Decision Analysis of Closed-Loop Supply Chain Under Competition Environment and Heterogeneous Consumers

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Abstract — We study competition between a manufacturer and a third-party firm. Different from the existing literature, we focus our attention on the duopoly environment where a third-party firm may intercept end-of-life (EOL) products made by the manufacturer to sell refurbished products. We characterize the heterogeneous demands with new and re-products (remanufactured and refurbished products) and investigate the impact of various parameters in the Nash equilibrium. The results show that there is a “bank run” effect between new products and re-products. When the third-party firm engages in refurbishing, it may steal from the manufacturer’s market share and decrease the manufacturer’s profit. However, no matter the threat of competition existed or not, remanufacturing is always a profitable strategy for the manufacturer.

Keywords - remanufacturing; refurbishing; price discrimination; competition

I. INTRODUCTION

With the increased environmental consciousness, environmental concerns and stringent environmental laws, recycling and reuse of end-of-life (EOL) products has received widespread attention from both business and academic research throughout this decade [1]. While legislation introduced in Europe, North America, and Japan encourages this awareness, many corporations have proactively taken measures in anticipation of recycling and reuse of EOL products, for example, Kodak, the worldwide manufacturer of photographic media and equipment has a very successful remanufacturing program for their family of single-use cameras [2]. The economic benefits of recycling have attracted more and more enterprises engage in the recovery business.

As is known to all, remanufacturing and refurbishing are the common ways of recycling [3]. Remanufacturing is a process in which used products are disassembled, and their cores that still have residual life are treated as work blanks used in the production of remanufactured products [4]. While refurbishing is often confused with remanufacturing, in fact, they are different. The basic technological process of refurbishing is the same as the process of repairing; the refurbished products only have some simple testing, basic cosmetic treatment and updates [5]. As remanufacturing and refurbishing can prolong the life cycle of the products and relieve the high emissions and high pollution status of equipments. Therefore, there are much potential for saving energy and reducing carbon emission during remanufacturing and refurbishing. Obviously, refurbishing is not that complicated as remanufacturing, because of this, many third-party firms have the economic motivation to engage in refurbishing activity and compete with the manufacturer.

The primary goal of this paper is to provide manufacturers with guidelines for production decisions when facing a third-party firm’s competition. The closed-loop supply chain model with a manufacturer and a competitor is presented, in which the original products, the remanufactured products and the refurbished products are clearly distinguishable. First, demand functions of various markets are derived based on consumer self-selection. And then the optimal strategies for a manufacturer under four different scenarios are obtained. Finally, the analytical insights for all cases are provided.

The rest of the paper is organized as follows. Section 2 presents the relevant literature. Section 3 presents the problem description and notations. Section 4 is devoted to the conceptualization and formulation of the four supply chain models. Following the development of the model, the comparisons of the four supply chain models are presented in section 5. Concluding remarks are presented in section 6.

II. RELEVANT LITERATURE

A large stream of literature has investigated competitive models where the manufacturer produces both new and remanufactured products and competes against other manufacturers or independent remanufacturers. Majumder and Groenevelt [6] studied a two-period model with one manufacturer and an independent remanufacturer, and derived the conditions on cost/price relations for different reverse logistics settings. Similar to Majumder and Groenevelt [7], Ferguson and Toktay [8] considered
monopoly and duopoly competitions in two-period, multiple-period, and infinite-horizon models. They derived the cost condition under which remanufacturing or collection is profitable. Ferrer and Swaminathan [9] studied the joint pricing of new and remanufactured products with one OEM and one independent remanufacturer in two-period and multi-period settings. They characterized the Nash equilibrium outcome and investigate the impact of various parameters when facing the competition of a local remanufacturer. Debo et al. [10] investigated a multi-period model with one OEM and one or more independent remanufacturers. They identified the joint technology selection and pricing decisions for new and remanufactured products.

Webster and Mitra [11] and Mitra and Webster (2008) analyzed a two-period model of an OEM and an independent operators (IO). Webster and Mitra (2007) studied the impact of take-back laws on firm profits and remanufacturing activity. Mitra and Webster (2008) investigated the impact of government subsidies on remanufacturing activity. In both studies it is assumed that the OEM does not engage in remanufacturing. Bulmus et al. (2014) studied a two-period model with an OEM and an IO to characterize the optimal policy. They established a Nash equilibrium and found that the acquisition price of the OEM only depends on its own cost structure.

Vorasayan and Ryan (2006) studied the optimal price and proportion to refurbish in a competitive market and found that refurbishing operations may increase profit or may be required to relieve a manufacturing capacity bottleneck. Kogan (2011) considered a two-period model with a manufacturer and a retailer to identify the interaction and competition between new product and refurbished product, which the refurbished products were sold in the secondary market. Atasu et al. [12] assume a market composed of primary and green segments, in which the green consumers always prefer to buy the remanufactured product. They derived the profitability conditions for remanufacturing in both monopolist and competition environment.

Interesting, all these articles mainly considered competition against local remanufacturer or other manufacturers. They all assumed that the market only exist two differentiated products (the new and remanufactured products or the new and refurbished products). In fact, the new, remanufactured and refurbished products exist in the market at the same time is more reasonable. Gao et al.[13] investigated this situation, they studied a heterogeneous environment with new, remanufactured and refurbished products, and derived the demand functions of various market situations, and then characterized the optimal differentiated pricing strategy for the new, remanufactured and refurbished products in a single-period and two-period horizon. This article differs from the aforementioned studies in two aspects. First, we consider a third-party firm’s competition in the recovery business, suppose that the competitor makes refurbished products and compete with the manufacturer’s new or remanufactured products. Second, we observe the manufacturer’s optimal decisions in four different scenarios. The “bank run” effect of three competing products and the competition between the manufacturer and the third-party firm will be analyzed.

III. PROBLEM DESCRIPTION

In this paper, suppose that the manufacturer has incorporated a remanufacturing process for EOL products into her original system, so that the manufacturer can not only produce new products directly from raw materials, but also produce remanufactured products from used ones. We consider a third-party firm may enter the market when the market exist EOL products. The third-party firm has the ability to refurbishing used products and he produces refurbished products to compete with the manufacturer. We assume the previous existence of product in the market. The manufacturer and the third-party firm both have unconstrained supply of reusable products from the previous periods. Hence, the focus of analysis is on the manufacturer’s optimal strategy when facing the third-party firm’s competition.

We use the following notation throughout the paper: \( \Delta \) will denote the total number of consumers in the market, \( c_n \) denote the unit cost of a new product, \( c_r \) denote the unit cost of a remanufactured product, and \( c_{n, r} \) denote the unit cost of a refurbished product, and \( c_{n} > c_{r} > c_{s} \). The manufacturer will sell the new products at a price \( p_n \), and sell the remanufactured products at a price \( p_r \). The third-party firm will sell the refurbished products at a price \( p_s \). Throughout our analysis we will consider cases where the remanufactured products price is lower than the new products and the refurbished products price is lower than the remanufactured products, i.e. \( p_n > p_r > p_s \). Let \( \pi_i^j \) denote the profit function for member \( j \) in model \( i \). Superscript \( i \) will take values N, NR, NS, and NRS, which denote the no remanufacturing or refurbishing scenario, manufacturer remanufacturing scenario, third-party firm refurbishing scenario, and manufacturer remanufacturing and third-party firm refurbishing scenario, respectively. The subscript \( j \) will take values M and 3P, which denotes the manufacturer and the third-party firm, respectively.

Suppose that a product is labeled as “new” or “remanufactured” or “refurbished” will affect consumer’s perception of value, which means consumers have heterogeneous preferences for new, remanufactured and refurbished products. In what follows, a useful lemma is presented to describe the demand functions under different scenario.

Lemma 1. Suppose consumers are heterogeneous with respect to their willingness to pay (alternatively called “consumption value”) \( \Theta \), assumed to be uniformly distributed between 0 and 1. Assume the consumers value the new product at \( \Theta \), according to their valuation of the new product. Let \( \alpha \in (0, 1) \) and \( \beta \in (0, 1) \) denote the consumers’
preference for remanufactured and refurbished products, respectively. Also, \( \beta \) is less than \( \alpha \). Given the assumptions and the definitions above, a consumer gets utility (\( \mu = \alpha - p \)) from the new products, utility (\( \mu = \beta - p \)) from the remanufactured products, and utility (\( \mu = \beta \alpha - p \)) from the refurbished products. And the demand functions of the new products, remanufactured products, and refurbished products in different cases can be described as follows:

If \( \alpha < p_c / p_s \) and \( \beta < p_c / p_s \), the consumer will only prefer the new products (Model N), hence the new products demand function is

\[
dq^N = \Delta(1 - p_s) \tag{1}
\]

If \( p_s / p_c \leq \alpha \leq 1 - (p_s - p_c) \) and \( \beta < p_s / p_c \), the consumer with high willingness to pay will buy the new products, the price-sensitive consumers will buy the remanufactured products (Model NR). The demand functions for new and remanufactured products are

\[
\begin{align*}
q^N & = \Delta(1 - p_s) \\
q^R & = \Delta(1 - p_s - p_c) \\
q^N & = \Delta(1 - p_s - p_c - \alpha p_c / \beta(1 - \beta)) \\
p_s / p_c & \leq \alpha \leq 1 - (p_s - p_c) \text{ and } \beta < p_s / p_c
\end{align*}
\tag{2}
\]

If \( \alpha < p_c / p_s \) and \( \alpha p_c / p_s \leq \beta \leq 1 - (1 - \alpha) / (p_s - p_c) / (p_s - p_c) \), the consumer with high willingness to pay will buy the new products, the price-sensitive consumers will buy the refurbished products (Model NS). The demand functions for new and refurbished products are

\[
\begin{align*}
q^N & = \Delta(1 - p_s - p_c - \alpha p_c / \beta(1 - \beta)) \\
q^F & = \Delta(1 - p_s - p_c - \alpha p_c / \beta(1 - \beta)) \\
p_s / p_c & \leq \alpha \leq 1 - (p_s - p_c) \text{ and } \beta < p_s / p_c \text{ and } \alpha p_c / p_s \leq \beta \leq 1 - (1 - \alpha) / (p_s - p_c) / (p_s - p_c)
\end{align*}
\tag{3}
\]

If \( \alpha < p_c / p_s \) and \( \alpha p_c / p_s \leq \beta \leq 1 - (1 - \alpha) / (p_s - p_c) / (p_s - p_c) \), the demand functions for new, remanufactured and refurbished products (Model NRS) are

\[
\begin{align*}
q^N & = \Delta(1 - p_s - p_c) \\
q^R & = \Delta(1 - p_s - p_c - \alpha p_c / \beta(1 - \beta)) \\
q^F & = \Delta(1 - p_s - p_c - \alpha p_c / \beta(1 - \beta)) \\
p_s / p_c & \leq \alpha \leq 1 - (p_s - p_c) \text{ and } \beta < p_s / p_c \text{ and } \alpha p_c / p_s \leq \beta \leq 1 - (1 - \alpha) / (p_s - p_c) / (p_s - p_c)
\end{align*}
\tag{4}
\]

Supply chain models

This section presents four supply chain models: the supply chain without remanufacturing or refurbishing scenario (Model N), the closed-loop supply chain with the manufacturer remanufacturing scenario (Model NR), the closed-loop supply chain with the third-party firm refurbishing scenario (Model NS), and the closed-loop supply chain with the manufacturer remanufacturing and the third-party firm refurbishing scenario (Model NRS).

IV. THE MODEL

A. Model N—no remanufacturing or refurbishing scenario

Assume first that both remanufacturing and refurbishing are not the option, which means the monopoly manufacturer maximizes profits by offering only the new product and the third-party firm didn’t enter the market. The manufacturer’s profit function would be

\[
\pi^N = (p_c - c) q^N 
\tag{5}
\]

Proposition 1. Under the N model, the optimal price of new products is

\[
p^N = \frac{1 + c}{2}, \quad \text{the optimal sales are} \quad q^N = \frac{1}{2}. 
\]

Proposition 1 is proved.

B. Model NR—manufacturer remanufacturing scenario

When the monopolist remanufactures, the remanufactured and new products are priced simultaneously to maximize profits. The profit function of the monopolist would be

\[
\pi^N = (p_c^N - c) q^N + (p_c^N - c) q^N 
\tag{6}
\]

Proposition 2. Under the NR model, the optimal price of new products is

\[
p^N = \frac{1 + c}{2}, \quad \text{the optimal price of remanufactured products is} \quad p^N = \frac{\alpha + c}{2}, \quad \text{the optimal sales of new product are} \quad q^N = \frac{1}{2(1 - \alpha)}, \quad \text{the optimal sales of remanufactured products are} \quad q^N = \frac{1}{2(1 - \alpha)}, \quad \text{the total sales are} \quad \frac{q^N}{2}. \quad \text{The optimal profit of}
\]

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the manufacturer equal

\[ \pi_M^{NS} = \frac{\Delta(\alpha(1-\alpha - 2(1-\alpha)c_n + c_s^2) - 2\alpha c_n c_s + c_s^2)}{4\alpha(1-\alpha)} \]

Proof. For model NR, it can be easily solved in a similar manner of model N.

C. Model NS—third-party firm refurbishing scenario

In model NS, suppose that the manufacturer makes only new products, and have been facing an unusual type of competition. A third-party firm has instituted his own used product collection and refurbishing system to make refurbished products and compete with the new products. Hence, the profit functions of the manufacturer and the third-party firm would be

\[ \pi_M^{NS} = (p_n^{NS} - c_n)q_n^{NS} \]
\[ \pi_F^{NS} = (p_s^{NS} - c_s)q_s^{NS} \] (7)

Under the third-party firm’s refurbishing option, the Nash equilibrium of the competitive game between the manufacturer and the competitor can be characterized as follows.

Proposition 3. Under the NS model, the optimal price of new products is:

\[ p_n^{NS*} = \frac{2 - 2\beta + 2c_n^2 + c_s}{4 - \beta} \]

the optimal price of refurbished products is:

\[ p_s^{NS*} = \frac{\beta + \beta^2 + \beta c_n^2 + 2c_n}{4 - \beta} \]

the optimal sales of new products are:

\[ q_n^{NS*} = \frac{\Delta(2 - 2\beta - (2 - \beta)c_n^2 + c_s)}{(4 - \beta)(1 - \beta)} \]

the optimal sales of refurbished products are:

\[ q_s^{NS*} = \frac{\Delta(\beta(1 - \beta + c_n^2) - (2 - \beta)c_s)}{\beta(4 - \beta)(1 - \beta)} \]

the total sales are:

\[ q^{NS*} = \frac{\Delta(2 - 2\beta - (2 - \beta)c_n^2 + c_s)}{(4 - \beta)^2 (1 - \beta)} \]

The optimal profit of the manufacturer equals:

\[ \pi_M^{NS*} = \frac{\Delta(\beta(1 - \beta + c_n) - (2 - \beta)c_s)}{\beta(4 - \beta)^2 (1 - \beta)} \]

Proof. For model NS, it can be easily solved in a similar manner of model N.

D. Model NRS—manufacturer remanufacturing and third-party firm refurbishing scenario

In model NRS, we consider the manufacturer offers both new and remanufactured products, the third-party firm offers refurbished products to compete with the manufacturer. Hence, the manufacturer and the third-party firm’s profit function can be given as follows:

\[ \pi_M^{NRS} = (p_n^{NRS} - c_n)q_n^{NRS} + (p_r^{NRS} - c_r)q_r^{NRS} \]
\[ \pi_F^{NRS} = (p_s^{NRS} - c_s)q_s^{NRS} \] (9)

Proposition 4. Under the NRS model, the optimal price of new products is:

\[ p_n^{NRS*} = \frac{\alpha(4 - 3\beta + 4c_n + 2c_s) - \beta(1 - \alpha - c_n)}{2(4\alpha - \beta)} \]

the optimal price of remanufactured products is:

\[ p_r^{NRS*} = \frac{\alpha(2\alpha - 2\beta + 2c_n + c_s)}{4\alpha - \beta} \]

the optimal price of refurbished products is:

\[ p_s^{NRS*} = \frac{\beta(\alpha - \beta + c_n) + 2\alpha c_s}{4\alpha - \beta} \]

the optimal sales of new products are:

\[ q_n^{NRS*} = \frac{\Delta(1 - \alpha - c_n)}{2(1 - \alpha)} \]

the optimal sales of remanufactured products are:

\[ q_r^{NRS*} = \frac{\Delta(\alpha(1 + \alpha c_n) + (\alpha(4 - 3\beta + 2\beta)c_n + (\alpha - \beta)(\alpha - \beta + c_n))}{2(\alpha - \beta)(4\alpha - \beta)(1 + \alpha)} \]

the optimal sales of refurbished products are:

\[ q_s^{NRS*} = \frac{\Delta(\alpha(\alpha - \beta + c_n) + (2\alpha + \beta)c_s)}{\beta(\alpha - \beta)(4\alpha - \beta)} \]

the total sales are:
Proof. For model NRS, it can be easily solved in a similar manner of model N.

V. COMPARISON OF THE FOUR SUPPLY CHAIN MODELS

Based on the results of Proposition 1 to Proposition 4, some interesting observations can be made on the performance of the four supply chain models.

Lemma 2. The unit cost of a remanufactured product satisfies \( c_r < \alpha c_n \), the unit cost of a refurbished product satisfies \( c_s < \beta(3 - c_n)/(2\alpha) \).

Proof. According to Proposition 1~Proposition 4, it can be easily get the range of \( c_r \) and \( c_s \).

Lemma 2 shows that when \( c_r \) satisfies \( c_r < \alpha c_n \), remanufacturing is profitable for the manufacturer, when \( c_s \) satisfies \( c_s < \beta(3 - c_n)/(2\alpha) \), refurbishing is profitable for the third-party firm.

Based on the range of \( c_r \) and \( c_s \) that given in Lemma 2, we can obtain the following corollaries.

Corollary 1. The optimal prices of new products are related as \( p_{NR} > p_{NS} > p_{NRS} \).

Corollary 1 shows that the manufacturer should use two different pricing strategies of new products depending on the market structures. When the third-party firm didn’t enter the market (i.e. the manufacturer as a monopolist exists in the market), whether the remanufactured product is offered or not, the optimal price of new products is keep the same. However, when the third-party firm enters the market and offers the refurbished product, the manufacturer should charge a lower price for the new product to capture more consumers and compete with the third-party firm, and under the competition environment, when the manufacturer offers remanufactured products, the manufacturer should charge the lowest price for the new products in order to compete with his own new products and the competitor’s refurbished products.

Having identified the optimal pricing strategy of the new products in different cases, we would like to know whether the manufacturer will also charge a lower price for the remanufactured product when both the manufacturer and the third-party firm take activity in the reuse of EOL products. We can compare the manufacturer remanufacturing (model NR) and manufacturer remanufacturing and third-party firm refurbishing (model NRS) scenario to answer this question. Corollary 2 states the optimal pricing strategy of the remanufactured product when facing the third-party firm’s competition.

Corollary 2. The optimal prices of remanufactured products under model NR and model NRS are related as \( p_{NR} > p_{NRS} \).

Corollary 2 shows that when the manufacturer faces the third-party firm’s competition, the manufacturer will also choose a lower pricing strategy of the remanufactured products to against the competitor’s competition. Obviously, the price decreasing of remanufactured product will enhance the utility of the consumers who prefer remanufactured products and capture some of price-sensitive consumers in the new products market and the refurbished products market. Hence, it is an effective response for the manufacturer to against the competitor’s competition.

Corollary 3. The optimal prices of refurbished products under model NS and model NRS are related as \( p_{NS} > p_{NRS} \).

In contrast to Corollary 1 and Corollary 2, Corollary 3 shows the best response for the third-party firm when facing the manufacturer’s different choices about whether engages in remanufacturing or not. As the consumers’ valuations for the refurbished products is lower than that for the remanufactured products, i.e. \( \beta < \alpha \). If the manufacturer engages in remanufacturing and offers remanufactured products to consumers, the third-party have to charge a lower price for the refurbished products to avoid the cannibalization.

To get a better understanding of the cannibalization effect in different type of products and the competition between the manufacturer and the third-party firm, the following examples will illustrate the influence of \( \alpha \) and \( \beta \) on the optimal policies.

The influence of \( \alpha \) on the optimal policies.

Suppose that \( \Delta \) normalized to 1, \( c_n = 0.5 \), \( c_s = 0.2 \), \( \beta = 0.55 \). The influences of \( \alpha \) on the optimal policies are shown in Figure 1, Figure 2 and Figure 3.
Figure 1 illustrates that as consumers’ preference $\alpha$ increase, the total quantity ($q_{NR}^{N}$) and the number of remanufactured units ($q_{r}^{N}$) are increase, but the number of new units ($q_{n}^{N}$) decrease. It shows that when the manufacturer engages in remanufacturing, both new and remanufactured products are present in the market simultaneously; the increased part of remanufactured product grab some market share from the new ones, but increasing the total market share.

Figure 2 illustrates that as consumers’ preference $\alpha$ increase, the total quantity ($q_{NRS}^{NRS}$) and the number of remanufactured units ($q_{r}^{NRS}$) are increase, but the number of new ($q_{n}^{NRS}$) and the number of refurbished ($q_{s}^{NRS}$) units decrease. It shows that when the manufacturer engages in remanufacturing and the third-party firm engages in refurbishing, the new, remanufactured and refurbished products are present in the market simultaneously, the increased parts of remanufactured products steals some market share from new and refurbished ones to form a “bank run” effect while the total quantity increasing.

Figure 3 illustrates that as consumers’ preference $\alpha$ increase, the manufacturer’s profit increases in model NR but decreases in model NRS, while maintains constant in model N. Considering model N as a benchmark scenario, compared model NR and model NRS with model N, it can be easily found that the manufacturer’s profit in model NR is always higher than that in model N, which means remanufacturing is profitable for the monopolist manufacturer. When the third-party firm enters the market, it will steal the manufacturer’s profit via offering the refurbished product even though the manufacturer engages in remanufacturing.

The influence of $\beta$ on the optimal policies.

Suppose that $\Delta$ normalized to 1, $c_{n} = 0.5$, $c_{r} = 0.3$, $c_{s} = 0.2$, $\alpha = 0.7$. The influences of $\beta$ on the optimal policies are shown in Figure 4, Figure 5 and Figure 6.
Figure 5. Influence of $\beta$ on the optimal sales in model NRS

Figure 5 presents the impact of $\beta$ on the optimal sales of new, remanufactured, refurbished and the total when the manufacturer offers both new and remanufactured products and the third-party-firm offers refurbished product. As $\beta$ increases, the number of refurbished products ($q_{NRS}^{r}$) increases, the number of remanufactured products ($q_{NRS}^{m}$) decreases, but the number of new ones ($q_{NRS}^{n}$) remains unchanged, while the total quantity ($q_{NRS}$) increases first and then decreases. This means that when the manufacturer offers new and remanufactured products, the third-party firm’s refurbished products only have cannibalization effect on the remanufactured product. This is because the consumers’ utility between the refurbished products and the remanufactured products is closer than that between the new products and the refurbished products.

VI. CONCLUSIONS

In this paper, we developed insights for manufacturers who may face potential competition from third-party firms refurbishing their EOL products. By using game theory, the optimal decisions are explored over four different supply chain models. The contribution of this paper is twofold. First, different from the current literature, this paper considers the cases, in which three differentiated (new, remanufactured and refurbished) products may exist in the market and consumers have heterogeneous preferences for them. We derived the demand functions of the new, remanufactured and refurbished products based on consumer self-selection in four different cases. Second, the competition between the manufacturer and the third-party firm were analyzed. We find that remanufacturing is not only profitable for a monopolist manufacturer, but also profitable in a competition environment, though the competitor would steal from the manufacturer’s market share via offering the refurbished products. Finally, we analyzed the results by numerical example and give some managerial analysis.

Several extensions to this study are possible. First, we assumed that there is sufficient supply of used products and only discussed single-period horizon, but in reality, the supply is not always sufficient, so we could further study the case with two-period horizon or multi-period horizon. Second, we could also study the impact of a secondary market segment, which consists of consumers who do not discount the value of the remanufactured products or the refurbished products. In addition, this paper does not consider the coordination problem of the supply chain under...
decentralized decision, and suppose that demand information is symmetric. The coordination problem of the supply chain with asymmetric information will be studied in the future.

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