PRICING NEW AND REMANUFACTURED PRODUCTS BASED ON CUSTOMER PURCHASING BEHAVIOR

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Abstract. Firms’ pricing strategies are largely influenced by customer purchasing behavior. By considering whether to invest in customer purchasing behavior analysis, firms can choose a discriminatory or a non-discriminatory pricing model. This paper presents a two-period duopoly that the original material supplier (OS) supplying new products faces a competition of an independent material supplier (IS) providing remanufactured products to analyze each party’s competitive strategy under each pricing model. We also identify situations under which the firms would obtain more profits and cause less environmental impact under the model with price discrimination compared with the model without price discrimination. A numerical study is provided to illustrate the performance of the model. A sensitivity analysis with respect to primary parameters is used to assess the stability of the model. The proposed model could be applied in many industrial fields where the managers have the full awareness of extended producer responsibility, and they are willing to engage in the project related to remanufacturing.

1. Introduction. Industrialization has increasingly consumed energy and materials, burdening natural resources. It is important to find an economical and environmentally friendly way to recovery used materials and products. Many countries, including 27 Member States of the European Union [43], 25 States in the United States [35], China [24], and Japan [40], have introduced legislation based on extended producer responsibility (EPR) to prompt product recovery. Under these policies, many firms have begun to recognize EPR to implement product recovery management [7, 14].

Product recovery is a way to extend the life of used materials and products, which consists of quality recovery, material recovery, and energy recovery [7, 15]. Used items are regarded as a valuable source of remanufactured products [37]. Firms can achieve cost savings by acquiring used items as remanufacturing materials. Since
there is no uniform definition for remanufactured products, our paper considers that the products formed by processing the used materials are remanufactured products as well. Material remanufacturing can be observed for wide application, such as steel, copper and plastic.

In the auto industry, remanufacturing saves over 80% of the energy and raw materials required to manufacture a new part, and keeps used cores out of landfills [42]. However, material remanufacturing has not been fully realized. For example, our experiences with auto manufacturers in China suggest that at least 30% of steel materials used for producing autos are wasteful, but these materials are not used up to the end of physical life. Steel accounts for 72% ∼ 88% of the total raw materials used to manufacture an auto. China’s auto annual sales volume reaches tens of millions [22]. With market demand for automobiles increasing, auto manufacturers need more steel products, meanwhile, the problem of waste of resources is getting worse. Consumer automobile markets have the greatest growth potential for material remanufacturing.

To make full use of the residual value of used material products, one option for the auto manufacturers is to sell them to their suppliers. Thus, we are interested in the production and marketing of material products for suppliers in the closed-loop supply chains. That means the used material products of auto manufacturers are bought-back and remanufactured by the supplier. Previous research has shown that firms have deployed a variety of remanufacturing ways. For the original equipment manufacturers (OEMs), they can choose not to remanufacture [42]. For the independent remanufacturers (IRs) or third party remanufacturers (3PRs), they can implement remanufacturing [33]. We use the term OEM and IR in the broadest sense to include original material suppliers (OSs, identified by subscript o) and independent material suppliers (ISs, identified by subscript i), respectively. The OS manufactures new products and the IS produces remanufactured products. Therefore, how do firms make price decisions in a competitive setting?

In the consumer market, customers’ willingness-to-pay (WTP) for remanufactured products is lower than new products because customers’ perceived value of the remanufactured products is lower in quality than new products [2, 13]. Therefore, we assume customers’ WTP for the remanufactured product is a fraction of for the new product, which we call customer discount factor. Accordingly, firms engaging in remanufacturing attract customers by offering a lower price for remanufactured products than new products. Consequently, a fraction of customers will switch from purchasing new products to remanufactured products. Pricing decisions made by firms and customers’ WTP have a significant impact for customers purchasing behaviors. In order to set optimal prices to maximize firms’ profits and minimize environmental impact, it is essential to analyze customer purchasing behavior. The analysis of customer purchasing behavior enables firms to discriminate pricing for different types of customers. Therefore, under what conditions will the firms invest in customer purchasing behavior analysis?

The goal of this paper is to study the impact of cost savings and customer discount factor for the optimal decisions of firms under different pricing models, to discuss the effects of different pricing models on firms’ profits and environment, and to find the condition that the firms invest in customer purchasing behavior analysis. Therefore, we present a duopoly model: an OS and an IS. The OS makes new products by using original raw materials. The IS produces remanufactured products by using used materials. Then, the OS and the IS competitively determine product
prices, which determine the respective quantity of the products. In a single period model, the price remains unchanged. However, in a two-period model, customer purchasing behavior plays an important role. Firms can adjust prices for different customer types based on customer purchasing behavior. We assume that each customer is rational. Thus, customers choose which supplier to purchase products based on their maximum utility. We consider two models for this question: (1) a benchmark model without firms’ price discrimination, (2) and a model with firms’ price discrimination based on customer purchasing behavior.

We analyze these models and provide realistic insights. We now summarize our key findings. Firstly, under both models, the two-period profits of the OS decrease in customer discount factor, but the two-period profits of the IS first decrease then increase in the customer discount factor. The increase in cost savings leads to the increase in the profitability of the IS’s, thus enhancing the motivation of the IS to produce remanufactured products. Furthermore, if customer discount factor is relatively high, price discrimination is more conducive to the increase in the IS’s profits. Secondly, by comparing the two scenarios, we find that when the cost savings are small, if customer discount factor is relatively high, the OS can obtain higher profits and has less impact for the environment through pricing discrimination based on customer purchasing behavior. In this case, the OS is more willing to invest in the customer purchasing behavior analysis. On the contrary, the IS’s profits increase and environmental impact decreases through pricing discrimination. In this case, the IS is more profitable by investing in the customer purchasing behavior analysis. And then, a higher customer discount factor gives the OS an incentive to invest in the customer purchasing behavior analysis from the perspective of profitability. Conversely, a higher customer discount factor facilitates the IS to adopt pricing discrimination based on environmental sustainability. Finally, when the cost savings and the customer discount factor are relatively low, the total environmental impact increases as both firms adopt pricing discrimination. Otherwise, pricing discrimination reduces total environmental impact and total profits of both firms. Therefore, to facilitate firms to make efforts to reduce total environment impact, policy makers can compensate firms’ profit losses by utilizing subsidy policy.

The study is organized as follows. Section 2 reviews related literature. Section 3 describes the models and discusses competitive strategies between the OS and the IS. Section 4 shows numerical study that illustrates the model. Section 5 conducts sensitivity analysis of the primary parameters. Section 6 concludes this paper and states future research directions.

2. Literature review. Our research draws on several streams of literature, each of which we review below. The literature on closed-loop supply chains is growing. Guide and Van Wassenhove [16] present the common processes for a closed-loop supply chain: product acquisition, reverse logistics, inspection, testing and disposition, remanufacturing, and distribution and selling. A good overview of closed-loop supply chains is provided by Souza [34]. From the remanufacturing operations management perspective, the author focuses on strategic and tactical decisions, such as remanufacturing and pricing strategies. Our research focus here is on pricing strategies based on customer purchasing behavior in a remanufacturing setting.

There is a general agreement that remanufacturing has focused on operational issues that involve disassembling, inspecting, repairing, replacing, and reassembling the components of a part or product to as-new condition and selling them again.
Production planning and inventory management are also notable aspects of remanufacturing operations. From the remanufacturable object of production planning perspective, the remanufacturing of cores or components (such as automotive parts, personal computers, photocopiers, telephones) has been concerned in reality and research domain [12, 36]. However, material remanufacturing has not gained too much attention from an academic perspective. Our experiences with firms engaged in material remanufacturing also suggest how to make the reuse of materials profitable has not been adequately addressed. Firms may gain profits by recycling these items, moreover, they may get greater economic benefits by remanufacturing them [31]. Thus, our focus is reusing these used materials to take full advantage of their remaining value.

From the inventory management perspective, Lotfi et al. [20] study a two-period newsvendor problem with unsatisfied demand or unsold quantity. The demand of different periods is interdependent. Furthermore, Lotfi et al. [21] develop a two-period newsvendor problem with interdependent demands to determine the start times and ordering plans of projects. The proposed model has been applied to the molding industry and has proven to provide a better solution than independent demand. Pervin et al. [28] develop a deteriorating inventory model with time-dependent demand and holding costs where shortages are allowed. Pervin et al. [29] extend their model by introducing a multi-item model and a two-level supply chain model in which the demand is stock-dependent and price-dependent. The retailer can adopt trade-credit policy to facilitate market competitiveness. Subsequently, Roy et al. [32] consider a two-warehouse probabilistic model for deteriorating items. Both the supplier and the retailer can adopt the trade-credit policy to promote market competition. Customers can obtain a price discount if they are willing to back-order their demand. In addition, Pervin et al. [30] develop an Economic Production Quantity inventory model for deteriorating items with stock-dependent and price-dependent demand, shortages, inflation under preservation technology investment. Later, a cloudy-fuzzy inventory model for deteriorating items with time-dependent demand and shortages under partially backlogging condition is constructed by Barman et al. [8].

This stream of literature studies market issues, for instance, how the competition between new and remanufactured products affects the pricing and quantity decisions of each party (a feature that also exists in our model) [11, 12, 25]. Ferguson and Toktay [11] develop models to analyze how the OEM makes decisions in the case where the internal competition exists between a new and remanufactured product, as well as the case where the external competition arises between a OEM and a 3PR. They find that the OEM can deter the entry of 3PR by remanufacturing. Ferrer and Swaminathan [12] also consider a monopoly environment and a duopoly environment. For the former, they suggest that the OEM should lower the price of new products in the first period to increase the availability of cores for remanufacturing in the second period. For the latter, they provide that the OEM should increase remanufacturing rate, and charge a lower price for remanufactured products than 3PRs. The literature makes different assumptions that each party whether takes remanufacturing strategy: a monopolist OEM produces the new and the remanufactured product (e.g., [11, 12, 26, 44]), an IR who only remanufacturing poses a threat to the OEM (e.g., [3, 12, 25]). We study competitive pricing strategies for an OS and an IS. The OS and the IS engage in Bertrand type price competition in our model as in [12], [26], and [41].
Table 1 Some Key Literature on Remanufacturing and Pricing Strategies

| Reference | Production planning | Component remanufacturing | Material remanufacturing | Market competition | Consumer behavior |
|-----------|---------------------|---------------------------|--------------------------|-------------------|------------------|
| Ferrer and Steinmann \[12\] | √ | | | | |
| Ferrer and Henry \[15\] | | | | | |
| Loff et al. \[28\] | | | | | |
| Loff et al. \[29\] | | | | | |
| Pervin et al. \[30\] | | | | | |
| Roy et al. \[31\] | | | | | |
| Ovchinnikov \[26\] | | | | | |
| Ovchinnikov \[27\] | | | | | |
| Ferguson and Toktay \[11\] | | | | | |
| Ferguson and Tulay \[11\] | | | | | |
| Ovchinnikov \[26\] | | | | | |
| Ovchinnikov \[27\] | | | | | |
| Abbott et al. \[2\] | | | | | |
| Weng et al. \[9\] | | | | | |
| Weng et al. \[9\] | | | | | |
| Atasu et al. \[5\] | | | | | |
| This paper | √ | √ | √ | | √ |

Recently, customer purchasing behavior is being explored by some scholars. Customer behavior choosing the remanufactured product may cannibalize the sales of the new product \[2, 11, 12, 41, 42, 45\]. However, the presence of remanufactured products can make the OEM relieve the effects of cannibalization and increase profitability \[1\]. Abbey et al. \[2\] study consumers’ WTP for remanufactured products and investigate perceived quality risk construct, the impact of quality for WTP, and the magnitude and distribution of discount factors for remanufactured products. Green consumers behave differently for remanufactured products and new products. Nevertheless, Atasu et al. \[5\] study the impacts of green consumer bases, cannibalization, competition and diffusion for a manufacturer’s remanufacturing decision, finding that the ratio of green consumers in the market is very low. Ovchinnikov \[26\] explores consumers’ switching behavior between the new and the remanufactured product within a firm. They find that a lower price will discourage customers from switching. Research combining remanufactured product pricing with customer behavior is only just emerging. We contribute to this emerging stream of literature by investigating the customer behavior under basic supply-loop constraints such as a special price discount offered by firms. We also discuss the impact of different pricing strategies based on customer purchasing behavior for firms’ profits and environment, and inspire firms to decide whether to invest in customer purchasing behavior analysis.

Table 1 presents an overview of the literature on remanufacturing and pricing problems. From the perspective of remanufacturing strategy, material remanufacturing has not been paid much attention in the literature. We complement this literature by considering firms’ pricing strategies based on remanufacturing to maximize the economic value and environmental benefits of material products. From the perspective of pricing strategy, in comparison to the extant literature, we highlight the critical role of customer purchasing behavior, which inspires firms to make more favorable operational decisions.

3. Model description and analysis. In this section, we build a duopoly with the OS and the IS in a two-period model. To clearly compare the pricing strategies, profits and environmental impacts of each party, we assume that the OS does manufacture and the IS engages in remanufacturing. The firms have access to sufficient new materials for manufacturing and used materials for remanufacturing. In
this model, subscripts $t \in \{1, 2\}$ are identified as period 1 and period 2, respectively. Producing a remanufactured product is less costly than manufacturing a new one, i.e., $C_r < C_n$ is the same for all remanufactured products [9, 25, 33, 34]. $C_s$ represents the cost savings for per remanufactured product relative to per new one, $C_s \equiv C_n - C_r$. $C_n$, $C_r$ and $C_s$ are treated as exogenous parameters. Where the subscript $n$ and $r$ refer to the new product and the remanufactured product, respectively.

Following the consumer preferences of Moorthy [23], the consumer willingness-to-pay $\theta$ of quality is heterogeneous and uniformly distributed over a support. Without loss of generality, we normalize to $\theta \in [0, 1]$. A customer of type $\theta$ has a valuation $\theta$ for a new product. We model consumer willingness to pay for the remanufactured product as a $\alpha$ fraction of the new product where $\alpha \in (0, 1)$. We call $\alpha$ customer discount factor. Although most remanufactured products make no less than new products, customers have heterogeneous valuations for quality [18]. In reality, customers would like to pay more for new products because customers often perceive the remanufactured product as being of inferior quality. The customer discount factor $\alpha$ is assumed to a constant as in most cases [10, 11, 25, 41, 42]. In each period, a customer uses at most one unit. The market size is normalized to 1.

The per-unit environmental impact of a new (remanufactured) product is $e_n$ ($e_r$) in each period. Environmental impact refers to the sum of corresponding production/use/disposal effect during the life cycle of a product. In the steel industry, environmental impact represents the environmental cost caused by energy consumptions and gas emissions [4, 19]. For brevity, we use the total environmental impact per unit of product. Because remanufacturing activities can reuse used materials and products, the total environmental impact per unit of remanufactured product is lower than that of new product, i.e., $e_r < e_n$. The total environmental impact of each firm depends on the quantity of products in each period multiplied by the per-unit impact of the product in each period [17, 38].

The timing of the game is as follows. At the beginning, both the OS and the IS decide whether to invest in customer purchasing behavior analysis to adopt pricing discrimination for different types of customers in the future. If the firms decide to invest, the amount of investment is $V$. In period 1, the OS charges a price for the new product. The IS sets the price of the remanufactured product. In period 2, if both firms choose not to invest in customer purchasing behavior analysis, the firms still set the same price for their products as the previous period. On the other hand, if the firms invest, they will adopt discriminatory pricing for different types of customers by observing customers’ early purchasing behavior. Then, customers choose to buy from the firm where they bought the product in previous period, or switch to another one. Our definitions are summarized below.

**Indices:**
- $t$: Index of periods ($t \in \{1, 2\}$),
- $x$: Index of models ($x \in \{A, B\}$),
- $y$: Index of players ($y \in \{o, i\}$),
- $z$: Index of customer types ($z \in \{l, v\}$),
- $\theta$: The consumer willingness to pay for quality ($\theta \in [0, 1]$);

**Parameters:**
- $\alpha$: Customer discount factor, that is, the ratio between consumer willingness to pay for the remanufactured product and for the new product,
- $C_n$: The unit production cost of a new product,
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\( C_r \): The unit production cost of a remanufactured product,

\( C_s \): The cost savings on per remanufactured product relative to per new product,

\( e_n \): The per-unit environmental impact of a new product,

\( e_r \): The per-unit environmental impact of a remanufactured product;

**Decision variables:**

- \( P_{tn}^x \): The new product price under model \( x \) in period \( t \),
- \( P_{tr}^x \): The remanufactured product price under model \( x \) in period \( t \),
- \( q_{tn}^x \): Quantity demand for new product under model \( x \) in period \( t \),
- \( q_{tr}^x \): Quantity demand for remanufactured product under model \( x \) in period \( t \),
- \( \delta_{nz} \): Discount of per unit that original supplier offers to \( z \) type customer,
- \( \delta_{rz} \): Discount of per unit that independent supplier offers to \( z \) type customer;

**Objectives:**

- \( \Pi_{ty}^x \): The player \( y \)’s profit under model \( x \) in period \( t \),
- \( E_{ty}^x \): The environmental impact of the player \( y \) under model \( x \).

Therefore, we analyze two pricing models, one is not to consider the firms’ price discrimination, the other is to consider the firms’ price discrimination based on customer purchasing behavior. Our primary goal is to find the impact of cost savings and customer discount factor for the pricing decisions and profits of firms under different models, to analyze the impact of the pricing discrimination based on customer purchasing behavior for firms’ profitability and environment, and to identify conditions when firms’ investment in customer purchase behavior analysis benefits both firms’ profits and environment. We start with a benchmark model (section 3.1) without firms’ pricing discrimination (Model A, Figure 1a). Next, we consider a model (section 3.2) with firms’ pricing discrimination based on customer purchasing behavior (Model B, Figure 1b). The comparison (section 3.3) between these models will allow us to observe how the pricing strategies made by each party affects its profits and environment.

![Figure 1: Pricing new and remanufactured products without or with price discrimination](image)

3.1. **Each party’s strategy without price discrimination.** Considering that firms wouldn’t make an investment in customer purchasing behavior analysis to distinguish customer types, in this section, we study the benchmark model where both firms don’t adopt price discrimination (Model A, Figure 1a). Thus, the two periods are independent and identical.

Let \( P_{tn}^A \) and \( P_{tr}^A \) denote the OS’s new product price and the IS’s remanufactured product price in period \( t \), respectively. The demand functions can be formulated
from customers’ maximum utility for purchasing each type of product. We follow the general approach that customer utility is derived from the customer’s intrinsic valuation and the value provided by the product similar to [23]. $U_0$ is the basic utility produced by the product to all customers. We assume $U_0$ is sufficiently high so that all customers purchase the product in each period. Thus the entire market size remains stable. A customer of type $\theta$ receives utility $U_{tn} = U_0 + \theta - P_{tn}$ from purchasing a new product, but derives utility $U_{tr} = U_0 + \alpha \theta - P_{tr}$ from a remanufactured product. If $U_{tn} > U_{tr}$, a customer $\theta$ will purchase a new product, otherwise, a customer $\theta$ will purchase a remanufactured product. Therefore, the following market demand functions $q_{tn}^A$ for the new products and $q_{tr}^A$ for the remanufactured products are presented.

$$q_{tn}^A = 1 - \frac{P_{tn} - P_{tr}}{1 - \alpha}$$ (1)

$$q_{tr}^A = \frac{P_{tn} - P_{tr}}{1 - \alpha}$$ (2)

Let $\pi_{t_o}^A$ and $\pi_{t_i}^A$ represent the OS’s and the IS’s each period profit, respectively. $\pi_{t_o}^A = \sum_{t=1}^{2} \pi_{t_{o}}^A (\pi_{t_{i}}^A = \sum_{t=1}^{2} \pi_{t_{i}}^A)$ is the two-period profits of the OS (IS). The OS only makes decisions on the new product. Thus, its per-period objective function is:

$$\max \pi_{t_o}^A = (P_{tn}^A - C_n)q_{tn}^A$$ (3)

The IS only makes decisions on the remanufactured product. The IS’s each period profit is as follows:

$$\max \pi_{t_i}^A = (P_{tr}^A - C_r)q_{tr}^A$$ (4)

The two-period environmental impact of the OS (IS) is $E_{t_o}^A = e_n q_{tn}^A (E_{t_i}^A = e_r q_{tr}^A)$. $q_{tn}^A (q_{tr}^A)$ is the total demand for new (remanufactured) products in two periods. The total environmental impact of both the OS and the IS is $E_{t}^A = E_{t_o}^A + E_{t_i}^A$. We analyze the Nash equilibrium and calculate each party’s profits and environmental impacts. The results are as follows.

$$P_{tn}^{A*} = \frac{2 - 2\alpha + 2C_n + C_r}{3}$$ (5)

$$P_{tr}^{A*} = \frac{1 - \alpha + C_n + 2C_r}{3}$$ (6)

$$q_{tn}^{A*} = \frac{2 - 2\alpha - C_n + C_r}{3(1 - \alpha)}$$ (7)

$$q_{tr}^{A*} = \frac{1 - \alpha + C_n - C_r}{3(1 - \alpha)}$$ (8)

$$\pi_{t_o}^{A*} = \frac{2(2 - 2\alpha - C_n + C_r)^2}{9(1 - \alpha)}$$ (9)

$$\pi_{t_i}^{A*} = \frac{2(1 - \alpha + C_n - C_r)^2}{9(1 - \alpha)}$$ (10)


\[ E^*_\alpha = \frac{2\epsilon_n(2 - 2\alpha - C_n + C_r)}{3(1 - \alpha)} \]  
(12)

\[ E^*_i = \frac{2\epsilon_r(1 - \alpha + C_n - C_r)}{3(1 - \alpha)} \]  
(13)

\[ E^*_r = \frac{2((1 - \alpha)(2\epsilon_n + \epsilon_r) - (C_n - C_r)(\epsilon_n - \epsilon_r))}{3(1 - \alpha)} \]  
(14)

**Proof.** See Appendix A.

Based on the solution, we make the following observations. First, the OS's two-period profits is higher than the IS's two-period profits if \( C_s < \frac{1 - \alpha}{2} \), vice versa. Then, we can observe that the impact of customer discount factor for the profits of the firms.

**Proposition 1.** In the benchmark model, the changes of each party’s two-period profits in relation to customer discount factor (\( \alpha \)) are as follows:

- If \( 0 < \alpha \leq 1 - \frac{C_s}{2} \), the OS’s two-period profits decrease in \( \alpha \).
- If \( 0 < \alpha < 1 - C_s \), the IS’s two-period profits decrease in \( \alpha \). If \( 1 - C_s < \alpha \leq 1 - \frac{C_s}{2} \), the IS’s two-period profits increase in \( \alpha \).

**Proof.** See Appendix B.

Proposition 1 shows that as \( \alpha \) increases, the two-period profits of the OS decrease, but the two-period profits of the IS do not always improve. Intuitively, with the increase of \( \alpha \), the customer’s perceived value difference between the new and the remanufactured product decreases, thereby intensifying the competition between firms. To reduce customer loss, both firms have to set lower prices. Moreover, a high \( \alpha \) results in an increase in the demand for remanufactured products, but a decrease in the demand for new products. Therefore, the two-period profits of the OS decrease as customer discount factor increases.

However, when \( \alpha \) is relatively low (\( 0 < \alpha < 1 - C_s \)), the two-period profits of the IS decrease in \( \alpha \). Otherwise, the two-period profits of the IS increase in \( \alpha \). The rationale behind this is as follows. When \( \alpha \) is relatively low, as \( \alpha \) increases, the increase in the demand for remanufactured products is dominated by the decrease in the price of the remanufactured product, as a result, the profits of the IS will increase. On the contrary, the decrease in the price of the remanufactured is dominated by the increase in the demand for remanufactured products, therefore, the profits of the IS will increase in \( \alpha \).

In addition, when \( C_s \) goes up, the corresponding range of the customer discount factor shrinks in the case that the profits of the IS decrease with \( \alpha \), and the corresponding range of the customer discount factor widens in the case that the profits of the IS increase with \( \alpha \). This result shows that the increase in cost savings will inevitably lead to the increase in the widened range of the customer discount factor, thereby increasing the IS’s profitability, which enhances the motivation of the IS to produce remanufactured products.

### 3.2. Each party’s strategy with price discrimination.

In this section, we study the model with firms’ price discrimination based on customer purchasing behavior (Model B, Figure 1b), which represents that both firms invest in customer purchasing behavior analysis. The amount of investment is \( V \). To find the subgame perfect equilibrium, we start with period 2. In this period, the OS sets discount price \( P_{2|nl} = \delta_{nl} P_{1n}^B \) for its loyal customers who keep on buying new products, where the
subscript $l$ represents customers’ repeated purchase behavior, and $P_{2nl} = \delta_{nl} P_{1n}^B$ for volatile customers who transfer from the IS, where the subscript $v$ represents customers’ transfer behavior. The IS responds with discount prices $P_{2rl} = \delta_{rl} P_{1r}^B$ for its loyal customers who keep on purchasing remanufactured products, and $P_{2rv} = \delta_{rv} P_{1r}^B$ for volatile customers who come from the OS. $\delta$ is the price discount provided by the firms to customers with different purchase behaviors.

We first analyze the customers’ second-period purchase decisions. We assume that $\theta_1$ is the customer indifferent between the new and the remanufactured products, and $P_{1n}^B (P_{1r}^B)$ is the price of the new (remanufactured) product in period 1. The rational customer $\theta \in (\theta_1, 1]$ purchased new products in period 1 will keep on buying $q_{2nl}$ new products from the OS in period 2 if $U_0 + \theta - \delta_{nl} P_{1n}^B > U_0 + \alpha \theta - \delta_{rl} P_{1r}^B$, i.e., $\theta > \theta_2 = \frac{\delta_{nl} P_{1n}^B - \delta_{rl} P_{1r}^B}{1 - \alpha}$, and will switch to the IS to buy remanufactured products otherwise. The switching capacity is $q_{2rv}$. The customer $\theta \in (0, \theta_1]$ purchased remanufactured products in period 1 will keep on buying $q_{2vl}$ remanufactured products from the IS in period 2 if $U_0 + \alpha \theta - \delta_{vl} P_{1r}^B > U_0 + \theta - \delta_{rv} P_{1r}^B$, i.e., $\theta < \theta_3 = \frac{\delta_{rl} P_{1r}^B - \delta_{rv} P_{1r}^B}{1 - \alpha}$, and will turn to the OS to buy new products otherwise. The switching capacity is $q_{2nv}$. The total demand for each products are $q_{2nl}^B$ and $q_{2vl}^B$ in period 2. The choice of the customer depends on their maximum net utility. Then, the demand for each product type is:

\[
q_{2nl} = 1 - \frac{\delta_{nl} P_{1n}^B - \delta_{rv} P_{1r}^B}{1 - \alpha} \quad (15)
\]

\[
q_{2nv} = \theta_1 - \frac{\delta_{nv} P_{1n}^B - \delta_{rl} P_{1r}^B}{1 - \alpha} \quad (16)
\]

\[
q_{2rl} = \frac{\delta_{nv} P_{1n}^B - \delta_{rl} P_{1r}^B}{1 - \alpha} \quad (17)
\]

\[
q_{2rv} = \frac{\delta_{nl} P_{1n}^B - \delta_{rv} P_{1r}^B}{1 - \alpha} - \theta_1 \quad (18)
\]

Let $\pi_{2n}^B$ and $\pi_{2v}^B$ represent the OS’s and the IS’s second-period profits, respectively. The OS and the IS decide the price discounts that maximize their profits. We formulate the problem as follows:

\[
\max \pi_{2n}^B = (P_{2nl} - C_n) q_{2nl} + (P_{2nv} - C_n) q_{2nv} \quad (19)
\]

and

\[
\max \pi_{2v}^B = (P_{2rl} - C_r) q_{2rl} + (P_{2rv} - C_r) q_{2rv} \quad (20)
\]

The equilibrium price discounts of the OS are $\delta_{nl}^* = \frac{(1-\alpha)(2-\theta_1) + 2C_n + C_r}{3 P_{1n}^B}$, and $\delta_{nv}^* = \frac{2(1-\alpha)\theta_1 + 2C_n + C_r}{3 P_{1n}^B}$. The equilibrium price discounts of the IS are $\delta_{rl}^* = \frac{(1-\alpha)\theta_1 + 2C_n + 2C_r}{3 P_{1r}^B}$, and $\delta_{rv}^* = \frac{(1-\alpha)(1-2\theta_1) + C_n + 2C_r}{3 P_{1r}^B}$. The OS’s and the IS’s second-period profits are $\pi_{2n}^* = \frac{(5(\theta_1)^2 - 4\theta_1 + 4)(1-\alpha)^2 - 2(C_n - C_r)((2+\theta_1)(1-\alpha) - C_n + C_r)}{9(1-\alpha)}$, $\pi_{2v}^* = \frac{(5(\theta_1)^2 - 4\theta_1 + 1)(1-\alpha)^2 - 2(3n - C_r)((1-\theta_1)(1-\alpha) + C_n - C_r)}{9(1-\alpha)}$, respectively.

Using backward induction, in period 1, the utility of customers is determined not only by current product prices but also by future anticipation. Since the customer $\theta_1$ is indifferent to the new and the remanufactured products. A customer will buy new products if $\theta > \theta_1$, otherwise, a customer will buy remanufactured products. Let $q_{1n}^B$ and $q_{1v}^B$ be the respective demand for the new and the remanufactured product in period 1. Customers in $(\theta_2, \theta_1]$ will switch from the IS to the OS, and
customers in \((\theta_1, \theta_2)\) will switch from the OS to the IS in period 2 when \(\theta_1 \in (\theta_2, \theta_2)\). Therefore, when the customer \(\theta_1\) buys a new product in period 1, the total expected utility of the customer is \(2U_0 + \theta_1 - P_{1\text{in}}^B + \alpha \theta_1 - \delta_{\text{nv}}P_{1\text{r}}^B\). When the customer \(\theta_1\) buys a remanufactured product in period 1, the total expected utility of the customer is \(2U_0 + \alpha \theta_1 - P_{1\text{r}}^B + \delta_{\text{nv}}P_{1\text{in}}^B\). \(u_{1\text{in}}^B = \frac{1-\alpha-(C_n-C_r)-(P_{1\text{in}}^B-P_{1\text{r}}^B)}{4(1-\alpha)}\) is derived from indifference to the new and the remanufactured products of the customer \(\theta_1\), as a result, \(\theta_1 = \frac{1-\alpha-(C_n-C_r)-(P_{1\text{in}}^B-P_{1\text{r}}^B)}{4(1-\alpha)}\).

The OS’s first-period profit is \(\pi_{1\text{in}}^B = (P_{1\text{in}}^B - C_n)q_{1\text{in}}^B\), thus the OS’s two-period profits are

\[
\max \pi_{1\text{in}}^B = (P_{1\text{in}}^B - C_n)q_{1\text{in}}^B + \pi_{2\text{in}}^B \tag{21}
\]

The IS’s first-period profit is \(\pi_{1\text{r}}^B = (P_{1\text{r}}^B - C_r)q_{1\text{r}}^B\), then the IS’s two-period profits are

\[
\max \pi_{1\text{r}}^B = (P_{1\text{r}}^B - C_r)q_{1\text{r}}^B + \pi_{2\text{r}}^B \tag{22}
\]

The environmental impact of the OS and the IS are \(E_o^B = c_n q_n^B\) and \(E_r^B = v_r q_r^B\), respectively. \(q_n^B\) (\(q_r^B\)) is the total demand for new (remanufactured) products in two periods. \(E^B = E_o^B + E_r^B\) is the total environmental impact of both the OS and the IS. We derive the equilibrium solution in this scenario. The results are as follows.

\[
P_{1\text{in}}^{B*} = \frac{19(1-\alpha) + 18C_n + 6C_r}{24} \tag{23}
\]

\[
P_{1\text{r}}^{B*} = \frac{13(1-\alpha) + 6C_n + 18C_r}{24} \tag{24}
\]

\[
\delta_{1\text{nl}}^{B*} = \frac{25(1-\alpha) + 30C_n + 18C_r}{2(19(1-\alpha) + 18C_n + 6C_r)} \tag{25}
\]

\[
\delta_{1\text{nv}}^{B*} = \frac{(7(1-\alpha) + 18C_n + 6C_r)}{19(1-\alpha) + 18C_n + 6C_r} \tag{26}
\]

\[
\delta_{1\text{rl}}^{B*} = \frac{7(1-\alpha) + 18C_n + 30C_r}{2(13(1-\alpha) + 6C_n + 18C_r)} \tag{27}
\]

\[
\delta_{1\text{rv}}^{B*} = \frac{(1-\alpha) + 6C_n + 18C_r}{13(1-\alpha) + 6C_n + 18C_r} \tag{28}
\]

\[
q_{1\text{in}}^{B*} = \frac{9 - 9\alpha - 2C_n + 2C_r}{16(1-\alpha)} \tag{29}
\]

\[
q_{1\text{r}}^{B*} = \frac{7 - 7\alpha + 2C_n - 2C_r}{16(1-\alpha)} \tag{30}
\]

\[
q_{1\text{nl}}^{B*} = \frac{25 - 25\alpha - 18C_n + 18C_r}{48(1-\alpha)} \tag{31}
\]

\[
q_{1\text{nv}}^{B*} = \frac{7 - 7\alpha - 6C_n + 6C_r}{24(1-\alpha)} \tag{32}
\]

\[
q_{1\text{rl}}^{B*} = \frac{7 - 7\alpha + 18C_n - 18C_r}{48(1-\alpha)} \tag{33}
\]
\[
q_{rv}^* = \frac{1 - \alpha + 6C_n - 6C_r}{24(1 - \alpha)}
\]
\[
q_{2n}^* = \frac{13 - 13\alpha - 10C_n + 10C_r}{16(1 - \alpha)}
\]
\[
q_{2r}^* = \frac{3 - 3\alpha + 10C_n - 10C_r}{16(1 - \alpha)}
\]
\[
\pi_{o}^* = \frac{1847(1 - \alpha)^2 - 12(149(1 - \alpha) - 45(C_n - C_r))(C_n - C_r)}{2304(1 - \alpha)}
\]
\[
\pi_{i}^* = \frac{599(1 - \alpha)^2 + 12(59(1 - \alpha) + 45(C_n - C_r))(C_n - C_r)}{2304(1 - \alpha)}
\]
\[
E_{o}^* = \frac{e_n(11 - 11\alpha - 6C_n + 6C_r)}{8(1 - \alpha)}
\]
\[
E_{i}^* = \frac{e_r(5 - 5\alpha + 6C_n - 6C_r)}{8(1 - \alpha)}
\]
\[
E_{r}^* = \frac{(1 - \alpha)(11e_n + 5e_r) - 6(C_n - C_r)(e_n - e_r)}{8(1 - \alpha)}
\] 

**Proof.** See Appendix C. \(\square\)

According to these results in this scenario, we can observe that both the OS and the IS offer a lower price discount to volatile customers than to loyal customers \((\delta_{nv} < \delta_{nl}, \delta_{rv} < \delta_{rl})\). Intuitively, both firms would expect to attract more volatile customers from rivals with lower price discounts. In addition, the number of volatile customers \((q_{rv})\) who switch from the IS to the OS is higher than volatile customers \((q_{2rv})\) who switch from the OS to the IS when the customer discount factor is low \((0 < \alpha < 1 - 2C_s)\) and the cost savings is low \((0 < C_s < \frac{1}{2})\). Otherwise, \(q_{2rv}\) is higher than \(q_{2nv}\) when \(\max\{0, 1 - 2C_s\} < \alpha < 1 - \frac{6C_s}{7}\). The reason is the following. When the cost savings and customer discount factor are low, the OS has a greater advantage in offering a lower price discount to competitor’s volatile customers, thus attracting more customers from the IS, vice versa. We can further observe that the OS’s two-period profits is higher than the IS’s two-period profits if \(C_s < \frac{1 - \alpha}{2}\), vice versa.

The following lemma describes the changes in period 2 in the case of equilibrium compared with the previous period.

**Lemma 3.1.** *Compared with the first period, the equilibrium results in the second period of the firms based on customer purchasing behavior are as follows:*

- The price of new (remanufactured) products for both loyal and volatile customers will decrease if \(0 < \alpha < 1 - \frac{6C_s}{7}\).
- The demand for new products will increase, and the demand for remanufactured products will decrease if \(0 < \alpha < 1 - 2C_s\), where \(0 < C_s < \frac{1}{2}\); The demand for new products will decrease, and the demand for remanufactured products will increase if \(\max\{0, 1 - 2C_s\} < \alpha < 1 - \frac{6C_s}{7}\).
- The OS’s and the IS’s profits will decrease if \(0 < \alpha < 1 - \frac{6C_s}{7}\).

**Proof.** See Appendix D. \(\square\)

Lemma 3.1 states that compared with period 1, price discrimination based on customer purchasing behavior decreases the profits of the OS and the IS in period.
2. The reason is the following. Based on customer purchasing behavior in previous period, both the OS and the IS lower the prices of their products for loyal customers and volatile customers in period 2. Although, low price leads to the increase or decrease in the demands for new and remanufactured products. The change in demand of each product is always dominated by the decrease in price. Therefore, even an increase in the demand of the product cannot compensate for loss caused by the reduction of prices, in consequence, both the profits of the OS and the IS in period 2 decrease relative to the previous period.

The impacts of customer discount factor for the profits of the firms are as follows.

**Proposition 2.** In the model with price discrimination based on customer purchasing behavior, the changes of each party’s profits in relation to customer discount factor ($\alpha$) are as follows:

- If $0 < \alpha < 1 - \frac{6\sqrt{689}C_s}{599}$, the OS’s two-period profits decrease in $\alpha$.
- If $0 < \alpha < 1 - \frac{6\sqrt{689}C_s}{599}$, the IS’s two-period profits decrease in $\alpha$. If $1 - \frac{6\sqrt{689}C_s}{599} < \alpha < 1 - \frac{6C_s}{7}$, the IS’s two-period profits increase in $\alpha$.

**Proof.** See Appendix E.

As stated in the above proposition, the higher the $\alpha$, the smaller the two-period profits of the OS. The rationale is that a high $\alpha$ leads to a loss of the OS’s customers. To prevent customer loss from becoming serious, the OS has to lower the price of new products. Therefore, the two losses caused by a high customer discount factor lead to the decline of the OS’s two-period profits.

The two-period profits of the IS first decrease then increase in $\alpha$. This result needs to be explained by analysing the impact of $\alpha$ for the IS’s profit in each period. The IS’s first-period profit decreases in $\alpha$ for $0 < \alpha < 1 - \frac{6\sqrt{689}C_s}{53}$, and increases in $\alpha$ for $\max\{0, 1 - \frac{6\sqrt{689}C_s}{53}\} < \alpha < 1 - \frac{6C_s}{7}$. When $\alpha$ is low, the IS’s first-period profit and second-period profit both decrease in $\alpha$, or as $\alpha$ increases, the increase in the IS’s second-period profit is dominated by the decrease in the IS’s first-period profit. In this case, as customer discount factor rises, the IS obtains lower two-period profits. On the contrary, the IS gains higher two-period profits.

Moreover, compared with Model A, price discrimination based on customer purchasing behavior enlarges the range that the profits of the IS increase with $\alpha$ in Model B, ceteris paribus. Therefore, price discrimination is more conducive to the increase in the IS’s profits when the customer discount factor is relatively high. Furthermore, greater cost savings reduce the range of the IS’s two-period profits to fall, and expand the range of the IS’s two-period profits to rise.

### 3.3. Comparing model B and model A.

In order to find the conditions when firms will invest in customer purchasing behavior analysis, we now compare the relative profitability and the relative environmental impact of the firms in model B and Model A. Firms have incentives to invest in customer purchasing behavior analysis if $\pi_B^* > \pi_A^*$ and $E_B^* < E_A^*$. Furthermore, firms will take action to invest in customer purchasing behavior analysis if $V < \bar{V} = \pi_B^* - \pi_A^*$.

**Proposition 3.** The profits and environmental impact in Model B and in Model A are related as follows. It is also showed in Figure 2.
If $0 < \alpha < 1 - 2C_s$, where $0 < C_s < \frac{1}{2}$, $\pi_o^{B*} < \pi_o^{A*}$, $E_o^{B*} > E_o^{A*}$. If $\max\{0, 1 - 2C_s\} < \alpha < 1 - \frac{(32\sqrt{22+130})C_s}{201}$, where $0 < C_s < \frac{87}{32\sqrt{22+158}}$, $\pi_o^{B*} < \pi_o^{A*}$, $E_o^{B*} < E_o^{A*}$. If $\alpha < \frac{6C_s}{7}$, $\pi_o^{B*} > \pi_o^{A*}$, $E_o^{B*} > E_o^{A*}$.

If $0 < \alpha < 1 - \frac{(32\sqrt{22+158})C_s}{87}$, where $0 < C_s < \frac{87}{32\sqrt{22+158}}$, $\pi_i^{B*} > \pi_i^{A*}$, $E_i^{B*} > E_i^{A*}$. If $\alpha < \frac{6C_s}{7}$, $\pi_i^{B*} < \pi_i^{A*}$, $E_i^{B*} < E_i^{A*}$. If $\alpha < \frac{6C_s}{7}$, $\pi_i^{B*} > \pi_i^{A*}$, $E_i^{B*} > E_i^{A*}$.

Proof. See Appendix F.

Figure 2. The difference between Model B and Model A with respect to the firms' profits and environmental impact.

Proposition 3 states that when $C_s$ is small ($0 < C_s < \frac{87}{32\sqrt{22+158}}$), if $\alpha$ is relatively high ($1 - \frac{(32\sqrt{22+130})C_s}{201} < \alpha < 1 - \frac{6C_s}{7}$), the OS can obtain higher profits and cause less impact on the environment through pricing discrimination based on customer purchasing behavior. If $\alpha$ is relatively low ($0 < \alpha < 1 - \frac{(32\sqrt{22+158})C_s}{87}$), the IS’s profits increase and environmental impact decreases through pricing discrimination based on customer purchasing behavior. This is because the OS attracts less volatile customers from the IS than the IS attracts from the OS with a relatively high $\alpha$. In addition, price discrimination lowers the OS’s period 2 prices in model B in comparison to that in model A, thus reducing the second-period profit of the OS. Therefore, the OS seizes a larger market share with a higher price in period 1 in model B than that in model A. In this case, the loss of the OS’s second-period profit is dominated by the gain of the OS’s first-period profit, thus, the OS’s two-period profit
profits increase. Moreover, the increase in market share of new products in period 1 is lower than the decrease in period 2, consequently the environmental impact of the OS decreases.

Similarly, when \( C_s \) is small, the IS attracts less volatile customers from the OS than the OS attracts from the IS with a relatively low \( \alpha \). At the same time, compared with model A, price discrimination intensifies price competition in model B, thus resulting in the decline of the IS’s second-period profit. As a result, pricing discrimination based on customer purchasing behavior in model B increases the price and demand of the remanufactured product in period 1. In this case, the IS’s first-period profit gain dominates its second-period profit loss, increasing its two-period profits. In addition, the decrease of market share of the remanufactured products in period 2 dominates the increase in period 1, thus the environmental impact of the IS decreases.

Therefore, when the cost savings are small, the OS can not only obtain higher profits but also reduce the environmental impact by investing in customer purchasing behavior analysis if the customer discount factor is relatively high. The IS can earn higher profits and reduce environmental impact by investing in customer purchasing behavior analysis if the customer discount factor is relatively low.

**Corollary 1.** The difference in each party’s profits and environmental impact in relation to customer discount factor \( \alpha \) are as follows:

- The relative two-period profits of the OS (\( \pi_{B^*}^{o} - \pi_{A^*}^{o} \)) increase in \( \alpha \), the relative environmental impact of the OS (\( E_{B^*}^{o} - E_{A^*}^{o} \)) decreases in \( \alpha \).
- The relative two-period profits of the IS (\( \pi_{B^*}^{i} - \pi_{A^*}^{i} \)) decrease in \( \alpha \), the relative environmental impact of the IS (\( E_{B^*}^{i} - E_{A^*}^{i} \)) increases in \( \alpha \).

**Proof.** See Appendix G.

Corollary 1 implies that when \( \alpha \) is high, the increase in the two-period profits of the OS would be strengthened, but the reduction in the environmental impact would be weakened caused by pricing discrimination based on customer purchasing behavior. This result shows that although a higher \( \alpha \) results in a higher extent of increasing in the two-period profits of the OS, it reduces the extent of decreasing in the environmental impact. Therefore, a higher customer discount factor gives the OS a profitability-based incentive to invest in the customer purchasing behavior analysis. Conversely, when \( \alpha \) is high, the increase in the two-period profits of the IS would be lessened, but the reduction in environmental impact would be intensified caused by pricing discrimination. This result states that although a higher \( \alpha \) results in a lower extent of increasing in the two-period profits of the IS, it improves the extent of decreasing in the environmental impact. Therefore, a higher customer discount factor facilitates the IS to invest in the customer purchasing behavior analysis based on environmental sustainability.

**Corollary 2.** The total environmental impact in Model B and in Model A are related as follows:

- If \( 0 < \alpha < 1 - 2C_s \), where \( 0 < C_s < \frac{1}{2} \), the total environmental impact in Model B is higher than that in Model A.
- If \( \max\{0, 1 - 2C_s\} < \alpha < 1 - \frac{6C_s}{7} \), the total environmental impact in Model B is lower than that in Model A.

**Proof.** See Appendix H.
### Table 2 Parameter settings

| Parameter | Parameter values |
|-----------|------------------|
| $C_s$     | 0.15 (low); 0.35 (medium); 0.55 (high) |
| $\alpha$ | 0.25 (low); 0.45 (medium); 0.65 (high) |
| $C_n$     | 0.65             |
| $\epsilon_n$ | 0.05           |
| $\epsilon_r$ | 0.01           |

When $C_s$ and $\alpha$ are relatively low, total environmental impact increases as the firms adopt pricing discrimination based on customer purchasing behavior. This is because that the increase in the environmental impact of new products dominates the decrease in the environmental impact of remanufactured products when $C_s$ and $\alpha$ are relatively low. On the contrary, pricing discrimination based on customer purchasing behavior reduces total environmental impact of the firms. This result is due to the advantage of the reduced environmental impact of new products. However, in this case, pricing discrimination based on customer purchasing behavior leads to less total profits of the firms as well. Therefore, to facilitate firms to make efforts to reduce their environment impact, policy makers can compensate firms' profits losses by utilizing subsidy policy.

4. **Numerical study.** In this section, we test our analytical results by numerical study. To obtain the optimal solution and compare firms’ decision-making under different models, we use the parameter values $C_s = 0.15, 0.35, 0.55$ to represent low, medium, and high levels for cost savings of remanufacturing. $\alpha = 0.25, 0.45, 0.65$ represents low, medium, and high levels for customer discount factor. We set $C_n = 0.65$, $\epsilon_n = 0.05$, $\epsilon_r = 0.01$. The parameter settings are provided in Table 2. Table 3 summarizes and compares the equilibrium profit. The positive sign ‘+’ in Table 3 is interpreted as the increase in profit and the negative sign ‘−’ in Table 3 is interpreted as the decrease in profit. Table 4 summarizes and compares the environment impact. The positive sign ‘+’ in Table 4 is interpreted as the increase in environment impact, the negative sign ‘−’ in Table 4 is interpreted as the decrease in environment impact, and zero ‘0’ in Table 4 is interpreted as the constant in environment impact.

As shown in Tables 3 and 4, it can be observed that, the OS can achieve higher profits and lower environment impact with higher cost savings of remanufacturing and higher customer discount factor. On the contrary, the IS can obtain higher profits and lower environment impact with lower cost savings of remanufacturing and lower customer discount factor. By comparing the profits of OS and IS, we can find that, in Model B and Model A, the profits of OS are higher than that of IS when the cost savings of remanufacturing are low and customer discount factor is low. By comparing the environment impact of OS and IS, the changes in the two models are consistent. Specially, the environmental impact of OS is lower than that of IS only when the cost savings of remanufacturing are high and customer discount factor is high.

5. **Sensitivity analysis.** In this section, we perform sensitivity analysis of equilibrium price, price discount, demand and profit with respect to the following parameters: cost savings of remanufacturing and customer discount factor.
5.1. Sensitivity analysis to customer discount factor. To understand the impact of customer discount factor under the two models, as inputs, we use the parameter values $C_n = 0.6, C_s = 0.4, c_n = 0.05, e_r = 0.01$. Figs.3a-6a (Figs.3b-6b) show the results of sensitivity analysis to $\alpha$ in Model A (Model B).

![Figure 3. Optimal prices as a function of $\alpha$](image)

Figs.3a and 4a together demonstrate how the price and the demand change as the customer discount factor changes in Model A. Intuitively, an increase in $\alpha$ results in an increase in the demand for remanufactured products, and a decrease in the price of the remanufactured product in each period. Interestingly, an increase in $\alpha$ leads...
to a decrease in the price of the new product, but a decrease in the demand for new products in each period. The reason for this is as follows. When $\alpha$ increases, the customer’s willingness to pay for remanufactured products rises, competition between firms enhances, therefore, the prices of new and remanufactured products decrease. Obviously, the decline in the price of the remanufactured product will increase the demand for the remanufactured product. However, the increased demand for the remanufactured product will cannibalize the sales of new products, thereby reducing the demand of new products.

In Fig. 5a, we present optimal profits as a function of $\alpha$ in Model A. The total profits of the OS are decreasing in $\alpha$. The total profits of the IS decreases first and then increases with $\alpha$. The impact of $\alpha$ for the OS’s (IS’s) profit of each period is consistent. For the OS, with the increase of $\alpha$, the price and demand of the new
product will decrease, so will the profit. For the IS, the implication of this result is that when $\alpha$ is low, the loss of price decline dominates the benefit of increased demand for the remanufactured product, so the profit of the IS declines with the increase of $\alpha$. When $\alpha$ is high, the benefit of increased demand is sufficient to compensate for the loss of price decline, thus the profit of the IS increases as the increase of $\alpha$. As shown in Fig.6a, an increase in $\alpha$ decreases the environment impact of the OS, and the total environment impact, but increases the environment impact of the IS in Model A. This is because as $\alpha$ increases, the demand for new products decreases and the demand for remanufactured products increases. As a result, the environmental impact of new products is reduced while that of remanufactured products increases. However, compared with the increase of environmental impact of remanufactured products, the environmental impact of new products is reduced by a larger extent, thus reducing the total environmental impact.

From Figs.3b and 4b, we can see how the price and the demand change as the customer discount factor changes in Model B. In period 1, the price of the new product and the remanufactured product are decreasing in $\alpha$. In period 2, the price discounts provided by the firms is increasing in $\alpha$. In addition, from the slope of the curve, we can observe that the price discount given by the OS to volatile customers is higher than the price discount given to loyal customers as $\alpha$ increases. The demand for new products in each period is decreasing in $\alpha$, and the demand for remanufactured products in each period is increasing in $\alpha$. Furthermore, compared with period 1, the demands in period 2 are more sensitive to the change of $\alpha$.

According to Fig.5b, We can observe the change in profit with respect to $\alpha$ in model B. The profits of the OS in each period or in two periods are decreasing in $\alpha$. The profit of the IS in period 1 is decreasing in $\alpha$, but the profit of the IS in period 2 is increasing in $\alpha$. The profits of the IS in two periods decrease first and then increases with $\alpha$. When $\alpha$ is high, although the increase in $\alpha$ will decrease the profit generated by remanufactured products in period 1, the increase of the second-period profit dominates the reduction of the first-period profit, which increases the total profits of the IS. Fig.6b shows the the change direction of environment impact to
α in Model B is consistent with that in Model A. But the changes in Model B are moderate.

5.2. Sensitivity analysis to cost savings. We analyze the effect of the cost savings on the optimal values of decision variables and objective functions by keeping all parameters fixed except $C_s$. Thus, we use the parameter values $C_n = 0.6$, $\alpha = 0.7$, $e_n = 0.05$, and $e_r = 0.01$. Fig.7a-10a (Figs.7b-10b) show the results of sensitivity analysis to $C_s$ in Model A (Model B).

![Figure 7. Optimal prices as a function of $C_s$](image)

As indicated in Fig.7a and 7b, the prices are decreasing in $C_s$ for both new and remanufactured products in both Models. Fig.7 also demonstrably presents that the effect of decrease in the price of new products caused by $C_s$ is lower than the decrease
effect of the price of remanufactured products. Moreover, Fig.7b suggests that the price discounts provided by the OS to volatile and loyal customers are decreasing in $C_s$. The price discount provided by the IS to loyal customers is increasing in $C_s$, while the price discount given by the IS to volatile customers is decreasing in $C_s$.

Fig.8 reveals that the demand for new products is decreasing in $C_s$, and the demand for remanufactured products is increasing in $C_s$. Fig.8a illustrates that the effect of cost savings on demand is the same in each period in Model A. Fig.8b shows that compared with the demand in period 1, the demands in period 2 are more sensitive to the change of $C_s$ in Model B.

From Fig.9, it can be observed that, as $C_s$ increases, the profits of the OS decrease, and the profits of the IS increase in both Models. As shown in Fig.10, an
increase in $C_s$ decreases the environment impact of the OS, and the total environment impact, but increases the environment impact of the IS in both models.

6. Conclusion and future work. In this paper, we first study how the cost savings and customer discount factor impact for firms' profitability. Then, we investigate the impact of different pricing strategies for firms' profitability and environmental impacts. Therefore, we introduce an OS who manufactures and sells new products and an IS who remanufactures and sells remanufactured products. We develop insights for the OS who faces competition from the IS based on customer purchasing behavior. Our model captures some of the key elements driving the choice of pricing strategies. Although our research was motivated by material suppliers, it could also be applied in many industrial fields where the managers have the full awareness of EPR, and they are willing to engage in the project related to remanufacturing.

Our key results are summarized below. First, under both pricing strategies, the two-period profits of the OS decrease in the customer discount factor, while the profits of the IS first decrease then increase in the customer discount factor. Moreover, when the cost savings go up, the IS has greater motivation to produce remanufactured products. Furthermore, pricing discrimination is more conducive to the increase in the IS's profits if the customer discount factor is relatively high.

Second, by comparing the two pricing models, we find that when the cost savings are small, if the customer discount factor is relatively high, the OS can obtain higher profits and have less impact on the environment through pricing discrimination based on customer purchasing behavior. In this case, the OS is more willing to invest in the customer purchasing behavior analysis. If the customer discount factor is relatively low, the IS's profits increase and environmental impact decreases through pricing discrimination based on customer purchasing behavior. In this case, the IS is more profitable by investing in the customer purchasing behavior analysis.

Third, a high customer discount factor gives the OS an incentive to adopt price discrimination from the perspective of firms' profitability. Conversely, a higher customer discount factor facilitates the IS to adopt price discrimination based on environmental sustainability. Last, when the cost savings and the customer discount factor are relatively low, total environmental impact increases as the firms adopt pricing discrimination based on customer purchasing behavior. On the contrary, pricing discrimination reduces total environmental impact and total profits of the firms. Therefore, to facilitate firms to make efforts to reduce their environment impact, policy makers can compensate firms' profit losses by utilizing subsidy policy.

Some limitations of our work need to be discussed in the near future. First, our analytic method is based on the conditions that the used materials are sufficient to meet the demand for remanufacturing. In reality, remanufacturing operations cannot always obtain adequate materials. Further research is needed to consider the situation that the supply of the used products is uncertain (i.e., sufficient, insufficient, or appropriate). At the same time, the demand for remanufactured products is also uncertain (i.e, raise or drop) in a product’s lifetime. How to regulate the supply-demand imbalance affects the decision-making process including price, yield, and profit. Moreover, it is the most difficult to grasp the customer behavior. Their purchasing decisions not only rely on consumers’ WTP. It is influenced by their psychological anticipation. When customers anticipate the price to change over time, they may behave strategically by timing their purchases to anticipated

periods of lower price. Strategic behaviors of customers have vital impacts for the policies of price, quantity and profit. Thus, our future work will explore the interactions between the different behaviors of firms and customers.

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Appendix A. The optimal solution for each party’s strategy in Model A. Substituting Equations (1) and (2) into Equations (3) and (4), maximizing π\textsuperscript{A}\textsubscript{t0} with respect to \( P_{tn}^{A} \) derives the unique solution \( P_{tn}^{A} = \frac{1-\alpha + P_{tn}^{A} + C_{n}}{4} \). Maximizing \( \pi^{A}_{ti} \) with respect to \( P_{tr}^{A} \) derives the unique solution \( P_{tr}^{A} = \frac{P_{tn}^{A} + C_{r}}{2} \). The two best-response curves intersect exactly once. First consider the lines \( P_{tn}^{A} = \frac{1-\alpha + P_{tn}^{A} + C_{n}}{4} \) and \( P_{tr}^{A} = \frac{P_{tn}^{A} + C_{r}}{2} \). Their intersection point is at \( P_{tn}^{A} = \frac{2-2\alpha + 2C_{n} + C_{r}}{3} \) and \( P_{tr}^{A} = \frac{1-\alpha + C_{n} + 2C_{r}}{3} \). We now need to check whether \( P_{tn}^{A} \geq C_{n} \) and \( P_{tr}^{A} \geq C_{r} \). We find that this condition holds if \( 0 < \alpha \leq 1 - \frac{C_{r}}{2} \). Therefore this is the unique Nash equilibrium when \( 0 < \alpha \leq 1 - \frac{C_{r}}{2} \). In this case, the equilibrium demands, profits and environmental impacts are obtained by substitution.

Appendix B. The proof of proposition 1. The optimal two-period profits of the OS is \( \pi^{A}_{o} \). \( \frac{\partial \pi^{A}_{o}}{\partial o} = \frac{2C_{n}C_{r}2-2(2-a)^{2}}{9(1-a)^{2}} \), when \( 0 < \alpha \leq 1 - \frac{C_{r}}{2} \), which is consistent with the previous equilibrium condition. \( \frac{\partial \pi^{A}_{o}}{\partial o} < 0 \). The optimal two-period profits of the IS is \( \pi^{A}_{i} \). \( \frac{\partial \pi^{A}_{i}}{\partial a} = \frac{2C_{n}C_{r}2-(1-a)}{9(1-a)^{2}} \), when \( 0 < \alpha < 1 - C_{s} \), \( \frac{\partial \pi^{A}_{i}}{\partial a} < 0 \). When \( \alpha > 1 - C_{s} \), \( \frac{\partial \pi^{A}_{i}}{\partial a} > 0 \). Combined with the above equilibrium condition, when \( \alpha < 1 - C_{s} \), \( \frac{\partial \pi^{A}_{i}}{\partial a} < 0 \). When \( 1 - C_{s} < \alpha \leq 1 - \frac{C_{r}}{2} \), \( \frac{\partial \pi^{A}_{i}}{\partial a} > 0 \).

Appendix C. The optimal solution for each party’s strategy in Model B. Substituting Equations (14)-(17) into Equations (18) and (19), the first-order conditions of Equations (18) and (19) with regard to \( \delta_{nl}, \delta_{nv}, \delta_{rl} \), and \( \delta_{rv} \) jointly lead to \( \delta_{nl} = \frac{(2-\theta_{i})(1-\alpha) + 2C_{n} + C_{r}}{3P_{tn}} \), \( \delta_{nv} = \frac{2(1-\alpha)\theta_{i} + 2C_{n} + C_{r}}{3P_{tn}} \), \( \delta_{rl} = \frac{1-\alpha}{3P_{tn}} \), and \( \delta_{rv} = \frac{(1-2\theta_{i})(1-\alpha) + C_{n} + 2C_{r}}{3P_{tn}} \). The first-order conditions of Equations (20) and (21) with regard to \( P_{tn}^{B} \) and \( P_{tr}^{B} \) jointly lead to \( P_{tn}^{B} = \frac{19(1-\alpha)+18C_{n}+6C_{r}}{24} \), and \( P_{tr}^{B} = \frac{13(1-\alpha)+6C_{n}+18C_{r}}{24} \). To check that \( \theta_{2} < \theta_{1} < \frac{\theta_{2}}{2} \), we obtain the condition \( 0 < \alpha < 1 \), \( \frac{6C_{r}}{2} \) by substitution method. When \( 0 < \alpha < 1 - \frac{6C_{r}}{2} \), above equilibrium values are unique. The others equilibrium prices, price discounts, demands and each party’s profits and environmental impacts can be calculated by substitution method.

Appendix D. The proof of lemma 3.1. The price discounts in period 2 are as follows. \( \delta_{nl}^{B} = \frac{25(1-\alpha)+30C_{n}+18C_{r}}{2[19(1-\alpha)+18C_{n}+6C_{r}]} < 1 \), \( \delta_{nv}^{B} = \frac{7(1-\alpha)+18C_{n}+6C_{r}}{[19(1-\alpha)+18C_{n}+6C_{r}]} < 1 \), \( \delta_{rl}^{B} = \frac{(1-\alpha)+6C_{n}+18C_{r}}{19(1-\alpha)+18C_{n}+6C_{r}} < 1 \). The difference between the period 2 demand and the period 1 demand is as follows. \( q_{2n}^{B} - q_{1n}^{B} = \frac{1-\alpha + 2C_{n} + 2C_{r}}{4(1-\alpha)} \), \( q_{2r}^{B} - q_{1r}^{B} = \frac{(1-\alpha - 2C_{n} + 2C_{r})}{4(1-\alpha)} \), when \( 0 < \alpha < 1 - 2C_{s}, 0 < C_{s} < \frac{\theta_{1}}{2} \). \( q_{2n}^{B} - q_{1n}^{B} > 0, q_{2r}^{B} - q_{1r}^{B} < 0 \); when \( \max(0, 1 - 2C_{s}) < \alpha < 1 - \frac{6C_{r}}{2} \), \( q_{2n}^{B} - q_{1n}^{B} < 0, q_{2r}^{B} - q_{1r}^{B} > 0 \). And the difference between the OS’s(IS’s) profit in period 2 and period
when max $\partial \pi_0$, $\partial \pi_1 = \frac{-205(1-\alpha)^2+36(19(1-\alpha)-11(C_n-C_t))(C_n-C_t)}{2304(1-\alpha)} < 0, (\pi_2^* - \pi_1^*) = \frac{-493(1-\alpha)^2+36(31(1-\alpha)-11(C_n-C_t))(C_n-C_t)}{2304(1-\alpha)} < 0$).

Appendix E. The proof of proposition 2. The optimal two-period profits of the OS is $\pi_o^*$. $\partial \pi_o^*/\partial \alpha = \frac{540((C_n-C_t)^2-1847(1-\alpha)^2)}{2304(1-\alpha)^2}$, when $0 < \alpha < 1 - \frac{6\sqrt{599}C_t}{7}$, which is combined with the previous equilibrium condition $0 < \alpha < 1 - \frac{6\sqrt{599}C_t}{7}$, then when $0 < \alpha < 1 - \frac{6\sqrt{599}C_t}{7}$, $\partial \pi_o^*/\partial \alpha < 0$.

The optimal two-period profits of the IS is $\pi_i^*$. $\partial \pi_i^*/\partial \alpha = \frac{540((C_n-C_t)^2-599(1-\alpha)^2)}{2304(1-\alpha)^2}$, when $0 < \alpha < 1 - \frac{6\sqrt{599}C_t}{7}$, $\partial \pi_i^*/\partial \alpha < 0$. When $\alpha > 1 - \frac{6\sqrt{599}C_t}{7}$, $\partial \pi_i^*/\partial \alpha > 0$.

Combined with the above equilibrium condition, when $0 < \alpha < 1 - \frac{6\sqrt{599}C_t}{7}$, $\partial \pi_i^*/\partial \alpha < 0$. When $1 - \frac{6\sqrt{599}C_t}{7} < \alpha < 1 - \frac{6\sqrt{599}C_t}{7}$, $\partial \pi_i^*/\partial \alpha > 0$.

Appendix F. The proof of proposition 3. This can be explained by the gap between the results in Model B and in Model A. $\pi_o^* - \pi_o^s = \frac{540((C_n-C_t)^2-1847(1-\alpha)^2)}{2304(1-\alpha)^2}$, when $0 < \alpha < 1 - \frac{6\sqrt{599}C_t}{7}$.

$\pi_n^0 = \frac{540((C_n-C_t)^2-599(1-\alpha)^2)}{2304(1-\alpha)^2}$, when $0 < \alpha < 1 - \frac{6\sqrt{599}C_t}{7}$.

$\pi_i^* - \pi_i^s = \frac{540((C_n-C_t)^2-599(1-\alpha)^2)}{2304(1-\alpha)^2}$, when $0 < \alpha < 1 - \frac{6\sqrt{599}C_t}{7}$.

$\pi_i^* - \pi_i^s = \frac{540((C_n-C_t)^2-599(1-\alpha)^2)}{2304(1-\alpha)^2}$, when $0 < \alpha < 1 - \frac{6\sqrt{599}C_t}{7}$.

$\pi_i^* - \pi_i^s = \frac{540((C_n-C_t)^2-599(1-\alpha)^2)}{2304(1-\alpha)^2}$, when $0 < \alpha < 1 - \frac{6\sqrt{599}C_t}{7}$.

$\pi_i^* - \pi_i^s = \frac{540((C_n-C_t)^2-599(1-\alpha)^2)}{2304(1-\alpha)^2}$, when $0 < \alpha < 1 - \frac{6\sqrt{599}C_t}{7}$.

Appendix G. The proof of corollary 1. $\partial (\pi_i^* - \pi_o^s) / \partial \alpha = \frac{201(1-\alpha)^2+28(C_n-C_t)}{2304(1-\alpha)^2} > 0$.

$\partial (\pi_i^* - \pi_o^s) / \partial \alpha = \frac{201(1-\alpha)^2+28(C_n-C_t)}{2304(1-\alpha)^2} > 0$.

$\partial (\pi_i^* - \pi_o^s) / \partial \alpha = \frac{201(1-\alpha)^2+28(C_n-C_t)}{2304(1-\alpha)^2} > 0$.

Appendix H. The proof of corollary 2. $\partial (E_i^* - E_o^s) / \partial \alpha = \frac{(1-\alpha^2)(C_n-C_t)}{24(1-\alpha)} > 0$.

when $0 < \alpha < 1 - 2C_s, 0 < C_s < \frac{1}{2}, E_i^* - E_o^s > 0$; when max$\{0, 1 - 2C_s\} < \alpha < 1 - \frac{6\sqrt{599}}{7}$, $E_i^* - E_o^s < 0$.

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