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Does Remanufacturing Always Benefit the Manufacturer and Hurt the Supplier?

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Abstract: Traditional wisdom claims that remanufacturing operations always benefit the manufacturer in monopolistic cases and hurt the supplier in a supply chain system. However, we show that this claim does not hold when firms face a mature market. In particular, we consider a case in which some consumers in the market possess old products before the selling season, i.e., some consumers are holders. A monopolistic manufacturer collects used products from holders and then sells the products to non-holders after furbishing and remanufacturing. In the integrated case, the manufacturer performs manufacturing and remanufacturing together. We find that remanufacturing may hurt the manufacturer when the fraction of non-holders in the market and the production cost are both low. In the separated case, in which an upstream supplier provides the core component to a downstream manufacturer, the downstream manufacturer undertakes the remanufacturing operation as well as manufacturing. We find that the supplier can benefit from the manufacturer's remanufacturing operation under a specific condition, even if the manufacturer always receives a higher profit.

Keywords: remanufacturing; closed-loop supply chain; market segment; recycling

1. Introduction

Nowadays, plenty of firms are incorporating remanufacturing into their practical operations because of the considerable value of used products [1,2]. One of the main reasons for the value placed on used products is that some consumers in the market prefer to purchase remanufactured products instead of new products because their willingness to pay is low [3,4]. On the other hand, firms are incentivized to collect used products from consumers since the demand market is gradually maturing [5,6]. In addition, more stringent environmental regulations have forced firms to collect used products from the market [7–9]. The collection process, to a certain extent, can stimulate some consumers who hold used products before the selling season to purchase new products to replace their older ones. For example, smartphone companies, such as Apple, Samsung, Huawei, etc., collect their used smartphones from consumers through their online platforms [10]. In addition, some automobile companies, such as BMW, Audi, and Ford, among others, also recycle used cars from the market and sell them as certificated secondhand cars.

However, some firms refuse to remanufacture because they worry about the cannibalization problem [11,12]. In particular, when remanufactured products are sold together with new products, consumers with low willingness to pay may choose to purchase remanufactured products instead of new ones, cannibalizing the market share of new products. In a supply chain environment, since the downstream firms' (i.e., manufacturers) remanufacturing operations may reduce the demand for core components, the upstream firms (i.e., suppliers) may have concerns about whether the downstream firms' remanufacturing operations will hurt them. However, when firms in the supply chain are facing a mature market, remanufacturing operations produce two-sided effects. On the one hand, remanufacturing may reduce the procurement of core components since firms can obtain some reusable core components from remanufactured products. On the other hand, the remanufacturing operations can induce some holders (i.e., consumers who possess old products before the selling season) to upgrade their old products, thus increasing both the demand for new products and the procurement of core components. Therefore, our main goal is to explore whether remanufacturing operations benefit the manufacturer and hurt the supplier.

To be specific, the questions that this paper aims to address include:

(1) In an integrated environment, in which the supplier and manufacturer are integrated, do remanufacturing operations absolutely benefit the integrated system?
(2) In a separated environment, in which the supplier and manufacturer behave independently, do the remanufacturing operations definitely benefit the manufacturer and hurt the supplier?

To answer the questions above, we consider a two-tier supply chain with a manufacturer and a supplier: the manufacturer sells new products to consumers directly and undertakes remanufacturing operations. Furthermore, consumers in the market are separated into two types, namely, holders who possess old products before the selling season and non-holders who do not have old products before the selling season. We first analyze consumer demand in the market on the basis of consumer utility theory and then consider the profit-maximization problem. We analyze the impacts that remanufacturing operations have on the optimal decisions and profit of the supplier and manufacturer by using an optimization approach. The results show that remanufacturing operations will hurt the integrated system if the production cost is small and the fraction of non-holders in the market is low (or most consumers in the market hold used products). However, in a separated environment, the outcome shows that the manufacturer always benefits from remanufacturing operations, and the supplier can also benefit from them under a certain condition.

Our study contributes to the literature in two aspects. First, we consider firms' remanufacturing strategy in a mature environment in which some consumers hold old products. Although the presence of remanufactured products results in a cannibalization problem, the remanufacturing operations can serve as a marketing tool to stimulate consumers who have old products in the market to upgrade to new ones in this case. Second, we examine the effects of market segmentation and production cost on firms' profitability when remanufacturing is involved. The results show that remanufacturing operations may hurt the manufacturer in the integrated case and benefit the supplier in the separated case. These conclusions are different from the traditional wisdom that dictates that remanufacturing is beneficial to the manufacturer and hurts the supplier [13,14]. Our study can complement the existing works related to closed-loop supply chains with remanufacturing.

The remainder of this paper is organized as follows. Section 2 reviews some related literature, and Section 3 describes the model. We consider an integrated case in Section 4 and a separated case in Section 5. Section 6 summarizes our results, provides conclusions and provides some future research directions.

2. Literature Review

Closed-loop supply chains with remanufacturing have received lots of attention for many years. Guide and Van Wassenhove [15] traced the development of remanufacturing over the past several years and claimed that closed-loop supply chain management would be a fruitful field since remanufacturing can generate some interest in firms that undertake this process. Since this study, much research related to remanufacturing has appeared, and researchers have studied firms' optimal pricing, reverse channel selection, and coordination decisions related to remanufacturing. An overview of this field can be found in Souza [16] and Govindan, et al. [17]. Our study is an extension of the existing literature on the closed-loop supply chain and remanufacturing. Two work streams are related to our research: the first one is remanufacturing in a monopolistic or non-distributional situation, and the other one is remanufacturing in a distribution channel.

Regarding the effects of remanufacturing operations in a monopolistic or non-distributional case, Ferrer and Swaminathan [18,19] found that the entry of an independent remanufacturer is detrimental to a monopolistic firm since the presence of remanufactured products will cause a cannibalization problem. In their opinion, the monopolistic firm should undertake the remanufacturing process on its own to pre-empt remanufacturing by new entrants. However, Wu and Zhou [20] studied whether the entry of an independent third-party remanufacturer hurts the manufacturer by considering two competitive original equipment manufacturers (OEMs). They showed that the manufacturer would benefit from the third-party remanufacturer's entry under a certain condition. Atasu, Sarvary and Wassenhove [14] considered a case in which some consumers in the market always prefer remanufactured products, and their results showed that remanufacturing would be regarded as a marketing strategy to achieve price discrimination and increase firms' profit. Zou, et al. [21] studied these types of choices using a third-party remanufacturing model and reported the conditions in which original equipment manufacturers should outsource or authorize the third party to undertake remanufacturing. Chai, et al. [22] explored the effects of the carbon cap mechanism on firms' remanufacturing strategies and discovered that the cap is beneficial. More importantly, the carbon cap increases the positive effect of remanufacturing operations. Steeneck and Sarin [23] explored how the extended producer responsibility regulation affects firms' product design strategy when an OEM produces products for lease and then remanufactures them at the end of the lease period. These works showed that remanufacturing can be regarded as a marketing strategy to improve firms' profit [24].

In terms of remanufacturing in a distributional situation, many works have focused on investigating how remanufacturing affects firms' pricing, collection, and production decisions, as well as their performance. De Giovanni, et al. [25] explored the incentive strategies in a dynamic closed-loop supply chain with one manufacturer and one retailer, and they derived the optimal decisions of the investment that would lead to an improved return rate. Panagiotidou, et al. [26] studied the joint optimization problem of remanufacturing and manufacturing given imperfect information on the quality of returned items. They found that the information regarding the quality of returns can improve firms' profitability. Jia, et al. [27] incorporated remanufacturing into the early stage of a product's lifetime and established that an efficient remanufacturing design strategy can help the firm to balance the supply and demand for collected products. Guide [28] defined a typical model of remanufacturing in closed supply chains and provided a brief overview of remanufacturing processes. Agrawal, Atasu and van Ittersum [4] explored how third-party competition and remanufacturing affected consumers' perceived value of new products, and they discovered that remanufacturing operations have a positive effect on consumers' perception. He [29] studied the optimal acquisition pricing and remanufacturing decisions when taking into account deterministic and stochastic demand. Furthermore, they proposed two contracts to coordinate the closed-loop supply chain. Wang, et al. [30] explored whether firms' profit-maximization objection hurts the firm when designing the reverse channel for remanufacturing. He, et al. [31] investigated how to increase the collection efficiency to mitigate recycling inconvenience in a closed-loop supply chain. Govindan, et al. [32] studied the product recovery optimization problem in a closed-loop supply chain in order to improve sustainability in manufacturing. These works explored the effects of remanufacturing on firms' pricing and collection decisions in a distribution channel environment and discovered that firms benefit from remanufacturing. However, most of them considered the effects of remanufacturing on the supplier. The study in Xiong, Zhou, Li, Chan and Xiong [13] is the work that is most closely related to ours, as they explored this problem considering a static channel structure and found that the manufacturer's remanufacturing operations hurt the supplier. Different from their works, we consider a more generalized case in which firms face a mature market before the sale season. Our outcomes show that the supplier can also benefit from remanufacturing operations.

Clearly, all of the above works showing that remanufacturing is good for firms to have a common and critical assumption, which is that consumers in the market do not possess any products before the selling period. In reality, however, some consumers in the market already have old products when firms are planning to undertake remanufacturing. Firms often need to pay some compensation (i.e., collection fee) in order to recycle used products from these consumers, and this may stimulate consumers to purchase new products again. In other words, remanufacturing can act as a marketing tool and induce some consumers who hold old products to upgrade their old products for new ones. For example, many companies in different industries implement a trade-in program to induce consumers to purchase their new-generation products. Obviously, the segmentation of these types of consumers plays an important role in driving firms' remanufacturing and manufacturing strategies. It is necessary to take different consumer types into account when studying the effects of remanufacturing on firms' operational decisions. Feng, Li, Xu and Deng [6] investigated the impacts of trade-in programs on firms' pricing decisions in a dual-channel supply chain in a mature market, and they found that market segmentation has an important effect on driving firms' optimal decisions. However, they did not consider the firms' remanufacturing operations. To fill the gap in the literature, our study incorporates remanufacturing into a closed-loop supply chain in the context of a mature market. The results show that manufacturers' remanufacturing operations may eventually hurt the manufacturer in a monopolistic case, which is contrary to the current wisdom and complements the current works in this field.

3. Model Description

We consider a case in which a manufacturer sells new products and a remanufacturer collects used products from consumers and sells them to consumers after refurbishing and remanufacturing. For example, Bayerische Motoren Werke (i.e., BMW) uses a trade-in program to collect its used cars from consumers in the market and then sells these refurbished and certificated cars to consumers who prefer to buy secondhand cars (https://www.bmwusa.com/). Different from existing studies, we assume that firms face a mature market wherein some consumers have old products before the selling season, i.e., holders. These consumers can elect to upgrade their products to new ones by selling the old product to the remanufacturer. On the other hand, consumers who do not have products before the selling season, i.e., non-holders, can elect to purchase new products or remanufactured ones depending on the net surplus. Assume that consumers' willingness to pay for a new product is v, and their willingness to pay for a remanufactured one is a fraction of v, i.e., ϕv. In addition, consumers are heterogeneous in their willingness to pay, which is uniformly distributed over $[0, 1]$. Given the prices of new and remanufactured products in the market p_n and p_r, a non-holding consumer can gain a surplus $v - p_n$ by purchasing a new product or $\phi v - p_r$ by purchasing a remanufactured product. For non-holders, given the collection price p_t, the net surplus is $v - p_n + p_t$ for an upgrade and θv otherwise. Here, we assume that the value of the old product is a proportion of that of the new product, which is denoted by $0 < \theta < \phi < 1$. Assume that the ratio of holders in the market is α and that of non-holders is $1 - \alpha$. Following Ferguson and Toktay [33] and Ferrer and Swaminathan [19], non-holders prefer to buy a new product when $v - p_n > \phi v - p_r$ and $v - p_n > 0$, and they prefer to buy a remanufactured product when $v - p_n < \phi v - p_r$ and $\phi v - p_r > 0$. Otherwise, a non-holder will not buy any products. Thus, the demands for new and remanufactured products in the market are

$$D_{n1} = \alpha\left(1 - \frac{p_n - p_r}{1 - \phi}\right) \text{ and } D_r = \alpha\left(\frac{p_n - p_r}{1 - \phi} - \frac{p_r}{\phi}\right). \tag{1}$$

Similarly, a holder is willing to update to a new product if $v - p_n + p_t > \theta v$, i.e., $v > (p_n - p_t)/(1 - \theta)$. So, we can obtain the demand for new products of holders in the market by

$$D_{n2} = (1 - \alpha)\left(1 - \frac{p_n - p_t}{1 - \theta}\right). \tag{2}$$

The production costs of new and remanufactured products are c_n and c_r, respectively, and $c_n > c_r$. To better explain the qualitative property, we first assume that the remanufacturing cost is zero, i.e., $c_r = 0$. Furthermore, we also assume that the salvage value of an old product is zero if it cannot be remanufactured and refurbished, i.e., $s = 0$. In addition, we assume that all recycled products can be refurbished or remanufactured. In other words, the rate of refurbishing or remanufacturing ρ is one. With the uncertainty of the quality of the old products, we can assume that the rate of refurbishing or remanufacturing is less than one, i.e., $\rho < 1$, so then the constraint $D_r < D_{n2}$ will become $D_r < \rho D_{n2}$. Although this change makes the calculation more complicated, it does not alter the results qualitatively.

4. An Integrated Case

First, we consider a case in which the supplier and manufacturer are integrated and act as a united firm in order to maximize the total profit. To explore the impacts of remanufacturing on the firm's profit, we first consider a benchmark case in which the integrated firm does not perform remanufacturing. Next, we study the integrated firm's optimal decision when remanufacturing exists.

4.1. Benchmark Case: No Remanufacturing

First, we consider a case in which the integrated firm does not undertake remanufacturing. Superscript "B" is used to denote the case in which the manufacturer does not undertake remanufacturing in an integrated case. When there are no remanufactured products in the market, the manufacturer's profit function is $\pi_M^B(p_n) = (p_n - c_n)(D_{n1} + \max\{D_{n2}, 0\})$. Using optimization theory, we can obtain $\partial^2 \pi_M^B / \partial (p_n)^2 = -2(1-\alpha\theta)/(1-\theta)$; thus, π_M^B is concave in p_n. By taking the first-order derivative of π_M^B with respect to p_n and letting it equal zero, we have

$$p_n^{B*} = \begin{cases} \frac{1-\theta+(1-\alpha\theta)c_n}{2(1-\alpha\theta)}, \ if c_n < \widetilde{c}_n(\alpha) = \frac{(1-\theta)(1-\alpha\theta)-\theta\sqrt{\alpha(1-\theta)(1-\alpha\theta)}}{1-\alpha\theta}, \\ \frac{1+c_n}{2}, \ if c_n \geq \widetilde{c}_n(\alpha) = \frac{(1-\theta)(1-\alpha\theta)-\theta\sqrt{\alpha(1-\theta)(1-\alpha\theta)}}{1-\alpha\theta}. \end{cases} \tag{3}$$

Consequently, the optimal profit is

$$\pi_M^{B*} = \begin{cases} \frac{(1-\theta-(1-\alpha\theta)c_n)^2}{4(1-\theta)(1-\alpha\theta)}, \ if c_n < \widetilde{c}_n(\alpha) = \frac{(1-\theta)(1-\alpha\theta)-\theta\sqrt{\alpha(1-\theta)(1-\alpha\theta)}}{1-\alpha\theta}, \\ \frac{\alpha(1-c_n)^2}{4}, \ if c_n \geq \widetilde{c}_n(\alpha) = \frac{(1-\theta)(1-\alpha\theta)-\theta\sqrt{\alpha(1-\theta)(1-\alpha\theta)}}{1-\alpha\theta}. \end{cases} \tag{4}$$

From the results above, we discover that when the production cost is high, the firm prefers to better serve the holders and give up the non-holders. Furthermore, the threshold value $\widetilde{c}_n$ is decreasing in α, i.e., $\partial\widetilde{c}_n/\partial\alpha < 0$. In other words, the firm will be more likely to exclude non-holders from its objectives as the ratio of holders in the market increases. It is evident that holders become the firm's consumer group when they dominate the market.

4.2. Manufacturer Implements Remanufacturing

When the manufacturing sells new products together with remanufactured products in the same market, consumers need to decide which one to purchase on the basis of consumer utility theory. In this case, the manufacturer needs to determine the prices of new and remanufactured products, as well as the collection price. The superscript "M" is used to denote the case in which the manufacturer undertakes remanufacturing in an integrated case. On the basis of Equations (1) and (2), we can obtain the manufacturer's profit maximization problem, which is given by

$$\max_{(p_n, p_r, p_t)} \pi_M^M = (p_n - c_n)(D_{n1} + D_{n2}) + p_r D_r - p_t D_{n2}, \ D_{n2} \geq D_r \tag{5}$$

where the constraint (i.e., $D_{n2} \geq D_r$) ensures that the sale of remanufactured products will never be higher than the number of collected products.

On the basis of Equation (3), we can obtain the manufacturer's optimal quantity decisions, which are summarized by Theorem 1.

Theorem 1. *When the manufacturer conducts manufacturing together with remanufacturing, the optimal pricing decisions are*

$$\text{If } c_n \geq \hat{c}_n(\alpha),\ p_n^{M*} = \frac{1+c_n}{2},\ p_t^{M*} = \frac{\phi(\alpha(2-\theta(2-\phi)-(2-\phi)\phi)-(1-\phi)(1-\theta-\phi)+(1+\alpha(\phi-\theta)-\phi)c_n)}{2(1-\phi)\phi+2\alpha(1-\theta-\phi+\phi^2)}$$
$$\text{and } p_r^{M*} = \frac{\alpha(1-\theta)\theta-(1-\alpha)(1-2\theta)\phi+(1-\alpha)(1-2\theta)\phi^2+(1+\alpha(\phi-\theta)-\phi)\phi c_n}{2(1-\phi)\phi+2\alpha(1-\theta-\phi+\phi^2)},\ \text{and } D_{n2}^{M*} = D_r^{M*};$$

$$\text{If } c_n < \hat{c}_n(\alpha),\ p_n^{M*} = \frac{1+c_n}{2},\ p_t^{M*} = \frac{\theta}{2} \text{ and } p_r^{M*} = \frac{\phi}{2},\ \text{and } D_{n2}^{M*} > D_r^{M*},\ \text{where } \hat{c}_n(\alpha) = \frac{(1-\theta)(1-\alpha)(1-\phi)}{1-\alpha\theta-(1-\alpha)\phi}.$$

Proof. Substituting Equations (1) and (2) into Equation (5), we have

$$\max_{(p_n,p_r,p_t)} \pi_M^M = (p_n-c_n)\left(\alpha\left(1-\frac{p_n-p_r}{1-\phi}\right)+(1-\alpha)\left(1-\frac{p_n-p_t}{1-\theta}\right)\right)+p_r\alpha\left(\frac{p_n-p_r}{1-\phi}-\frac{p_r}{\phi}\right)-p_t(1-\alpha)\left(1-\frac{p_n-p_t}{1-\theta}\right),$$
$$\text{s.t. } (1-\alpha)\left(1-\frac{p_n-p_t}{1-\theta}\right) \geq \alpha\left(\frac{p_n-p_r}{1-\phi}-\frac{p_r}{\phi}\right).$$

By taking the second-order derivative of π_M^M with respect of p_n, p_r, and p_t successively, we can get the Hessian matrix, that is,

$$H = \begin{vmatrix} -\frac{2(1-\alpha)}{1-\theta}-\frac{2\alpha}{1-\phi} & \frac{2\alpha}{1-\phi} & \frac{2(1-\alpha)}{1-\theta} \\ \frac{2\alpha}{1-\phi} & \frac{-2\alpha}{(1-\phi)\phi} & 0 \\ \frac{2(1-\alpha)}{1-\theta} & 0 & -\frac{2(1-\alpha)}{1-\theta} \end{vmatrix}.$$

It is easy to prove that π_M^M is jointly concave in p_n, p_r, and p_t. Therefore, we can obtain the Lagrange function, which can be expressed by

$$\begin{aligned} L((p_n,p_r,p_t)) = \quad & (p_n-c_n)\left(\alpha\left(1-\frac{p_n-p_r}{1-\phi}\right)+(1-\alpha)\left(1-\frac{p_n-p_t}{1-\theta}\right)\right) \\ & +p_r\alpha\left(\frac{p_n-p_r}{1-\phi}-\frac{p_r}{\phi}\right)-p_t(1-\alpha)\left(1-\frac{p_n-p_t}{1-\theta}\right) \\ & +u\left((1-\alpha)\left(1-\frac{p_n-p_t}{1-\theta}\right)-\alpha\left(\frac{p_n-p_r}{1-\phi}-\frac{p_r}{\phi}\right)\right). \end{aligned}$$

□

According to the first-order derivative conditions, we can get the following:

(1) if $c_n < \frac{(1-\theta)(1-\alpha)(1-\phi)}{1-\alpha\theta-(1-\alpha)\phi}$, then $p_n = \frac{1+c_n}{2}$, $p_r = \frac{\phi}{2}$ and $p_t = \frac{\theta}{2}$;

(2) if $c_n > \frac{(1-\theta)(1-\alpha)(1-\phi)}{1-\alpha\theta-(1-\alpha)\phi}$, then $p_r = \frac{\alpha(1-\theta)\theta-(1-\alpha)(1-2\theta)\phi+(1-\alpha)(1-2\theta)\phi^2+(1+\alpha(\phi-\theta)-\phi)\phi c_n}{2(1-\phi)\phi+2\alpha(1-\theta-\phi+\phi^2)}$, $p_n = \frac{1+c_n}{2}$, and $p_t = \frac{\phi(\alpha(2-\theta(2-\phi)-(2-\phi)\phi)-(1-\phi)(1-\theta-\phi)+(1+\alpha(\phi-\theta)-\phi)c_n)}{2(1-\phi)\phi+2\alpha(1-\theta-\phi+\phi^2)}$.

If we let $\hat{c}_n(\alpha) = \frac{(1-\theta)(1-\alpha)(1-\phi)}{1-\alpha\theta-(1-\alpha)\phi}$, then we can obtain Theorem 1.

Theorem 1 illustrates that only part of the collected products will be remanufactured when the production cost is low. However, all collected products are remanufactured when the manufacturer suffers from a high production cost. When the production cost is low, the marginal profit of the new product is higher than the remanufactured product. To decrease the competition between the new and remanufactured products, the manufacturer remanufactures some of the collected products. However, when the production cost is high, the advantage of selling new products gradually disappears. In this case, the manufacturer prefers to remanufacture all collected products. Furthermore, we find that the collection price will increase, i.e., $p_t^{M*} > \theta/2$ when $c_n > \hat{c}_n$. In other words, more used products will be collected and remanufactured when the manufacturer suffers from a high production cost. Interestingly, we find that the price of the remanufactured product can be higher or lower than $\phi/2$.

When the demand for remanufactured products is very high, the manufacturer increases the selling price so that it is greater than $\phi/2$.

4.3. Value of Remanufacturing

This section explores how remanufacturing affects the manufacturer's optimal decision and profit. At the same time, the effects of market segmentation on the manufacturer's optimal strategy and profit are studied. Since the values of parameters θ and ϕ satisfy $0 < \phi < 1$, let $\theta = 0.4$ and $\phi = 0.6$ in the numerical experiments. On the basis of the analytical results in Sections 3 and 4, we can obtain some further conclusions as follows.

Proposition 1. *For any given θ and ϕ, we have $p_n^{M*} > p_n^{B*}$ if $c_n < min\{\widetilde{c}_n(\alpha), \hat{c}_n(\alpha)\}$; otherwise, $p_n^{M*} = p_n^{B*}$.*

Proposition 1 illustrates that when the production cost is low, the retail price is lower without remanufacturing than that with remanufacturing. When the production cost exceeds a threshold, however, the retail price in both cases remains the same. In this case, the manufacturer will give up all holders in the market if there is no remanufacturing and better serve the non-holders group. Nevertheless, if the manufacturer undertakes remanufacturing, holders will be served by upgrading to a new product at a discounted price and returning their old products. Furthermore, some or all of these returned products will be remanufactured and sold to non-holders in the market.

Proposition 2. *For any given θ and ϕ, (i) if both the production cost and the fraction of non-holders in the market are low, the remanufacturing operation may hurt the manufacturer; otherwise, (ii) if the production cost or the fraction of non-holders in the market is high, the manufacturer can benefit from the remanufacturing operation.*

From Proposition 2 and Figure 1, we find that the remanufacturing may hurt the manufacturer's profit under some conditions. To be specific, when both the production cost and the ratio of non-holders in the market are low, the manufacturer can benefit from giving up remanufacturing. In other words, the manufacturer should not undertake remanufacturing in this case. The reasons are as follows: first, when the fraction of non-holders in the market is small, it implies that the demand for remanufactured products is small. Second, the cannibalization problem that results from the remanufacturing operation will become fiercer with the decrease in the production cost. However, we also find that the manufacturer can benefit from the remanufacturing operation if the fraction of non-holders in the market is high or the production cost is substantial. This result is different from the traditional wisdom that claims that remanufacturing is always beneficial to the firm [14]. The main reason for this difference is that we consider a mature market in which some consumers possess old products before the selling season. In this case, the firm needs to determine whether to serve all types of consumers in the market and balance the tradeoff between the market coverage effect and the cannibalization problem due to the remanufacturing.

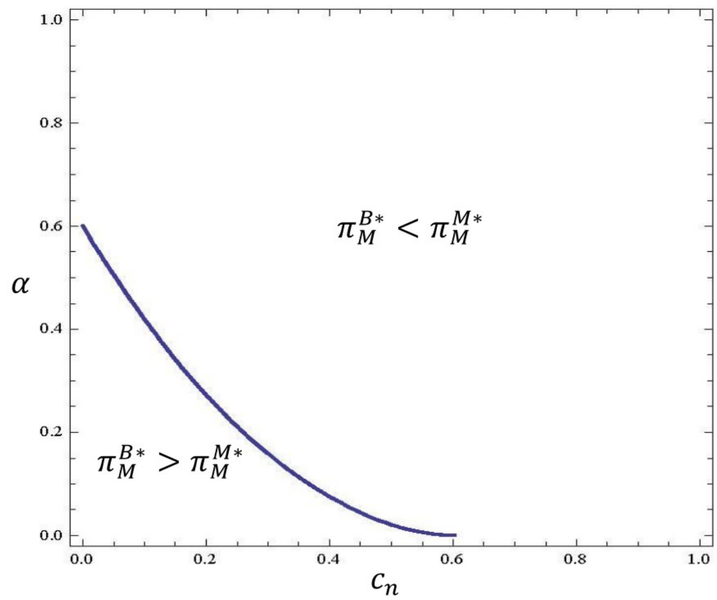

Figure 1. Impact of remanufacturing on the manufacturer's profit.

5. Remanufacturing in a Distribution Channel

In the previous section, we explore the optimal decision of a monopolistic manufacturer and find that it may be hurt by the remanufacturing operation. In this section, we further study the effect of remanufacturing on the firms' decisions and profit in a supply chain environment. In particular, we consider a two-tier supply chain consisting of an upstream supplier and a downstream manufacturer. We conduct a Stackelberg game in which the supplier acts as a game leader and the manufacturer acts as a game follower. The event sequence is as follows: the supplier first determines the wholesale price of the core component, and the manufacturer determines the retail price(s) of new products and remanufactured products if remanufacturing operations are undertaken. Analogously, we consider two cases: (i) a benchmark case without remanufacturing, and (ii) the case in which the manufacturer undertakes remanufacturing. We assume that the wholesale price is w, and the other parameters remain the same as that in Section 4.1.

5.1. Benchmark Case Without Remanufacturing

When the manufacturer in a supply chain does not undertake remanufacturing, the supplier initially establishes the wholesale price of the core component, and the manufacturer determines the retail price of new products. In this case, the manufacturer encounters a cost w. Superscript "SB" is used to denote the case in which the manufacturer does not undertake remanufacturing in a distribution channel. According to the analyses in Section 3, we can obtain the profit functions of the supplier and manufacturer, which are given by

$$\pi_S^{SB}(w) = (w - c_n)(D_{n1} + \max\{D_{n2}, 0\}) \tag{6}$$

$$\pi_M^{SB}(p_n) = (p_n - w)(D_{n1} + \max\{D_{n2}, 0\}). \tag{7}$$

Using backward induction, we can obtain the optimal decisions of the supplier and the manufacturer. We summarize them in Theorem 2.

Theorem 2. *In a distribution channel, the optimal decisions of the supplier and the manufacturer are as follows:*

$$\begin{cases} p_n^{SB*} = \frac{3(1-\theta)+(1-\alpha\theta)c_n}{4(1-\alpha\theta)} \text{ and } w^{SB*} = \frac{1-\theta+(1-\alpha\theta)c_n}{2-2\alpha\theta},\ if c_n < \frac{(1-\theta)(1-\alpha\theta)-\theta\sqrt{\alpha(1-\theta)(1-\alpha\theta)}}{1-\alpha\theta}, \\ p_n^{SB*} = \frac{3+c_n}{4} \text{ and } w^{SB*} = \frac{1+c_n}{2},\ if c_n \geq \frac{(1-\theta)(1-\alpha\theta)-\theta\sqrt{\alpha(1-\theta)(1-\alpha\theta)}}{1-\alpha\theta}. \end{cases}$$

Consequently, the optimal profits of the supplier and manufacturer are

$$\begin{cases} \pi_M^{SB*} = \frac{(1-\theta-(1-\alpha\theta)c_n)^2}{16(1-\theta)(1-\alpha\theta)} \text{ and } \pi_S^{SB*} = \frac{(1-\theta-(1-\alpha\theta)c_n)^2}{8(1-\theta)(1-\alpha\theta)},\ if c_n < \frac{(1-\theta)(1-\alpha\theta)-\theta\sqrt{\alpha(1-\theta)(1-\alpha\theta)}}{1-\alpha\theta}, \\ \pi_M^{SB*} = \frac{\alpha(1-c_n)^2}{16} \text{ and } \pi_S^{SB*} = \frac{\alpha(1-c_n)^2}{8},\ if c_n \geq \frac{(1-\theta)(1-\alpha\theta)-\theta\sqrt{\alpha(1-\theta)(1-\alpha\theta)}}{1-\alpha\theta}. \end{cases}$$

Proof. Similar to the calculation in Section 4.1, for any given w, the manufacturer's optimal decision is as follows:

$$p_n^{SB*}(w) = \begin{cases} \frac{1-\theta+(1-\alpha\theta)w}{2(1-\alpha\theta)},\ if w < \frac{(1-\theta)(1-2\alpha\theta)}{1-\alpha\theta}, \\ \frac{1+w}{2},\ if w \geq \frac{(1-\theta)(1-2\alpha\theta)}{1-\alpha\theta}. \end{cases}$$

Furthermore, by substituting $p_n^{SB*}(w)$ in Equation (6) and taking the first-order derivative of Equation (6) with respect to w, we have

$$\begin{cases} w^{SB*} = \frac{1-\theta+(1-\alpha\theta)c_n}{2-2\alpha\theta},\ if c_n < \frac{(1-\theta)(1-\alpha\theta)-\theta\sqrt{\alpha(1-\theta)(1-\alpha\theta)}}{1-\alpha\theta}, \\ w^{SB*} = \frac{1+c_n}{2},\ if c_n \geq \frac{(1-\theta)(1-\alpha\theta)-\theta\sqrt{\alpha(1-\theta)(1-\alpha\theta)}}{1-\alpha\theta}. \end{cases}$$

□

By substituting w^{SB*} in $p_n^{SB*}(w)$, we can obtain the optimal retail price p_n^{SB*}. Furthermore, we can obtain the optimal profits of the supplier and manufacturer by substituting w^{SB*} and p_n^{SB*} in Equations (6) and (7), respectively.

This optimal decision-making structure is similar to that in the integrated case without remanufacturing. At the same time, the total profit of the supply chain system decreases since the double marginalization problem exists in the supply chain. Next, we explore the optimal decisions of the supplier and the manufacturer in a distribution channel with remanufacturing.

5.2. Manufacturer Undertakes Remanufacturing

When the manufacturer sells new products together with remanufactured products in the same market, consumers need to decide which one to purchase on the basis of consumer utility theory. In this case, the manufacturer needs to determine the prices of new and remanufactured products, as well as the collection price. The superscript "SM" is used to denote the case in which the manufacturer undertakes remanufacturing in a distribution channel. On the basis of Equations (1) and (2), we can obtain the manufacturer's profit maximization problem, which is given by

$$\max_{(p_n,p_r,p_t)} \pi_S^{SM} = (w - c_n)(D_{n1} + D_{n2}) \tag{8}$$

$$\max_{(p_n,p_r,p_t)} \pi_M^{SM} = (p_n - w)(D_{n1} + D_{n2}) + p_r D_r - p_t D_{n2} \tag{9}$$

Similarly, we can obtain the optimal decisions of the supplier and the manufacturer when remanufacturing is conducted in the supply chain. We summarize these results in Theorem 3.

Theorem 3. *When the manufacturer conducts manufacturing together with remanufacturing in a distribution channel, the optimal pricing decisions of the supplier and manufacturer are those summarized in Table 1.*

Table 1. The optimal pricing decisions of the supplier and manufacturer in Case SM.

Conditions	$c_n \geq \hat{\hat{c}}_n$ **and** $D_{n2}^{SM*} = D_r^{SM*}$	$c_n < \hat{\hat{c}}_n$ **and** $D_{n2}^{SM*} > D_r^{SM*}$
w^{SM*}	$\frac{1-\theta-(1-\alpha)(\phi-\theta)\phi+c(1+\alpha(\phi-\theta)-\phi)}{2(1+\alpha(\phi-\theta)-\phi)}$	$\frac{1-\theta-\phi+\theta\phi+c_n(1+\alpha(\phi-\theta)-\phi)}{2(1+\alpha(\phi-\theta)-\phi)}$
p_n^{SM*}	$\frac{(2+c_n)(1+\alpha(\phi-\theta)-\phi)+1-\theta-(1-\alpha)(\phi-\theta)\phi}{4(1+\alpha(\phi-\theta)-\phi)}$	$\frac{(1+\alpha(\phi-\theta)-\phi)c_n+3-\theta-\alpha\theta-(3-2\alpha-\theta)\phi}{2(1+\alpha(\phi-\theta)-\phi)}$
p_t^{SM*}	$\frac{(1-\phi)\phi(3\theta+\phi-1+c_n)-\alpha\left(2\theta^2+\theta((4+c_n-3\phi)\phi-2)-\phi(2-\phi(2-c_n-\phi))\right)}{4(1-\phi)\phi+4\alpha(1-\theta-\phi+\phi^2)}$	$\frac{\theta}{2}$
p_r^{SM*}	$\frac{\phi\left((1-\alpha)(4-c_n-\theta)\phi+c_n+4\alpha+\theta-1-4\alpha\theta-c_n\alpha\theta-3(1-\alpha)\phi^2\right)}{4(1-\phi)\phi+4\alpha(1-\theta-\phi+\phi^2)}$	$\frac{\phi}{2}$

where

$$\hat{\hat{c}}_n = \frac{\left(\alpha\left(1-\theta+\theta\phi-\phi^2\right)-\alpha^2(\theta-\phi)\phi\right)\frac{\sqrt{(1-\theta)(1-\phi)(1-\alpha(\theta-\phi)-\phi)}}{\sqrt{(1-\alpha(\theta-\phi)-\phi)((1-\phi)\phi+\alpha(1-\theta-\phi+\phi^2))}}+(1-\theta+\phi+\theta\phi}{(1-\alpha(\theta-\phi)-\phi)\left(\alpha\frac{\sqrt{(1-\theta)(1-\phi)(1-\alpha(\theta-\phi)-\phi)}}{\sqrt{(1-\alpha(\theta-\phi)-\phi)((1-\phi)\phi+\alpha(1-\theta-\phi+\phi^2))}}+1\right)}$$

Proof. In a manner similar to that used in the proofs for Theorems 1 and 2, we can get the results in Theorem 3. □

5.3. Effects of Remanufacturing In a Distribution Channel

Here, we seek to explore how the remanufacturing operation affects the profitability of the manufacturer and the supplier in a supply chain system. On the basis of Theorems 2 and 3, we obtain the result below.

Proposition 3. *In a distribution channel, the manufacturer always benefits from the remanufacturing operation, and the supplier can also benefit from the remanufacturing operation under a certain condition.*

Proposition 3 illustrates that the remanufacturing operation is always beneficial to the manufacturer in a supply chain system, which is consistent with the current wisdom about the value of remanufacturing. However, it interestingly shows that the supplier can be better off with the remanufacturing operation under a certain condition. This finding is different from the previous studies that claim that the downstream firm's remanufacturing operation always hurts the supplier [13]. The main reason for this difference is that we consider a mature market in which some consumers hold used products before the selling season. In this case, the remanufacturing operation can incentivize part of this consumer segment to upgrade their used products to new ones, increasing the demand for core components. On the other hand, the remanufacturing operation will cannibalize the market share of new products, thus decreasing the demand for core components. When the positive effect dominates the negative effect, the remanufacturing operations increase the supplier's profit. Otherwise, it leads to a decrease in the supplier's profit. Figure 2 numerically shows the result in proposition 3. Figure 2 also reveals that the supplier can benefit from the manufacturer's remanufacturing operation under a specific condition. In particular, when the production cost is high, the manufacturer has to increase the retail price of the new products. As a result, the demand for remanufacturing products significantly increases, and therefore, the demand for holders in the market improves.

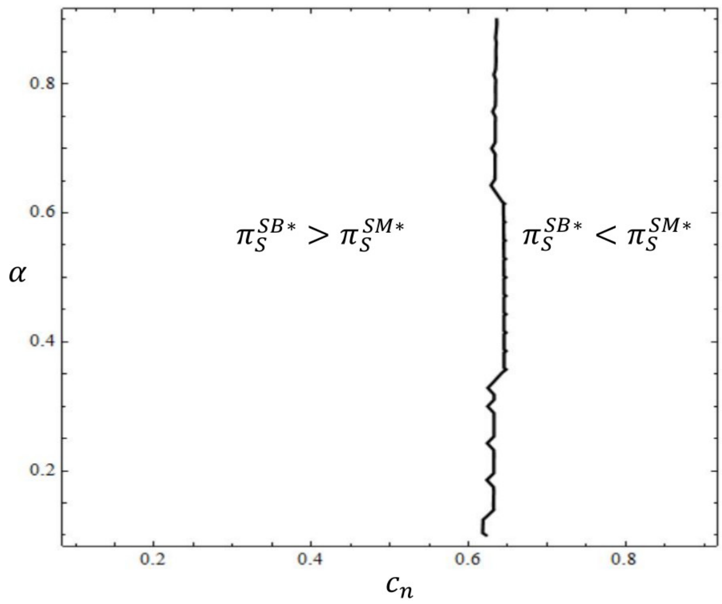

Figure 2. Impact of remanufacturing on the supplier's profit.

6. Discussion

Traditional wisdom maintains that remanufacturing operations always benefit the manufacturer in both decentralized and centralized cases, and remanufacturing hurts the supplier in decentralized cases [10,13,14]. However, our study shows that these conclusions may not always hold when firms face a mature market in which some consumers hold old products before the selling season. Clearly, a mature market environment is more favorable than a completely new one. Many companies, such as BMW, Ford, and Audi, are implementing recycling, refurbishing, and remanufacturing programs in such situations. Therefore, it is necessary and meaningful to study how remanufacturing operations affect firms' decisions and profitability.

From our theoretical analyses, the results show that the firm cannot benefit from remanufacturing operations in an integrated case (i.e., a centralized case) if the production cost and the proportion of non-holders in the market are both low. In this case, the demand for remanufactured products is low and the cannibalization problem due to the remanufacturing operations is very fierce. However, in a separated case (i.e., a decentralized case), the supplier can also benefit from the manufacturer's remanufacturing operations when the production cost is high. In this case, the cost advantage of remanufactured products is enhanced, and the manufacturer prefers to recycle more used products. This can stimulate consumers who have old products to upgrade for new ones and indirectly increase the manufacturer's procurement of core components. As a result, it increases the supplier's profit. These outcomes imply that firms should pay more attention to the market environment and their production costs. They should invest in market surveys and gather crucial information about the demand market and consumer segmentation before establishing remanufacturing operations.

7. Conclusions

In this paper, we considered a supply chain consisting of a supplier and a manufacturer. The supplier provides core components to the manufacturer, and the manufacturer decides whether to undertake remanufacturing. More importantly, the manufacturer faces a mature market in which some consumers possess old products before the selling season. During remanufacturing operations, the manufacturer collects used products from the holders and sells them together with new products to the non-holders in the market after refurbishing and remanufacturing. By theoretical modeling and analyses, we obtain some interesting results.

First, in the integrated case, in which the manufacturer implements remanufacturing together with manufacturing, the results show that remanufacturing operations may hurt the manufacturer. In particular, when both the production cost and the fraction of non-holders in the market are low, remanufacturing operations are detrimental to the manufacturer. This is because the demand for remanufactured products is low when the fraction of non-holders in the market is small, and the cannibalization problem between new products and remanufactured products becomes fiercer when the production cost is low. Therefore, firms that are going to perform remanufacturing should conduct surveys to apprehend the details and information about market segmentation. Otherwise, the act of remanufacturing will result in a negative impact on their production operations. Second, in the separated case, in which an upstream supplier sells core components to the downstream manufacturer, we show that the manufacturer's remanufacturing operations will be beneficial to the supplier. In particular, the supplier obtains a higher profit from the manufacturer's remanufacturing operations when the production cost is high. The rationale is that the manufacturer prefers to collect more used products from consumers to reduce the total production cost when this cost is high. This action induces more holders in the market to upgrade their used products and purchase new products again. Consequently, the demand for core components increases, and so does the supplier's profit.

Our research complements existing works related to remanufacturing and also provides some novel managerial insights. Our study also offers some directions for further investigation in the future. First, we consider a case in which a manufacturer conducts remanufacturing. In the future, we can consider other cases in which a third-party remanufacturer or a supplier undertakes remanufacturing. Second, we do not consider the innovation of new products. In reality, firms always invest in and must decide on product innovation when facing a mature market. Last but not least, the selection of reverse channel mode should be incorporated into the current theoretical model.

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