PRICING AND REMANUFACTURING DECISIONS FOR TWO
SUBSTITUTABLE PRODUCTS WITH A COMMON RETAILER

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Abstract. This paper studies pricing and remanufacturing decisions for two
substitutable products in a supply chain with two manufacturers and one com-
mon retailer. The two manufacturers produce two substitutable products and
sell them to the retailer. Specifically, the first manufacturer is a traditional
manufacturer who produces the new product directly from raw material, while
the second manufacturer has incorporated a remanufacturing process for used
product into his original production system, so that he can manufacture a
new product directly from raw material, or remanufacture part or whole of a
returned unit into a new product. We establish seven game models by con-
sidering the chain members’ horizontal and vertical competitions, and obtain
the corresponding closed-form expressions for equilibrium solution. Then, the
equilibrium characteristics with respect to the second manufacturer’s remanu-
facturing decision and all channel members’ pricing decisions are explored, the
sensitivity analysis of equilibrium solution is conducted for some model param-
eters, and the maximal profits and equilibrium solutions obtained in different
game models are compared by numerical analyses. Based on these results, some
interesting and valuable economic and managerial insights are established.

1. Introduction. Over the last few years, the rapid development of high technol-
gy and corporations’ internationalization has led to higher production efficiency,
shorter product life-cycle. Firms are facing unprecedented challenges to meet the

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increasingly higher standards on consumption personalization and demand diversity, and accompanying rapid price depreciation and intense price competition of products. More and more manufacturers have increased product variety by differentiating one or several attributes of the product (such as technical attributes, appearance, or color, etc.) in order to compete for market share and profit gain. To end consumers, some of these products maybe substitutable because of their functional similarities. For example, the print cartridges made by Xerox and/or Canon, the copiers made by Agfa and/or Xerox, the Personal Computers and Printers made by Hewlett Packard Corporation and/or Lenovo, and the operating systems Mac and Windows made by Apple and Microsoft respectively.

The industrialization and the population growth has increasingly burdened the environment. The consumer awareness, oversight from non-governmental organizations, and legislative pressures have encouraged manufacturers to produce green and eco-friendly products, and thus, more and more manufacturers now set up a program for collection and remanufacturing of used products from customers. Remanufacturing is the industrial process in which used, end of life products are restored to like-new conditions and put back into the distribution system like the “new products”. In some industries, equipment manufacturers manage the product collection process in parallel with the distribution of new products. For instance, Xerox has been a leader in reusing their high-value, end-of-lease copiers in the manufacturing of new copiers that meet the same strict quality standards [13]. Similar activities are undertaken by Hewlett Packard Corporation for computers and peripherals, and by Canon for print and copy cartridges. Remanufacturing process may offer companies a unique opportunity to improve their profits on one hand and to serve social responsibility on the other hand. In 1996, Ford avoided disposal of more than 67,700 pounds of toner cartridges, and saved $180,000 in disposal costs, and Ford collected more than 332,000 pounds of toner cartridges for remanufacturing and saved $1.2 million from 1991 to 1997 [8]. According to a recent report by Global Industry Analysts (2010), global automotive manufacturing is growing, and by 2015, it is forecasted to reach US $104.8 billion. There are a growing number of research papers on remanufacturing. For example, Hong et al. [4] considered a closed-loop supply chain with remanufacturing under hybrid dual-channel collection. Sun et al. [15] studied a multiperiod acquisition pricing and remanufacturing decision problem under random price-sensitive return. Choi et al. [3] considered a closed-loop supply chain with a retailer, a collector, and a manufacturer, and examined the performance of different closed-loop supply chain under different channel leadership. Li et al. [6] established some insights into the acquisition management and production planning of a hybrid manufacturing/remanufacturing system.

Differing from those of prior studies on remanufacturing, this paper focuses on price competition and remanufacturing decision for two substitutable products in the most common channel type: duopoly manufacturers and monopoly common retailer. The two manufacturers produce two differential but substitutable products and sell them to the common retailer. Specifically, one manufacturer is a traditional manufacturer that produces a new product directly from raw material, while the other manufacturer has incorporated the remanufacturing process for used product into his original production system, so that he can manufacture a new substitutable product directly from raw material, or remanufacture part or whole of a returned unit into the new substitutable product. The first manufacturer determines the wholesale price to the retailer, the second manufacturer determines the wholesale
price to the retailer and his remanufacturing effort, and the common retailer determines the retail prices of two substitutable products to the market. Many real-world examples fit the scenario considered in this paper. For instance, Amazon.com sells print cartridges and copiers made by different manufacturers (e.g., Xerox, Canon and Hewlett Packard), one of them may have incorporated a remanufacturing process for used product into his original production system (e.g., Xerox).

Based on different market power structures, there may be different competitions not only between the manufacturers and the common retailer but also between the two manufacturers. When the firms implement Bertrand competition, they make their decisions simultaneously. When the firms implement Stackelberg competition, they play make their decisions sequentially. The important issues have arisen in management of such a supply chain of substitutable products, for example, how are the decisions affected by channel members’ different competitions? Whether the industry and each channel member will be better off if one of the two manufacturers adopts the remanufacturing process for used product into the original production system? When the manufacturers implement different competitions, how should the common retailer set the retail price for each product so that her profit is maximized? How should the manufacturers make pricing decision and remanufacturing decision to maximize their own profits facing different channel power structures? How does the channel members’ different competitions affect the remanufacturing decision?

To the best of our knowledge, no research has studied the above mentioned problems in a two-echelon supply chain.

Quite a large number of research have been done about substitutable products [1, 17, 10, 21, 22 etc.). For example, Tang and Yin [16] developed a base model with deterministic demand to examine how a retailer determines the order quantity and the retail prices of two substitutable products jointly under the fixed and variable pricing strategies. Zhao and Atkins [21] considered the competitive newsboy model with price competition and product substitution. Netessine and Rudi [10] obtained optimality conditions for both competitive and centralized versions of the single period multiproduct inventory problem with partial substitution. Pasternack and Drezner [11] considered a centralized two-product inventory model with full substitution. They proved that the total expected profit function is concave and derived the analytical expressions of the optimal inventory levels. Stavrulaki [14] studied a retailer’s inventory policy for two products, which are substitutable and have inventory dependent demand. Choi [2] considered two manufacturers using two common buyers that price-compete with each other. Xia [20] studied competition between two coexisting suppliers in a two-echelon supply chain, where each supplier offers one type of the two substitutable products to multiple buyers.

Our research is most related to that of Choi [1]. Choi [2] analyzed different power structures in a supply chain with two manufacturers selling substitutable products through a common retailer, and developed manufacturer Stackelberg, retailer Stackelberg, and vertical Nash pricing models. The major differences between the study of Choi [1] and our research are as follows: (i) In Choi [2], the manufacturers are two traditional manufacturers that produce the new products directly from raw materials. However, in our paper, one of the two manufacturers has incorporated a remanufacturing process for used product into his original production system, so that he can manufacture a new product directly from raw material, or remanufacture part or whole of a returned unit into a new product. (ii) Choi [1] only considered the Bertrand competition between two manufacturers in manufacturer
Stackelberg and retailer Stackelberg cases. Unlike the study of Choi [1], in our article, we embrace the concepts of sequential commitment at the same stage of a supply chain and attempt to report analytical results in a supply chain with two manufacturers and one retailer. We investigate how the manufacturer, the remanufacturer and the retailer determine their decisions in the presence of different power structures. Especially, this paper extends the work in Choi [1] by considering Stackelberg competition between two manufacturers where the manufacturer’s decision and the remanufacturer’s decision can be set sequentially.

Our main contribution is exploring the chain members’ pricing and remanufacturing decisions facing different power structures by using seven game models. We derive the equilibrium decisions and maximum profits of the chain members and investigate the effect of retail substitutability on the equilibrium decisions and maximum profits of the chain members in these models. Some valuable insights are obtained. For example, we find that, for the two manufacturers, the firm who is the leader does not have the advantage to get the higher profit, whereas the firm who is the follower does have the advantage to get the higher profit. The remanufacturer will employ less remanufacturing approach to produce a new product when he is a leader, although he sells the new product at a higher price. On the contrary, the remanufacturer will employ more remanufacturing approach to produce the new product when he is a follower, although he sells the new product at a lower price. Moreover, the remanufacturer will spend the highest remanufacturing effort when there is no channel leadership among three channel members.

The rest of the paper is organized as follows. Section 2 gives the problem description and notations. Section 3 details our key analytical results. Discussions on comparison and managerial implications are presented in Section 4. Section 5 concludes the article with a summary of the results and some future research directions. Proofs of all propositions appear in Appendices.

2. Problem description. Consider a supply chain with one common retailer and two manufacturers, labeled manufacturer 1 and manufacturer 2. (In the following discussion, “he” represents one of the two manufacturers, and “she” represents the retailer. Moreover, in many instances, we use “manufacturer 2” and “remanufacturer” interchangeably, and we refer to both the manufacturer and the remanufacturer as the “two manufacturers” in other instances.) The two manufacturers produce two substitutable products and sell them to the retailer. Specifically, the manufacturer 1 is a traditional manufacturer who produces a new product (product 1) directly from raw material with unit manufacturing cost \( c_{m1} \), and sells the product 1 to the retailer with unit wholesale price \( w_1 \), while the manufacturer 2 has incorporated a remanufacturing process for used product into his original production system, so that he can manufacture a new product (product 2) directly from raw material with unit manufacturing cost \( c_{m2} \), or remanufacture part or whole of a returned unit into a new product with unit remanufacturing cost \( c_r \), and then sells the product 2 to the retailer with unit wholesale price \( w_2 \). Following Savaskan et al. (2004) and Savaskan and Van Wassenhove (2006), in this paper, we consider product categories in which there is no distinction between a remanufactured and a manufactured product made by the manufacturer 2. There are many examples in the field of remanufacturing, one industrial case is the high-value copiers of Xerox in which the used copiers are collected directly by Xerox as new ones are installed. The Kodak line of single-use cameras is the other case. The monopolistic retailer
then sells the two products to the end consumer with unit retail price $p_i, i = 1, 2$, respectively.

The manufacturer 1 determines the wholesale price $w_1$ for product 1, the manufacturer 2 determines the wholesale price $w_2$ and the remanufacturing effort $\tau$ for product 2. The remanufacturing effort $\tau$, $0 \leq \tau \leq 1$, can be considered the fraction of current generation product 2 supplied from returned and thus remanufactured units, which characterizes the manufacturer 2’s reverse channel performance. Then, the average unit manufacturing cost for product 2 can be expressed as $c_{m2}(1-\tau) + c_r\tau$ or $c_{m2} - \delta\tau$ where $\delta = c_{m2} - c_r > 0$ which denotes the cost-savings from the remanufacturing. We assume that the recycling process incurs a total collection cost, which is characterized as a function of the remanufacturing effort of used products and is given by $\frac{B\tau^2}{2}$, for the manufacturer 2, where $B$ is a scaling parameter (Savaskan et al., 2004; Savaskan and Van Wassenhove, 2006). The common retailer must determine the retail price $p_i$ for product $i$.

We assume that all activities occur in a single period, under a single-period static setting, the (re-)manufacturing system is unconstrained and myopic, that assumes an abundant supply of returned products and does not consider the effect of current pricing decisions on the future profit stream generated by the remanufactured product. We also assume that the channel members are independent, risk-neutral, and they must make their decisions in order to achieve their own maximal profits respectively and behave as if they have complete information of the demands and the cost structures of other channel members.

We suppose that the market demand $D_i$ for product $i$ is a general linear demand function of its own sale price $p_i$ and the substitutable product’s sale price $p_j, i = 1, 2, j = 3 - i$, which is commonly adopted in the literature [1, 2, 5, 7, 17, 19]. The general demand function is given as follows:

$$D_i = a_i - \beta p_i + \gamma p_j, \quad i = 1, 2, j = 3 - i,$$

where the parameter $a_i$ represents the market base of product $i$, the parameter $\beta$ is self-price elastic coefficient and $\gamma$ is the cross-price elastic coefficient, which denote the measure of the responsiveness of each product’s market demand to its own sale price and to its competitive product’s sale price, respectively. We assume parameters $\beta$ and $\gamma$ satisfy $\beta > \gamma > 0$, which means that the demand for a product is more sensitive to the changes in its own sale price than to the changes in the sale price of the other competitive product. This assumption is reasonable in reality.

According to the above description, we can formulate the chain members’ profit functions as follows. The common retailer’s profit function is

$$\pi_r = \sum_{i=1}^{2} [(p_i - w_i)(a_i - \beta p_i + \gamma p_j)].$$

The two manufacturers’ profit functions are

$$\pi_{m1} = (w_1 - c_{m1})(a_1 - \beta p_1 + \gamma p_2),$$

$$\pi_{m2} = (w_2 - c_{m2} + \delta\tau)(a_2 - \beta p_2 + \gamma p_1) - \frac{B\tau^2}{2}.$$  

For the sake of clarity, some notations used in this paper are listed in Appendix A.
3. Analytical results.

3.1. Decision models in MS game. In this subsection, we assume that the two manufacturers act as the Stackelberg leaders and the common retailer acts as the Stackelberg follower. The game-theoretical approach is used to analyze the decision problem. The leader in every decision scenario makes his decision to maximize his profit, conditioned on the follower’s response. The problem is solved backwards. Namely, the decision of the follower is solved first, given that the leader’s decision has been observed. Based on different market power structures, there are different competitions between the two manufacturers, e.g. Bertrand competition and Stackelberg competition. So, we will establish three decision models in this subsection: (i) The decision model when the two manufacturers implement the Bertrand competition (MSB); (ii) The decision model when the two manufacturers implement Stackelberg competition, and the manufacturer 1 is the leader (MSM); (iii) The decision model when the two manufacturers implement Stackelberg competition, and the manufacturer 2 is the leader (MSR).

3.1.1. The MSB model. The MSB model arises in the markets where two manufacturers who have equal market powers produce two substitutable products (e.g. print cartridges), and the common retailer’s power is smaller compared to her manufacturers’. For example, manufacturers (e.g. Canon who has not incorporated a remanufacturing process and Hewlett & Packard who has incorporated a remanufacturing process) play a more dominant role than their common small-and medium-sized agents. In these real-world supply chains, the manufacturers will act as the Stackelberg leaders and the common retailer will act as the Stackelberg follower. In the MSB model, the two manufacturers first announce their decisions, the common retailer observes the two manufacturers’ decisions and then decides the retail prices she is going to charge for the products. We first derive the retailer’s decisions as follows. Given earlier decisions \( w_1 \), \( w_2 \) and \( \tau \) made by the two manufacturers respectively, we can derive the retailer’s best response functions, by setting \( \frac{\partial \pi_r}{\partial p_1} \) and \( \frac{\partial \pi_r}{\partial p_2} \) to zero and solving for \( p_1 \) and \( p_2 \), as follows

\[
p_1 = \frac{w_1}{2} + \frac{a_1 \beta + a_2 \gamma}{2(\beta^2 - \gamma^2)}, \quad (5)
\]

\[
p_2 = \frac{w_2}{2} + \frac{a_1 \gamma + a_2 \beta}{2(\beta^2 - \gamma^2)}. \quad (6)
\]

Having the information about the decisions of the common retailer, the two manufacturers would then use them to maximize their profits simultaneously. Substituting \( p_1 \) and \( p_2 \) in equations (5) and (6) into the two manufacturers’ profit functions in equations (3) and (4), and applying the first-order conditions to the resulting profit functions in terms of the wholesale prices \( w_1 \), \( w_2 \) and the remanufacturing effort \( \tau \) gives the manufacturer 1’s wholesale price \( w_{mb1}^* \) and the manufacturer 2’s wholesale price \( w_{mb2}^* \) and remanufacturing effort \( \tau_{mb}^* \), at equilibrium as follows

\[
w_{mb1}^* = \frac{\gamma(2B(a_2 + \beta c_{m2}) - a_2 \beta \delta^2) + \beta(a_1 + \beta c_{m1})(4B - \beta \delta^2)}{2\beta^2(4B - \beta \delta^2) - \gamma^2(2B - \beta \delta^2)}, \quad (7)
\]

\[
w_{mb2}^* = \frac{\gamma(2B - \beta \delta^2)(a_1 + \beta c_{m1}) - 2\beta(a_2 \beta \delta^2 - 2a_2 B - 2B \beta c_{m2})}{2\beta^2(4B - \beta \delta^2) - \gamma^2(2B - \beta \delta^2)}, \quad (8)
\]

\[
\tau_{mb}^* = \frac{a_2 + \beta c_{m2}}{\beta \delta} + \frac{\gamma}{\beta \delta} w_{mb1}^* - \frac{2}{\delta} w_{mb2}^*. \quad (9)
\]
Hence, with equations (7)-(9), we can easily see that the common retailer’s equilibrium retail prices in the MSB model, denoted as \( p^*_{mb1} \) and \( p^*_{mb2} \) respectively, are

\[
p^*_{mb1} = \frac{w^*_{mb1}}{2} + \frac{a_1 \beta + a_2 \gamma}{2(\beta^2 - \gamma^2)},
\]

\[
p^*_{mb2} = \frac{w^*_{mb2}}{2} + \frac{a_1 \gamma + a_2 \beta}{2(\beta^2 - \gamma^2)},
\]

where \( w^*_{mb1} \) and \( w^*_{mb2} \) are defined as in equations (7) and (8).

**Proposition 1.** In the MSB model, the manufacturer 1’s equilibrium wholesale price \( w^*_{mb1} \) is given in equation (7), the manufacturer 2’s equilibrium wholesale price \( w^*_{mb2} \) and equilibrium remanufacturing effort \( \tau^*_{mb} \) are given in equations (8) and (9) respectively, and the common retailer’s equilibrium retail prices \( p^*_{mb1}, p^*_{mb2} \) are given in equations (10) and (11).

**Proof.** Proof of Proposition 1, as well as the other remaining Proofs of the Propositions in this article, appears in Appendix D.

### 3.1.2. The MSB model.

The MSM model arises in the markets where two manufacturers produce two substitutable products (e.g. copiers), and the common retailer’s power is smaller compared to her manufacturers’. Two manufacturers have different market powers and play Stackelberg game, and the manufacturer who does not adopt the remanufacturing process has more market power and is a leader, the manufacturer who has incorporated a remanufacturing process is a follower. For example, copier manufacturers (e.g. Lenovo who has not incorporated a remanufacturing process and Xerox who has incorporated a remanufacturing process) play a more dominant role than their common small- and medium-sized agents. In these real-world supply chains, two manufacturers play Stackelberg game, and the manufacturer 1 who has not incorporated a remanufacturing process first announces the wholesale price of product 1, then the manufacturer 2 who has incorporated a remanufacturing process decides the wholesale price and the remanufacturing effort of product 2 to maximize his profit, the retailer finally decides the retail prices when knows the two manufacturers’ decisions. So, we first need to derive the retailer’s decisions. Similar to the MSB model, given earlier decisions \( w_1, w_2, \) and \( \tau \) made by the two manufacturers respectively, we can have the retailer’s best response functions as in equations (5) and (6). Having the information about the decisions of the common retailer, the manufacturer 2 would then use them to maximize his profit \( \pi_{m2} \) for given wholesale price \( w_1 \). Substituting \( p_1 \) and \( p_2 \) in equations (5) and (6) into the manufacturer 2’s profit in equation (4), and applying the first-order condition to the resulting profit function in terms of the wholesale price \( w_2 \) and the remanufacturing effort \( \tau \) gives the manufacturer 2’s wholesale price and remanufacturing effort, denoted as \( w^*_{msm2}, \tau^*_{msm} \), at equilibrium as follows

\[
w^*_{msm1} = \frac{\beta(4B - \beta \delta^2)(a_1 + \beta c_{m1}) + \gamma(2B - \beta \delta^2)(a_2 - \gamma c_{m1}) + 2B\beta \gamma c_{m2}}{2(\beta^2(4B - \beta \delta^2) - \gamma^2(2B - \beta \delta^2))}.
\]

With equations (5), (6), (12)-(14), one can easily have the manufacturer 2’s optimal wholesale price \( w^*_{msm2} \) and optimal remanufacturing effort \( \tau^*_{msm} \), and the common retailer’s optimal retail prices \( p^*_{msm1}, p^*_{msm2} \) at equilibrium in the MSM.
model as follows

\[ w^*_{msm2} = \frac{2a_2B + 2B\beta c_{m2} - \beta^2 a_2}{4B\beta - \beta^2 \delta^2} + \frac{2B\gamma - \beta \gamma \delta^2}{4B\beta - \beta^2 \delta^2} w^*_{msm1}, \quad (15) \]

\[ \tau^*_{msm} = \frac{a_2\delta - \beta \delta c_{m2}}{4B - \beta \delta^2} + \frac{\gamma \delta}{4B - \beta \delta^2} w^*_{msm1}, \quad (16) \]

\[ p^*_{msm1} = \frac{w^*_{msm1}}{2} + \frac{a_1\beta + a_2\gamma}{2(\beta^2 - \gamma^2)}, \quad (17) \]

\[ p^*_{msm2} = \frac{w^*_{msm2}}{2} + \frac{a_1\gamma + a_2\beta}{2(\beta^2 - \gamma^2)}, \quad (18) \]

where \( w^*_{msm1} \) is defined as in equation (14).

**Proposition 2.** In the MSM model, the manufacturer 1’s equilibrium wholesale price \( w^*_{msm1} \) is given in equation (14), the manufacturer 2’s equilibrium wholesale price \( w^*_{msm2} \) and equilibrium remanufacturing effort \( \tau^*_{msm} \) are given in equations (15) and (16) respectively, and the common retailer’s equilibrium retail prices \( p^*_{msm1}, p^*_{msm2} \) are given in equations (17) and (18).

### 3.1.3. The MSR model.

The MSR model arises in the markets where two manufacturers produce two substitutable products (e.g., copiers), and the common retailer’s power is smaller compared to her manufacturers’. Two manufacturers have different market powers and play Stackelberg game, and the manufacturer who does not adopt the remanufacturing process has lower market power and is a follower, the manufacturer who has incorporated a remanufacturing process is a leader. For example, copier manufacturers (e.g., Agfa who has not incorporated a remanufacturing process and Xerox who has incorporated a remanufacturing process) play a more dominant role than their common small- and medium-sized agents. In these real-world supply chains, two manufacturers play Stackelberg game, and manufacturer 2 who has incorporated a remanufacturing process first announces the wholesale price and the remanufacturing effort of product 2, then manufacturer 1 who has not incorporated a remanufacturing process decides the wholesale price of product 1 to maximize his profit, the retailer finally decides the retail prices when knows the two manufacturers’ decisions. Similar to the MSB model, given earlier decisions \( w_1, w_2, \) and \( \tau \) made by the two manufacturers respectively, we can have the retailer’s best response functions as in equations (5) and (6).

Having the information about the decisions of the common retailer, the manufacturer 1 would then use them to maximize his profit \( \pi_{m1} \) for given wholesale price \( w_2 \) and remanufacturing effort \( \tau \). Substituting \( p_1 \) and \( p_2 \) in equations (5) and (6) into the manufacturer 1’s profit function in equation (3), and applying the first-order condition to the resulting profit function in terms of the wholesale price \( w_1 \) gives the manufacturer 1’s wholesale price, denoted as \( w_{msr1} \), at equilibrium as follows

\[ w_{msr1} = \frac{a_1 + \beta c_{m1}}{2\beta} + \frac{\gamma}{2\beta} w_2. \quad (19) \]

Substituting \( p_1 \) and \( p_2 \) in equations (5) and (6) and the manufacturer 1’s wholesale price in equation (19) into the manufacturer 2’s profit function in (4), and applying the first-order condition to the resulting profit function in terms of the wholesale price \( w_2 \) and remanufacturing effort \( \tau \) gives the manufacturer 2’s optimal
wholesale price $w^*_{msr2}$ and optimal remanufacturing effort $\tau^*_{msr}$, at equilibrium as follows

\[
\begin{align*}
  w^*_{msr1} &= \frac{a_1 + \beta c_m}{2\beta} + \frac{\gamma}{2\beta} w^*_{msr2}, \\
  p^*_{msr1} &= \frac{w^*_{msr1}}{2} + \frac{a_1\beta + a_2\gamma}{2(\beta^2 - \gamma^2)}, \\
  p^*_{msr2} &= \frac{w^*_{msr2}}{2} + \frac{a_1\gamma + a_2\beta}{2(\beta^2 - \gamma^2)}.
\end{align*}
\]

where $w^*_{msr2}$ is defined as in equation (20).

**Proposition 3.** In the MSR model, the manufacturer 1’s equilibrium wholesale price $w^*_{msr1}$ is given in equation (22), the manufacturer 2’s equilibrium wholesale price $w^*_{msr2}$ and equilibrium remanufacturing effort $\tau^*_{msr}$ are given in equations (20) and (21) respectively, and the common retailer’s equilibrium retail prices $p^*_{msr1}; p^*_{msr2}$ are given in equations (23) and (24).

### 3.2. Decision models in RS game.

In this subsection, we assume that the common retailer acts as the Stackelberg leader and the two manufacturers act as the Stackelberg followers. Similar to the decision models in MS game, we will also establish three decision models in this subsection: (i) The decision model when the two manufacturers implement the Bertrand competition (RSB); (ii) The decision model when the two manufacturers implement Stackelberg competition, and the manufacturer 1 is the leader (RSM); (iii) The decision model when the two manufacturers implement Stackelberg competition, and the manufacturer 2 is the leader (RSR).

#### 3.2.1. The RSB model.

The RSB model arises in the markets where two manufacturers who have equal market powers produce two substitutable products (e.g. copiers), and the common retailer’s power is larger compared to her manufacturers’. For example, the retailer (e.g. WalMart) plays a more dominant role than her agents/manufacturers (e.g. Canon who has not incorporated a remanufacturing process and Hewlett & Packard who has incorporated a remanufacturing process). In these real-world supply chains, the manufacturers will act as the Stackelberg followers and the common retailer will act as the Stackelberg leader. In this decision case, the common retailer first announces the retail prices she is going to charge for the two substitutable products, the two manufacturers observe the retail prices and then make their decisions simultaneously. Namely, the manufacturer 1 gives the wholesale price $w_1$ he is going to charge for product 1, and the manufacturer 2
gives the wholesale price \( w_2 \) and the remanufacturing effort \( \tau \) he is going to charge for product 2. So, we first derive the two manufacturers’ decisions as follows.

Without loss of generality, let \( m_i \) be the margin of product \( i \) enjoyed by the retailer, namely,

\[
p_i = w_i + m_i,
\]

where \( m_i > 0, i = 1, 2 \).

Given earlier decisions \( p_1 \) and \( p_2 \) made by the retailer, we can derive the two manufacturers’ best response functions, by setting \( \frac{\partial \pi_{m1}}{\partial w_1}, \frac{\partial \pi_{m2}}{\partial w_2} \) and \( \frac{\partial \pi_{m2}}{\partial \tau} \) to zero and solving for \( w_1, w_2 \) and \( \tau \), as follows

\[
w_1 = \frac{a_1 + \beta c m_1}{\beta} - p_1 + \frac{\gamma}{\beta} p_2, \tag{26}
\]
\[
w_2 = A_1 p_1 + A_2 p_2 + A_3, \tag{27}
\]
\[
\tau = \frac{a_2 \delta}{B} + \frac{\gamma \delta}{B} p_1 - \frac{\beta \delta}{B} p_2, \tag{28}
\]

where \( A_1, A_2, A_3 \) are constants defined in Appendix B.

Having the information about the decision of the two manufacturers, the common retailer would then use them to maximize her profit. Substituting \( w_1, w_2 \) and \( \tau \) in equations (26)-(28) into the common retailer’s profit function in equation (2), and applying the first-order conditions to the resulting profit function in terms of the retail prices \( p_1, p_2 \) gives the common retailer’s optimal retail prices, denoted as \( p_{r \text{rsb}1}^* \) and \( p_{r \text{rsb}2}^* \), at equilibrium as follows

\[
p_{r \text{rsb}1}^* = \frac{A_5 A_9 - A_8 A_6}{A_4 A_8 - A_5 A_7}, \tag{29}
\]
\[
p_{r \text{rsb}2}^* = \frac{A_6 A_7 - A_9 A_4}{A_4 A_8 - A_5 A_7}, \tag{30}
\]

where \( A_4, A_5, \ldots, A_9 \) are constants defined in Appendix B.

Hence, with equations (26)-(30), we can easily see that the two manufacturers’ equilibrium wholesale prices and remanufacturing effort in the RSB model, denoted as \( w_{r \text{rsb}1}^*, w_{r \text{rsb}2}^* \) and \( \tau_{r \text{rsb}}^* \) respectively, are

\[
w_{r \text{rsb}1}^* = \frac{a_1 + \beta c m_1}{\beta} - p_{r \text{rsb}1}^* + \frac{\gamma}{\beta} p_{r \text{rsb}2}^*, \tag{31}
\]
\[
w_{r \text{rsb}2}^* = A_1 p_{r \text{rsb}1}^* + A_2 p_{r \text{rsb}2}^* + A_3, \tag{32}
\]
\[
\tau_{r \text{rsb}}^* = \frac{a_2 \delta}{B} + \frac{\gamma \delta}{B} p_{r \text{rsb}1}^* - \frac{\beta \delta}{B} p_{r \text{rsb}2}^*, \tag{33}
\]

where \( A_1, A_2, A_3 \) are constants defined in Appendix B, and \( p_{r \text{rsb}1}^*, p_{r \text{rsb}2}^* \) are defined as in equations (29) and (30).

**Proposition 4.** In the RSB model, the manufacturer 1’s equilibrium wholesale price \( w_{r \text{rsb}1}^* \) is given in equation (31), the manufacturer 2’s equilibrium wholesale price \( w_{r \text{rsb}2}^* \) and equilibrium remanufacturing effort \( \tau_{r \text{rsb}}^* \) are given in equations (32) and (33) respectively, and the common retailer’s equilibrium retail prices \( p_{r \text{rsb}1}^*, p_{r \text{rsb}2}^* \) are given in equations (29) and (30).

**3.2.2. The RSM model.** The RSM model arises in the markets where two manufacturers who have different market powers produce two substitutable products (e.g. copiers), and the common retailer’s power is larger compared to her manufacturers’. Two manufacturers play Stackelberg game, and the manufacturer who does not adopt the remanufacturing process has more market power and is a leader,
the manufacturer who has incorporated a remanufacturing process is a follower. For example, the retailer (e.g. WalMart) plays a more dominant role than her agents/manufacturers (e.g. Lenovo who has not incorporated a remanufacturing process and Xerox who has incorporated a remanufacturing process). In these real-world supply chains, two manufacturers play Stackelberg game, and the common retailer first announces the retail prices, manufacturer 1 who has not incorporated a remanufacturing process then decides the wholesale price to maximize his profit, and finally, manufacturer 2 who has incorporated a remanufacturing process decides the wholesale price and remanufacturing effort $\tau$ of product 2 he is going to charge.

Given earlier decisions $w_1$, $p_1$ and $p_2$ made by the manufacturer 1 and the common retailer respectively, we can derive the manufacturer 2’s best response function, by applying the first-order conditions to the manufacturer 2’s profit function in terms of the wholesale price $w_2$ and $\tau$, as shown in equations (27) and (28).

Having the manufacturer 2’s response function, the manufacturer 1 would make his wholesale price decision for given retail prices $p_1$ and $p_2$. Substituting $w_2$ and $\tau$ in equations (27) and (28) into the manufacturer 1’s profit function in equation (3), and applying the first-order condition to the resulting profit function in terms of the wholesale price $w_1$ gives the manufacturer 1’s wholesale price at equilibrium as follows

$$w_{rsm1} = \frac{a_1 + \beta c_{m1} - \gamma c_{m1} A_1}{\beta - \gamma A_1} - \frac{\beta}{\beta - \gamma A_1} p_1 + \frac{\gamma}{\beta - \gamma A_1} p_2,$$  \hspace{1cm} (34)

where $A_1$ is constant defined in Appendix B.

Having the response functions of manufacturers 1 and 2, the common retailer would make her retail price decisions to maximize her profit. Substituting $w_1, w_2$ and $\tau$ in equations (34), (27) and (28) into the common retailer’s profit function in equation (2), and applying the first-order conditions to the resulting profit function in terms of the retail prices $p_1$ and $p_2$ gives the retailer’s optimal retail prices $p_{rsm1}$ and $p_{rsm2}$ at equilibrium as follows

$$p_{rsm1}^* = \frac{E_5 E_8 - E_6 E_8}{E_4 E_8 - E_7 E_8},$$  \hspace{1cm} (35)

$$p_{rsm2}^* = \frac{E_6 E_7 - E_4 E_9}{E_3 E_8 - E_5 E_7}.$$  \hspace{1cm} (36)

where $E_1, E_2, E_3, \ldots, E_9$ are constants defined in Appendix B.

Based on equations (27), (28), (34), (35), and (36), we can easily see that the manufacturer 1’s optimal wholesale price $w_{rsm1}^*$ and the manufacturer 2’s optimal wholesale price $w_{rsm2}^*$ and optimal remanufacturing effort $\tau_{rsm}^*$ in the RSM model are

$$w_{rsm1}^* = \frac{a_1 + \beta c_{m1} - \gamma c_{m1} A_1}{\beta - \gamma A_1} - \frac{\beta}{\beta - \gamma A_1} p_{rsm1}^* + \frac{\gamma}{\beta - \gamma A_1} p_{rsm2}^*,$$  \hspace{1cm} (37)

$$w_{rsm2}^* = A_1 p_{rsm1}^* + A_2 p_{rsm2}^* + A_3,$$  \hspace{1cm} (38)

$$\tau_{rsm}^* = \frac{a_2 \delta}{B} + \frac{\gamma \delta}{B} p_{rsm1}^* - \frac{\beta \delta}{B} p_{rsm2}^*.$$  \hspace{1cm} (39)

where $A_1, A_2, A_3$ are constants defined in Appendix B, and $p_{rsm1}^*, p_{rsm2}^*$ are defined as in equations (35) and (36) respectively.

**Proposition 5.** In the RSM model, the manufacturer 1’s equilibrium wholesale price $w_{rsb1}^*$ is given in equation (37), the manufacturer 2’s equilibrium wholesale price $w_{rsb2}^*$ and equilibrium remanufacturing effort $\tau_{rsb}^*$ are given in equations (38)
and (39) respectively, and the common retailer’s equilibrium retail prices $p^*_{rsb1}, p^*_{rsb2}$ are given in equations (35) and (36).

### 3.2.3. The RSR model

The RSR model arises in the markets where two manufacturers who have different market powers produce two substitutable products (e.g., copiers), and the common retailer’s power is larger compared to her manufacturers’. Two play Stackelberg game, and the manufacturer who has adopt a remanufacturing process has more market power and is a leader, the manufacturer who does not incorporate a remanufacturing process is a follower. For example, the retailer (e.g. WalMart) plays a more dominant role than her agents/manufacturers (e.g. Agfa who has not incorporated a remanufacturing process and Hewlett & Packard who has incorporated a remanufacturing process). In these real-world supply chains, two manufacturers play Stackelberg game, and the common retailer first announces the retail prices, manufacturer 2 who has incorporated a remanufacturing process then decides the wholesale price $w^*_2$ and remanufacturing effort $\tau^*$ of product 2 to maximize his profit, and finally, manufacturer 1 who has not incorporated a remanufacturing process decides the wholesale price $w^*_1$ of product 1 he is going to charge.

Given earlier decisions $w_2, \tau, p_1$ and $p_2$ made by the manufacturer 2 and the common retailer respectively, we can derive the manufacturer 1’s best response function, by applying the first-order conditions to the manufacturer 1’s profit function in terms of the wholesale price $w^*_1$, as shown in equation (26).

Substituting $w_1$ in equation (26) into the manufacturer 2’s profit function in equation (4) and solving the first-order condition of the resulting profit for $w^*_2$ and $\tau$ gives manufacturer 2’s best response functions

$$w^*_2 = F_1 p_1 + F_2 p_2 + F_3,$$  \hspace{1cm} (40)

$$\tau = \frac{\delta}{B} (a_2 + \gamma p_1 - \beta p_2),$$  \hspace{1cm} (41)

where $F_1, F_2, F_3$ are constants defined in Appendix B.

Substituting $w_1$, $w_2$ and $\tau$ in equations (26), (40) and (41) into the common retailer’s profit function in equation (2), and applying the first-order conditions to the resulting profit function in terms of the retail prices $p_1$ and $p_2$ gives the common retailer’s optimal retail prices, denoted as $p^*_{rsr1}$ and $p^*_{rsr2}$, at equilibrium as follows

$$p^*_{rsr1} = \frac{F_5 F_9 - F_6 F_8}{F_4 F_8 - F_5 F_7},$$ \hspace{1cm} (42)

$$p^*_{rsr2} = \frac{F_6 F_7 - F_4 F_9}{F_4 F_8 - F_5 F_7},$$ \hspace{1cm} (43)

where $F_4, F_5, \ldots, F_9$ are constants defined in Appendix B.

With equations (26), (40)-(43), we can easily see that the manufacturer 1’s optimal wholesale price $w^*_{rsr1}$ and the manufacturer 2’s optimal wholesale price $w^*_{rsr2}$ and optimal remanufacturing effort $\tau^*_{rsr}$ in the RSR model are

$$w^*_{rsr1} = \frac{a_1 + \beta c m_1}{\beta} - p^*_{rsr1} + \frac{\gamma}{\beta} p^*_{rsr2},$$  \hspace{1cm} (44)

$$w^*_{rsr2} = F_1 p^*_{rsr1} + F_2 p^*_{rsr2} + F_3,$$  \hspace{1cm} (45)

$$\tau^*_{rsr} = \frac{\delta}{B} (a_2 + \gamma p^*_{rsr1} - \beta p^*_{rsr2}),$$  \hspace{1cm} (46)
where $F_1, F_2, F_3$ are constants defined in Appendix B, and $p_{rsr1}^*, p_{rsr2}^*$ are defined as in equations (42) and (43) respectively.

**Proposition 6.** In the RSR model, the manufacturer 1’s equilibrium wholesale price $w_{rsb1}^*$ is given in equation (44), the manufacturer 2’s equilibrium wholesale price $w_{rsb2}^*$ and equilibrium remanufacturing effort $\tau^*_{rsb}$ are given in equations (45) and (46) respectively, and the common retailer’s equilibrium retail prices $p_{rsb1}^*, p_{rsb2}^*$ are given in equations (42) and (43).

3.3. The Vertical Nash model (NG model). In the NG model, we assume that every firm has equal bargaining power and thus makes their decisions simultaneously. This scenario arises in a market in which there are relatively small to medium-sized manufacturers and retailers. Since a manufacturer cannot dominate the market over the retailer, his decision is conditioned on how the retailer price the product. On the other hand, the retailer must also condition her retail price decision on the manufacturer’s decision. Consider that the decisions for the two manufacturers and the common retailer are already derived in the MSB and RSB models.

Based on $p_1$ and $p_2$ in equations (5), (6), and $w_1, w_2$ and $\tau$ in equations (26), (27), (28) respectively, we can easily obtain the equilibrium values of the chain members’ decisions in the NG model, denoted as $p_{n1}^*, p_{n2}^*, w_{n1}^*, w_{n2}^*$, and $\tau_n^*$ respectively, as follows

$$p_{n1}^* = \frac{(A_2 - 2)(\beta H_1 + a_1 + \beta c_{m1}) - \gamma (A_3 + H_2)}{A_1 + 3\beta(A_2 - 2)},$$

$$p_{n2}^* = \frac{-A_1(\beta H_1 + a_1 + \beta c_{m1}) - 3\beta(A_3 + H_2)}{A_1 + 3\beta(A_2 - 2)},$$

$$w_{n1}^* = 2p_{n1}^* - H_1,$$

$$w_{n2}^* = 2p_{n2}^* - H_2,$$

$$\tau_n^* = \frac{a_2 \delta - \beta \delta p_{n2}^* + \gamma \delta p_{n1}^*}{B},$$

where $A_1, A_2, A_3, H_1, H_2$ are constants defined in Appendix B.

4. Comparisons and managerial implications. In this section, we consider the special case that the parameters in seven decision models established above are all symmetric, that is, $a_1 = a_2 = a$, and $c_{m1} = c_{m2} = c_m$. The reason for restricting the two substitutable products to have identical parameter values is to enable a comparison of the seven decision models and to gain more insights into the managerial implication. The asymmetry between the products creates problems during comparison of decision models (Tsay and Agrawal, 2000; and Mishra and Raghunathan, 2004). Thus, a comparison using simplified parameter structures can separate the effects of different competition strategies and different power structures in the models from the effects of differences in each parameter.

4.1. Comparison and analysis of the equilibrium solutions. Consider that it is very difficult to analyze the changes of equilibrium decisions and chain members’ equilibrium profits with the parameters $a, \delta, \beta, \gamma$, and $B$ in the seven decision models by analytic approach because the equilibrium solutions are complicated. So, in this subsection, we carry out the sensitivity analysis through numerical studies of the parameters $\beta, \gamma, a, B$, and $\delta$ for examining their influences on the equilibrium solutions and chain members’ optimal profits. On the basis of comparison and analysis,
some managerial insights are derived. In each decision model, for the two manufacturers to be profitable, the contribution margins for the two manufacturers have to be nonnegative, namely, \( w_i - c_m > 0 \), \( i = 1, 2 \), and the remanufacturing effort has to satisfy \( 0 \leq \tau \leq 1 \). However, due to the complicated form of the analytic results \( w_1, w_2, \) and \( \tau \), it is very difficult to obtain the analytic conditions for parameters \( a, \delta, \beta, \gamma, \) and \( B \) which make the contribution margins for two manufacturers, the demands for two products be nonnegative and the remanufacturing effort for the remanufacturer satisfy \( 0 \leq \tau \leq 1 \). In the following numerical examples, we can apply the simulation method to choose the appropriate parameter values which make sure the two manufacturers and the retailer are all profitable, and the remanufacturing effort satisfies \( 0 \leq \tau \leq 1 \).

**Discussion 1.** Sensitivity analysis of the parameters \( \beta \) and \( \gamma \).

First, we explore how the optimal retail prices, wholesale prices, remanufacturing effort, and the chain members’ maximum profits are affected by changes in the self-price sensitivity \( \beta \). Figs. 1-3 show the changes of the optimal prices, remanufacturing effort, and the chain members’ maximum profits with parameter \( \beta \) in the MSM model, where default values of parameters are \( a = 80, c_m = 20, c_r = 18, \gamma = 0.4, B = 200, \) and \( \beta \in \{0.8, 0.84, 0.88, 0.92, 0.96\} \).

Next, the mechanism by which the optimal retail prices, wholesale prices, remanufacturing effort, and the maximum profits are affected by the changes in the cross-price sensitivity \( \gamma \) is investigated. Figs. 4-6 present the changes of the optimal prices, remanufacturing effort, and the chain members’ maximum profits with the parameter \( \gamma \) in the MSM model, where default values of parameters are \( a = 80, c_m = 20, c_r = 18, \beta = 0.8, B = 200, \) and \( \gamma \in \{0.26, 0.28, 0.26, 0.32, 0.34\} \).

It follows from Figs. 1-6 that the optimal wholesale prices (i.e., \( w_1^*, w_2^* \)), the optimal retail prices (i.e., \( p_1^*, p_2^* \)), the optimal remanufacturing effort \( \tau^* \), and the corresponding chain members’ maximum profits (i.e., \( \pi_{m1}^*, \pi_{m2}^*, \) and \( \pi_r^* \)) all decrease in the self-price sensitivity \( \beta \), and all increase in the cross-price sensitivity \( \gamma \) in the MSM model. Similarly, the same result can be obtained in the other six decision models, and the details are not discussed in this article. From which, we can have the following managerial insight. Regardless of the leader-follower relationship of
the game, the optimal prices, the optimal remanufacturing effort, and the maximum
profits decrease with decreasing values of self-price sensitivity $\beta$ and with increasing
values of cross-price sensitivity $\gamma$. This is because the demand for the two products
are negatively correlated to $\beta$ and are positively correlated to $\gamma$.

Discussion 2. Sensitivity analysis of the parameters $a$, $B$ and $\delta$.
First, we explore how the optimal retail prices, wholesale prices, remanufacturing
effort, and the chain members’ maximum profits are affected by changes in the
market base $a$. Figs. 7-9 present the changes of the optimal prices, remanufacturing
effort, and the chain members’ maximum profits with parameter $a$ in the MSM
model, where default values of parameters are $c_m = 20, c_r = 18, \beta = 0.8, \gamma =
0.4, B = 200$, and $a \in \{86, 88, 90, 92, 94\}$.

Second, the mechanism by which the optimal retail prices, wholesale prices, re-
manufacturing effort, and the chain members’ maximum profits are affected by the
changes in the scaling parameter $B$ for the collecting process is investigated. Figs.
10-12 present the changes of the optimal prices, remanufacturing effort, and the
chain members’ maximum profits with the parameter $B$ in the MSM model, where
default values of parameters are $a = 80, c_m = 20, c_r = 18, \beta = 0.6, \gamma = 0.4$, and
$B \in \{240, 280, 320, 360, 400\}$.

Third, the effects of changes in the cost-savings from the remanufacturing, i.e.,
$c_m - c_r$, or $\delta$, on optimal retail prices, wholesale prices, remanufacturing effort,
and the chain members’ maximum profits in the MSM model are as shown in Figs. 13-15;
here $a = 80, c_m = 20, \beta = 0.6, \gamma = 0.4, B = 200$, and $c_r \in \{16.8, 17.1, 17.4, 17.7, 18\}$.

From Figs. 7-15, we can draw the following conclusions for the MSM model:
(2.1) The optimal retail prices, wholesale prices, remanufacturing effort, and the chain members’ maximum profits increase as parameter $a$ increases.

(2.2) The optimal retail prices, wholesale prices, and the manufacturer 1’s maximum profit increase as parameter $B$ increases. On the contrary, the remanufacturer’s remanufacturing effort and maximum profit and the retailer’s maximum profit decrease as parameter $B$ increases.

(2.3) The optimal retail prices, wholesale prices, and the manufacturer 1’s maximum profit decrease as parameter $\delta$ increases. On the contrary, the remanufacturer’s remanufacturing effort and maximum profit and the retailer’s maximum profit increase as parameter $\delta$ increases.

**Remark.** Graphs similar to those in Figs. 7-15 can be obtained in the MSB, MSR, RSB, RSM, RSS, and NG models when the parameters $a, B$ and $\delta$ vary. For brevity, these graphs, discussions, and sensitivity analyses are not presented in this article.

From the above discussions, the following results are obtained:

(2.4) Regardless of the leader-follower relationship of the channel members, the optimal retail prices, wholesale prices, remanufacturing effort, and the chain members’ maximum profits will increase as the market base increases.

(2.5) When scaling parameter $B$ increases, the optimal retail prices, wholesale prices, and the manufacturer 1’s maximum profit will increase, whereas the remanufacturer’s remanufacturing effort and maximum profit, and the common retailer’s maximum profit will decrease. This result shows that, although the two products are sold at higher prices, both the remanufacturer and the common retailer obtain less profit except the manufacturer 1. This is partly because of the decrease in product 2’s demand due to the higher retail price and the increase in the product 1’s demand due to the increase of the product 2’s retail price is larger than the increase of the product 1’s retail price. Moreover, the revenue resulting from the higher wholesale price of product 2 can not offset the loss resulting from product 2’s decreased demand for the manufacturer 2 and the increased revenue from product 1 can not offset the loss resulting from product 2 for the common retailer.

(2.6) The remanufacturer’s remanufacturing effort and maximum profit and the common retailer’s maximum profit will increase when the cost-savings from the remanufacturing $\delta$ increases, whereas the increase has an adverse effect on the optimal retail prices, wholesale prices, and the manufacturer 1’s maximum profit. This is because the decrease in product 2’s average unit manufacturing cost causes the decrease of product 2’s wholesale price and eventually causes the decreases of product 1’s wholesale price and two products’ retail prices, and the increases of two products’ demands. For the remanufacturer and the common retailer, the increased total demand resulting from lower sale prices more than offsets the loss of revenue per unit due to the lower sale prices. However, for the manufacturer 1, the increased total demand resulting from lower sale price can not offset the loss of revenue per unit due to the lower sale price.

**4.2. Numerical example.** Due to the complicated form of the analytic results, in this subsection, we compare the analytical results obtained from the above seven decision models using numerical approach and study the behavior of firms facing the changing decision environment. Consider the case where the default values of the model parameters are as follows: $c_m = 20$, $c_r = 18$, $a = 80$, $\beta = 0.8$, $\gamma = 0.4$, and $B = 200$. The corresponding results are shown as in Tables 1 and 2.

**Discussions 3.** From Table 1, we can have the following results.
Table 1. Chain members’ maximum profits in different decision models

| Scenario | $\pi_{m1}$ + $\pi_{m2}$ + $\pi_r$ | $\pi_{m1}$ | $\pi_{m2}$ | $\pi_r$ |
|----------|---------------------------------|-------------|-------------|--------|
| MSB      | 13549.7                         | 2701.4      | 2713.6      | 8134.7 |
| MSM      | 13361.2                         | 2744.0      | 2976.9      | 7640.3 |
| MSR      | 13357.5                         | 2966.4      | 2756.9      | 7634.2 |
| RSB      | 13553.5                         | 1351.7      | 1353.8      | 10848.0|
| RSM      | 13066.1                         | 1332.4      | 1672.7      | 10061.0|
| RSR      | 13047.6                         | 1667.6      | 1343.0      | 10037.0|
| NG       | 13082.6                         | 4103.7      | 4124.0      | 4854.9 |

Table 2. Optimal prices and remanufacturing effort in different decision models

| Scenario | $p_i^*$ | $w_i^*$ | $p_j^*$ | $w_j^*$ | $\tau^*$ |
|----------|---------|---------|---------|---------|----------|
| MSB      | 257.45  | 114.89  | 257.34  | 114.68  | 0.28575  |
| MSM      | 264.20  | 128.40  | 259.58  | 119.17  | 0.29929  |
| MSR      | 259.72  | 119.44  | 264.16  | 128.32  | 0.25393  |
| RSB      | 257.39  | 67.54   | 257.18  | 66.97   | 0.28650  |
| RSM      | 272.92  | 82.92   | 262.32  | 72.32   | 0.31775  |
| RSR      | 262.72  | 72.72   | 273.16  | 83.16   | 0.21194  |
| NG       | 151.35  | 102.70  | 151.08  | 102.16  | 0.49893  |

(3.1) The whole supply chain achieves the highest profit in the RSB model, followed by the RSB model, and achieves the lowest profit in the RSR model.

(3.2) Comparing among the seven decision cases, the manufacturer 1 achieves his highest profit in the NG model, followed by the MSR model, and achieves the lowest profit in the RSM model, whereas the remanufacturer achieves his highest profit in the NG model, followed by the MSM model, and achieves the least profit in the RSR model. Moreover, the common retailer achieves her highest profit in the RSB model, followed by the RSM model, and achieves the lowest profit in the NG model.

(3.3) Comparing among the three MS decision cases (i.e, MSB, MSM and MSR models), the manufacturer 1 achieves his highest profit in the MSR model, followed by the MSM model, and then the MSB model. However, the remanufacturer achieves his highest profit in the MSM model, followed by the MSR model, and then the MSB model. The result shows that, for the two manufacturers, the firm who is the leader does not have the advantage to get the higher profit, whereas the firm who is the follower does have the advantage to get the higher profit. The same results is also valid for the three RS decision cases (i.e, RSB, RSM and RSR models). This is because the sale price of product $i$ when the manufacturer $i$ is a leader is higher than that when the manufacturer $i$ is a follower in the MS or RS decision cases, which directly causes the decrease of the product $i$'s market demand, and eventually causes the decrease of manufacturer $i$'s profit.

(3.4) The common retailer’s profit in the RS decision cases (i.e, RSB, RSM and RSR models) is larger than that in the MS decision cases (i.e, MSB, MSM and MSR models). This indicates that the retailer holds advantage in getting the higher profit when she is the leader in the supply chain.
Comparing among the three RS decision cases (i.e., RSB, RSM and RSR models), the retailer obtains the largest profit in the RSB model, i.e., when the two manufacturers implement the Bertrand competition, followed by the RSM model and then the RSR model. Similarly, comparing among the three MS decision cases (i.e., MSB, MSM and MSR models), the retailer obtains the largest profit in the MSB model, i.e., when the two manufacturers implement the Bertrand competition, followed by the MSM model and then the MSR model. This indicates that the Bertrand competition involving two manufacturers is more beneficial to the common retailer than their Stackelberg competition.

Discussions 4. From Table 2, the following results can be derived.

(4.1) Product 1 achieves the highest retail price in the RSM model; this is followed by the MSM model, RSR model, MSR model, MSB model and then the RSB model, and the lowest retail price is obtained in the NG model, whereas product 2 achieves the highest retail price in the RSR model, followed by the MSR model, RSM model, MSM model, MSB model and then the RSB model, the lowest retail price in the NG model.

(4.2) The two products achieve the highest wholesale prices in the MS game scenario, followed by the NG game and then the RS game scenario. This indicates that the two manufacturers will charge the highest wholesale prices when they are the leaders in the supply chain, and the lowest wholesale prices when they are the followers.

(4.3) Compared with the three MS decision cases (i.e., MSB, MSM and MSR models), product 1 achieves the highest wholesale price in the MSM model, followed by the MSR model, and then the MSB model, whereas product 2 achieves the highest wholesale price in the MSB model, followed by the MSM model, and then the MSB model. On the other hand, comparing among the three RS decision cases (i.e., RSB, RSM and RSR models), product 1 achieves the highest wholesale price in the RSM model, followed by the RSR model, and then the RSB model, whereas product 2 achieves the highest wholesale price in the RSR model, followed by the RSM model, and then the RSB model. From these results, we can see that (i) The two manufacturers’s Bertrand competition will make they charge the lowest wholesale prices in MS and RS game scenarios; (ii) In the MS game scenario, product 1 achieves the highest wholesale price when the manufacturer 1 is a leader, whereas product 2 achieves the highest wholesale price when the manufacturer 2 is a leader. The same results can be obtained in the RS game scenario. It indicates that, for the two manufacturers, the firm who is the leader in the supply chain holds advantage in getting the higher sale price.

(4.4) Compared with the seven decision models, the remanufacturer’s remanufacturing effort obtains the highest value in the NG model, followed by the RSM model then the MSM model, and the lowest value in the RSR model. Moreover, in the MS game scenario, the remanufacturer’s remanufacturing effort achieves the highest value in the MSM model where the manufacturer 1 is a leader; this is followed by the MSB model where the two manufacturers pursue the Bertrand competition, and the lowest value is obtained in the MSR where the remanufacturer is a leader. The same result can be obtained in the RS game scenario. The result shows that the remanufacturer will employ less remanufacturing approach to produce product 2 when he is a leader, although he sells the product 2 at a higher price. On the contrary, the remanufacturer will employ more remanufacturing approach to produce product 2 when he is a follower, although he sells the product 2 at a lower price.
Moreover, the remanufacturer will spend the highest remanufacturing effort when there is no channel leadership among the three channel members.

5. Some concluding comments. This article studies two manufacturers’ and one common retailer’s remanufacturing effort and/or pricing decisions for two substitutable products by considering the two manufacturers’ three kinds of horizontal interactions and three kinds of vertical interactions between the two echelon. First, seven decision models in decentralized decision cases (e.g. the MSB, MSM, MSR, RSB, RSM, RSR and NG models) are established, and the corresponding analytic equilibrium solutions for every decision model are also obtained. Second, we provide comparison and analysis of the equilibrium solutions and perform the sensitivity analysis on some key parameters through numerical approach. Finally, the numerical example is given with the intent to study the behavior of firms facing the changing decision environment. Some interesting managerial insights are derived.

However, our results are based upon some assumptions about the models of substitutable products. Thus, several extensions to the analysis in this paper are possible. First, as opposed to the risk neutral channel members considered in this paper, one could study the case where the channel members with different attitudes towards risk and could also examine the influence of their attitudes towards risk on individual decisions and profits. Second, this paper considers a case with two-product, deterministic-linear-demand function in a single-period, one can study the case with multiple-products and other forms of demand function in stochastic/fuzzy multiple periods environment. Third, we assume that only one manufacturer adopts the remanufacturing approach, one can consider the case where the two manufacturers both adopt the remanufacturing approach. Fourth, we assume that both the two manufacturers and the common retailer have symmetric information about costs and demands. So, an extension would be to consider the case with information asymmetry, such as asymmetry in cost information and demand information.

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Appendix A. Notations for Problem Description

| Symbol | Description |
|--------|-------------|
| $p_i$  | unit retail price of product $i$, $i = 1, 2$, |
| $w_i$  | unit wholesale price of product $i$, |
| $c_{mi}$ | unit manufacturing cost of product $i$, $i = 1, 2$ |
| $c_r$  | unit remanufacturing cost of product 2 |
| $\beta$ | self-price sensitivity of a product’s demand to its own price |
| $\gamma$ | cross-price sensitivity of one product’s demand to the other product’s price |
| $D_i$  | the demand for product $i$, $i = 1, 2$ |
| $\tau$ | the manufacturer 2’s remanufacturing effort |
| $B$    | scaling parameter of the manufacturer 2’s recycling process |
Appendix B. Notations for decision models in RS Game

\[ A_1 = \frac{\gamma}{\beta} - \frac{\delta^2}{\beta}, \quad A_2 = \frac{\beta\delta^2}{\beta}, \quad A_3 = \frac{a_2}{\beta} + c_{m2} - \frac{a_2\delta^2}{\beta}, \quad A_4 = -4\beta - 2A_1 \gamma, \]
\[ A_5 = 4\gamma + A_1 \beta - 2A_2 \gamma, \quad A_6 = a_1 + \beta c_{m1} - A_1 a_2 - \gamma A_3, \quad A_7 = 4\gamma - \gamma A_2 + \beta A_1, \]
\[ A_8 = -2\beta - 2\beta + 2\beta A_2, \quad A_9 = -2m - \gamma c_{m1} + (1 - A_2) a_2 + \beta A_3, \]
\[ E_1 = -\frac{\beta}{\beta - \gamma A_1}, \quad E_2 = \frac{\gamma}{\beta - \beta - \gamma A_1}, \quad E_3 = \frac{a_1 + \beta c_{m1} - \gamma c_{m1} A_3}{\beta - \gamma A_1}, \quad E_4 = -2\beta(1 - E_1) - 2\gamma A_1, \]
\[ E_5 = \beta(A_1 + E_2) + \gamma(2 - E_1 - A_2), \quad E_6 = a_1(1 - E_1) + \beta E_3 - a_2 A_1 - \gamma A_3, \]
\[ E_7 = \beta(A_1 + E_2) + \gamma(2 - E_1 - A_2), \quad E_8 = -2\gamma E_2 - 2\beta(1 - A_2), \]
\[ E_9 = -a_1 E_2 - \gamma E_3 + a_2(1 - A_2) + \beta A_3, \]
\[ F_1 = \frac{\beta^2}{\beta - \gamma}, \quad F_2 = \frac{\beta}{\beta - \gamma}, \quad F_3 = a_2 \left( \frac{\beta}{\beta - \gamma} - \frac{\delta^2}{\beta} \right) + c_{m2}, \quad F_4 = -4\beta - 2\gamma F_1, \]
\[ F_5 = 4\gamma + \beta F_1 - \gamma F_2, \quad F_6 = 3a_1 - a_2 F_1 + \beta c_{m1} - \gamma F_3, \quad F_7 = 4\gamma + \beta F_1 - \gamma F_2, \]
\[ F_8 = 2\beta F_2 - 2\beta - \frac{\gamma^2}{\beta}, \quad F_9 = \frac{2a_1 \gamma}{\beta} + a_2(1 - F_2) + \beta F_3 - \gamma c_{m1}, \quad H_1 = \frac{a_1 \gamma + a_2 \gamma}{2(\beta - \gamma)}, \quad H_2 = \frac{a_1 \gamma + a_2 \gamma}{2(\beta - \gamma)}. \]

Appendix C. Conditions for Model Parameters. To ensure that the various profit expressions will be well behaved and possess a unique optimum, similar to Tsay and Agrawal (2000), we impose the following conditions on the parameters:

\[ B > \max \left\{ \frac{\beta \delta^2 (\beta^2 - \gamma^2)}{2(2\beta^2 - \gamma^2)}, \frac{\beta \delta^2}{2}, \frac{\beta \delta^2}{2}, \frac{\beta \delta^2}{2}, \frac{\beta \delta^2}{2} \right\}, \quad (a1) \]
\[ A_4 A_8 - A_5 A_7 > 0, \quad (a2) \]
\[ E_4 < 0, E_8 < 0, E_4 E_8 - E_5 E_7 > 0, \quad (a3) \]
\[ F_4 < 0, F_8 < 0, F_4 F_8 - F_5 F_7 > 0. \quad (a4) \]

Appendix D. Proof of Proposition 1. It follows from equation (2) that the first order partial derivatives of \( \pi_r \) to \( p_i, i = 1, 2 \), can be shown as

\[ \frac{\partial \pi_r}{\partial p_i} = a_i - 2\beta p_i + 2\gamma p_j + \beta w_i - \gamma w_j, \quad i = 1, 2, j = 3 - i, \quad (b1) \]

and the Hessian is

\[ \left( \begin{array}{cc}
\frac{\partial^2 \pi_r}{\partial^2 p_i} & \frac{\partial^2 \pi_r}{\partial p_i \partial p_j} \\
\frac{\partial^2 \pi_r}{\partial p_j \partial p_i} & \frac{\partial^2 \pi_r}{\partial^2 p_j}
\end{array} \right) = \left( \begin{array}{cc}
-2\beta & 2\gamma \\
2\gamma & -2\beta
\end{array} \right). \]

We have a negative definite Hessian Matrix with the assumption that self-price sensitivities are greater than cross-price sensitivities. Therefore, the profit \( \pi_r \) is jointly concave in \( p_1 \) and \( p_2 \). By setting equations (b1) to zero and solving them, simultaneously, we obtain equations (5) and (6).

It follows from equations (3)-(6) that the first order derivative of \( \pi_{m1} \) to \( w_1 \) and the first order partial derivatives of \( \pi_{m2} \) to \( w_2 \) and \( \tau \) can be shown as

\[ \frac{\partial \pi_{m1}}{\partial w_1} = a_1 \frac{1}{2} - \beta w_1 + \frac{\beta c_{m1}}{2}, \quad (b2) \]
\[ \frac{\partial \pi_{m2}}{\partial w_2} = a_2 \frac{1}{2} - \beta w_2 + \frac{\beta c_{m2}}{2} - \frac{\beta \delta}{2}, \quad (b3) \]
\[ \frac{\partial \pi_{m2}}{\partial \tau} = \delta \left( \frac{a_2}{2} - \beta w_2 + \frac{\gamma}{2} w_1 \right) - B \tau. \quad (b4) \]
Using equations (b2)-(b4) and the assumption (a1), we know that $\pi_{m1}$ is concave in $w_1$ and $\pi_{m2}$ is jointly concave in $w_2$ and $\tau$. Therefore, by setting equations (b2)-(b4) to zero and solving them simultaneously, equations (7)-(9) can be obtained. With equations (5)-(9), Proposition 1 can be obtained.

**Proof of Proposition 2.** It follows from equations (4)-(6) that the first order partial derivatives of $\pi_{m2}$ to $w_2$ and $\tau$ can be shown as in equations (b3) and (b4). By setting equations (b3) and (b4) to zero and solving them simultaneously, equations (12) and (13) can be obtained.

It follows from equations (3), (12) and (13) that the first and second order derivatives of $\pi_{m1}$ to $w_1$ can be shown as

$$
\frac{\partial \pi_{m1}}{\partial w_1} = \frac{a_1}{2} + \frac{2B\gamma^2 - 2\beta \gamma^2 \delta^2 - 4\beta^2 B + \beta^3 \delta^2}{4\beta B - \beta^2 \delta^2} w_1 + \frac{\beta c_{m1}}{2} + \frac{\gamma (a_2 \beta \delta^2 - 2a_2 B - 2B \beta c_{m2} - \beta \gamma \delta^2 c_{m1} + 2B \gamma c_{m1})}{2(\beta^2 \delta^2 - 4B \beta)}.
$$

(b5)

$$
\frac{\partial^2 \pi_{m1}}{\partial w_1^2} = \frac{\beta^2 \delta^2 - 2B \beta^2 + 4B \beta^2}{\beta^2 \delta^2 - 4B \beta} < 0.
$$

(b6)

By setting equation (b5) to zero and solving it, equation (14) can be obtained. Using equations (5), (6), (12)-(14), Proposition 2 can be obtained.

**Proof of Proposition 3.** From equations (3), (5) and (6), the first order derivative of $\pi_{m1}$ with respect to $w_1$ can be shown as in equation (b2), and we can prove that $\pi_{m1}$ is concave in $w_1$. By setting equation (b2) to zero and solving it, equation (19) can be obtained.

It follows from equations (4)-(6), and equation (19) that the first order partial derivatives of $\pi_{m2}$ to $w_2$ and $\tau$ can be shown as

$$
\frac{\partial \pi_{m2}}{\partial w_2} = \frac{\gamma^2 - 2\beta \gamma^2}{2} w_2 + \frac{\delta (\gamma^2 - 2\beta^2)}{4\beta} \tau + \frac{2a_2 + \gamma c_{m1}}{4} + \frac{a_1 \gamma - c_{m2}(\gamma^2 - 2\beta^2)}{4\beta},
$$

(b7)

$$
\frac{\partial \pi_{m2}}{\partial \tau} = \frac{\delta (\gamma^2 - 2\beta^2)}{4\beta} - B \tau + \frac{\delta (2a_2 + \gamma c_{m1})}{4} + \frac{\gamma \delta a_1}{4\beta}.
$$

(b8)

Under the condition (a1), we can see that $\pi_{m2}$ is jointly concave in $w_2$ and $\tau$. By setting equations (b7) and (b8) to zero and solving them, simultaneously, we obtain equations (20) and (21). With equations (5), (6), (19), (20), and equation (21), one can easily have equations (22)-(24). So, Proposition 3 can be obtained.

**Proof of Proposition 4.** From equations (3), (4), and equation (25), the first order derivative of $\pi_{m1}$ to $w_1$ and the first order partial derivatives of $\pi_{m2}$ to $w_2$ and $\tau$ can be shown as

$$
\frac{\partial \pi_{m1}}{\partial w_1} = a_1 - \beta p_1 + \gamma p_2 + \beta c_{m1} - \beta w_1,
$$

(b9)

$$
\frac{\partial \pi_{m2}}{\partial w_2} = a_2 - \beta p_2 + \gamma p_1 - \beta w_2 + \beta c_{m2} - \beta \delta \tau,
$$

(b10)

$$
\frac{\partial \pi_{m2}}{\partial \tau} = \beta a_2 - \beta \delta p_2 + \gamma \delta p_1 - B \tau.
$$

(b11)

With equations (b9)-(b11) and the condition (a1), we can know that $\pi_{m1}$ is concave in $w_2$ and $\pi_{m2}$ is jointly concave in $w_2$ and $\tau$. By setting equations (b9)-(b11) to zero and solving them, simultaneously, we obtain equations (26)-(28).
It follows from equations (2), (25)-(28) that the first order partial derivatives of $\pi_r$ to $p_1$ and $p_2$ can be shown as
\[
\frac{\partial \pi_r}{\partial p_1} = A_4p_1 + A_5p_2 + A_6, \quad (b12)
\]
\[
\frac{\partial \pi_r}{\partial p_2} = A_7p_1 + A_8p_2 + A_9. \quad (b13)
\]

With the condition (a1) and (a2), we can know that $\pi_r$ is jointly concave in $p_1$ and $p_2$. By setting equations (b12) and (b13) to zero and solving them, simultaneously, we obtain equations (29) and (30). From equations (26)-(30), it can be seen that Proposition 4 holds.

**Proof of Proposition 5.** Similar to the proof of Proposition 4, we can easily obtain the results in (27) and (28). It follows from equations (3), (25), (27), and (28) that the first order derivative of $\pi_m$ to $w_1$ can be shown as
\[
\frac{\partial \pi_m}{\partial w_1} = a_1 + (\beta - \gamma A_1)c_{m1} - \beta p_1 + \gamma p_2 - (\beta - \gamma A_1)w_1. \quad (b14)
\]

With the condition (a1), we can know that $\pi_m$ is concave in $w_1$. By setting equation (b15) to zero and solving it, we obtain equation (34).

It follows from equations (2), (27), (28) and (34) that the first order partial derivatives of $\pi_r$ to $p_1$ and $p_2$ can be shown as
\[
\frac{\partial \pi_r}{\partial p_1} = E_4p_1 + E_5p_2 + E_6, \quad \frac{\partial \pi_r}{\partial p_2} = E_7p_1 + E_8p_2 + E_9. \quad (b15)
\]

With the condition (a3), we can know that $\pi_r$ is jointly concave in $p_1$ and $p_2$. By setting equation (b15) to zero and solving them, simultaneously, we can obtain Proposition 5.

**Proof of Proposition 6.** Similar to the proof of Proposition 4, we can easily obtain the result in (26). It follows from equations (4), (25), and (26) that the first order partial derivatives of $\pi_m$ to $w_2$ and $\tau$ can be shown as
\[
\frac{\partial \pi_m}{\partial w_2} = \frac{\gamma^2 - \beta^2}{\beta}w_2 + \frac{\delta(\gamma^2 - \beta^2)}{\beta} \tau + a_2 - \beta p_2 + \gamma p_1 - c_{m2}(\gamma^2 - \beta^2), \quad (b16)
\]
\[
\frac{\partial \pi_m}{\partial \tau} = \delta(a_2 - \beta p_2 + \gamma p_1) - B\tau. \quad (b17)
\]

With equations (b16) and (b17) and the condition (a1), we can prove that $\pi_m$ is jointly concave in $w_2$ and $\tau$. By setting equations (b16) and (b17) to zero and solving them, simultaneously, we can obtain equations (40) and (41).

It follows from equations (2), (26), (40) and (41) that the first order partial derivatives of $\pi_r$ to $p_1, p_2$ can be shown as
\[
\frac{\partial \pi_r}{\partial p_1} = F_4p_1 + F_5p_2 + F_6, \quad \frac{\partial \pi_r}{\partial p_2} = F_7p_1 + F_8p_2 + F_9. \quad (b18)
\]

With the condition (a4), we can know that $\pi_r$ is jointly concave in $p_1$ and $p_2$. By setting equation (b18) to zero and solving them, simultaneously, we can obtain equations (42) and (43). From equations (26), (40)-(43), we can obtain Proposition 6.
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