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DESIGN OF THE REVERSE CHANNEL FOR THE THIRD-PARTY REMANUFACTURING CONSIDERING CONSUMER EDUCATION

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Abstract. Different stakeholders pay more attention to consumer education for remanufacturing. They expect to promote the advancement of the remanufacturing industry by increasing the number of consumers willing to pay for remanufactured products. In the context of consumer education, this paper investigates the influence of different collection and remanufacturing capabilities on the reverse channel designs. The results show that increased consumer education makes the OEM partially forgo the remanufacturing right and more focus on the control of the collection process of reverse channels. We further explore the impact of consumer education on different stakeholders. We find that consumer education significantly improves individual profits and supply chain profit. However, for consumers, the temperate consumer education is all-around desirable, and excessive consumer education will reduce consumer surplus. For the environment, only when the environmental friendliness of RPs is relatively high, improving consumer education will reduce the environmental impact. Furthermore, we also examine the reverse channel designs from multiple criteria and discover that profitability, consumers, and environmental goals can be consistent under certain conditions. Our study provides new insights for the design of reverse channels in the context of consumer education.

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1. Introduction

With the aggravation of natural resource shortage and tightening of environmental regulations, the original equipment manufacturers (OEMs) need to be more responsible for their sustainability operations [33]. Engaging in the collection and remanufacturing operations of used products is an effective approach to realize sustainability operations, which owns positive environmental outcomes while simultaneously increases the firm's profit by extracting value from used items [12]. As remanufacturing technology and education popularize gradually, more OEMs would like to engage in remanufacturing production. Some OEMs who carry out used product operations have achieved satisfying results. For example, Dell and Apple engage in refurbishing work and resell refurbished products on their official websites (in-house remanufacturing). However, not all OEMs possess the infrastructure

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and expertise to remanufacture used products in a profitable manner. According to a survey from the United States, only 6% of more than 2000 remanufacturing firms were OEMs [17]. The majority of recycling and remanufacturing operations are accomplished by third parties (TPs) [26].

In practice, some OEMs do not directly engage in used products business. They usually outsource the recycling or remanufacturing process to TPs. The business outsourcing of used products is not a purely make-or-buy decision but involves a control transfer of reverse channel, which determines the recovery rate from customers and affects sustainable performance [11]. Therefore, some OEMs choose to outsource partial business. For instance, most well-known mobile phone manufacturers (such as Huawei, Samsung, etc.) only outsource the collection process of used iPhone to TPs, including Huishoubao (`www.huishoubao.com`) in China and Call2Recycle (`www.call2recycle.org`) in the United States. The recycling control right of the reverse channel is given to the TPs, but the remanufacturing produce still is affected by the OEMs by setting different outsourcing fees [23]. In fact, the channel selection of the remanufacturing process is also critical and many OEMs outsource the production process of used products to TPs [46]. The control of the remanufacturing business can determine the transfer price of the remanufacturing process, which in turn affects the retail price of RPs, and ultimately decides the market demand for NPs with higher margins. Although some OEMs outsource their remanufacturing business, they still control the reverse channel by collecting old products from consumers, which protects their sales of NPs. For example, Sun Microsystems, one of the global leading IT server firms, collects used products by itself but outsources the remanufacturing process to the TPs. These OEMs only outsource the remanufacturing activity of used products to the TPs. They still control the collection process of the reverse channel. Furthermore, some OEMs also choose full outsourcing, which means outsource the whole reverse channel to TPs. BMW outsources the collection and production of used vehicles to a select set of dismantlers in Germany and gives them the proprietary right to do so. Similarly, Land Rover signs an agreement that outsources collection and remanufacturing activities to Caterpillar Remanufacturing Services[1]. Most existing publications on reverse channel designs do not distinguish between the remanufacturing process and the recycling process [32, 35, 48]. They usually obscure the remanufacturing process and focus on who is responsible for the recycling channel. However, in practice, OEMs usually decided to outsource the recycling process and remanufacturing process separately or completely based on different abilities, including the recycling capability, remanufacturing capability, and the control ability of reverse channels. Therefore, under what conditions will OEMs choose to partial outsourcing, and under what conditions will they choose full outsourcing?

The existing publications assume that all consumers are willing to buy RPs at a low price [35, 37]. However, the growing literature on consumer behavior shows that not all consumers are willing to buy and use RPs. A large proportion of consumers will significantly prefer NPs regardless of the price discount of RPs, only a small number of consumers who believe that RPs and NPs have the same function are willing to pay for RPs [1, 47]. Due to the popularization of consumer education, more and more consumers are willing to buy RPs. The value of the remanufacturing market has also increased, but the OEM has given control of partial business of remanufacturing market to TPs. The literature on the design of reverse channel usually does not consider the role of consumers [30, 42], they believe that all consumers are willing to pay for RPs. The reality is that some consumers are unwilling to buy RPs. Education can increase their willingness to purchase RPs, and many business leaders, environmentalists, and policymakers all engage in consumer education, such as Apple, Boeing, and Caterpillar. So how does consumer education affect the design of reverse channels?

Since concern for the environment is also part of the motivation for remanufacturing, we consider the consequences not just for OEM profitability but also the environmental impact of remanufacturing activities. According to the official statement of the Chinese government, the purpose of the consumer education measures is to promote the development of the remanufacturing industry except for protecting the environment. It is also necessary to pay attention to the performance of the supply chain and consumer surplus goals. Focused on these

[1] `https://www.theautochannel.com/news/2005/08/04/139416.html2017`.

different reverse channel strategies, we explore the following research questions:

(1) What are the key drivers of the performance of remanufacturing policies (owning *vs.* outsourcing)? What are the optimal reverse channel choices for the OEM and the TP considering different recycling efficiency and remanufacturing capability?
(2) How does the level of education affect the reverse channel selections? Is it necessary to improve the proportion of functional consumers by increasing consumer education?
(3) Considering supply chain profit, consumer surplus, and environmental impact, which model is more beneficial? Does profit-maximization harm the environment?

To answer the above issues, we develop a stylized model of the reverse channel between the OEM and the TP by using game theory. Specifically, we characterize the effects of consumer education using the consumer segment and explore the equilibrium results of different reverse channels. And then we focus on the impact of consumer education and remanufacturing cost advantages on recovery rates, transfer prices, and firms' profits. By analyzing the OEM's profitability under different channels, we give the optimal choices of the reverse channels. Furthermore, we also compare the consumer surplus and environmental impact in four reverse channel structures. There exist triple-win regions for the OEM, which can simultaneously achieve the goal of maximizing OEM profitability and consumer surplus while minimizing the environmental impact. However, if only focus on public goals consisting of the supply chain, consumers, and the environment, the conflict regions between the reverse channel selections will increase instead. Increasing consumer education can partially ease the conflict.

Our study makes the following contributions. First, few publications study the outsourcing problems of reverse channel considering collection and remanufacturing operations simultaneously. Our research has developed two new reverse channel designs: only outsourcing the recycling business but controlling the remanufacturing process, only outsourcing the remanufacturing process but controlling the recycling business. Exploring partial business outsourcing of reverse channels is an essential complement to the relevant literature on full outsourcing. Second, the literature on the design of reverse channel design usually does not consider the role of consumers. Our work explores the effects of consumer education by consumer segment. Third, we evaluate reverse channels from multiple performance metrics: profitability, supply chain, consumers, and environment, whereas the most existing literature on the CLSCs focuses solely on profit performance. Despite the multiple goals that are often in conflict, they align in certain scenarios. This benefits the regulator to make different incentive schemes to guide the OEM and the TP.

The rest of the paper is organized as follows. The next section reviews the relevant literature. Problem descriptions and assumptions are listed in Section 3. In Section 4, the decision models and analytical results of reverse channels are developed. Section 5 discusses the optimal reverse channel selections between the OEM and the TP and explores the role of consumer education. Section 6 performs the optimal reverse channel selections from three sustainable perspectives. Section 7 concludes the paper by generating managerial implications and discussing directions for future research. Finally, proofs are provided in the Appendix A.

2. Literature review

Three streams of literature are closely related to our paper: reverse channel management; outsourcing operations in CLSCs, and consumer education in CLSCs.

The reverse channel management problems have been extensively studied. Previous studies on reverse channel management can be classified into those related to strategic, tactical, or operational issues [34]. Our paper is more focused on the strategic decisions, or more specifically, the reverse channel designs. Savaskan *et al.* [32] analyzed three reverse channel structures for the collection of used products through a manufacturer, a retailer, or a third party in a monopoly setting, and show that the retailer is the most effective undertaker of product collection activity for the OEM. Then, Savaskan and Van Wassenhove [31] further explored the reverse channel choice with a competitive supply chain consisting of one manufacturer and two retailers. Atasu *et al.* [5] discussed the impact of collection cost structure on the OEM's reverse channel choice. Dou and Cao [8] jointly measured the environmental and economic performances of three CLSCs, where the collection is implemented by the retailer, manufacture, or a third-party. They show that the retailer collection can be both environmentally and economically better off to achieve a Pareto-improvement. Iqbal and Sarkar [20] investigated the recycling problem of deteriorated products by designing a forward and reverse supply chain system. Other studies on reverse channel choice focus on return policy [13, 36], and carbon emission permits [38]. However, the above research on reverse channel design usually focus on who is responsible for the recycling channel, ignoring the choice of remanufacturing process, especially the remanufacturing channel of TP-managed. Moreover, they all assumed all consumers are willing to pay for RPs, which ignored the role of consumers. In practice, more and more business leaders and environmentalists engage in consumer education to improve the consumer perception for RPs. Exploring the impact of consumer education on the design of reverse channel is helpful to understand the remanufacturing marketing practice.

Our work is also related to outsourcing management of reverse channels. Focusing on who is the best undertaker among the supply chain members, Huang and Wang [19] put forward three kinds of remanufacturing patterns, namely, manufacturer self-owned remanufacturing, distributor's licensed remanufacturing, and third-party's licensed remanufacturing. Yan *et al.* [39] considered the OEM's remanufacturing outsourcing strategy and analyzed how the OEM would choose between supplier remanufacturing or TP remanufacturing. When the OEM has outsourced its remanufacturing production to TP, Yan *et al.* [40] compared OEM self-owned recycling with TP recycling and investigated which recycling strategy would be more conducive to the realization of economic, social, and environmental goals. For outsourcing to retailers, Wang *et al.* [35] explored how the monopoly profit-maximizing retailer chooses between in-house remanufacturing and outsourced remanufacturing based on two goals: profit maximization and environmental impact. Qian *et al.* [28] showed that in-house remanufacturing potentially facilitates greater economic, social, and environmental sustainability, but it has costs for the retailer. Some works focused on the selection of outsourcing mode and authorization mode. Zou *et al.* [48] found the full outsourcing is always the optimal choice for the OEM compared to authorized remanufacturing. Zhang *et al.* [47] developed an evolutionary game model to investigate the optimal selection of outsourcing and authorization modes and showed that the duopoly OEMs always prefer the outsourcing strategy. Considering the impact of capital constraint and financing behavior on the operations of small- and medium-sized OEMs, Zhang *et al.* [46] suggested that the OEM's choice preference shifts from outsourcing mode to authorization mode. Moreover, Hallak *et al.* [15] explored the impact of recycling modes (outsourcing *vs.* in-house recycling) on inventory systems. Different from them, we focus on the OEM's control of reverse channels, from in-house remanufacturing, partial business outsourcing, to full outsourcing, and discuss and analyze the profitability of different channels design, consumer surplus, and environmental impact. More importantly, we examine the impacts of consumer education behavior on the reverse channel selection of the OEM and TP by model analysis.

Another related stream is consumer education and sustainable operations. Empirical and experimental studies claim that education is effective at reducing consumers' resistance to RPs [1, 14]. Zhou *et al.* [47] examined the implications of consumer education on a CLSC and they showed that the manufacturer will switch the choice from remanufacturing to no remanufacturing identify as consumer education improves. Many studies are related to the successful implementation of consumer education, for example, eco-certification for RPs [16], transparency of the remanufacturing process [7]. They verified that consumer education can improve consumers' awareness of the quality and environmental attributes of RPs. However, most of these studies only discuss the role of consumer education from the perspective of empirical analysis and rarely discuss the impact of education on channels from the perspective of model analysis. Our research divides the impact of education through the characterization of consumer groups, and thus derives the effect of education on the design of reverse channels. Moreover, our results provide a better understanding of the reverse channel selections from the perspective of the economy, supply chain, consumers, and the environment in the context of consumer education. Table 1 shows the main difference between this study and the most related literature.

Although many research efforts focus on the issue of reverse channel selections, our paper differs from them in several aspects. First, we not only examine the outsourcing of the entire reverse supply chain, but also

TABLE 1. Comparison of this study with related literature.

Literature	Model IR	Model OC	Model OR	Model FO	Consumer education	Multiple criteria
Savaskan *et al.* [32]	✓	✓	✘	✘	✘	✘
Karakayali *et al.* [23]	✘	✓	✘	✘	✘	✘
Dou and Cao [8]	✓	✓	✘	✘	✘	✓
Wang *et al.* [35]	✓	✘	✘	✓	✘	✓
Zou *et al.* [48]	✘	✘	✘	✓	✘	✓
Zhou *et al.* [47]	✓	✘	✘	✘	✓	✓
Present study	✓	✓	✓	✓	✓	✓

distinguish the collection process and the remanufacturing process, and explore partial outsourcing business. We draw upon and extend prior research in remanufacturing to study an OEM's strategic choice among four remanufacturing modes. Second, we consider a more realistic market in which no matter how low the price discount of RPs, some consumers will not buy them. We examine the impact of consumer education on the reverse channel designs. Moreover, we demonstrate that consistent regions of the reverse channel design from the perspectives of the supply chain, consumers, and the environment.

3. Problem descriptions and model assumptions

In this study, we investigate the different channel strategies between the OEM and the TP and examine the implications of the consumer education upon the reverse channel designs. Specifically, we consider four business models on handling process of used products: (1) The OEM engages in the collection and the remanufacturing process (in-house remanufacturing, Model IR, Fig. 1a); (2) The OEM only outsources the collection process to a TP (outsourcing collection, Model OC, Fig. 1b); (3) The OEM only outsources remanufacturing process to a TP (outsourcing remanufacturing, Model OR, Fig. 1c); (4) The OEM outsources collection and remanufacturing process to a TP (full outsourcing, Model FO, Fig. 1d).

In Model IR, the OEM not only produces NPs, but collects and remanufactures the used products. The OEM controls completely the recycling and producing channels for both NPs and RPs. In Model OC, recycling controlling of the reverse channel is given to the TP, and the OEM pays the TP collection outsourcing fee. The OEM produces NPs, remanufactures used products from the TP, and retails both the NPs and RPs. In Model OR, the OEM outsources remanufacturing right to the TP and pays the TP remanufacturing outsourcing fee. However, recycling controlling of the reverse channel and remarketing rights still belongs to the OEM. In Model FO, the OEM outsources two tasks to the TP, and only manufactures NPs and retails NPs and RPs. The collection and remanufacturing operations are contracted to the TP, and the OEM pays the TP outsourcing fee. We denote the profit of player i as π_i^j in model j, where the subscript $i \in \{M, T\}$ stands for the OEM and the TP, and the superscript $j \in \{\mathrm{IR}, \mathrm{OC}, \mathrm{OR}, \mathrm{FO}\}$ stands for Model IR, Model OC, Model OR, and Model FO, respectively. We first discuss Model IR (Sect. 4.1), next Model OC (Sect. 4.2), then Model OR (Sect. 4.3), and Model FO (Sect. 4.4).

In a CLSC, the OEM has the dominant channel power over the TP, hence it is a Stackelberg leader. Now we discuss the key assumptions in this study.

Assumption 3.1. *Consumer's willingness-to-pay for NPs is heterogeneous and uniformly distributes over the interval* $[0, 1]$. *Each FOC's willingness-to-pay for RPs is a fraction* δ *of that for the new one, and all NCCs' willingness-to-pay for RPs is* 0.

The relevant remanufacturing literature generally assumes that all consumers are willing to buy RPs at a low price [30]. However, the latest empirical results show that there are two types of consumers: functionality-oriented

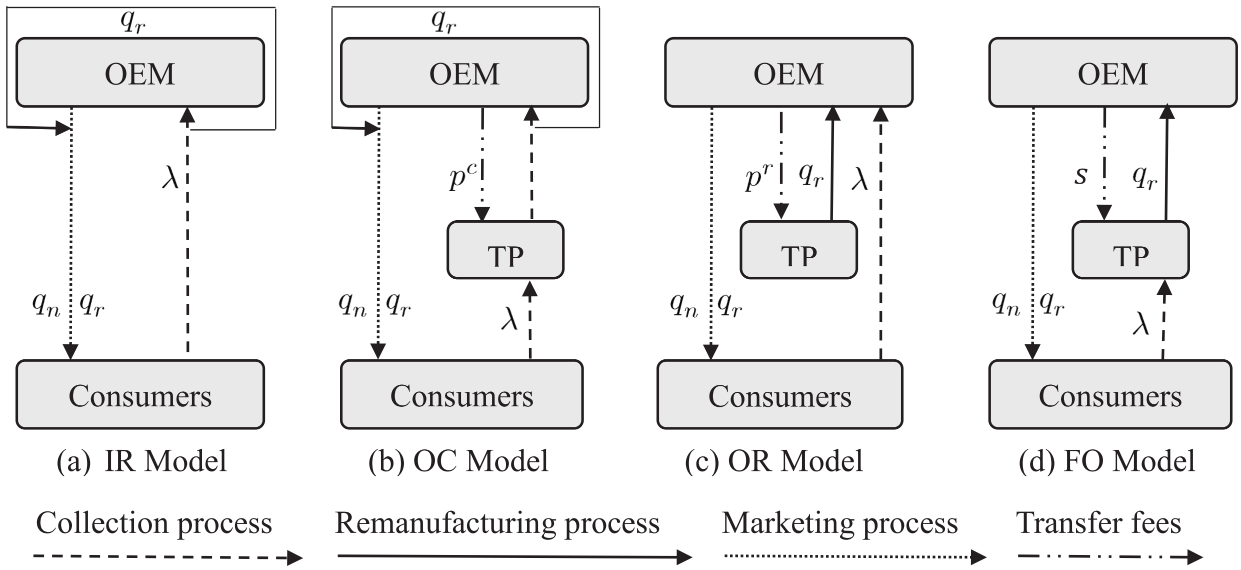

Figure 1. Four basic models between the OEM and the TP.

consumers (FOCs) and newness-conscious consumers (NCCs), where FOCs represents that consumers who think that the function of RPs is the same as that of NPs, and display high sensitivity to price discounts, while NCCs are consumers who only buy NPs regardless of the price discount of RPs [1]. The market size is normalized to 1. The size of the FOC segment is $\phi \in (0, 1)$, so the size of the NCC segment is $(1 - \phi)$. Let $q_n(q_r)$ denotes the production quantity of NPs (RPs), and $p_n(p_r)$ represents the retail price of NPs (RPs). NCCs buy NPs and get the net utility $NU_n = v - p_n$; FOCs get the net utility $FU_n = v - p_n$ if buying one NP, and $FU_r = \delta v - p_r$ if buying one RP. Consumers get zero utility if they are inactive. Following Zhou *et al.* [47], the demands for NPs and RPs are $q_n = (1-\phi)(1-p_n) + \phi\left(1 - \frac{p_n - p_r}{1-\delta}\right)$ and $q_r = \phi\left(\frac{p_n - p_r}{1-\delta} - \frac{p_r}{\delta}\right)$, respectively. Further, we can derive the inverse demand functions,

$$p_n = 1 - q_n - \delta q_r \tag{3.1}$$

$$p_r = \delta(1 - q_n - \delta q_r) - \frac{\delta(1-\delta)q_r}{\phi}. \tag{3.2}$$

Assumption 3.2. *The unit production cost of RPs is lower than that of NPs, i.e., $c_r < c_n$. The unit production cost of RPs for TPs is c_r, and the unit production cost of RPs for OEMs is $c_r + g$, where $g > 0$ represents the TP has the remanufacturing cost advantage; otherwise, the OEM has the remanufacturing cost advantage.*

As a cost-saving alternative to traditional production, the cost of remanufacturing is 40%–65% lower than the cost of producing NPs [34]. Hence, we assume that remanufacturing used products is less costly than producing NPs, *i.e.*, $c_r < c_n$. TP's remanufacturing cost is c_r. Considering the differences in remanufacturing capability of different players, in line with the literature of Liu *et al.* [24] and Fang *et al.* [9], we denote the parameters c_r and $c_r + g$ as the unit remanufacturing costs of the OEM and TP, respectively. The positive g means that the TP has a remanufacturing cost advantage. The negative g indicates that the OEM has a remanufacturing cost advantage. When g equals 0, it means that the two remanufacturing processes of two parties are the same and have the remanufacturing efficiency.

Assumption 3.3. *The collection cost of used products is convex increasing in the collected quantity. Without loss of generality, the collection cost functions of the OEM and TP are assumed to be $\frac{1}{2}(\lambda q_n)^2$ and $\frac{1}{2}\eta(\lambda q_n)^2$.*

TABLE 2. Notation.

Parameters	
v	Consumer willingness-to-pay for NPs
δ	Consumer acceptance for RPs
ϕ	Size of the functionality-oriented consumer segment
λ	Recovery rate
k/η	Recycling scale parameter for the OEM and the TP
c_n/c_r	Unit production cost of NPs or RPs
g	Remanufacturing cost advantage
e_n/e_r	Unit environmental impact of NPs or RPs
π_i^j	Profit of player i in model j
SC^j	Supply chain profit in model j
CS^j	Consumer surplus in model j
EI^j	Environmental impact in model j
Decisions	
q_n^j/q_r^j	Quantity of NPs or RPs in model j
p_n^j/p_r^j	Retail price of NPs or RPs in model j
p^c	The transfer price of collection business
p^r	The transfer price of remanufacturing business
s	Full outsourcing fee charged by the TP

The recycling scale parameters are usually related to the layout of recycling outlets, the deployment of recycling personnel, and the distance from consumers [21]. OEMs and TPs have different efforts to the collection equipment, so their collection costs are also different. Specifically, OEMs are usually farther away from consumers, and they are more focused on the consumer's experience of buying NPs. TPs are closer to consumers, and usually take the recycling business as their main business and invest more effort. Therefore, their recycling scale parameters are different. So we denote the recycling scale parameters for the OEM and the TP as k and η, respectively. The collection cost functions are widely used in previous research [5,32], where λ is the recovery rate. The larger values of k and η represent the lower collection efficiency.

Assumption 3.4. *All decisions are considered in a single-period setting.*

Remanufacturing is a typical multiple-period problem because used products are recycled and remanufactured only if NPs have been used. To examine the channel designs on CLSC without the distraction of initial and terminal time period effects, following the literature [22,27,41], we study a steady single-period model, meaning that all players use the same strategies in every period.

The quantity constraint is another salient feature of the remanufacturing, which requires the producing quantity of RPs in the current period is less than the quantity of NPs in the previous period. In the steady-state setting, the quantity of NPs is the same in all periods. The quantity constraint in the representative period can be represented $q_r \leq q_n$, which requires $\phi \leq \max\left\{1, \frac{2\delta(1-\delta)(1-c_n)}{2(\delta c_n-c_r-g)(1+\delta)-k(1-c_n)}, \frac{\delta(1-\delta)(1-c_n)}{(\delta c_n-c_r-g)(1+\delta)-\eta(1-c_n)}, \frac{4\delta(1-\delta)(1-c_n)}{(\delta c_n-c_r)(1+\delta)-(2k+3\delta^2)(1-c_n)}\right\}$ in our models. Table 2 summarizes the key notation in this paper.

4. MODEL FORMULATIONS

4.1. In-house remanufacturing (Model IR)

In the literature on managing closed-loop supply chains, many studies, such as Majumder and Groenevelt [25], Ferrer and Swaminathan [10], and Hong *et al.* [18], suggest that the OEMs usually develop their own remanufacturing strategy as a response to the threat of TPs. As shown in Figure 1a, the OEM owns the capabilities of collection and remanufacturing. At the same time, the OEM retains the marketing operations of NPs and RPs simultaneously. The OEM determines the quantity of the NPs (q_n) and the recovery rate (λ) from consumers to maximize profit. The OEM's problem is as follow

$$\max \pi_M^{\mathrm{IR}}(q_n, \lambda) = (p_n - c_n)q_n + (p_r - c_r - g)q_r - \frac{1}{2}k(\lambda q_n)^2. \tag{4.1}$$

The first part of the formula (4.1) is the revenue obtained from NPs, the second part is the revenue derived from RPs, and the last part is the cost of collecting used products. In this paper, we consider deterministic demand and only recycle products that can be used for remanufacturing. Similar to the literature of Zou *et al.* [48], the quantity of used products collected equals the demand for RPs, which is $\lambda q_n = q_r$. Then, we solve the problem by substituting the inverse demand functions into formula (4.1). The following lemma characterizes the equilibrium results.

Lemma 4.1. *In Model IR, the equilibrium quantities, prices, and profit can be formed*

$$q_n^{\mathrm{IR}^*} = \frac{1-c_n}{2} - \frac{\delta\phi(\delta c_n - c_r - g)}{k\phi + 2\delta - 2\delta^2} \qquad q_r^{\mathrm{IR}^*} = \frac{\phi(\delta c_n - c_r - g)}{k\phi + 2\delta - 2\delta^2}$$

$$\lambda^{\mathrm{IR}^*} = \frac{2\phi(\delta c_n - c_r - g)}{(k\phi + 2\delta - 2\delta^2)(1-c_n) - 2\delta\phi(\delta c_n - c_r - g)} \qquad p_n^{\mathrm{IR}^*} = \frac{1+c_n}{2}$$

$$p_r^{\mathrm{IR}^*} = \delta\left(\frac{1+c_n}{2} - \frac{(1-\delta)(\delta c_n - c_r - g)}{k\phi + 2\delta - 2\delta^2}\right) \qquad \pi_M^{\mathrm{IR}^*} = \frac{(1-c_n)^2}{4} + \frac{\phi(\delta c_n - c_r - g)^2}{2(k\phi + 2\delta - 2\delta^2)}.$$

As consumer's acceptance for remanufactured product (δ) increases, the quantity of RPs increases, while the quantity of NPs decreases. The higher cost saving of remanufacturing ($c_n - c_r - g$), the lower quantity difference between two products. Increased FOC segment (ϕ) will improve the recovery rate and the demand for RPs while reduce the demand for NPs.

From Lemma 4.1, we find that the price of NPs will not be influenced by the remanufacturing cost and collection cost, but the price of RPs will be affected by the production cost of NPs, the remanufacturing cost, and collection cost. As δ increases, the price of RPs rises. When the OEM waives used products business, *i.e.*, only produce and sell NPs, the OEM's profit is $\frac{(1-c_n)^2}{4}$. If the OEM engages in used products business, the increased remanufacturing profit is $\frac{\phi(\delta c_n - c_r - g)^2}{2(k\phi+2\delta-2\delta^2)}$, which increases in δ and ϕ.

Proposition 4.2. *The total demand for NPs and RPs increases with the FOC segment (ϕ). As consumer acceptance for RPs (δ) increases, the total demand first increases and then decreases. Furthermore, when $\delta \to 1$, the total demand equals $\frac{1-c_n}{2}$.*

As the FOC segment (ϕ) enlarges, the demand for RPs increases owing to more consumers are willing to buy RPs. However, the demand for NPs reduces because of the cannibalization effect. Finally, increased ϕ makes more consumers with low willingness-to-pay buy RPs, the total demand for NPs and RPs increases. As δ increases, the substitutability between RPs and NPs becomes evident. When δ is small, the market expansion effect of RPs is stronger, so the total market demand increases with δ. When δ is large, the internal competition dominates, so the total market demand decreases with δ. When $\delta \to 1$, they can perfectly substitute each other and the total demand for two products equals the demand in which only sells NPs.

4.2. Outsourcing collection (Model OC)

In Model OC, the TP is a supplier of core components of used products, earning the residual value of old products, so the OEM pays the transfer price for the TP [39]. The OEM retains the marketing operations of NPs and RPs. Recent research efforts widely adopt manufacturer-led models [6, 48]. Thus, we also focus on the case in which the OEM is the Stackelberg leader and the TP is the follower. The sequence of events is as follows: first, the OEM determines the quantity of the NPs (q_n) and the transfer price of collection business (p^c). Subsequently, according to the outsourcing collection fee, the TP determines the recovery rate of used products (λ). The OEM's problem and the TP's problem are given, respectively,

$$\max \pi_M^{\mathrm{OC}}(q_n, p^c) = (p_n - c_n)q_n + (p_r - c_r - g - p^c)\lambda q_n \tag{4.2}$$

$$\max \pi_T^{\mathrm{OC}}(\lambda) = p^c q_r - \frac{1}{2}\eta(\lambda q_n)^2. \tag{4.3}$$

We solve these problems by backward induction to determine the subgame perfect equilibrium. Thus, we obtain the Lemma 4.3.

Lemma 4.3. *In Model OC, the equilibrium quantities, the transfer price of collection business, prices, and profits are*

$$\begin{aligned}
q_n^{\mathrm{OC}^*} &= \frac{1-c_n}{2} - \frac{\delta\phi(\delta c_n - c_r - g)}{2(\eta\phi + \delta - \delta^2)} & q_r^{\mathrm{OC}^*} &= \frac{\phi(\delta c_n - c_r - g)}{2(\eta\phi + \delta - \delta^2)}\\
p^{c^*} &= \frac{\eta\phi(\delta c_n - c_r - g)}{2(\eta\phi + \delta - \delta^2)} & \lambda^{\mathrm{OC}^*} &= \frac{\phi(\delta c_n - c_r - g)}{(\eta\phi + \delta - \delta^2)(1-c_n) - \delta\phi(\delta c_n - c_r - g)}\\
p_n^{\mathrm{OC}^*} &= \frac{1+c_n}{2} & p_r^{\mathrm{OC}^*} &= \delta\left(\frac{1+c_n}{2} - \frac{(1-\delta)(\delta c_n - c_r - g)}{2(\eta\phi + \delta - \delta^2)}\right)\\
\pi_M^{\mathrm{OC}^*} &= \frac{(1-c_n)^2}{4} + \frac{\phi(\delta c_n - c_r - g)^2}{4(\eta\phi + \delta - \delta^2)} & \pi_T^{\mathrm{OC}^*} &= \frac{\eta\phi^2(\delta c_n - c_r - g)^2}{8(\eta\phi + \delta - \delta^2)^2}.
\end{aligned}$$

As the remanufacturing cost of the OEM ($c_r + g$) increases, the own remanufacturing motivation of the OEM will be weak. Hence, he will decrease the transfer price of collection business $\left(p^{c^*}\right)$ to reduce the recycled quantity from the TP. When the production cost of NPs (c_n) increases, the OEM will raise p^{c^*} to incentive the TP to collect more used products to remanufacture. Furthermore, p^{c^*} increases with TP's recycling scale parameter (η) and consumer's acceptance for RPs (δ).

From Lemma 4.3, we find when the OEM only engages in reproducing business of used products, the total profit of two players will increase $\frac{\phi\left(3\eta\phi+2\delta-2\delta^2\right)(\delta c_n - c_r - g)^2}{8(\eta\phi+\delta-\delta^2)^2}$. Then, $\frac{\phi(\delta c_n - c_r - g)^2}{4(\eta\phi+\delta-\delta^2)}$ is allocated to the OEM, and the other is allocated to the TP. Similarly, when $\delta \to 1$, the total quantity of NPs and RPs also equals $\frac{1-c_n}{2}$.

4.3. Outsourcing remanufacturing (Model OR)

In Model OR, the OEM outsources the remanufacturing business to the TP and the TP is an intermediate processor, earning processing outsourcing costs, so the OEM needs to pay the transfer price for the TP [42]. The OEM controls the collection channel of used products and still retains the marketing operations of NPs and RPs. The sequence of events is as follows: first, the OEM determines the quantity of the NPs (q_n). Sequentially, the TP releases the transfer price of remanufacturing business (p^r). Finally, the OEM determines the recovery rate (λ) from consumers. The OEM's problem and the TP's problem are as follows,

$$\max \pi_M^{\mathrm{OR}}(q_n, \lambda) = (p_n - c_n)q_n + (p_r - p^r)\lambda q_n - \frac{1}{2}k(\lambda q_n)^2 \tag{4.4}$$

$$\max \pi_T^{\mathrm{OR}}(p^r) = (p^r - c_r)\lambda q_n. \tag{4.5}$$

Similar to Section 4.2, we solve the game with backward induction. The following lemma characterizes the equilibrium decisions.

Lemma 4.4. *In Model OR, the equilibrium quantities, the transfer price of remanufacturing business, prices, and profits are*

$$
\begin{aligned}
q_n^{\mathrm{OR}^*} &= \frac{1-c_n}{2} - \frac{\delta\phi(\delta c_n - c_r)}{2((2k+3\delta^2)\phi + 4\delta - 4\delta^2)} \\
q_r^{\mathrm{OR}^*} &= \frac{\phi(\delta c_n - c_r)}{2((2k+3\delta^2)\phi + 4\delta - 4\delta^2)} \\
p^{r^*} &= \frac{\left((k+\delta^2)\phi + 2\delta - 2\delta^2\right)(\delta c_n + c_r) + \delta^3\phi c_n}{(2k+3\delta^2)\phi + 4\delta - 4\delta^2} \\
\lambda^{\mathrm{OR}^*} &= \frac{\phi(\delta c_n - c_r)}{((2k+3\delta^2)\phi + 4\delta - 4\delta^2)(1-c_n) - \phi\delta(\delta c_n - c_r)} \\
p_n^{\mathrm{OR}^*} &= \frac{1+c_n}{2} - \frac{\delta\phi(\delta c_n - c_r)}{2((2k+3\delta^2)\phi + 4\delta - 4\delta^2)} \\
p_r^{\mathrm{OR}^*} &= \delta\left(\frac{1+c_n}{2} - \frac{(2-2\delta+\phi\delta)(\delta c_n - c_r)}{2((2k+3\delta^2)\phi + 4\delta - 4\delta^2)}\right) \\
\pi_M^{\mathrm{OR}^*} &= \frac{(1-c_n)^2}{4} + \frac{\phi(\delta c_n - c_r)^2}{4((2k+3\delta^2)\phi + 4\delta - 4\delta^2)} \\
\pi_T^{\mathrm{OR}^*} &= \frac{\phi\left((k+2\delta^2)\phi + 2\delta - 2\delta^2\right)(\delta c_n - c_r)^2}{((2k+3\delta^2)\phi + 4\delta - 4\delta^2)^2}.
\end{aligned}
$$

Different from the Model OC, no matter how the production cost of NPs (c_n) or RPs (c_r) increases, the transfer price of remanufacturing business $\left(p^{r^*}\right)$ always increases. This is mainly because when c_n increases, the TP increases the processing fee to capture more remanufacturing profit. So the OEM needs to pay higher p^{r^*} for the TP to stimulus the TP engaged in remanufacturing production. When c_r increases, the TP can also increase the processing fee to share more production costs with the OEM.

Moreover, when the OEM only engages in collection business of used products, the total profit of two players will increase $\frac{\phi\left(\left(6k+11\delta^2\right)\phi+12\delta-12\delta^2\right)(\delta c_n-c_r)^2}{4((2k+3\delta^2)\phi+4\delta-4\delta^2)^2}$. Then, $\frac{\phi(\delta c_n-c_r)^2}{4((2k+3\delta^2)\phi+4\delta-4\delta^2)}$ is allocated to the OEM, and the other is allocated to the TP. Similarly, when $\delta \to 1$, the total quantity of NPs and RPs also equals $\frac{1-c_n}{2}$.

4.4. Full outsourcing (Model FO)

In Model FO, the OEM outsources the whole reverse channel operations to the TP and pays the TP outsourcing fee. The OEM owns only the marketing operations of NPs and RPs. The TP controls the recycling quantity of used products and the remanufacturing process. The sequence of events is as follows: first, the OEM determines the quantity of the NPs (q_n) and outsourcing collection fee (s). Subsequently, according to the outsourcing collection fee, the TP determines the recovery rate (λ). The OEM's problem and the TP's problem are as follows,

$$\max \pi_M^{\mathrm{FO}}(q_n, s) = (p_n - c_n)q_n + (p_r - s)\lambda q_n \tag{4.6}$$

$$\max \pi_T^{\mathrm{FO}}(\lambda) = (s - c_r)\lambda q_n - \frac{1}{2}\eta(\lambda q_n)^2. \tag{4.7}$$

Lemma 4.5. *In Model OT, the equilibrium quantities, outsourcing fee, prices, and profits are*

$$
\begin{aligned}
q_n^{\mathrm{FO}^*} &= \frac{1-c_n}{2} - \frac{\delta\phi(\delta c_n - c_r)}{2(\eta\phi + \delta - \delta^2)} & q_r^{\mathrm{FO}^*} &= \frac{\phi(\delta c_n - c_r)}{2(\eta\phi + \delta - \delta^2)} \\
s^{\mathrm{FO}^*} &= \frac{\eta\phi(\delta c_n + c_r) + 2\delta c_r(1-\delta)}{2(\eta\phi + \delta - \delta^2)} & \lambda^{\mathrm{FO}^*} &= \frac{\phi(\delta c_n - c_r)}{(\eta\phi + \delta - \delta^2)(1-c_n) - \delta\phi(\delta c_n - c_r)} \\
p_n^{\mathrm{FO}^*} &= \frac{1+c_n}{2} & p_r^{\mathrm{FO}^*} &= \delta\left(\frac{1+c_n}{2} - \frac{(1-\delta)(\delta c_n - c_r)}{2(\eta\phi + \delta - \delta^2)}\right)
\end{aligned}
$$

$$\pi_M^{\mathrm{FO}^*} = \frac{(1-c_n)^2}{4} + \frac{\phi(\delta c_n - c_r)^2}{4(\eta\phi + \delta - \delta^2)} \qquad \pi_T^{\mathrm{FO}^*} = \frac{\eta\phi^2(\delta c_n - c_r)^2}{8(\eta\phi + \delta - \delta^2)^2}.$$

From Lemma 4.5, the increased FOC segment and the cost saving of remanufacturing will raise the recovery rate. The price of NPs still remains unchanged, while the price of RPs will be affected by NP production cost, RP production cost, consumer acceptance for RPs, and scale parameter of recycling cost. When the OEM only engages in marketing for NPs and RPs, the total profit of two players will increase $\frac{\phi\left(3\eta\phi+2\delta-2\delta^2\right)(\delta c_n-c_r)^2}{8(\eta\phi+\delta-\delta^2)^2}$, where $\frac{\phi(\delta c_n-c_r)^2}{4(\eta\phi+\delta-\delta^2)}$ is allocated to the OEM and the other is allocated to the TP. Moreover, when $\delta \to 1$, the total quantity of NPs and RPs also equals $\frac{1-c_n}{2}$.

Next, we compare the equilibrium results under four models and have the following corollaries.

Corollary 4.6. *The transfer prices and outsourcing fees satisfy $p^{r^*} > s^{\mathrm{FO}^*} > p^{c^*}$ and increase with ϕ.*

Corollary 4.6 indicates that the transfer price of collection business is always the lowest, while the transfer price of remanufacturing business is the highest. This is because when the remanufacturing process is outsourced, the TP controls the remanufacturing process and can determine the transfer price of the remanufacturing business. Although the OEM controls the number of key components of the recycled product, the transfer price of remanufacturing is controlled by TP. In order to obtain more remanufacturing revenue, a higher transfer price is set. When the collection process is outsourced, the transfer price of collection is controlled by the OEM. In order to reduce the cost of recycling key components of the old product, the OEM usually sets a lower transfer price. In the case of full outsourcing, since both the recovery cost and the remanufacturing cost are borne by TP, the OEM will set a higher outsourcing fee to stimulate the TP recycling and remanufacturing process. However, considering the profit of the marketing market, OEMs are reluctant to set high outsourcing costs, so the fee of full outsourcing will not be very high or low. Moreover, the increased ϕ makes the remanufacturing activity more attractive, so the OEM is willing to pay more outsourcing fees to encourage the TP to engage in the collection or remanufacturing business of used products.

Corollary 4.7. *The retail prices of NPs satisfy $p_n^{\mathrm{OR}^*} < p_n^{\mathrm{IR}^*} = p_n^{\mathrm{OC}^*} = p_n^{\mathrm{FO}^*}$. However, the price of RPs is affected by reverse channel choices, and the retail prices of RPs increase with ϕ.*

The retail price of NPs will hardly change no matter how the reverse channel changes. In Model OR, the OEM only controls the recycled quantity of used products, and the TP sets the higher transfer price of remanufacturing to get more remanufacturing profit. The OEM's remanufacturing profit reduces and has to decrease the retail price of NPs to incentive the sales of NPs to obtain more NP's profit. Hence, the retail price of Model OR is the lowest. In Model OC and Model FO, the OEM can indirectly control the recycling quantity from the TP by setting different transfer prices of collection and outsourcing fees. For example, the OEM sets a lower transfer price of collection to avoid the excessive collection of used products when the demand for RPs is low but setting a higher transfer price of collection to stimulus the supply of key components of used products to meet the higher market demand for RPs. Therefore, the OEM always sustains a dominant position in the two models, enabling it to maintain the retail price of NPs unchanged. However, the price of RPs is affected by reverse channel choices. As ϕenlarges, more consumers with low willingness-to-pay buy RPs, so the OEM usually sets a higher retail price to catch more remanufacturing profit.

5. Decisions analysis in the four different channel choices

In this section, we analyze the optimal reverse channel choices for the OEM and the TP and explore the impact of the FOC segment (ϕ) and consumer acceptance for RPs (δ) on the reverse channel selections. The numerical analysis graphically shows the result of the reverse channel selection. Our base case is $c_n = 0.3, c_r = 0.1, \eta = 2, \delta = 0.5, \phi = 0.8$. The values are taken according to previous numerical examples [47].

First, we focus on the OEM's reverse channel choices and have the following proposition.

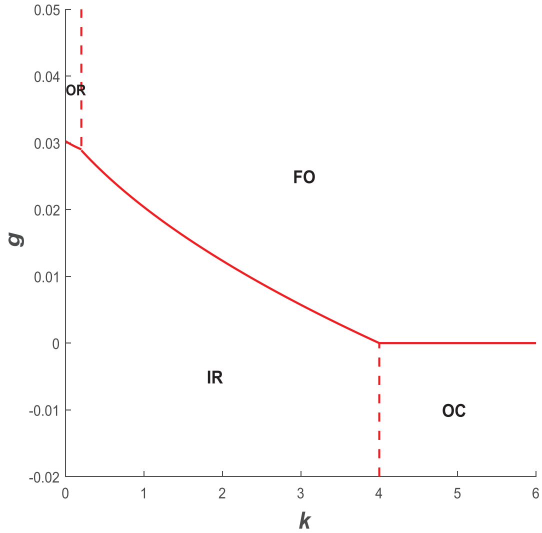

FIGURE 2. OEM's reverse channel choices.

Proposition 5.1. *Reverse channel choices for the OEM*

The recycling scale parameter for the OEM	*Remanufacturing cost advantage*	*Optimal reverse channel choices*
Low collection cost ($k \le k_m$)	*Small* ($g \le 0$) *Large* ($g > 0$)	*Outsourcing collection* *Full outsourcing*
Medium collection cost ($k_m < k < 2\eta$)	*Small* ($g \le g_{m1}$) *Large* ($g > g_{m1}$)	*In-house remanufacturing* *Full outsourcing*
High collection cost ($k > 2\eta$)	*Small* ($g \le g_{m2}$) *Large* ($g > g_{m2}$)	*In-house remanufacturing* *Outsourcing remanufacturing*

where $k_m = \frac{(\eta-3\delta^2)\phi-3\delta+3\delta^2}{2\phi}$, $g_{m1} = (\delta c_n - c_r)\left(1-\sqrt{\frac{k\phi+2\delta-2\delta^2}{2((2k+3\delta^2)\phi+4\delta-4\delta^2)}}\right)$, *and* $g_{m2} = (\delta c_n - c_r)\left(1-\sqrt{\frac{k\phi+2\delta-2\delta^2}{2(\eta\phi+\delta-\delta^2)}}\right)$.

This proposition states that the optimal reverse channel choices for the OEM. Figure 2 illustrates the findings of Proposition 5.1. As shown in the figure, the recycling scale parameter for the OEM (k) and the remanufacturing cost advantage (g) jointly determine the optimal reverse channel choices. The parameters k and g divide the plane into four regions, each region represents the strategy under which one condition is optimal.

Figure 2 yields several interesting results. First, for partial outsourcing strategies (OR), the OEM chooses outsourcing the remanufacturing process only when his own recycling efficiency is very high, *i.e.*, the recycling cost of the OEM is negligible. For the OC strategy, when the TPs' recycling efficiency is twice high OEM's, the OEM will only outsource the collection business if he owns remanufacturing cost advantage. Second, when the TP has a greater remanufacturing cost advantage, no matter what the OEM's recycling ability is, full outsourcing is the optimal choice for the OEM. There are two main reasons: one is the total demand under full outsourcing is higher than partial outsourcing, the other the unit outsourcing fee under full outsourcing is lower than partial outsourcing. Finally, when the OEM's recycling ability and remanufacturing capability are stronger or slightly weaker than those of the TP, in-house remanufacturing is the optimal choice for the OEM.

TABLE 3. The impacts of ϕ and δ on the OEM's reverse channel selections.

Parameters	Critical values of strategy			The regions of channel strategy			
	k_m	g_{m1}	g_{m2}	IR	FO	OR	OC
ϕ	$\uparrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\uparrow$	$=$
δ	$\downarrow$	$\uparrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\downarrow$	$=$

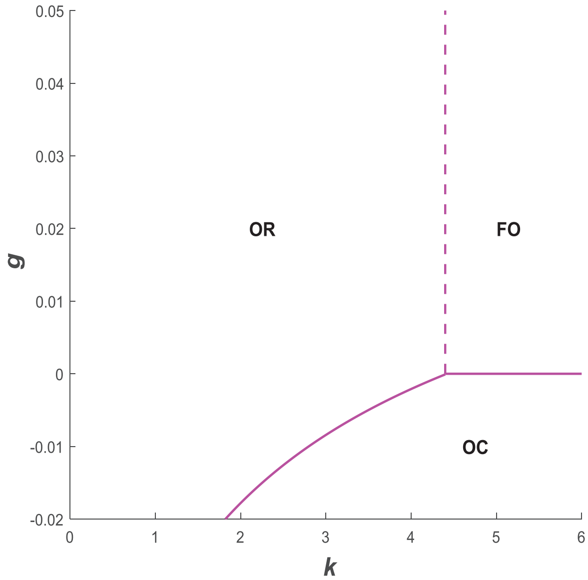

FIGURE 3. TP's reverse channel choices.

Next, to examine the impact of consumer education (ϕ) and consumer acceptance for RPs (δ) on the OEM's reverse channel selection, we have the following Corollary.

Corollary 5.2. *Increased FOC segment* (ϕ) *and consumer acceptance for RPs* (δ) *might help the OEM choose IR strategy and forgo FO strategy; that is, as* ϕ *and* δ *increase, the region of IR-dominant expands but the region of FO-dominant shrinks. The region of OR-dominant will increase with* ϕ *while decrease with* δ*. The region of OC-dominant remains unchanged.*

Consistent with the conventional wisdom, increased ϕ and δ make the whole remanufacturing activity more attractive, so the OEM is more willing to choose in-house remanufacturing to fully control the reverse channel. For full outsourcing, the critical value of remanufacturing production rises obviously, resulting in the region of FO-dominant shrinks. The external market expansion (ϕ) makes the part of FO-dominant region shift to the region of OR-dominant, which shows that the control right of the collection process becomes more important for the OEM. However, the internal expansion (δ) makes the OEM willing to partially forgo the control right of the collection process to ease the inner double marginalization. The region of OC-dominant will not be affected by ϕ and δ. Table 3 specifically demonstrates how the parameters ϕ and δaffect the critical values and reverse channel selections of the OEM.

Then, we analyze the equilibrium profit of TP under three outsourcing strategies and draw the following proposition.

TABLE 4. The impacts of ϕ and δ on the TP's reverse channel selections.

Parameters	Critical values of strategy		The regions of channel strategy		
	k_t	g_t	FO	OR	OC
ϕ	$\downarrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\uparrow$
δ	$\downarrow$	$\downarrow$	$\uparrow$	$\downarrow$	$\downarrow$

Proposition 5.3. *Reverse channel choices for the TP*

The recycling scale parameter for the OEM	*Remanufacturing cost advantage*	*Optimal reverse channel choices*
Low collection cost	*Small* ($g \le 0$)	*Outsourcing collection*
($k \le k_t$)	*Large* ($g > 0$)	*Full outsourcing*
High collection cost	*Small* ($g \le g_t$)	*Outsourcing collection*
($k > k_t$)	*Large* ($g > g_t$)	*Outsourcing remanufacturing*

where $k_t = \frac{\eta\phi^2\left(2\eta-3\delta^2\right)+2\delta^2(1-\delta)^2+2\left(\eta\phi+\delta-\delta^2\right)\sqrt{\eta\phi((\eta+\delta^2)\phi+2\delta-2\delta^2)+\delta^2(1-\delta)^2}}{2\eta\phi^2}$ *and* $g_t = (\delta c_n - c_r)\left(1-\sqrt{\frac{8((k+2\delta^2)\phi+2\delta-2\delta^2)(\eta\phi+\delta-\delta^2)^2}{\eta\phi((2k+3\delta^2)\phi+4\delta-4\delta^2)^2}}\right)$.

This proposition states that the optimal reverse channel choices for the TP. Similar to the Proposition 5.1, the recycling scale parameter for the OEM (k) and the remanufacturing cost advantage (g) divide the plane into three regions, each region represents the strategy under which one condition is optimal. Figure 3 graphically shows the results in Proposition 5.3.

When the TP has a remanufacturing cost advantage ($g > 0$) or slight disadvantage ($g_t < g < 0$), no matter how much the OEM's collection efficiency is higher ($k < \eta$) or lower ($\eta < k < k_t$) than that of TP, accepting remanufacturing outsourcing is optimal for the TP. Accepting full outsourcing requires the TP to have both remanufacturing cost advantage and very high collection efficiency ($\eta \ll k$). As for strategy OC, it is optimal when the TP has no remanufacturing advantage but a high collection efficiency.

Corollary 5.4. *The increased FOC segment* (ϕ) *and consumer acceptance for RPs* (δ) *will expand the region FO-dominant strategy but shrink the region OR-dominant. The region of OC-dominant will increase with* ϕ *while decrease with* δ.

As ϕ increases, the TP has more motivation to accept full outsourcing strategy (FO), while the outsourcing remanufacturing process (OR) gradually loses attractiveness. This is because the increased ϕ expands the remanufacturing market, which makes more low willingness-to-pay consumers enter the product market. Hence, the TP would like to control the whole reverse channel to get more remanufacturing profit. Similarly, the full outsourcing strategy (FO) still keeps high attractive because of increased δ.

Interestingly, increased ϕ makes the part of OR-dominant region shift to the region of OC-dominant, while increased δ makes the part of OC-dominant region shift to the region of OR-dominant. It implies that the external market expansion will make the TP more willing to control the remanufacturing process of reverse channels, while the internal expansion will make the TP only focus on the collection process. Table 4 specifically illustrates how the parameters ϕ and δ affect the critical values and reverse channel selections of the TP.

Corollary 5.5. *The increased* ϕ *and* δ *will expand the consistent range (FO vs. FO) but shrink the main channel conflict (FO vs. OR) between the OEM and the TP. The consistent range (OR vs. OR) increases with* ϕ *but decreases with* δ.

Corollary 5.5 points out how the consistent and conflict regions evolve with ϕ and δ. As ϕ and δ enlarge, the TP would like to accept full outsourcing to get more remanufacturing profit, so the consistent region on (FO *vs.* FO) increases, the main conflict region on (FO *vs.* OR) shrinks. Increased ϕ makes the OEM more willing to control the recycling channel, so the consistent range (OR *vs.* OR) increases, while δ has an opposite effect.

6. Supply chain, consumers, and environmental impact

6.1. Value for the supply chain

In this section, we discuss the optimal reverse channel choices from the supply chain's perspective. The supply chain profit includes OEM's profit and the TP's profit:

$$\mathrm{SC} = \pi_M + \pi_T. \tag{6.1}$$

The following lemma characterizes supply chain profit in the three outsourcing models when the OEM and the TP form a Nash equilibrium.

Lemma 6.1. *The supply chain profits in Model OC, Model OR, and Model FO are given by*

$$\begin{aligned}
\mathrm{SC}^{\mathrm{OC}^*} &= \frac{(1-c_n)^2}{4} + \frac{\phi\big(3\eta\phi + 2\delta - 2\delta^2\big)(\delta c_n - c_r - g)^2}{8(\eta\phi + \delta - \delta^2)^2}\\
\mathrm{SC}^{\mathrm{OR}^*} &= \frac{(1-c_n)^2}{4} + \frac{\phi\big((6k + 11\delta^2)\phi + 12\delta - 12\delta^2\big)(\delta c_n - c_r)^2}{4((2k + 3\delta^2)\phi + 4\delta - 4\delta^2)^2}\\
\mathrm{SC}^{\mathrm{FO}^*} &= \frac{(1-c_n)^2}{4} + \frac{\phi\big(3\eta\phi + 2\delta - 2\delta^2\big)(\delta c_n - c_r)^2}{8(\eta\phi + \delta - \delta^2)^2}.
\end{aligned}$$

Lemma 6.1 shows that the supply chain profit decreases with the recycling scaling parameter while increases with the FOC segment. This is because the higher recycling parameter means a weak recycling efficiency, but the larger ϕ shows that more consumers with low willingness can enter the product market to buy RPs. Consistent with the conventional wisdom, the larger cost saving of remanufacturing makes supply chain obtain more value.

Proposition 6.2. *Comparison of supply chain profit*

The recycling scale parameter for the OEM	*Remanufacturing cost advantage*	*Optimal reverse channel choices*
Low collection cost ($k \le k_{s1}$)	*Small* ($g \le g_{s1}$)	*In-house remanufacturing*
	Large ($g > g_{s1}$)	*Outsourcing remanufacturing*
Medium collection cost ($k_{s1} < k < k_{s2}$)	*Small* ($g \le g_{s2}$)	*In-house remanufacturing*
	Large ($g > g_{s2}$)	*Full outsourcing*
High collection cost ($k \ge k_{s2}$)	*Small* ($g \le 0$)	*Outsourcing collection*
	Large ($g > 0$)	*Full outsourcing*

where $k_{s1} = \frac{12\eta^2\phi^2 - 5\delta^2(1-\delta)^2}{2\phi(3\eta\phi + 2\delta - 2\delta^2)} - \frac{3\eta + 3\delta^2}{2} + \frac{(\eta\phi + \delta - \delta^2)\sqrt{2\phi\delta(9\eta + 4\delta^2 - 4\delta^3) + 3\eta\phi(3\eta\phi + 4\phi\delta^2 - 6\delta^2) + 9\delta^2(1-\delta)^2}}{2\phi(3\eta\phi + 2\delta - 2\delta^2)}$, $k_{s2} = \frac{2\eta(2\eta\phi + \delta - \delta^2)}{3\eta\phi + 2\delta - 2\delta^2}$, $g_{s1} = (\delta c_n - c_r)\left(1 - \frac{\sqrt{2(k\phi + 2\delta - 2\delta^2)((6k + 11\delta^2)\phi + 12\delta - 12\delta^2)}}{2((2k + 3\delta^2)\phi + 4\delta - 4\delta^2)}\right)$, *and* $g_{s2} = (\delta c_n - c_r)\left(1 - \frac{\sqrt{(k\phi + 2\delta - 2\delta^2)(3\eta\phi + 2\delta - 2\delta^2)}}{2(\eta\phi + \delta - \delta^2)}\right)$.

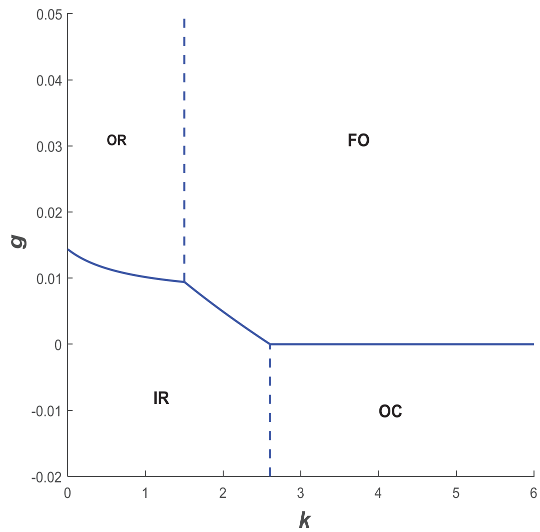

Figure 4. Optimal channel choices for the SC.

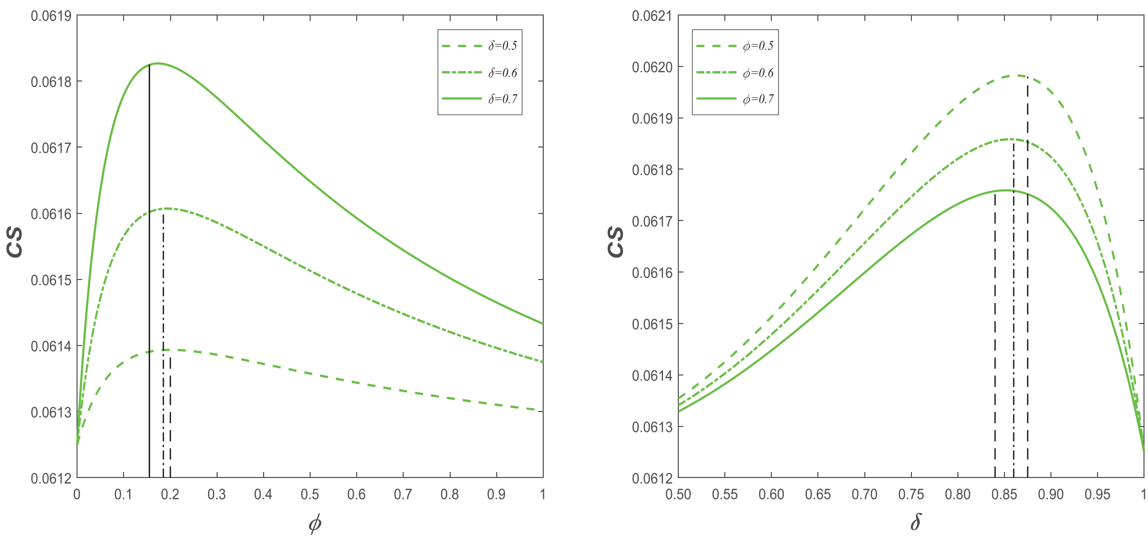

Figure 5. Impact of consumer education and acceptance for RPs on CS.

The optimal reverse channel selections in view of the supply chain are graphically illustrated in Figure 4. As shown in the figure, two key conditions jointly determine the optimal strategies: the recycling scale parameter and the remanufacturing cost advantage. Compared to the OEM's reverse channel selection, the areas of Model OR and OC increase significantly, while the areas of Model IR and FO decrease obviously. It implies that if focusing on the goal of supply chain profit, partial outsourcing strategies become more attractive, and the in-house remanufacturing and full outsourcing strategies require more strict conditions. However, the overall orientation of the optimal reverse channel selection remains unchanged.

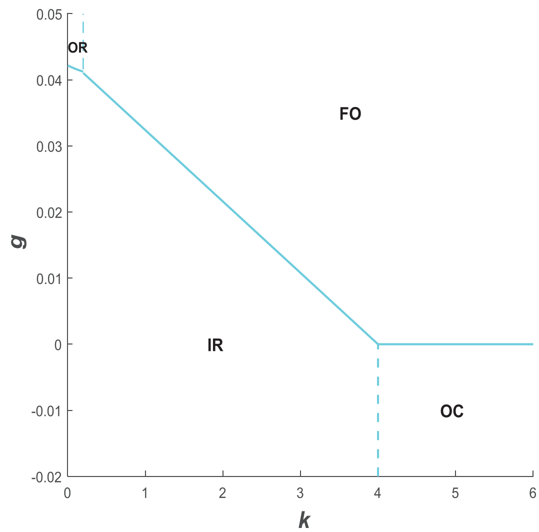

FIGURE 6. Optimal channel choices for CS.

6.2. Value for consumers

In this subsection, we discuss the optimal reverse channel choices from consumers' perspective and explore the value of consumer education. Following Örsdemir *et al.* [26], the formula of consumer surplus (CS) is shown as follow:

$$\begin{aligned}\mathrm{CS} &= \int_{1-q_n}^{1}(v-p_n)\mathrm{d}v + \int_{1-q_n-q_r}^{1-q_n}(\delta v - p_r)\mathrm{d}v\\ &= \frac{\phi(q_n+\delta q_r)^2+\delta(1-\delta)(2-\phi)q_r^2}{2\phi}.\end{aligned} \tag{6.2}$$

From Lemmas 4.1–4.5, we know the equilibrium demands for NPs and RPs $\left(q_n^{j^*}, q_r^{j^*}\right)$. Substituting $q_n^{j^*}$ and $q_r^{j^*}$ into formula (6.2), we have Lemma 6.3.

Lemma 6.3. *The consumer surplus in Model IR, Model OC, Model OR, and Model FO are given*

$$\begin{aligned}\mathrm{CS}^{\mathrm{IR}^*} &= \frac{(1-c_n)^2}{8} + \frac{\phi\delta(1-\delta)(2-\phi)(\delta c_n - c_r - g)^2}{2(k\phi+2\delta-2\delta^2)^2}\\ \mathrm{CS}^{\mathrm{OC}^*} &= \frac{(1-c_n)^2}{8} + \frac{\phi\delta(1-\delta)(2-\phi)(\delta c_n - c_r - g)^2}{8(\eta\phi+\delta-\delta^2)^2}\\ \mathrm{CS}^{\mathrm{OR}^*} &= \frac{(1-c_n)^2}{8} + \frac{\phi\delta(1-\delta)(2-\phi)(\delta c_n - c_r)^2}{8((2k+3\delta^2)\phi+4\delta-4\delta^2)^2}\\ \mathrm{CS}^{\mathrm{FO}^*} &= \frac{(1-c_n)^2}{8} + \frac{\phi\delta(1-\delta)(2-\phi)(\delta c_n - c_r)^2}{8(\eta\phi+\delta-\delta^2)^2}.\end{aligned}$$

Obviously, the CS decreases with the recycling scale parameter but increases with the remanufacturing cost saving. Since ϕ and δ have the same influence on each strategy, we then take IR strategy as the main analysis object to examine how they affect CS. The results are presented in Proposition 6.4.

Proposition 6.4. *If $\phi < \phi^{\mathrm{IR}} = \frac{2\delta-2\delta^2}{k+2\delta-2\delta^2}$, consumer surplus increases with ϕ; otherwise, consumer surplus decreases with ϕ. For δ, there exists $\frac{1}{2} < \delta^{\mathrm{IR}} < 1$, when $\delta < \delta^{\mathrm{IR}}$, consumer surplus increases with δ; otherwise, consumer surplus decreases with δ.*

The impacts of ϕ and δ on consumer surplus are shown in Figure 5. As ϕ enlarges, CS first increases then decreases. When ϕ is small, consistent with the conventional wisdom, CS increases with ϕ because more consumers have one more option of buying RPs; in particular, consumers with low willingness-to-pay who cannot afford NPs can buy RPs and obtain positive net utility. However, when ϕ is large, the CS decreases with ϕ. On the one hand, the higher ϕ represents consumers with low willingness-to-pay who cannot afford NPs can buy RPs and obtain positive net utility, which leads to an increase in the CS. On the other hand, the higher ϕ makes the retail price of RPs rise, some FOCs have to buy the new one and obtain lower utility, and others have to be inactive and obtain the utility of zero, which leads to a significant decrease in the CS. Hence, the CS decreases with the higher ϕ. Moreover, the optimal level of consumer education decreases with k and δ.

Interestingly, CS will not always increase with δ. When δ is large enough, the CS decreases with δ. There are two main reasons. On the one hand, when δ is large, the degree of substitution between RPs and NPs is high, the internal competition is intensified, and the demands for NPs and RPs decrease. On the other hand, increasing δ leads to a higher market-clearing price of RPs so that the CS could be relatively low. The optimal δ decreases with ϕ.

Next, we analyze the optimal reverse channel selections from the perspective of consumers.

Proposition 6.5. *Comparison of consumer surplus*

The recycling scale parameter for the OEM	*Remanufacturing cost advantage*	*Optimal reverse channel choices*
Low collection cost	*Small* ($g \leq g_{c1}$)	*In-house remanufacturing*
($k \leq k_m$)	*Large* ($g > g_{c1}$)	*Outsourcing remanufacturing*
Medium collection cost	*Small* ($g \leq g_{c2}$)	*In-house remanufacturing*
($k_m < k < 2\eta$)	*Large* ($g > g_{c2}$)	*Full outsourcing*
High collection cost	*Small* ($g \leq 0$)	*Outsourcing collection*
($k > 2\eta$)	*Large* ($g > 0$)	*Full outsourcing*

where $k_c = k_m = \frac{(\eta-3\delta^2)\phi-3\delta+3\delta^2}{2\phi}$, $g_{c1} = \frac{3((k+2\delta^2)\phi+2\delta-2\delta^2)(\delta c_n-c_r)}{2((2k+3\delta^2)\phi+4\delta-4\delta^2)}$, *and* $g_{c2} = \frac{\phi(2\eta-k)(\delta c_n-c_r)}{2(\eta\phi+\delta-\delta^2)}$.

This proposition states that the optimal reverse channel choices for consumers. As shown in Figure 6, two key conditions jointly determine the optimal strategies: the recycling scale parameter and the relative remanufacturing cost advantage. The overall orientation of the optimal reverse channel selection also remains unchanged.

6.3. Environmental impact

In this subsection, we examine the impacts of the consumer education and acceptance for RPs on the environment. Following the relevant literature, *e.g.*, Raz *et al.* [29], Atasu and Souza [5], Zhang and Zhang [43], the environmental performance depends on the product volume multiplied by its per-unit impact at each stage. The unit environmental impacts of NPs and RPs in the manufacturing stage are e_n and e_r, where $e_r < e_n$. We denote the environmental impact as EI^j in Model j, thus the formula of environmental impact is

$$\mathrm{EI} = e_n q_n + e_r q_r. \tag{6.3}$$

The following lemma shows the environmental impacts of the four models.

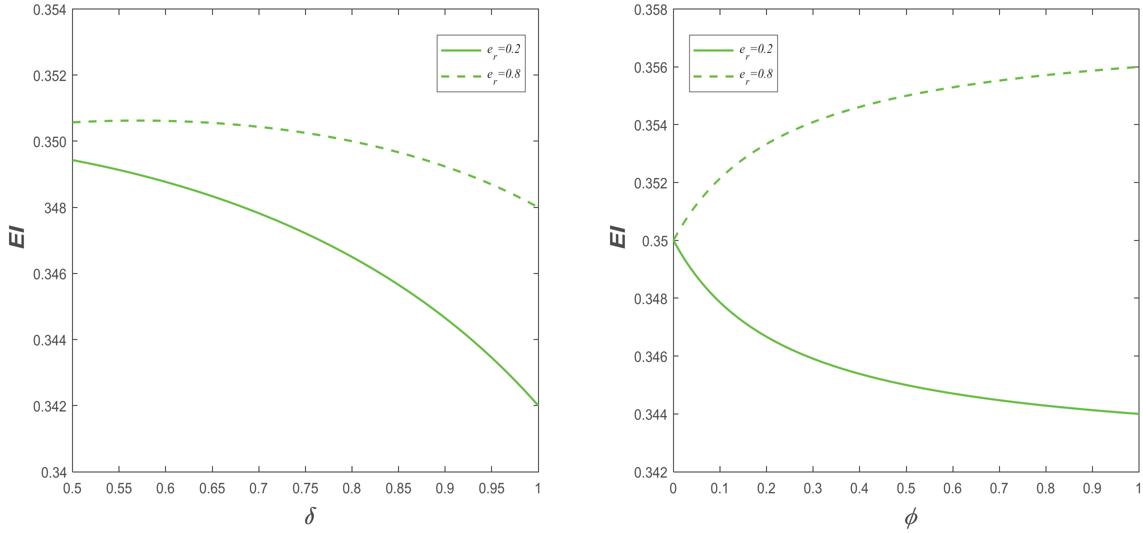

FIGURE 7. The impact of consumer education and acceptance for RPs on EI.

Lemma 6.6. *The environmental impacts in Model IR, Mode OC, Model OR, and Model FO are*

$$\mathrm{EI}^{\mathrm{IR}^*} = \frac{(1-c_n)e_n}{2} - \frac{\phi(\delta c_n - c_r - g)(\delta e_n - e_r)}{k\phi + 2\delta - 2\delta^2}$$
$$\mathrm{EI}^{\mathrm{OC}^*} = \frac{(1-c_n)e_n}{2} - \frac{\phi(\delta c_n - c_r - g)(\delta e_n - e_r)}{2(\eta\phi + \delta - \delta^2)}$$
$$\mathrm{EI}^{\mathrm{OR}^*} = \frac{(1-c_n)e_n}{2} - \frac{\phi(\delta c_n - c_r)(\delta e_n - e_r)}{2((2k + 3\delta^2)\phi + 4\delta - 4\delta^2)}$$
$$\mathrm{EI}^{\mathrm{FO}^*} = \frac{(1-c_n)e_n}{2} - \frac{\phi(\delta c_n - c_r)(\delta e_n - e_r)}{2(\eta\phi + \delta - \delta^2)}.$$

Lemma 6.6 shows that the environmental impacts will increase with the recycling scale parameter because the quantity of greener RPs decreases in the recycling scale parameter. The larger cost saving of remanufacturing makes the environment become more sustainable.

Proposition 6.7. *The environmental impact decreases with consumer acceptance for RPs (δ). However, the impact of consumer education (ϕ) on the environment depends heavily on the relative environmental friendliness of RPs; that is, if $e_r < \delta e_n$, environmental impact decreases with ϕ. Otherwise, environmental impact increases.*

Proposition 6.7 sheds light on the impact of the acceptance for RPs (δ) and consumer education (ϕ) on the environment. Figure 7 graphically illustrates the results by analyzing Model IR. The increased δ makes the demand for RPs rise rapidly, so the emission reduction effect caused by greener RPs is far more than the environmental impact from NPs. Hence, the total environmental impact always decreases regardless of the relative environmental friendliness of RPs. For consumer education, only when the environmental friendliness of RPs is relatively high, the emission reduction effect caused by greener RPs is more than the environmental impact from NPs.

We analyze the environmental impact under different models and find the optimal reverse channel selection from the environment is the same as the reverse channel selection from consumers. We then compare the optimal reverse channel selections from different criteria.

6.4. Comparison of reverse channel selections

From the perspectives of the market leader OEM, consumers, and environment, we have the following proposition.

Proposition 6.8. *Consistent areas among the OEM, consumer, environment*

The recycling scale parameter for the OEM	*Remanufacturing cost advantage*	*The triple-win areas*
$k < k_m$	$g > g_{c1}$	I (OR *vs.* OR)
$k > k_m$	$g > \max\{g_{c2}, 0\}$	II (FO *vs.* FO)
$k < 2\eta$	$g \leq \min\{g_{m1}, g_{m2}\}$	III (IR *vs.* IR)
$k \geq 2\eta$	$g < 0$	IV (OC *vs.* OC)

Proposition 6.8 illustrates the channel selections from the OEM, consumers, and the environment. Figure 8 graphically shows the results. We can observe easily the consistent areas among the OEM, consumer, environment (the green areas) are very large. It implies that in the third-party remanufacturing outsourcing strategy, if the outsourcing business is assigned according to the optimal reverse channel selections of the OEM, a triple-win situation for the OEM, consumers, and environment can be achieved to a large extent.

Considering some responsible firms, we have the following proposition from the perspectives of the supply chain, consumers, and environment.

Proposition 6.9. *Consistent areas among the supply chain, consumer, environment*

The recycling scale parameter for the OEM	*Remanufacturing cost advantage*	*The triple-win areas*
$k < k_m$	$g > g_{c1}$	I (OR *vs.* OR)
$k > k_{s1}$	$g > \max\{g_{c2}, 0\}$	II (FO *vs.* FO)
$k < k_{s2}$	$g \leq \min\{g_{s1}, g_{s2}\}$	III (IR *vs.* IR)
$k \geq 2\eta$	$g < 0$	IV (OC *vs.* OC)

Figure 9 graphically presents the results in Proposition 6.9, which shows the consistent and conflict regions with respect to the three criteria (supply chain, consumers, and environment). Full outsourcing or in-house remanufacturing still occupy a significant share. The existence of consistent regions (the blue areas) demonstrates that the supply chain, consumers, and environment are not always in conflict. If you additionally consider the OEM's profit, the size of the consistent areas will not change, but the conflict areas will become more complicated.

Furthermore, the conflict regions (white areas) always happen when the TP's remanufacturing cost advantage is not very obvious. Therefore, when the TP's remanufacturing cost advantage is not obvious or the recycling efficiency of the OEM slightly higher than of the TP, the participants should pay attention to the focus of pursuing goals.

7. Conclusions and implications

In recent years, the used products business has become more profitable due to improved remanufacturing technologies and increased consumer perception for RPs. Under consumer education, more and more consumers are paying attention to the attributes of RPs and are willing to pay for them. This paper investigates how the recycling efficiency and remanufacturing ability between the OEM and TP affect the design of the reverse channel from multiple criteria when considering consumer education activity.

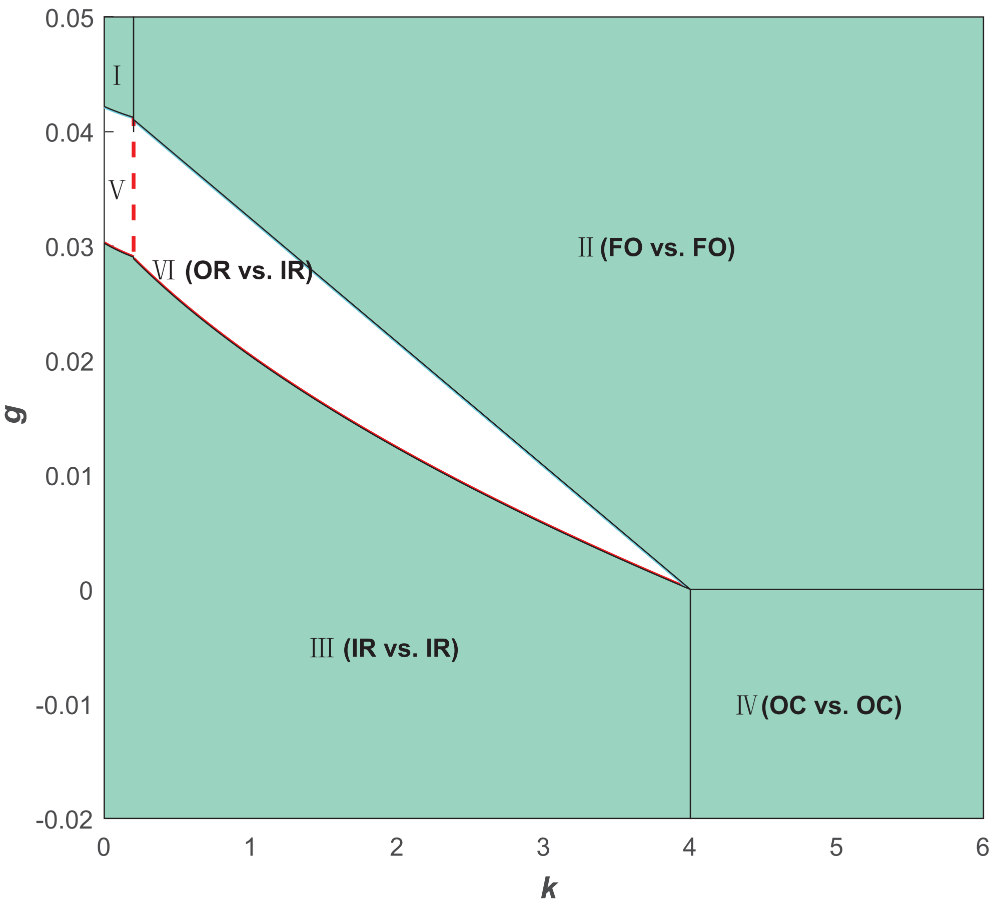

FIGURE 8. Reverse channel selections from the OEM, consumers, the environment.

Our research mainly has two aspects of theoretical contributions. On the one hand, according to industrial practice, we have developed two new reverse channel designs: outsourcing the recycling business but controlling the remanufacturing process, outsourcing the remanufacturing process but controlling the recycling. These two partial outsourcing strategies complement and enrich the outsourcing literature. Different from the conclusion of Zou *et al.* [48], the full outsourcing strategy will not always be the best choice for the OEM. The existence of FO-dominant region requires that the TP both has strong recycling and reproducing advantages. On the other hand, our work explores the effects of consumer education on the design of the reverse channel, which fills the gap that reverse channel design does not consider consumers' behavior. The result shows that the increased consumer education will make the FO-dominant region shift to the OR-dominant region, but the increased consumer acceptance for RPs will shrink the regions of FO-dominant and OR-dominant. Contrary to the OEM, the increased consumer education helps the TP more control the remanufacturing process of reverse channels and forgo the collection process. Moreover, we evaluate reverse channels from multiple performance metrics: profitability, supply chain, consumers, and environment, whereas the most existing literature on the design of reverse channels mainly focuses on profit performance. Consistent areas on full outsourcing and in-house remanufacturing always dominate, remanufacturing process outsourcing has a very small consistent area, and recycling process outsourcing has a consistent area where only TP has recycling advantages and OEM remanufacturing capability is weaker than half of TPs'.

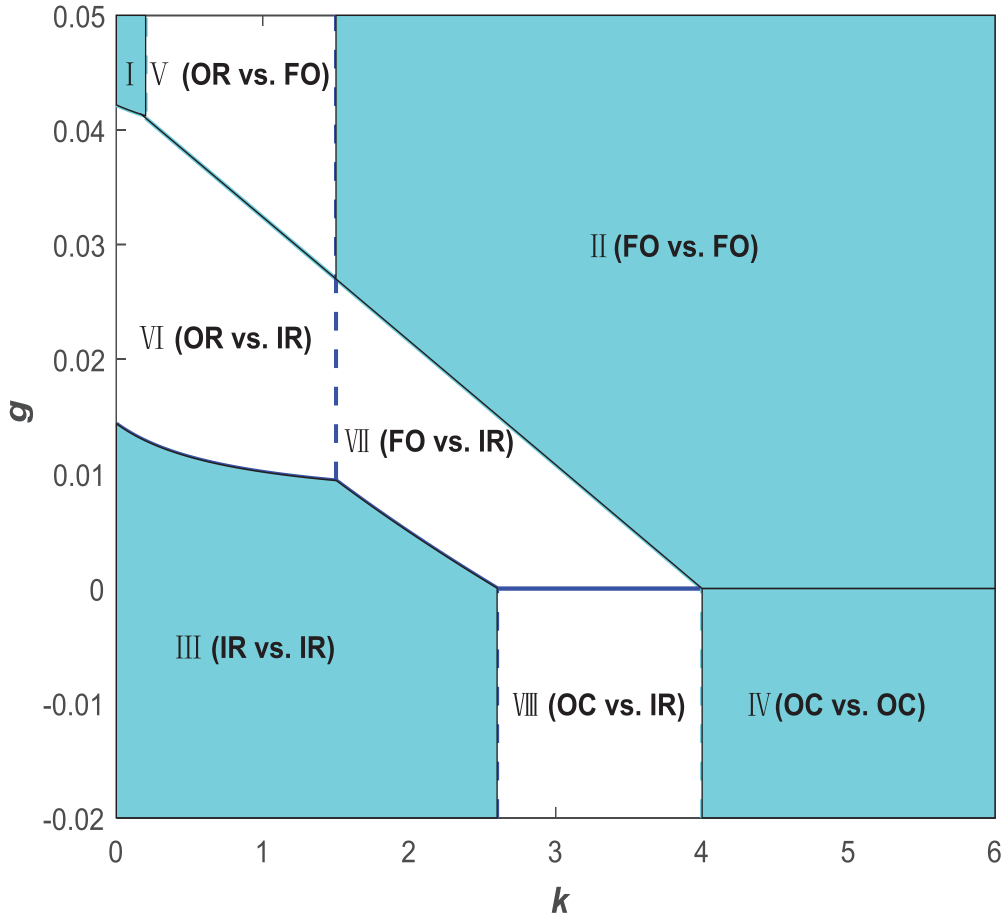

FIGURE 9. Reverse channel choices from the supply chain, consumers, the environment.

Managerial implications can be summarized as follows. When the OEM's recycling capability is very strong or remanufacturing cost advantage is high, partial control of the reverse channel is most beneficial, *i.e.*, the outsourcing collection process or remanufacturing process strategy will be optimal. When the recycling capability of the OEM is stronger than twice that of TP and the TP owns remanufacturing cost advantage, choosing full outsourcing will be the best. For the OEM, the increased consumer education will improve the willingness of in-house remanufacturing while reducing the willingness of full outsourcing. Hence, when the level of consumer education is very high, OEMs should completely control the reverse channel (in-house remanufacturing) to prevent TPs from carrying out excessive remanufacturing activities to erode the sales of NPs. Different from the OEM, the increased consumer education helps the TP control the remanufacturing process and forgo the collection right of reverse channels. The transfer price of remanufacturing business is always higher than the fee of full outsourcing. When OEMs only outsource the remanufacturing process to the TP, they need to pay a higher unit transfer fee. Consequently, OEMs should be careful when choosing remanufacturing outsourcing strategy. For the TP, full outsourcing and outsourcing remanufacturing models always dominate. Only in extreme cases will the TP choose to accept outsourcing collection. Moreover, if the outsourcing business is assigned according to the optimal reverse channel selections of the OEM, a triple-win situation for the OEM, consumers, and environment can be achieved to a large extent. However, if focusing on the supply chain, consumers, and the environment, the conflict regions of the reverse channel selections will become large. Accordingly, the participants should adjust the reverse channel selections according to the pursuing goals.

Although we believe that our work will help understand how the OEM should design the reverse channels under consumer education situation, it is not without limitations. First, our model assumes that a uniform distribution of consumer willingness-to-pay; whether all results will hold under a general distribution remains an open question. Second, uncertainty in the quality and quantity of used products is a major concern in CLSCs. Future research can examine the impact of remanufacturing risks from uncertainty on remanufacturing strategies. Finally, our paper considers a single-period setting, exploring the impact of consumer education on the reverse channel selections under multiple periods might be interesting.

Appendix A.

Proof of Lemma 4.1. In this paper, we consider deterministic demand and return, so the quantity of used products collected by the OEM equals the demand for RPs, *i.e.*, $\lambda q_n = q_r$. Substituting the inverse demand functions (3.1) and (3.2) into (4.1), we can rewrite the OEM's problem as follows:

$$\max \pi_M^{\mathrm{IR}}(q_n,\lambda) = (1-q_n-\delta\lambda q_n - c_n)q_n + \left(\delta(1-q_n-\delta\lambda q_n) - \frac{\delta(1-\delta)\lambda q_n}{\phi} - c_r - g\right)\lambda q_n - \frac{1}{2}k(\lambda q_n)^2.$$

The first- and second-order derivatives of π_M^{IR} with respect to with respect to q_n and λ are as follows:

$$\begin{aligned}
\frac{\partial \pi_M^{\mathrm{IR}}}{\partial q_n} &= 1-c_n+\lambda(\delta-c_r-g) - \left(k\lambda^2+4\delta\lambda+2+2\delta^2\lambda^2\right)q_n - \frac{2\delta(1-\delta)\lambda^2 q_n}{\phi}\\
\frac{\partial \pi_M^{\mathrm{IR}}}{\partial \lambda} &= \frac{q_n((\delta-c_r-g)\phi - ((k\lambda+2\delta)\phi+2\delta\lambda(1-\delta+\delta\phi))q_n)}{\phi}\\
\frac{\partial \pi_M^{\mathrm{IR}}}{\partial \lambda} &= \frac{q_n((\delta-c_r-g)\phi - ((k\lambda+2\delta)\phi+2\delta\lambda(1-\delta+\delta\phi))q_n)}{\phi}\\
\frac{\partial^2 \pi_M^{\mathrm{IR}}}{\partial q_n^2} &= -\frac{2\delta\lambda^2(1-\delta+\delta\phi)+\left(k\lambda^2+4\delta\lambda+2\right)\phi}{\phi}\\
\frac{\partial^2 \pi_M^{\mathrm{IR}}}{\partial \lambda^2} &= -\frac{\left(\left(k+2\delta^2\right)\phi+2\delta-2\delta^2\right)q_n^2}{\phi}\\
\frac{\partial^2 \pi_M^{\mathrm{IR}}}{\partial q_n \partial \lambda} &= \frac{\partial^2 \pi_M^{\mathrm{IR}}}{\partial \lambda \partial q_n} = \frac{\phi(\delta-c_r-g)-2((k\lambda+2\delta)\phi+2\delta\lambda(1-\delta+\delta\phi))q_n}{\phi}.
\end{aligned}$$

The determinant of the Hessian matrix according to π_M^{IR} with respect to q_n and λ is as follows:

$$\begin{aligned}
|H| &= \begin{vmatrix} -\frac{2\delta\lambda^2(1-\delta+\delta\phi)+\left(2+k\lambda^2+4\delta\lambda\right)\phi}{\phi} & \frac{\phi(\delta-c_r-g)-2(2\delta\lambda(1-\delta+\delta\phi)+(k\lambda+2\delta)\phi)q_n}{\phi}\\ \frac{\phi(\delta-c_r-g)-2(2\delta\lambda(1-\delta+\delta\phi)+(k\lambda+2\delta)\phi)q_n}{\phi} & -\frac{\left(\left(k+2\delta^2\right)\phi+2\delta-2\delta^2\right)q_n^2}{\phi}\end{vmatrix}\\
&= \frac{\left(\left(k+2\delta^2\right)\phi+2\delta-2\delta^2\right)\left(2\phi(1+\delta\lambda)^2+\lambda^2\left(k\phi+2\delta-2\delta^2\right)\right)q_n^2}{\phi^2}\\
&\quad - \frac{\left(\phi(\delta-c_r-g)-2\left(2\delta\phi(1+\delta\lambda)+\lambda\left(k\phi+2\delta-2\delta^2\right)\right)q_n\right)^2}{\phi^2}.
\end{aligned}$$

Since $|H|>0$ and $\frac{\partial^2\pi_M^{\mathrm{IR}}}{\partial q_n^2}<0$, $\frac{\partial^2\pi_M^{\mathrm{IR}}}{\partial\lambda^2}<0$, the profit function π_M^{IR} is concave in q_n and λ. Letting $\frac{\partial\pi_M^{\mathrm{IR}}}{\partial q_n}=0$ and $\frac{\partial\pi_M^{\mathrm{IR}}}{\partial\lambda}=0$, we get $q_n^{\mathrm{IR}^*}=\frac{1-c_n}{2}- \to \frac{\delta\phi(\delta c_n-c_r-g)}{k\phi+2\delta-2\delta^2}$ and $\lambda^{\mathrm{IR}^*}=\frac{2\phi(\delta c_n-c_r-g)}{(k\phi+2\delta-2\delta^2)(1-c_n)-2\delta\phi(\delta c_n-c_r-g)}$. Then, we have $q_r^{\mathrm{IR}^*} = \frac{\phi(\delta c_n - c_r - g)}{k\phi + 2\delta - 2\delta^2}$, $p_n^{\mathrm{IR}^*} = \frac{1+c_n}{2}$, $p_r^{\mathrm{IR}^*} = \delta\left(\frac{1+c_n}{2} - \frac{(1-\delta)(\delta c_n - c_r - g)}{k\phi+2\delta-2\delta^2}\right)$. Finally, the OEM profit is $\pi_M^{\mathrm{IR}^*} = \frac{(1-c_n)^2}{4} + \frac{\phi(\delta c_n - c_r - g)^2}{2(k\phi+2\delta-2\delta^2)}$.

The proof of Lemma 4.1 is completed. $\square$

Proof of Proposition 4.2. The total demand for NPs and RPs is $q = \frac{1-c_n}{2} + \frac{\phi(1-\delta)(\delta c_n - c_r - g)}{k\phi+2\delta-2\delta^2}$. Hence, we have $\frac{\partial q}{\partial \phi} = \frac{2\delta(1-\delta)^2(\delta c_n - c_r - g)}{(k\phi+2\delta-2\delta^2)^2} > 0$ and $\frac{\partial q}{\partial \delta} = \frac{\phi\left(k\phi(c_n+c_r+g)+2(1-\delta)^2(c_r+g)-2k\phi\delta c_n\right)}{(2\delta-2\delta^2+k\phi)^2}$. When $\delta < 1 - \frac{\sqrt{k^2\phi^2c_n^2+2k\phi(c_r+g)(c_n-c_r-g)}-k\phi c_n}{2(c_r+g)}$, $\frac{\partial q}{\partial \delta} > 0$; otherwise, $\frac{\partial q}{\partial \delta} \le 0$. Because $\lim\limits_{\delta\to 1} \frac{\phi(1-\delta)(\delta c_n - c_r - g)}{k\phi+2\delta-2\delta^2} = 0$, $\lim\limits_{\delta\to 1} q = \frac{1-c_n}{2}$. $\square$

Proof of Lemma 4.3. Similar to the Lemma 4.1, substituting $q_r = \lambda q_n$ into (4.3), we can rewrite the TP's problem as follows:

$$\max \pi_T^{\mathrm{OC}}(\lambda) = p^c \lambda q_n - \frac{1}{2}\eta(\lambda q_n)^2.$$

Because the second-order sufficient condition, *i.e.*, $\frac{\mathrm{d}^2\pi_T^{\mathrm{OC}}}{\mathrm{d}\lambda^2} = -\eta q_n^2 < 0$, the profit function π_T^{OC} is concave in λ. Then get the reaction function $\lambda = \frac{p^c}{\eta q_n}$. Anticipating the TP's response to the transfer price of collection business p^c, the OEM will choose q_n and p^c to maximize its profit. Substituting the inverse demand functions (3.1) and (3.2) into (4.2), we rewrite the OEM's problem:

$$\max \pi_M^{\mathrm{OC}}(q_n, p^c) = \left(1 - q_n - \frac{\delta p^c}{\eta} - c_n\right)q_n + \left(\delta\left(1 - q_n - \frac{\delta p^c}{\eta}\right) - \frac{\delta p^c(1-\delta)}{\eta\phi} - c_r - p^c\right)\frac{p^c}{\eta}.$$

Similar to the proof of Lemma 4.1, we obtain the Lemma 4.3. $\square$

Proof of Lemmas 4.4 and 4.5. Proof of Lemmas 4.4 and 4.5 are similar to that of Lemma 4.3, so we omit the proof process. $\square$

Proof of Corollary 4.6. We have $p^{r^*} - s^{\mathrm{FO}^*} = \frac{\delta\left(2(1-\delta)\left(\left(k+2\delta^2\right)\phi+2\delta-2\delta^2\right)+\eta\delta\phi^2\right)(\delta c_n - c_r)}{2(\eta\phi+\delta-\delta^2)((2k+3\delta^2)\phi+4\delta(1-\delta))} > 0$ and $s^{\mathrm{FO}^*} - p^{c^*} = c_r + \frac{\eta\phi g}{2(\eta\phi+\delta-\delta^2)} > 0$. $\square$

Proof of Proposition 5.1. We compare the equilibrium profits of the OEM among four strategies:

(1) IR *vs.* OC. From Lemmas 4.1 and 4.3, we get $\pi_M^{\mathrm{IR}^*} - \pi_M^{\mathrm{OC}^*} = \frac{(2\eta-k)\phi^2(\delta c_n - c_r - g)^2}{4(k\phi+2\delta-2\delta^2)(\eta\phi+\delta-\delta^2)}$. Thus, $\pi_M^{\mathrm{IR}^*} > \pi_M^{\mathrm{OC}^*}$ if $k < 2\eta$.

(2) IR *vs.* OR. From Lemmas 4.1 and 4.4, we get $\pi_M^{\mathrm{IR}^*} - \pi_M^{\mathrm{OR}^*} = \frac{2\phi\left(\left(2k+3\delta^2\right)\phi+4\delta-4\delta^2\right)(\delta c_n - c_r - g)^2 - \left(k\phi+2\delta-2\delta^2\right)\phi(\delta c_n - c_r)^2}{4(k\phi+2\delta-2\delta^2)((2k+3\delta^2)\phi+4\delta-4\delta^2)}$. Thus, $\pi_M^{\mathrm{IR}^*} > \pi_M^{\mathrm{OR}^*}$ requires $g < g_{13} = (\delta c_n - c_r)\left(1 - \sqrt{\frac{k\phi+2\delta-2\delta^2}{2((2k+3\delta^2)\phi+4\delta-4\delta^2)}}\right)$.

(3) IR *vs.* FO. From Lemmas 4.1 and 4.5, we get $\pi_M^{\mathrm{IR}^*} - \pi_M^{\mathrm{FO}^*} = \frac{2\phi\left(\eta\phi+\delta-\delta^2\right)(\delta c_n - c_r - g)^2 - \left(k\phi+2\delta-2\delta^2\right)\phi(\delta c_n - c_r)^2}{4(k\phi+2\delta-2\delta^2)(\eta\phi+\delta-\delta^2)}$. Thus, $\pi_M^{\mathrm{IR}^*} > \pi_M^{\mathrm{FO}^*}$ requires $g < g_{14} = (\delta c_n - c_r)\left(1 - \sqrt{\frac{k\phi+2\delta-2\delta^2}{2(\eta\phi+\delta-\delta^2)}}\right)$.

(4) OC *vs.* OR. From Lemmas 4.3 and 4.4, we get $\pi_M^{\mathrm{OC}^*} - \pi_M^{\mathrm{OR}^*} = \frac{\phi\left(\left(\left(2k+3\delta^2\right)\phi+4\delta-4\delta^2\right)(\delta c_n - c_r - g)^2 - \left(\eta\phi+\delta-\delta^2\right)(\delta c_n - c_r)^2\right)}{4(\eta\phi+\delta-\delta^2)((2k+3\delta^2)\phi+4\delta-4\delta^2)}$. Thus, $\pi_M^{\mathrm{OC}^*} > \pi_M^{\mathrm{OR}^*}$ requires $g < g_{23} = (\delta c_n - c_r)\left(1 - \sqrt{\frac{\eta\phi+\delta-\delta^2}{(2k+3\delta^2)\phi+4\delta-4\delta^2}}\right)$.

(5) OC *vs.* FO. From Lemmas 4.3 and 4.5, we get $\pi_M^{\mathrm{OC}^*} - \pi_M^{\mathrm{FO}^*} = -\frac{g\phi(2\delta c_n - 2c_r - g)}{4(\eta\phi+\delta-\delta^2)}$. Thus, $\pi_M^{\mathrm{OC}^*} > \pi_M^{\mathrm{FO}^*}$ requires $g < 0$.

(6) OR *vs.* FO. From Lemmas 4.4 and 4.5, we get $\pi_M^{\mathrm{OR}^*} - \pi_M^{\mathrm{FO}^*} = -\frac{\phi(\delta c_n - c_r)^2\left((2k-\eta+3\delta^2)\phi+3\delta-3\delta^2\right)}{4((2k+3\delta^2)\phi+4\delta-4\delta^2)(\eta\phi+\delta-\delta^2)}$. Thus, $\pi_M^{\mathrm{OR}^*>\pi_M^{\mathrm{FO}^*}}$ requires $k < k_m = \frac{(\eta-3\delta^2)\phi-3\delta+3\delta^2}{2\phi}$.

□

We find $k_m < 2\eta$. When $k < k_m$, $g_{13} < g_{14}$, but $k > k_m$, $g_{13} > g_{14}$. When $k < 2\eta$, $g_{14} > 0$, but $k > 2\eta$, $g_{14} < 0$. Let $g_{m1} = g_{13}$ and $g_{m2} = g_{14}$, we get the optimal channel selection of the OEM in Proposition 4.2.

Proof of Corollary 5.2. The first-orders of critical value (k_m, g_{m1}, g_{m2}) with ϕ and δ are as follows:

$$\frac{\partial k_m}{\partial \phi} = \frac{3\delta(1-\delta)}{2\phi^2} > 0 \frac{\partial k_m}{\partial \delta} = -\frac{3(1+2\delta\phi-2\delta)}{2\phi} < 0$$

$$\frac{\partial g_{m1}}{\partial \phi} = \frac{3\delta^3(1-\delta)(\delta c_n - c_r)}{\sqrt{2(k\phi+2\delta-2\delta^2)((2k+3\delta^2)\phi+4\delta-4\delta^2)^3}} > 0$$

$$\frac{\partial g_{m2}}{\partial \phi} = \frac{\delta(1-\delta)(\delta c_n - c_r)(2\eta-k)}{\sqrt{8(k\phi+2\delta-2\delta^2)(\eta\phi+\delta-\delta^2)^3}} > 0$$

$$\frac{\partial g_{m1}}{\partial \delta} = c_n\left(1-\sqrt{\frac{k\phi+2\delta-2\delta^2}{2((2k+3\delta^2)\phi+4\delta-4\delta^2)}}\right) + \frac{3\delta\phi(k\phi+\delta)(\delta c_n - c_r)}{\sqrt{2(k\phi+2\delta-2\delta^2)((2k+3\delta^2)\phi+4\delta-4\delta^2)^3}} > 0$$

$$\frac{\partial g_{m2}}{\partial \delta} = c_n\left(1-\sqrt{\frac{k\phi+2\delta-2\delta^2}{2(\eta\phi+\delta-\delta^2)}}\right) + \frac{\phi(2\delta-1)(\delta c_n - c_r)(2\eta-k)}{\sqrt{8(k\phi+2\delta-2\delta^2)(\eta\phi+\delta-\delta^2)^3}} > 0.$$

Then, we get the impact of consumer education (ϕ) and the consumer acceptance of RPs (δ) on the choice of the reverse channel. □

Proof of Proposition 5.3. Similar to the proof of Proposition 5.1, we compare the equilibrium profits of the TP under three models and get $k_t = \frac{\eta\phi^2(2\eta-3\delta^2)+2\delta^2(1-\delta)^2+2(\eta\phi+\delta-\delta^2)\sqrt{\eta\phi((\eta+\delta^2)\phi+2\delta-2\delta^2)+\delta^2(1-\delta)^2}}{2\eta\phi^2}$, $g_t = (\delta c_n - c_r)\left(1-\sqrt{\frac{8((k+2\delta^2)\phi+2\delta-2\delta^2)(\eta\phi+\delta-\delta^2)^2}{\eta\phi((2k+3\delta^2)\phi+4\delta-4\delta^2)^2}}\right)$. When $k < k_t$, $g_t < 0$, but $k > k_t$, $g_t > 0$. Hence, we get Proposition 5.3. □

Proof of Corollary 5.4. Similar to Corollary 5.2, we have the first-orders of critical value (k_t, g_t) with ϕ and δ, then we get the impact of consumer education (ϕ) and the consumer acceptance of RPs (δ) on the choice of the reverse channel. □

Proof of Proposition 6.2. Similar to the proof of Proposition 5.1, we compare the supply chain profit under four models. Then we get $k_{s1} = \frac{12\eta^2\phi^2-5\delta^2(1-\delta)^2}{2\phi(3\eta\phi+2\delta-2\delta^2)} - \frac{3\eta+3\delta^2}{2} + \frac{(\eta\phi+\delta-\delta^2)\sqrt{2\phi\delta(9\eta+4\delta^2-4\delta^3)+3\eta\phi(3\eta\phi+4\phi\delta^2-6\delta^2)+9\delta^2(1-\delta)^2}}{2\phi(3\eta\phi+2\delta-2\delta^2)}$, $k_{s2} = \frac{2\eta(2\eta\phi+\delta-\delta^2)}{3\eta\phi+2\delta-2\delta^2}$, $g_{s1} = (\delta c_n - c_r)\left(1-\frac{\sqrt{2(k\phi+2\delta-2\delta^2)((6k+11\delta^2)\phi+12\delta-12\delta^2)}}{2((2k+3\delta^2)\phi+4\delta-4\delta^2)}\right)$, and $g_{s2} = (\delta c_n - c_r)\left(1-\frac{\sqrt{(k\phi+2\delta-2\delta^2)(3\eta\phi+2\delta-2\delta^2)}}{2(\eta\phi+\delta-\delta^2)}\right)$. Hence, we get Proposition 6.2. □

Proof of Proposition 6.4. The first-orders of consumer surplus under Model IR with ϕ and δ are

$$\frac{\partial \mathrm{CS}^{\mathrm{IR}^*}}{\partial \phi} = \frac{\delta(1-\delta)(\delta c_n - c_r - g)^2\left(2\delta-2\delta^2-(k+2\delta-2\delta^2)\phi\right)}{(k\phi+2\delta-2\delta^2)^3}$$

$$\frac{\partial \mathrm{CS}^{\mathrm{IR}^*}}{\partial \delta} = \frac{(2-\phi)\phi(\delta c_n - c_r - g)\big(\delta\big((3-4\delta)k\phi + 2\delta - 2\delta^2\big)c_n + (2\delta-1)\big(k\phi - 2\delta + 2\delta^2\big)(g+c_r)\big)}{2(k\phi + 2\delta - 2\delta^2)^3}.$$

Let $\frac{\partial \mathrm{CS}^{\mathrm{IR}^*}}{\partial \phi} = 0$, we have $\phi^{\mathrm{IR}} = \frac{2\delta - 2\delta^2}{k + 2\delta - 2\delta^2}$. If $\phi < \phi^{\mathrm{IR}}$, $\frac{\partial \mathrm{CS}^{\mathrm{IR}^*}}{\partial \phi} > 0$, if else, $\frac{\partial \mathrm{CS}^{\mathrm{IR}^*}}{\partial \phi} \leq 0$. If $\delta < \frac{1}{2}$, $\frac{\partial \mathrm{CS}^{\mathrm{IR}^*}}{\partial \delta} > 0$. When $\frac{1}{2} < \delta^{\mathrm{IR}} < 1$, δ^{IR} is the positive solution in which the formula $\delta\big((3-4\delta)k\phi + 2\delta - 2\delta^2\big)c_n + (2\delta-1)\big(k\phi - 2\delta + 2\delta^2\big)(g+c_r) = 0$. □

Proof of Proposition 6.5. Similar to the proof of Proposition 5.1, we compare the consumer surplus under four strategies. Then we get $k_c = k_m = \frac{\left(\eta - 3\delta^2\right)\phi - 3\delta + 3\delta^2}{2\phi}$, $g_{c1} = \frac{3\left(\left(k + 2\delta^2\right)\phi + 2\delta - 2\delta^2\right)(\delta c_n - c_r)}{2\left((2k + 3\delta^2)\phi + 4\delta - 4\delta^2\right)}$, and $g_{c2} = \frac{\phi(2\eta - k)(\delta c_n - c_r)}{2(\eta\phi + \delta - \delta^2)}$. Hence, we get Proposition 6.5. □

Proof of Proposition 6.7. The first-orders of EI under Model IR with δ and ϕ are

$$\frac{\partial \mathrm{EI}^{\mathrm{IR}^*}}{\partial \delta} = -\frac{\phi\big(\big(k\phi + 2\delta^2\big)(c_r + g) - 2\delta c_n(k\phi + \delta)\big)e_n + \big(2(2\delta-1)(g+c_r) - \big(k\phi + 2\delta^2\big)c_n\big)e_r\big)}{\left(k\phi + 2\delta - 2\delta^2\right)^2} < 0$$

$$\frac{\partial \mathrm{EI}^{\mathrm{IR}^*}}{\partial \phi} = \frac{2\delta(1-\delta)(\delta c_n - c_r - g)(e_r - \delta e_n)}{\left(k\phi + 2\delta - 2\delta^2\right)^2}.$$

If $e_r < \delta e_n$, $\frac{\partial \mathrm{EI}^{j*}}{\partial \phi} < 0$; otherwise, $\frac{\partial \mathrm{EI}^{j*}}{\partial \phi} \geq 0$. □

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