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Remanufacturing Mode Selection

-- Profitability and Environmental Implications

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Abstract

Three kinds of decision models for closed supply chain (CLSC) with remanufactured products are developd in this paper, including the centralized sales (Model C), the original equipment manufacturer (OEM) sales (Model M), and the Third-party remanufacturer (TPR) sales (Model R). We obtain equilibrium optimal solutions under three models, including the price and quantity of new and remanufactured products, the profit of each participant in the Closed-loop supply chain (CLSC), and environmental impact. By comparing the optimal solutions for the different models, we find some conclusions about the economic performance of the involved parties. Specifically, Model M dominates Model R in terms of the profits of the manufacturer and the profits of the whole supply chain; Model R dominates Model M in terms of TPR's profit when the consumer value discount for the remanufactured product is lower, otherwise Model M dominates Model R. In addition, we also draw some interesting conclusions about environmental performance, that is, when the cost of remanufacturing is lower, the environmental performance of the centralized Model C is better than the other two Models, otherwise the environmental performance of the Model R is the best.

Keywords

Closed-loop Supply Chain; Remanufacturing; Third-party Remanufacturer; Environment Impact.

1. Introduction

Compelled by environmental pollution and resource shortage, green legislations and financial instruments (e.g., greentaxation and subsidies) hold original equipment manufacturers (OEMs) to be more responsible for their operations[1]. Remanufacturing, which can play a central role in these environmentally conscious industrial efforts, has become globally popular within a variety of industries[2]. Remanufacturing operations involve taking end-of-life (EOL) products, bringing them back to as-new condition, and selling them agai n, often with the same warranty as a new product[3][4]. The restoring or recovering process tends to be energy-saving, less material-consuming, and often has a lower impact on environment than manufacturing brand-new products from virgin materials[5]. Remanufacturing offers some very appealing potentials: enabling positive environmental outcomes while simultaneously increasing firm profits by extracting value from used items[6]. Many OEMs who actively carry out remanufacturing operations have achieved satisfying results. For example, Caterpillar established a remanufacturing division which had over a business volume of $2 billion in 2007 [7]. Xerox saved 40–65% manufacturing costs through its green remanufacturing program[8].

In practice, most remanufacturing operations are performed by Third-party remanufacturers (TPRs) [9]. However, two different options exist for OEMs: outsourcing and authorization remanufacturing remanufacturing. In the outsourcing remanufacturing operations model, a

TPR only performs the remanufacturing operations, and the marketing of the remanufactured products is still performed by the OEM itself. In the US and Europe, many OEMs prefer to outsource remanufacturing operations [10]. These OEMs not only outsource new product manufacturing but also their remanufacturing operations to outside contractors. For example, Land Rover and Caterpillar signed an agreement where Caterpillar Remanufacturing Services will act as Land Rover’s lead global remanufacturing services provider[11]. In contrast, authorization remanufacturing refers to the practice in which a TPR acquires the proprietary rights from the OEMs to remanufacture EOL products and resell the remanufactured products without the involvement of the OEM. Such practice has gained momentum in some developing countries in recent years because there is increasing awareness of remanufacturing’s potential benefits [12]. For example, in 2010, China’s National Development and Reform Commission (CNDRC) announced that Chinese government would pay special attention to the development of remanufacturing industry[13]. As of 2013, twenty-eight remanufacturers had been approved by CNDRC with majority of them being 3PRs, and most of them conduct their business with the authorization remanufacturing approach [14]. In 2015, Apple signed an agreement with Foxconn in which the latter acquires the proprietary rights to remanufacture the EOL iPhone mobile phones and remarket them in the Chinese market[15] However, it is unclear that which of the two remanufacturing modes (outsource and authorization) is a better choice. Our literature search revealed that extant research has not compared these two approaches and provided meaningful guidelines on how to select the most appropriate remanufacturing mode.

Drawing on existing results, our work provides three Models to analyze the CLSC with remanufactured products. Our model and results provide new insights for better understanding and management the CLSC with remanufactured products. We summarize our main contributions as follows: (1)In terms of economic performance, we investigate how remanufacturing strategy has on impact on firms' profit in three Models, including Model C, Model M, and Model R. Meanwhile, we provide the optimal strategy for the OEM, the TPR, and the CLSC system. (2) We analyze the environmental performance in these CLSC Models with remanufactured products. We find that the environmental performance of the centralized Model C is better than the other two Models when the cost of remanufacturing is lower, otherwise the environmental performance of the Model R is the best.

The rest of this paper is organized as follows. After reviewing relevant literature in Section 2, we introduce three remanufacturing models in Section 3. Section 4 solves the equilibrium in these two models. Section 5 presents a comparison of equilibrium results, the consumer surplus, the social welfare, and environmental impact between the two remanufacturing modes. Additional numerical experiments are presented in Section 6, which is followed by the conclusion and implications in Section 7.

2. Related Literature

We limit our review to the literature closely related to the topic of interest. Firstly, the literature of channel selection is pertinent to our study. Existing research of channel selection mainly focuses on the impacts of different marketing channels or operation channels on supply chain members’ operations or profifits. Some studies have investigated the channel selection issue in the remanufacturing area. For example, Savaskan et al. [8]compared three options of collecting EOL products and found that the retailer is the most effective undertaker of EOL product collection operations. Savaskan and Van Wassenhove[16]later verified that such result is still valid when retailers compete on prices. Recently, Yan et al.[17]studied two options to market remanufactured products: marketing through the company’s own e-channel or subcontracting the marketing operation to a third party. They found that both the OEM and the retailer prefer subcontracting to a third party although marketing through its own e-channel has less

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environment impacts. In our paper, we also compare these two marketing options. However, the key difference between our study and their research is that in Yan et al.'s[17]study, it is the OEM who carries out the remanufacturing operation, but in our study it is a third party who performs this operation. The scenario in our study is a more common arrangement in practice, and we therefore believe our study has wider implications to practices.

In addition, two other remanufacturing research streams are also relevant to our study. One is about outsourcing remanufacturing operations. Savaskan et al. [8]found that outsourcing the EOL product collection process to a retailer is more effective than doing it by the OEM itself or a third party. Ordoobadi[18]presented a multi-phased decision model for strategic analysis of outsourcing remanufacturing operation in which a comprehensive tool for effective decision making by considering both economic and strategic factors. Karakayali et al. [10] considered two dencentralized collection and remanufacturing modes – remanufacturer-driven channel and collector-driven channel, and identifified situations in which each mode will be the best option for the OEM. Ferguson and Souza [7]pointed out that because many OEMs lack the infrastructure and expertise to collect and remanufacture EOL units in a profifitable manner, and thus they would outsource the remanufacturing to outside contractors. Ferrer and Whybark[19]described several tradeoffs between conducting remanufacturing within an OEM's own plants or facilities and outsourcing remanufacturing to third parties. Tsai et al. [20]discussed cost savings resulted from the remanufacturing outsourcing decision and concluded that the more the fifirm is uncertain about the costs and the inputs of materials, unit- and batch-level activities, the more it might benefifit from the information of costs transferred by the outsourcing partner [21]. In a scenario where the OEM outsources the recycling operation to a third party, Zhang et al. [22]constructed a dynamic game model and demonstrated that government subsidy to the OEM instead of the third party will improve recovery rate.

The research stream that focuses on authorization remanufacturing operations is also relevant to our study. Hashiguchi[22]analyzed the conflflicts between remanufacturing operations and patent rights protection, and concluded that courts in the US and Japan have not tolerated acts of patent infringement in spite of their resulting recycling effects and positive impact on the environment. Hashiguchi [23] proposed 3PRs who purchase licenses from the OEMs can be immunized from allegations of patent infringement. In most authorization remanufacturing operations, the OEMs charge patent license fees from the 3PRs. Abdulrahman et al. [24]and Peng and Su[25]suggested the OEMs should increase remanufacturing patent license fees to achieve an effificient allocation of excess benefifit from remanufacturing operations. However, Oraiopoulos et al. [26]described another type of authorization remanufacturing which is widely used in the information technology industry in the US: the OEMs charge the patent license fees from the consumers who buy the remanufactured products. An active secondary market not only generates relicensing revenues for the OEMs but also increases the marginal revenue of the new products.

An obvious gap of the above mentioned research is that none of the existing studies compared outsourcing remanufacturing and authorization remanufacturing simultaneously. Such comparison is important to OEMs because it will provide meaningful results to facilitate effective decision making related to how to perform the remanufacturing operations. In addition, we also explore the effect of mode selection on the environmental impact, which are largely overlooked by extant research.

3. Model Assumptions and Notations

As illustrated in Figure 1, we consider three CLSC models: Model C, Model M, and Model R. These models reflect different supply chain settings. In the centralized Model C, the OEM and TPR belong to one integrated firm that is in charge of production and sales of new and old products. In Model M, the OEM outsources the remanufacturing activity to the TPR and pays the TPR outsourcing fee. The OEM is only responsible for the marketing of new and remanufactured products and the new product manufactures. In Model R, both remanufacturing and remarketing operations are authorized to the TPR and the TPR pays licensing fees to the OEM, and the OEM is responsible for new product manufactures and sales. Model C is a theoretical model and acts as a benchmark to evaluate two decentralized models, namely, Model M and Model R. In practice, both Model M and Model R are common. Similar to previous research (e.g.,Xiong et al.[27]; Souza[28]; Atasu et al.[29]), we assume that the new products and remanufactured products coexist in the same market. Table 1 summarizes the key notations in this paper. Next, we present the main assumptions of this study:

Assumption 1.A consumer owns at most one product, whether new or remanufactured, and the total market size is normalized to 1. And Customers are heterogeneous in their willingness to pay v for a new product , which is uniformly distributed on [0, 1].

Assumption 2.Consumer willingness to pay for the remanufactured product is a fraction α(0<=α<=1) of their willingness to pay for the new product.

Assumption 3.A consumer shows no preference between the two different marketing channels.

Based on the above assumptions, we make the following derivation. Given the new product price p_n, the remanufactured product price is p_r, the unit consumption subsidy for consumers who purchase the remanufactured product is s, a consumer makes purchasing decision based on his net utility. The condition for the consumer to buy a new product is that the utility from buying a new product($u_n = v - p_n$) is higher than a remanufactured product ($u_r = \alpha v - p_r + s$), that is $\frac{p_n - p_r + s}{1-\alpha} < v < 1$; If $u_n < u_r$ and $u_r > 0$, that is $\frac{p_r - s}{\alpha} < v < \frac{p_n - p_r + s}{1-\alpha}$, then the consumers will choose to buy refurbished product.

So the demand for the new and remanufactured products can be expressed as follows:

$$q_n = \int_{\frac{p_n - p_r + s}{1-\alpha}}^{1} 1 dv = 1 - \frac{p_n - p_r + s}{1-\alpha}, \tag{1}$$

$$q_r = \int_{\frac{p_r - s}{\alpha}}^{\frac{p_n - p_r + s}{1-\alpha}} 1 dv = \frac{p_n - p_r + s}{1-\alpha} - \frac{p_r - s}{\alpha}. \tag{2}$$

Further,we can derive the inverse demand functions for new and remanufactured products from the demand functions:

$$p_n = 1 - q_n - \alpha q_r, \tag{3}$$

$$p_r = \alpha(1 - q_n - q_r) + s. \tag{4}$$

Assumption 4.In the models,all players have access to the same information.The assumption allows us to control for inefficiencies and risk-sharing issues resulting from information asymmetry[31]

Assumption 5. We use $\frac{1}{2} k q_r^2$ to represent the total collection cost . We borrow this collection cost form from the Closed-loop supply chain literature ,which suggests that achieving larger recovery volumes requires additional effort, due to the fact that collecting from increasingly distant locations becomes more and more expensive.

Assumption 6. In both models,all decisions are considered in a single-period setting.

The single period here can be viewed as the maturity stage of the product's life cycle, in which prices, demand, and recovery rates are stable. Thus, a single period model can be thought of as a slice of an infinite horizon model when the market is stable (Atasu and Souza[30]; Örsdemir et al.[9]). This approach facilitates analytical tractability.

Assumption 7. The unit cost of new product via OEM is cn, while the unit cost of remanufactured product via the OEM or the third party is cr. And the cost of a remanufactured products is lower than the cost of a new products, i.e., cr < cn.

Some parts can be reused in remanufacturing, so the cost of remanufacturing will always be lower than the cost of producing a new product. (Ferguson and Souza[7]).Through the remanufacturing operation, companies can save 40–65% in manufacturing costs (Savaskan et al.[8]).

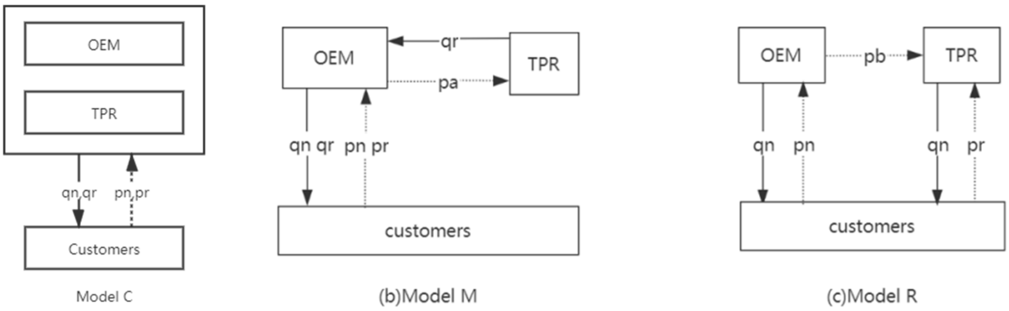

Figure 1. The Three remanufacturing and remarketing Channel Models

4. Model Formulation and Solution

The players in the CLSC system aim to maximize their own total profit by solving their respective optimization problems. In this section, we discuss three models --Model C, Model M and Model R--in which π_t^x stands for the profit for player t under supply chain model x. Superscript x ∈ {C, M, R} denotes Model C, Model M and Model R, respectively, while subscript t ∈ {M, R, S} represents the OEM, the third party remanufacturer, and the supply chain, respectively.

4.1. Model C

The production and sales of new products and used products are all conducted by an integrated firm in the centralized decision model. Thus, both new product output q_n and remanufactured product output q_r are determined by the integrated firm. The optimal problem under Model C can be written as follows:

$$\max_{q_n, q_r} \pi_S^C = (p_n - c_n)q_n + (p_r - c_r)q_r - \frac{1}{2}kq_r^2 \tag{5}$$

We solve this problem to determine the equilibrium solution. Table 1 characterizes the optimal decisions. The optimal profit function is

$$\pi_S^C = \frac{(1-c_n)^2}{4} + \frac{(\alpha c_n - c_r + s)^2}{2(k + 2\alpha - 2\alpha^2)} \tag{6}$$

For clarity, all proofs are provided in the appendix.

Table 1. Notation summary

Symbol	Definition
v	The consumer willingness-to-pay for the new product
α	The consumer value discount for the remanufactured product
k	The scaling parameter of the collection cost
s	The Unit consumption subsidy for consumers who purchase the remanufactured product
c_n/c_r	The Unit manufacturing/remanufacturing cost
p_n/p_r	The Unit sales price of new/remanufactured product
q_n/ q_r	The quantity of a new/remanufactured product
p_o	The piece-rate outsourcing fee
p_s	The piece-rate authorization fee
$\pi_m/\pi_R/\pi_S$	The profit of the OEM/the TPR
i_j	The Per-unit environmental impact parameters,j={p_1,p_2,u_1,u_2} ,where p_1= production impact of new product, p_2=production impact of remanufacture product, u_1=use impact of new product, u_2=use impact of remanufacture product.
$E^C/E^M/E^R$	The total environmental impact in Model C/M/R

4.2. Model M

In Model M, the remanufacturing activity is outsourced to the TPR. At the same time, OEM pays outsourcing fee to the TPR. Then the OEM markets new and remanufactured products simultaneously. The game between the OEM and the TPR is Stackelberg. The OEM is the leader of Stackelberg, and the TPR is the follower. The decision sequence of the event is: first, the OEM determines the new product output qn and the outsourcing fee pa. And then the TPR determines the quantity of old products to be recovered qr according to the OEM's decision. The OEM's problem and the 3PR's problem are as follows respectively,

$$\begin{cases} \max\limits_{q_n, p_a} \Pi_M^M = (p_n - c_n)q_n + (p_r - p_a)q_r \\ \max\limits_{q_r} \Pi_R^M = (p_a - c_r)q_r - \frac{1}{2}kq_r^{\ 2} \end{cases} \tag{7}$$

In this problem, the OEM first makes a decision on the new product output q_n and the outsourcing cost p_a, and 3PR makes a decision on the waste product recycling amount q_r based on the new product output. According to the two-stage Stackelberg reverse order solution, the optimal decision of OEM and 3PR can be obtained. Substituting them into equation (3)and(4) can obtain the optimal price as shown in Table 1. The optimal profit function is

$$\pi_M^M = \frac{(1-c_n)^2}{4} + \frac{(\alpha c_n - c_r + s)^2}{4(k+\alpha-\alpha^2)} \tag{8}$$

$$\pi_R^{M*} = \frac{k(\alpha cn - cr + s)^2}{8(k+\alpha-\alpha^2)^2} \tag{9}$$

4.3. Model R

In Model R, both remanufacturing and remarketing operations are authorized to the TPR and the TPR pays licensing fees to the OEM. On the one hand, the OEM and the TPR are partners, because the OEM charges the TPR an authorization fee and the TPR benefits from remanufacturing operations. On the other hand, they are also competitors, because the TPR's remanufactured products potentially cannibalize the sales of the OEM's new products. Therefore, the OEM will charge appropriate licensing fees to maximize its profit. Similar to Model M, in Model R, the OEM is the leader of Stackelberg and the TPR is the follower. The decision sequence of the event is: first, the OEM decides the quantity of new product production qn and the authorization fee pb. Then the TPR decides the quantity of old products to be recovered based on qn and pb. The OEM’s problem and the 3PR’s problem are as follows respectively,

$$\begin{cases} \max\limits_{q_n, p_b} \Pi_M^R = (p_n - c_n)q_n + p_b q_r \\ \max\limits_{q_r} \Pi_R^R = (p_r - c_r - p_b)q_r - \frac{1}{2}kq_r^2 \end{cases} \tag{10}$$

Similar to subsection 4.2, we solve the game with backward induction. The Table 2 characterizes the equilibrium decisions. And the optimal profit function is as follows

$$\pi_M^R = \frac{(1-c_n)^2}{4} + \frac{(\alpha c_n - c_r + s)^2}{4(k + 2\alpha - \alpha^2)} \tag{11}$$

$$\pi_R^R = \frac{(2\alpha + k)(\alpha cn - cr + s)^2}{8(k + 2\alpha - \alpha^2)^2} \tag{12}$$

Table 2. The equilibrium optimal solutions under three models

Model	C	M	R
qn	$\frac{(k+2\alpha-2\alpha^2)-(2\alpha+k)cn+2\alpha cr-2\alpha s}{2(k+2\alpha-2\alpha^2)}$	$\frac{(k+\alpha-\alpha^2)-(\alpha+k)cn+\alpha cr-\alpha s}{2(k+\alpha-\alpha^2)}$	$\frac{(k+2\alpha-\alpha^2)-(2\alpha+k)cn+\alpha cr-\alpha s}{2(k+2\alpha-\alpha^2)}$
qr	$\frac{\alpha cn-cr+s}{k+2\alpha-2\alpha^2}$	$\frac{\alpha cn-cr+s}{2(k+\alpha-\alpha^2)}$	$\frac{\alpha cn-cr+s}{2(k+2\alpha-\alpha^2)}$
pn	$\frac{1+cn}{2}$	$\frac{1+cn}{2}$	$\frac{1+cn}{2}$
pr	$\frac{\alpha(k+2\alpha-2\alpha^2)+\alpha kcn+2\alpha(1-\alpha)cr+2(k+\alpha-\alpha^2)s}{2(k+2\alpha-2\alpha^2)}$	$\frac{\alpha(k+\alpha-\alpha^2)+\alpha kcn+\alpha(1-\alpha)cr+(2k+\alpha-\alpha^2)s}{2(k+\alpha-\alpha^2)}$	$\frac{\alpha(k+2\alpha-\alpha^2)+\alpha(\alpha+k)cn+\alpha(1-\alpha)cr+(2k+3\alpha-\alpha^2)s}{2(k+2\alpha-\alpha^2)}$
pa	N/A	$\frac{\alpha kcn+(2\alpha+k-2\alpha^2)cr+ks}{2(k+\alpha-\alpha^2)}$	N/A
pb	N/A	N/A	$\frac{\alpha-cr+s}{2}$
t	$\frac{2(\alpha cn-cr+s)}{(k+2\alpha-2\alpha^2)-(2\alpha+k)c_n+2\alpha cr-2\alpha s}$	$\frac{\alpha cn-cr+s}{(k+\alpha-\alpha^2)-(\alpha+k)cn+\alpha cr-\alpha s}$	$\frac{\alpha cn-cr+s}{(k+2\alpha-\alpha^2)-(2\alpha+k)cn+\alpha cr-\alpha s}$

Proposition 1. 1)Whether in the centralized mode or the two decentralized modes, the higher the α, lower q_n^*, i.e.,$\frac{\partial q_n^*}{\partial \alpha} < 0$;

2)In centralized mode (Model C), when $c_n > c_{n1}$, q_r^* is an increasing function of α, otherwise it is a decreasing function;In the outsourcing mode (Model M), when $c_n > c_{n2}$, q_r^* is an increasing function of α, otherwise it is a decreasing function;In the authorization mode (Model R), when $c_n > c_{n3}$, q_r^* is the increasing function of α, otherwise it is decreasing function. where $c_{n1} = \frac{2(2\alpha - 1)(c_r - s)}{k + 2\alpha^2}$, $c_{n2} = \frac{(2\alpha - 1)(c_r - s)}{k + \alpha^2}$ and $c_{n3} = \frac{2(\alpha - 1)(c_r - s)}{k + \alpha^2}$.

Proposition 1 shows that, no matter what kind of remanufacturing mode, the higher consumers value the remanufactured products, the lower the output of new products. The reason is that when two types of products are simultaneously sold in the market, remanufactured products gain greater competitiveness due to cost savings and higher consumer value evaluation, which squeezes the output of new products. And the higher the willingness of consumers to pay for remanufactured products, the higher the degree of squeezing of new products and therefore the lower the output.

Regardless of which remanufacturing mode the OEM adopts, the output of remanufactured products is related to consumers' valuation of remanufactured products and the production cost of new products. In particular, when the production cost of the new product is lower than the threshold, the output of the remanufactured product is a decreasing function of α; and when the production cost of the new product is higher than the threshold, it is an increasing function of α.

5. Comparisons of Different Models

In this part, we compare the equilibrium decisions and profits of the three models based on Section 4, and then we analyze the environmental impacts.

5.1. Comparison of Equilibrium Decisions and Profits

Proposition 2. The comparison results of equilibrium prices of new and remanufactured products are as follows: $p_{\rm n}^{C*} = p_n^{M*} = p_n^{R*}$, $p_r^{C*} < p_r^{M*} < p_r^{R*}$.

In Model M, the OEM can control the quantity of remanufactured product through outsourcing fee. In Model R, the OEM charges license fee from the 3PR to adjust the quantity of remanufactured product. Therefore, the OEM sustains a dominant position in both models, enabling it to maintain the retail price of new product unchanged. Moreover, the price of new product will be the same as that in the centralized system Model C. In Model R, the OEM and the TPR sell the new product and the remanufactured product to consumers respectively, so they compete with each other. Therefore, the price of remanufactured product in Model R is higher than that in Model O.

Proposition 3. The comparison results of equilibrium quantities of new and remanufactured products are as follows: $q_{\rm n}^{C*} < q_n^{M*} < q_n^{R*}$, $q_r^{C*} > q_r^{M*} > q_r^{R*}$.

Proposition 3 shows that compared with the two decentralized models, model C, the centralized system

produces more remanufactured products, but produces fewer new products. In addition, we find that the TPR produces more remanufactured products in Model M than Model R; Compared to Model M, the OEM produces more new products in Model R. That's because in the decentralized supply chain, the profit of a TPR is essentially derived from remanufacturing

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operations, while the OEM is the leader in the Stackelberg game and the TPR is the follower, which results in more production of new products in the decentralized supply chain model than centralized supply chains, and less production of remanufactured products. Next we compare two decentralized supply chain models: Model M and Model R. In Model M, the OEM and the TPR do not compete with each other to sell the product, but in Model R, they do compete with each other. In the presence of competition, the OEM increases the quantity of new product to reduce the market of remanufactured product. Because the quantity of new product in Model R is larger than that in Model M, quantity increase of new products in Model R poses a threat to remanufactured product sales. In addition, the OEM strategically sets license fee to control the quantity of remanufactured product by the TPR. Therefore, the TPR produces less product in Model R than in Model M.

Proposition 4. For OEMs, the profit under the outsourcing model is always higher than the patent licensing model, i.e., $\pi_M^M > \pi_M^R$. When α is less than the threshold α_0, TPR prefers the patent authorization model; otherwise, TPR prefers the outsourcing model. i.e., if $\alpha<\alpha_0$, $\pi_R^M < \pi_R^R$; otherwise $\pi_R^M \geq \pi_R^R$, where $\alpha_0 \in (0.5,1)$ and α_0 is the unique solution to the equation $2\alpha(1-\alpha)^2 + k(1-2\alpha) = 0$.

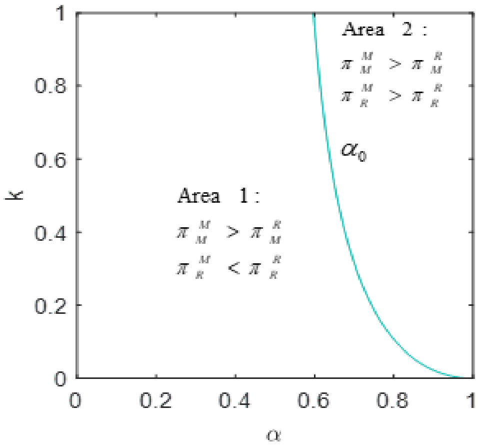

Figure 2. Supply chain model selection

It can be seen from Proposition 4 that the OEM's remanufacturing mode selection has nothing to do with consumers' valuation of remanufactured products, and it can always get more profit under the outsourcing model. This is because under the outsourcing remanufacturing model, the OEM only outsources the remanufacturing of the product to the TPR, and re-sells the manufactured product by itself; but under the authorized remanufacturing model, the OEM will give the TPR the right to sell the manufactured product. Therefore, under Model M, OEMs have greater control over the remanufacturing market, and therefore can obtain higher profits. For TPR, when consumers have a lower valuation of remanufactured products, the profit of remanufactured products is thinner, so OEMs charge lower patent fees for remanufactured products. At this time, the TPR adopts the patent authorization model Higher profits; When consumers have higher valuations of remanufactured products, the profit of remanufactured products becomes considerable. Therefore, OEMs will increase the patent fees of remanufactured products. At this time, TPR adopts the outsourcing remanufacturing model for higher profits.

Proposition 5. The profit of the supply chain under the centralized model is always higher than that of the decentralized model; and the profit of the supply chain under the outsourcing model is always higher than that of the patent authorization model. i.e., $\pi_S^C > \pi_S^M > \pi_S^R$.

From Proposition 5, it is clear that for economic performance, the centralized system C model performs better than the other two decentralized systems in terms of supply chain profit. As for the two decentralized models, OEM as the leader of the supply chain, its profit under the patent licensing model is always inferior to that of the outsourcing model. Although TPR has different model preferences under different conditions, its profit is far less than that of OEM, therefore its influence is very small. Then it is concluded that the profit of the supply chain under the outsourcing model is higher than that of the authorized model.

For economic performance, it is obvious that Model C, the centralized system, performs better than the other two decentralized systems in terms of the supply chain's profit. As for the two decentralized models, the OEM has the power to control the retail price of new and remanufactured products, which helps improve his profit. Therefore, the profit gained by the OEM under Model M is more than that under Model R. For similar reasons, the supply chain is better off in Model M than in Model R.

We see that the OEM having power over the remarketing of remanufacturing rather than the TPR plays a more important role in the supply chain to improve profits. Furthermore, we evaluate the decentralized supply chain's efficiency by the ratio of profits between the integrated supply chain and the decentralized supply chain (Perakis and Roels 2007). The results are shown in the following corollary.

Proposition 6. The efficiency of the decentralized models are shown as follow. We can see from the following two formulas that the proportional expression is very complicated. Therefore, we conduct numeracal experiments to show the supply chain's efficiency under decentralized models in Table 3. The result shows that Model M is more efficient than Model R,which is consistent with the system's comparing result in proposition 5 .

$$\frac{\pi_S^C}{\pi_S^M}=\frac{\frac{(1-c_n)^2}{4}+\frac{(\alpha c_n-c_r+s)^2}{2(k+2\alpha-2\alpha^2)}}{\frac{(1-c_n)^2}{4}+\frac{(\alpha c_n-c_r+s)^2}{4(k+\alpha-\alpha^2)}+\frac{k(\alpha c_n-c_r+s)^2}{8(k+\alpha-\alpha^2)^2}} \tag{13}$$

$$\frac{\pi_S^C}{\pi_S^R}=\frac{\frac{(1-c_n)^2}{4}+\frac{(\alpha c_n-c_r+s)^2}{2(k+2\alpha-2\alpha^2)}}{\frac{(1-c_n)^2}{4}+\frac{(\alpha c_n-c_r+s)^2}{4(k+2\alpha-\alpha^2)}+\frac{(2\alpha+k)(\alpha c_n-c_r+s)^2}{8(k+2\alpha-\alpha^2)^2}} \tag{14}$$

Table 3. Numerical example of performance of the decentralized models (cn=0.8;cr=0.4;k=3;s=0.5)

α	π_S^C	π_S^M	π_S^R	π_S^C/π_S^M	π_S^C/π_S^R
0.4	0.0353	0.0299	0.0284	1.1816	1.2428
0.5	0.0457	0.0381	0.0356	1.1996	1.2857
0.6	0.0583	0.0480	0.0439	1.2159	1.3294
0.7	0.0737	0.0598	0.0535	1.2326	1.3767
0.8	0.0925	0.0739	0.0646	1.2515	1.4303

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Following Raz et al. (2013), we consider environmental impacts of manufacturing stage and use stage. Similar to previous research (e.g. Raz et al., 2013; Atasu and Souza, 2013; Orsdemir et al., 2014), we denote the environmental impacts of manufacturing stage and use stage as i_j, which reprensent the per-unit environmental impact parameters, j={p_1,p_2,u_1,u_2,} ,where p_1= production impact of new product, p_2=production impact of remanufactured product, u_1=use impact of new product, u_2=use impact of remanufactured product. Therefore, the environmental impacts can be written as follows: $E=\left(i_{p1}+i_{u1}\right)q_n+\left(i_{p2}+i_{u2}\right)q_r$. According to empirical evidence (e.g., Hauser and Lund, 2003), it is almost always the case that less energy and raw material are consumed to produce a remanufactured product than producing a new product because some parts and components can be reused. As a result, carbon emission is less for producing remanufactured product. Thus, we assume $i_{p1}>i_{p2}$. We denote environmental impact as E* in Model *, where superscript *∈{C,M,R}; The following proposition characterizes the environmental impacts in the three models.

In this part, we compare the equilibrium decisions and profits of the three models based on Section 4, and then we analyze the resulting consumer surplus and social welfare. Finally, we discuss the environmental impacts.

5.2. Comparison of Environmental Impacts

Proposition 7. The environmental impacts in Model O and Model R are given by, respectively. The environmental impacts in Model C, Model O and Model R satisfy following relationships: If $\frac{i_{p2}+i_{u2}}{i_{p1}+i_{u1}}>\alpha$, then $E^C>E^M>E^R$, and vice versa.

$$E^C=\left(i_{p1}+i_{u1}\right)\frac{k+2\alpha-2\alpha^2-(2\alpha+k)cn+2\alpha cr-2\alpha s}{2\left(k+2\alpha-2\alpha^2\right)}+\left(i_{p2}+i_{u2}\right)\frac{\alpha cn-cr+s}{k+2\alpha-2\alpha^2} \tag{15}$$

$$E^M=\left(i_{p1}+i_{u1}\right)\frac{k+\alpha-\alpha^2-(\alpha+k)cn+\alpha cr}{2\left(k+\alpha-\alpha^2\right)}+\left(i_{p2}+i_{u2}\right)\frac{\alpha cn-cr+s}{2\left(k+\alpha-\alpha^2\right)}, \tag{16}$$

$$E^R=\left(i_{p1}+i_{u1}\right)\frac{k+2\alpha-\alpha^2-(2\alpha+k)cn+\alpha cr-\alpha s}{2\left(k+2\alpha-\alpha^2\right)}+\left(i_{p2}+i_{u2}\right)\frac{\alpha cn-cr+s}{2\left(k+2\alpha-\alpha^2\right)}. \tag{17}$$

Environmental impact is not only related to the quantity of remanufactured product but also related to the quantity of new product. When the acceptance of remanufactured product is relatively low, the OEM supplies less new products in Model R than that in Model M and the two decentralized models supplies less new products than the centralized model, but the difference in quantities of remanufactured product is small. Therefore, Model R is more environmentally friendly than Model M and the two decentralized models is more environmentally friendly than Model C.

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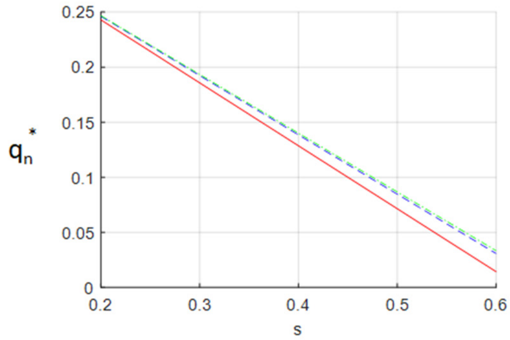
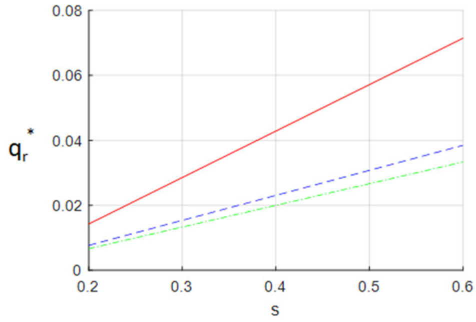
6. Numerical Analysis

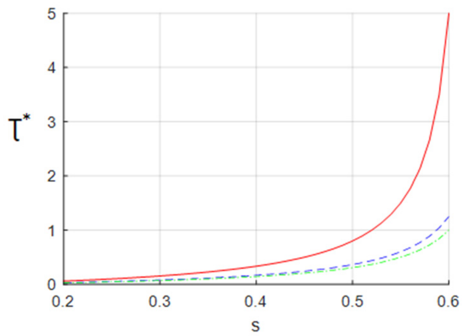
In this section, we conduct several numerical studies to complement aforementioned analysis.



(a)



(b)



(c)

Figure 3. Comparisons of q_n^*, q_r^* and τ^* under the three CLSC models

Figure 3 illustrates the comparison results of qn,qr in Corollary 5 when cn=0.3; cr=0.2; k=3; alpha=0.5. In order to ensure the quantity of new and remanufactured product to be positive and the return rate to be less than 1, we take the values s∈[0.2,0.6]. Under the three CLSC models, As s increases, sales of new products decrease and sales of remanufactured products increase. In addition, for the sales volume of new products, model C is lower than model M, and model M is lower than model R; for the sales volume of remanufactured products, the opposite is true. (as shown in Figure 3(a) and (b)), which is also consistent with Corollary 4. Additionally, Figure 3(c) shows the comparison of the return rate $\tau^* = q_r^*/q_n^*$. We observe that the return rate under the C model does exceed the other two models. An increase in s can improve the return rate.

In addition, we compare π_M^*, π_R^* and π_S^* in Corollary 5 through numerical examples in Figure 4 where cn=0.3; cr=0.2; k=3; s=0.5. The results of numerical examples are consistent with Corollary 5. Besides, in Figure 4, we find that an increase in α can improve the profits of the manufacturer and the CLSC system's profit. We also compare E^C, E^M and E^R in corollary 7 through numerical examples in Figure 5 where cn=0.3; cr=0.2; k=3; s=0.5. The results of numerical examples are consistent with Corollary 7. And we found that with the increase of i_{p2}, the environmental impact of the three models showed an upward trend, which is in line with common sense.

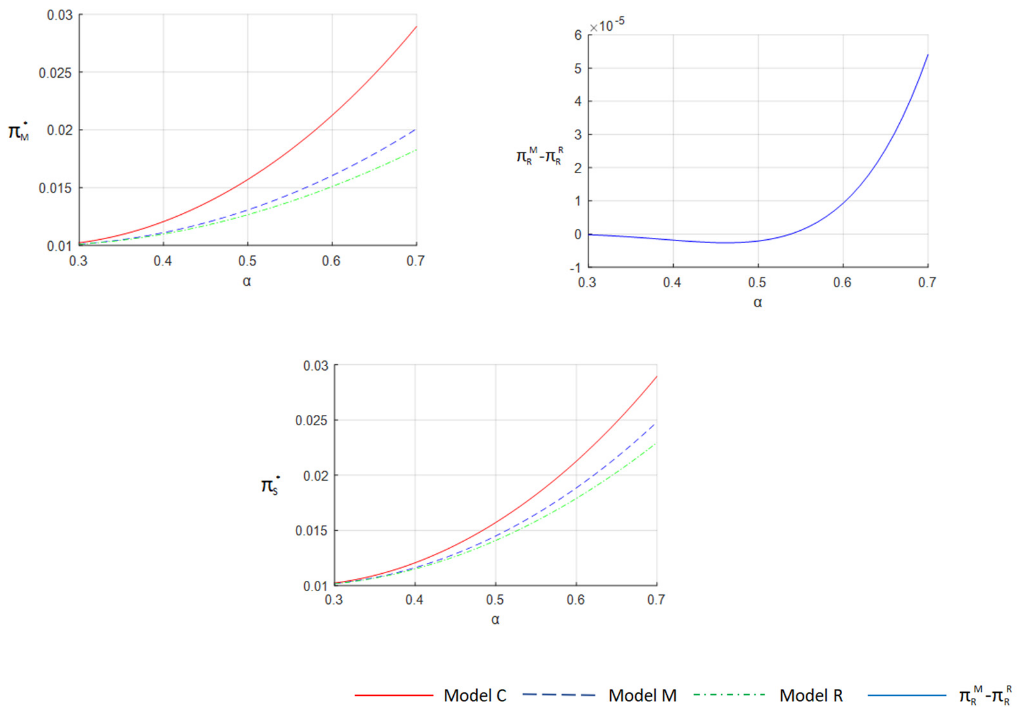


Figure 4. Comparisons of π_M^*, π_R^* and π_S^* under the three CLSC models

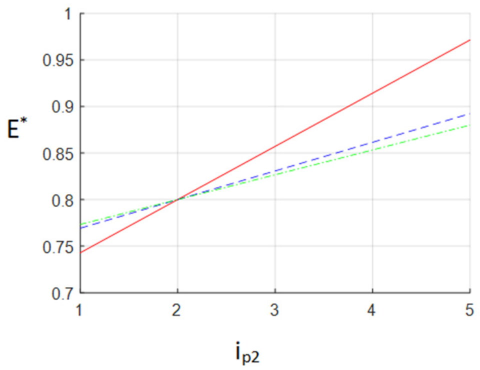


Figure 5. Comparisons of E^C, E^M and E^R under the three CLSC models

7. Conclusion

Three forms of Closed-loop supply chain models with remanufactured products are developed in this paper, including the centralized sales(Model C), the OEM sales(Model M), and TPR sales(Model R). We provide the optimal solutions for each remanufacturing strategy of the three models. Furthermore, we analyze the advantages and disadvantages in the perspectives of economic and environmental performance.

We obtain a number of general results for the three CLSC models, summarized as follows: (1) We identify the optimal solutions of the three CLSC models. (2) We compared the quantity of new products and remanufactured products in the three models, and find that the quantity of new products in the centralized model C is always smaller than that of the decentralized model, and in the decentralized model, the quantity of new products in the model M is always smaller than that of the model C, for the quantity of remanufactured products, we draw the opposite conclusion.

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Based on these results, we further compare the economic and environmental performance under the three CLSC models with remanufactured and draw a few interesting conclusions. On one hand, in terms of economic performance, (1) Model C is superior to the other two decentralized models for the supply chain, (2) For the two decentralized models, the OEM can obtain more profits under Model M than under Model R. (3) In terms of profits obtained by the TPR, We find that when a is less than the threshold a_0, TPR can obtain a higher profit under model R than under model M. Otherwise, TPR will obtain a higher profit under model M, on the other hand , in terms of environmental performance, in the case of low remanufacturing production costs, the centralized model is superior to the decentralized model, and in the decentralized model, the model M is superior to the model R, vice versa.

Based on the consumer's willingness to pay, this paper first establishes the product demand functions, and then analyzes the players' equilibrium optimal solutions under the three typical CLSC models with remanufactured products. A natural extension of this paper is to consider the product upgrade, because product upgrade as a marketing strategy will affect the demand function and may lead to more effective strategies together with remanufacturing. Moreover, it is interesting to extend our models to allow dual channels. It would be interesting to study how such a supply chain structure will affect the optimal strategy when the remanufactured product exists.

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