (\theta_h - \theta_l) \tilde{\delta}_r\varphi, \)
then \( \bar{\Delta}^c = \theta_h\delta q - \min \frac{\{n_h, m_l\}}{n_h} (\theta_l\delta_r\varphi - c_\varphi) \) and \( \Delta^m = \theta_h\delta q. \) Thus, \( \Pi^c_t = \Pi^m_t + \rho n_h \left[ \min \frac{\{n_h, m_l\}}{n_h} (\theta_l\delta_r\varphi - c_\varphi) \right] > \Pi^{m*}_t. \)

If \( \theta_l\delta_r\varphi - c_\varphi < \theta_l\delta_r\varphi - \tilde{c}_r, \theta_h\delta q - \min \frac{\{n_h, m_l\}}{n_h} (\theta_l\delta_r\varphi - c_\varphi) \geq (\theta_h - \theta_l) \tilde{\delta}_r\varphi, \) and \( \theta_h\delta q \leq (\theta_h - \theta_l) \tilde{\delta}_r\varphi, \)
then \( \bar{\Delta}^c = \theta_h\delta q - \min \frac{\{n_h, m_l\}}{n_h} (\theta_l\delta_r\varphi - c_\varphi) \) and \( \Delta^m = (\theta_h - \theta_l) \tilde{\delta}_r\varphi. \) Thus, \( \Pi^c_t = \Pi^m_t + \rho n_h \left[ \min \frac{\{n_h, m_l\}}{n_h} (\theta_l\delta_r\varphi - c_\varphi) \right] + \rho n_h [(\theta_h - \theta_l) \tilde{\delta}_r\varphi - \theta_h\delta q] > \Pi^{m*}_t. \)

If \( \theta_l\delta_r\varphi - c_\varphi < \theta_l\delta_r\varphi - \tilde{c}_r, \) and \( \theta_h\delta q > (\theta_h - \theta_l) \tilde{\delta}_r\varphi \geq (\theta_h - \theta_l) \tilde{\delta}_r\varphi > \theta_h\delta q - \min \frac{\{n_h, m_l\}}{n_h} (\theta_l\delta_r\varphi - c_\varphi), \)
then \( \Delta^c = (\theta_h - \theta_l) \tilde{\delta}_r\varphi \) and \( \Delta^m = \theta_h\delta q. \) Thus, \( \Pi^c_t = \Pi^m_t + \theta_h\delta q - (\theta_h - \theta_l) \tilde{\delta}_r\varphi > \Pi^{m*}_t. \)

If \( \theta_l\delta_r\varphi - c_\varphi < \theta_l\delta_r\varphi - \tilde{c}_r, \) and \( (\theta_h - \theta_l) \tilde{\delta}_r\varphi \geq \theta_h\delta q \geq (\theta_h - \theta_l) \tilde{\delta}_r\varphi > \theta_h\delta q - \min \frac{\{n_h, m_l\}}{n_h} (\theta_l\delta_r\varphi - c_\varphi), \)
then \( \Delta^c = (\theta_h - \theta_l) \tilde{\delta}_r\varphi \) and \( \Delta^m = (\theta_h - \theta_l) \tilde{\delta}_r\varphi. \) Thus, \( \Pi^c_t = \Pi^m_t + \rho n_h \left[ (\theta_h - \theta_l) \tilde{\delta}_r\varphi - (\theta_h - \theta_l) \tilde{\delta}_r\varphi \right] > \Pi^{m*}_t. \)

In conclusion, \( \Pi^c_t > \Pi^{m*}_t \) if \( \theta_l\delta_r\varphi - c_\varphi \geq \theta_l\delta_r\varphi - \tilde{c}_r \) and \( \theta_h\delta q > (\theta_h - \theta_l) \tilde{\delta}_r\varphi \) or if \( \theta_l\delta_r\varphi - c_\varphi < \theta_l\delta_r\varphi - \tilde{c}_r, \theta_h\delta q > (\theta_h - \theta_l) \tilde{\delta}_r\varphi; \) else \( \Pi^c_t = \Pi^{m*}_t. \)
B. Tables

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<th>Definition</th>
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<td>Quality of new product</td>
</tr>
<tr>
<td>$c_n$</td>
<td>Marginal cost of producing new product</td>
</tr>
<tr>
<td>$p_1$ ($p_2$)</td>
<td>Price of new product in first (second) period</td>
</tr>
<tr>
<td>$Q_1$ ($Q_2$)</td>
<td>Sales quantity of new product in first (second) period</td>
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<tr>
<td>$\rho$</td>
<td>Discount factor for second period</td>
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<tr>
<td>$\delta q$</td>
<td>Quality of used product</td>
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<tr>
<td>$p_u$ ($\tilde{p}_u$)</td>
<td>Price of used product set by OEM (3PR)</td>
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<tr>
<td>$Q_u$ ($\tilde{Q}_u$)</td>
<td>Quantity of used product acquired by OEM (3PR)</td>
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<tr>
<td>$\delta_r q$ ($\tilde{\delta}_r q$)</td>
<td>Quality of remanufactured product offered by OEM (3PR)</td>
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<tr>
<td>$h$ ($l$)</td>
<td>High-end (low-end) consumer segment</td>
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<td>$\theta_h$ ($\theta_l$)</td>
<td>Willingness to pay of high-end (low-end) consumer segment</td>
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<td>$n_h$ ($n_l$)</td>
<td>Number of consumers in high-end (low-end) consumer segment</td>
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<td>$\Pi_t$</td>
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<td>Profit of OEM (3PR) from acquisition and remanufacturing of used product</td>
</tr>
<tr>
<td>$m$ ($c$)</td>
<td>Superscript to represent an optimal solution in the monopoly (competition)</td>
</tr>
</tbody>
</table>

Table 1: Notation

| $m$ ($c$) | Superscript to represent an optimal solution in the monopoly (competition) |

### Equilibrium Solution

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Equilibrium Solution</th>
</tr>
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<tbody>
<tr>
<td>$\theta_l \delta_r q - c_r \geq \theta_l \tilde{\delta}_r q - \tilde{c}_r$</td>
<td>$n_h \leq n_l \quad n_h \quad n_h \quad \theta_l \delta_r q \quad 0 \quad 0 \quad -- \quad \theta_l \delta_r q - \tilde{c}_r$</td>
</tr>
<tr>
<td>$\theta_l \delta_r q - c_r &lt; \theta_l \tilde{\delta}_r q - \tilde{c}_r$</td>
<td>$n_h \leq n_l \quad 0 \quad 0 \quad -- \quad n_h \quad n_h \quad \theta_l \delta_r q \quad \theta_l \delta_r q - c_r$</td>
</tr>
<tr>
<td>$\theta_l \delta_r q - c_r \geq \theta_l \tilde{\delta}_r q - \tilde{c}_r$</td>
<td>$n_h &gt; n_l \quad n_h \quad n_l \quad \theta_l \delta_r q \quad 0 \quad 0 \quad -- \quad \theta_l \delta_r q - \tilde{c}_r$</td>
</tr>
<tr>
<td>$\theta_l \delta_r q - c_r &lt; \theta_l \tilde{\delta}_r q - \tilde{c}_r$</td>
<td>$n_h &gt; n_l \quad 0 \quad 0 \quad -- \quad n_h \quad n_l \quad \theta_l \delta_r q \quad \frac{n_l}{n_h} (\theta_l \delta_r q - \tilde{c}_r)$</td>
</tr>
</tbody>
</table>

Table 2: Competition: Acquisition and Remanufacturing of Used Products
\[ p^c_2 = \theta h q - (\theta h \delta q - p^c_u) \]
\[ \theta h \delta q - p^c_u \geq (\theta h - \theta l) \delta r q \]
\[ \theta l \delta r q - c_r \geq \theta l \delta r q - \tilde{c}_r \]

\[ p^c_2 = \theta h q - (\theta h \delta q - p^c_u) \]
\[ \theta h \delta q - p^c_u \geq (\theta h - \theta l) \tilde{\delta} r q \]
\[ \theta l \delta r q - c_r < \theta l \delta r q - \tilde{c}_r \]

\[ p^c_2 = \theta h q - (\theta h - \theta l) \delta r q \]
\[ \theta h \delta q - p^c_u < (\theta h - \theta l) \delta r q \]
\[ \theta l \delta r q - c_r \geq \theta l \delta r q - \tilde{c}_r \]

\[ p^c_2 = \theta h q - (\theta h - \theta l) \tilde{\delta} r q \]
\[ \theta h \delta q - p^c_u < (\theta h - \theta l) \tilde{\delta} r q \]
\[ \theta l \delta r q - c_r < \theta l \delta r q - \tilde{c}_r \]

Table 3: Solution for New Product of the Second Period in Competition