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Manufacturer-remanufacturing vs supplier-remanufacturing in a closed-loop supply chain

Yu Xiong [a], Quanwu Zhao [b], Yu Zhou [b,*]

[a] Newcastle Business School, Northumbria University, Newcastle NE1 8ST, UK
[b] School of Economics and Business Administration, Chongqing University, 174 Shazhengjie, Chongqing 400044, PR China

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ABSTRACT

Remanufacturing at the component level could be performed by either a manufacturer or a supplier. In this paper, we analyze the performance of manufacturer-remanufacturing and supplier-remanufacturing in a decentralized closed-loop supply chain, and examine their desirability from different stakeholder perspectives. We find that the manufacturer may engage in remanufacturing of used components even if remanufacturing is costlier than traditional manufacturing; given remanufacturing is costlier, the manufacturer may forgo remanufacturing due to a marginal increase in consumer willingness-to-pay for the remanufactured product. If the unit remanufacturing cost is high enough, the manufacturer and consumers prefer manufacturer-remanufacturing, while the supplier and the environment prefer supplier-remanufacturing; otherwise, the manufacturer, the supplier, and consumers prefer supplier-remanufacturing, while the environment's preference is contingent on the environmental impact discount for the remanufactured product. Finally, the key findings are distilled into a roadmap to guide the development of remanufacturing.

1. Introduction

In recent years, executives around the world are rallying behind sustainability, and have experienced a dramatic increase of interest in remanufacturing. Successful examples from many industries show that remanufacturing can be both faster-growing and more profitable than traditional manufacturing (Ayres et al., 1997, Guide and Wassenhove, 2003, Geyer et al., 2007). However, the remanufacturability of used products as a whole is restricted by increasing technical complexity, shorted product life cycle, rising costs and uncertainties.

Remanufacturing at the component level is an alternative that may help maximize the revenue generated from the return stream (Fleischmann et al., 2003), which has been a consensus between researchers and managers. In theory, remanufacturing is defined as "a production strategy whose goal is to recover the residual value of used products by reusing components that are still functioning well" (Debo et al., 2005). In practice, the remanufacturing process of Caterpillar (2010) can be briefly described as:

- First, used products collected from customers are disassembled into their constituent components.
- Next, the individual components are remanufactured to exact specifications to ensure they provide the same quality, reliability and durability as they did when they ware new.
- Last, remanufactured components are assembled, tested and made ready for sale as the remanufactured product.

In addition, nowadays, few manufacturers rely on only themselves to design and produce the whole product, which implies that most components are provided by their suppliers. Thus, remanufacturing at the component level can be performed by manufacturers such as Caterpillar, or by their key component suppliers. In 2008, Chinese National Development and Reform Commission launched a pilot program of auto part remanufacturing, and 14 firms were selected and supported to start up remanufacturing, seven of which are auto manufacturers (or their subsidiaries) and the other seven are part suppliers (Sina, 2008).

Thus, a research question is naturally emerging: what is the difference between manufacturer-remanufacturing and supplier-remanufacturing? Our primary objective in this paper is to develop a general understanding of the desirability of manufacturer-remanufacturing and supplier-remanufacturing from different stakeholder perspectives.

The literature on managing the closed-loop supply chain with remanufacturing is abundant, we refer the reader to Atasu et al. (2008a), Guide and Van Wassenhove (2009), and Souza (2013) for a thorough discussion. It has been demonstrated that remanufacturing

* Corresponding author. Tel.: +86 13883305292.
E-mail addresses: yu.xiong@northumbria.ac.uk (Y. Xiong), zhaoquanwumx@cqu.edu.cn (Q. Zhao), zhouyu@cqu.edu.cn (Y. Zhou).

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can be an effective marketing strategy for manufacturers to defend their market share and render a higher profit (Heese et al., 2005, Atasu et al., 2008b, Chen and Chang, 2013, Wu, 2015). However, to the best of our knowledge, few papers consider the possibility of supplier-remanufacturing and identify the "right" remanufacturer, especially from the perspectives of the consumers and the environment. Xiong et al. (2013) make the first attempt to analyze how the interaction between the manufacturer and the supplier on new product production influences to the economic and environmental performance of remanufacturing. We extend Xiong et al. (2013)'s model to analyze and compare the implications of manufacturer-remanufacturing and supplier-remanufacturing.

More importantly, our model deviates from the literature by allowing remanufacturing a used component does not cost less than manufacturing a new one. On one hand, this deviation is greatly motivated by the industrial practice: although some pioneers have made a profit, most manufacturers have no infrastructure and expertize to remanufacture in a profitable manner (Ferguson, 2010). Specifically, in the globalized world today, remanufacturing is still largely a local business because many countries prohibit the international trade of used products. Huawei (2015), the world's third largest cell phone producer, capitalizes on recycling in Europe, but does not remanufacture. This may be driven by the possibility that producing a remanufactured cell phone in Europe costs more than producing a new one in China. On the other hand, this derivation leads us to some very interesting findings on firms' remanufacturing strategy. The prior literature on remanufacturing typically defaults that remanufacturing costs less than traditional manufacturing, e.g., in a seminal research, Ferrer and Swaminathan (2006) use the remanufacturing savings as the key parameter to define the strategy space. To the best of our knowledge, only one paper, Caner et al. (2013), considers the situation where remanufacturing is costlier for an integrated manufacturer. However, it finds remanufacturing is seldom profitable in this situation and suggests the manufacturer focus on situations where remanufacturing costs less. In contrast, our work demonstrates the manufacturer could be better off by engaging in remanufacturing even if it costs more than manufacturing in a decentralized supply chain. In addition, given remanufacturing is costlier, the analytical result shows that the manufacturer may decide to forgo remanufacturing as a result of a marginal increase in consumer willingness-to-pay for the remanufactured product. These findings make an excellent complement to the current literature on remanufacturing.

The rest of this paper is organized as follows. Section 2 delineates our modeling assumptions and notation. Section 3 presents the analysis and solutions of two models with manufacturer-remanufacturing and supplier-remanufacturing, respectively. Section 4 discusses firms' remanufacturing strategy and identifies the "right" remanufacturer from different stakeholder perspectives. Section 5 concludes this paper. Appendices contains the detailed proofs of all propositions. Hereinafter, for convenience, we use pronouns '*she*' and '*he*' to refer to the supplier and the manufacturer, respectively.

2. Assumptions and notation

We consider an industry with only one product but two versions: the new product and the remanufactured product. To focus our attention on the desirability of manufacturer-remanufacturing and supplier-remanufacturing from different stakeholder perspectives, we consider a simple bilateral monopoly, as depicted in Figs. 1 and 2. In this paper, we do not consider the reverse channel choice, which has been widely studied in the existing literature, e.g., Xiong et al. (2014), Hong et al. (2015), and Wei et al. (2015).

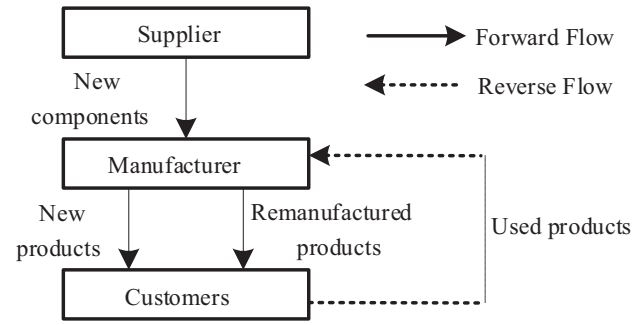

Fig. 1. The closed-loop supply chain model with manufacturer-remanufacturing.

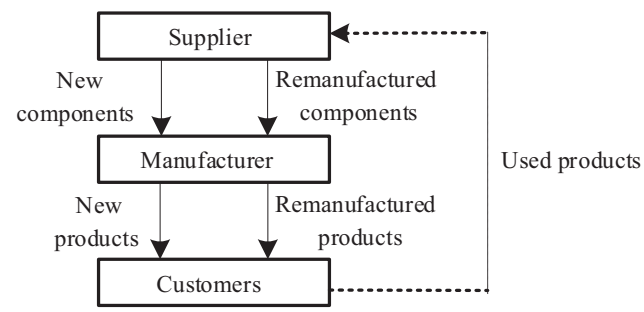

Fig. 2. The closed-loop supply chain model with supplier-remanufacturing.

Therefore, it is reasonable to assume that used products are collected (by the retailer, or the manufacturer, or the third-party operator) at a constant cost, which is normalized to 0.

To isolate the strategic issue of remanufacturing, our model rules out the distortion due to efficiency variance by assuming that either the manufacturer or the supplier costs c_r to remanufacture a used component. Similar assumptions have been widely used in the literature, e.g., Savaskan et al. (2004) assume a manufacturer and a retailer incur a same cost to collect used products, and demonstrate the retailer-managed collection is always preferred by the manufacturer; Zhou et al. (2013) assume centralization and decentralization within a manufacturer are equivalent in terms of the cost structure, and find decentralization outperforms centralization under certain conditions. For the sake of clarity, we assume that, except for the cost to obtain the new/remanufactured component, the manufacturer's other operating costs are constant and normalized to 0.

Other key assumptions concerning consumer preference, environmental performance, and decision-making rule are borrowed from the literature on closed-loop supply chain management, e.g., Galbreth et al. (2013), Xiong et al. (2013), Chang et al. (2015), and Gu et al. (2015). Here, we present the following set of assumptions, but skip the detailed discussion on their justification. For convenience, Table 1 summarizes the notation used in the model.

Assumption 1. The inverse demand functions for new and remanufactured products are

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

$$p_r = \delta(1 - q_n - q_r). \tag{2}$$

Assumption 1 implies that the consumer willingness-to-pay for the new product is heterogeneous and distributed over the interval $[0, 1]$ with the density of 1; each consumer's willingness-to-pay for the remanufactured product is a fraction $\delta \in (0, 1)$ of that for the new one; and each customer buys at most one product that offers the most utility, as long as the net utility is positive. Thus,

Table 1
Notation.

Symbol	Definition
c_n, c_r	The unit production cost of the new/remanufactured component
q_n, q_r	The production quantity of the new/remanufactured product
p_n, p_r	The market clearing price of the new/remanufactured product
w_n, w_r	The wholesale price of the new/remanufactured component
δ	The consumer value discount for the remanufactured product
ϕ	The environmental impact discount for the remanufactured product
Π^j_{ik}	The player i's profit in scenario k of the model of j
v^j_k	The consumer surplus in scenario k of the model of j
E^j_k	The supply chain's environmental performance in scenario k of the model of j

the linear inverse demand functions, (Eqs. (1) and 2), can be derived from consumers' utility functions.

Assumption 2. The weighted production quantity of new products and remanufactured products $q_n+\phi q_r$ is used as a proxy of the closed-loop supply chain's environmental performance.

It is broadly agreed that the process of remanufacturing has less negative impact on the environmental. Assumption 2 implies that the life-cycle environmental impact of one unit remanufactured product is a fraction $\phi \in (0,1)$ of that of one unit new product. Therefore, the closed-loop supply chain' environmental performance is equal to one unit new product's life-cycle environmental impact multiplied by the weighted production quantity of new products and remanufactured products. Regardless of the value of environmental impact, $q_n+\phi q_r$ can be a proxy.

Assumption 3. All decisions are considered in a steady-state period: the supplier moves first to price the new component (and the remanufactured component), and then the manufacturer responds by determining the production quantity of new and remanufactured products.

Closed-loop supply chain management is a typical multiple-period problem because new products are used for a certain period and then become cores for remanufacturing. The steady-state period model implies that players use the same policy in every period after the ramp-up in the first period in an infinite horizon setting. It enables us to analytically address our research question without the distraction of initial and terminal time-period effect. Thus, in our model, by assuming that each product can be used for one period and remanufactured at most once, the production quantity of remanufactured products in the current period is bounded by the production quantity of new products in the previous period, which is equal to the production quantity of new products in the current period, i.e., $q_r \le q_n$. Admittedly, not all used products could be collected; in practice, we have $q_r \le \tau q_n$, $\tau \in [0,1]$. However, assuming $\tau = 1$ in this paper does not change any of qualitative insights.

In addition, we assume that the manufacturer and the supplier are risk-neutral and profit seeking, and have perfect knowledge of the demand and cost information – a reasonable assumption in the steady-state period model. In order to guarantee the market demand of new and remanufactured products is non-negative, our model requires $c_n \le 1$ and $c_r \le \delta$.

In the following analysis, we call the firm who performs remanufacturing as the remanufacturer; subscript $i \in \{M,S\}$ refers to the manufacturer and the supplier, respectively; superscript $j \in \{M,S\}$ manufacturer-remanufacturing and supplier-remanufacturing, respectively. The firms' strategic decisions are analyzed under various scenarios, which are distinguished by parameters c_n, c_r, and δ. Subscript $k \in \{1,2,3\}$ indicates the scenario under which our analysis is proceeding.

3. Models and solutions

3.1. The model of manufacturer-remanufacturing

In this subsection, we analyze the model of manufacturer-remanufacturing, in which the suppliers supplies only the new component to the manufacturer. The supplier's and the manufacturer's profit functions can be written as

$$\Pi^M_S = (w_n - c_n)q_n, \tag{3}$$

$$\Pi^M_M = (p_n(q_n,q_r) - w_n)q_n + (p_r(q_n,q_r) - c_r)q_r, \text{ s.t.}, 0 \le q_r \le q_n. \tag{4}$$

The interaction between the supplier and the manufacturer can be analyzed using backward induction. For a given w_n, the manufacturer determines q_n and q_r to maximize his profit. The optimal production quantity decisions are characterized by the following proposition.

Proposition 1. In the model of manufacturer-remanufacturing, the manufacturer's optimal production quantity decision with respect to the supplier's new component wholesale price is

(1) $q^M_{n1} = (1-w_n)/2$, $q^M_{r1} = 0$, if $w_n < c_r/\delta$;
(2) $q^M_{n2} = (1-w_n-\delta+c_r)/2(1-\delta)$, $q^M_{r2} = (\delta w_n - c_r)/2\delta(1-\delta)$, if $c_r/\delta \le w_n \le \left(c_r+\delta c_r+\delta-\delta^2\right)/2\delta$;
(3) $q^M_{n3} = q^M_{r3} = (1-w_n+\delta-c_r)/2(1+3\delta)$, if $w_n > \left(c_r+\delta c_r+\delta-\delta^2\right)/2\delta$.

Next, when setting w_n, the supplier does so with anticipation that the manufacturer will respond as above. Since the manufacturer's optimal response is contingent on the value of w_n, the process to derive the supplier's optimal new component wholesale price consists of two steps: (1) we analyze the scenario in which the supplier induces the manufacturer to choose a certain decision; and then (2) we identify the optimal solution by comparing the supplier's profit in all scenarios. For parsimony we restrict our following analysis to the case of $\delta \le 2/3$. The optimal new component wholesale price for the case of $\delta > 2/3$ is available in the Proof of Proposition 2, which is a simplification of that for the case of $\delta \le 2/3$.

Proposition 2. In the model of manufacturer-remanufacturing, the supplier's optimal new component wholesale price is

(1) $w^M_{n1} = (1+c_n)/2$, if $c_r > c^M_1$;
(2) $w^M_{n2-1} = c_r/\delta$, if $c^M_2 < c_r \le c^M_1$;
(3) $w^M_{n2-2} = (1+c_n-\delta+c_r)/2$, if $c^M_3 < c_r \le c^M_2$;
(4) $w^M_{n3} = (1+c_n+\delta-c_r)/2$, if $c_r \le c^M_3$; here, $c^M_1 = \delta(1+c_n)/2$, $c^M_2 = \delta(1+c_n-\delta)/(2-\delta)$,
$c^M_3 = \left(c_n+\delta c_n+2\delta^2-1-\delta+\sqrt{A}\right)/2\delta$,
$A = 1-2c_n+c_n{}^2+2\delta-4\delta c_n+2\delta c_n{}^2+3\delta^2+6\delta^2 c_n-3\delta^2 c_n{}^2$.

It is worth noting that, the supplier has taken the manufacturer's optimal response into account when setting w_n. So, if the supplier's optimal decision is w^M_{nk}, then the manufacturer's optimal decision must be $\{q^M_{nk}, q^M_{rk}\}$. Substituting these optimal decisions back into Eqs. (3) and (4) gives the supplier's and the manufacturer's profits, as shown in Table 2.

3.2. The model of supplier-remanufacturing

In the model of supplier-remanufacturing, the supplier supplies both the new and the remanufactured components to the manufacturer. Their profit functions are

$$\Pi^S_S = (w_n - c_n)q_n + (w_r - c_r)q_r, \tag{5}$$

$$\Pi_M^S = (p_n(q_n, q_r) - w_n)q_n + (p_r(q_n, q_r) - w_r)q_r, \text{ s.t.}, 0 \le q_r \le q_n. \quad (6)$$

Following from Eqs. (4) and (6), we have, replacing c_r in the manufacturer's profit function in the model of manufacturer-remanufacturing with w_r gives his profit function in the model of supplier-remanufacturing. Thus, intuitively, replacing c_r in Proposition 1 with w_r gives the manufacturer's optimal production quantity decision in the model of supplier-remanufacturing.

Similarly, we identify the supplier's optimal decision in two steps, as follows.

Proposition 3. . In the model of supplier-remanufacturing, the supplier's optimal wholesale prices for new and remanufactured components are

(1) $w_{n1}^S = (1+c_n)/2$,.$w_{r1}^S = \delta(1+c_n)/2$., if $c_r > c_1^S$;
(2) $w_{n2}^S = (1+c_n)/2$, $w_{r2}^S = (\delta + c_r)/2$, if $c_2^S \le c_r \le c_1^S$;
(3) $w_{n3}^S = \left(1+4\delta-\delta^2+(1+\delta)(c_n+c_r)\right)/2(1+3\delta)$, $w_{r3}^S = \delta(2\delta+c_n+c_r)/(1+3\delta)$, if $c_r < c_2^S$; here, $c_1^S = \delta c_n$, $c_2^S = \delta(2c_n+\delta-1)/(1+\delta)$.

Substituting these optimal decisions back into Eqs. (5) and (6) gives the supplier's and the manufacturer's profits, as shown in Table 3.

4. Comparison and discussion

4.1. Whether to remanufacture

In this subsection, we examine the decision on whether to remanufacturing. Substituting the optimal wholesale price(s) in Propositions 2 and 3 back into the manufacturer's optimal response function gives the production quantity of new and remanufactured products. We say the remanufacturer decides to engage in remanufacturing if $q_r > 0$. It is easy to get the following Corollaries:

Corollary 1. In the model of manufacturer-remanufacturing, there exists a threshold value c_2^M such that the manufacturer should engage in remanufacturing if $c_r \le c_2^M$; the threshold value $c_2^M > c_n$ if $c_n < \delta/2$.

Corollary 2. In the model of supplier-remanufacturing, there exists a threshold value c_1^S such that the supplier should engage in remanufacturing if $c_r < c_1^S$; the threshold value $c_1^S < c_n$.

Corollaries 1 and 2 show that in both models, the impact of the remanufacturing cost c_r on the decision of whether to remanufacture is monotone, i.e., the lower the value of c_r is, the more likely the remanufacturer is to engage in remanufacturing. What is more interesting and important, we find that the manufacturer may engage in remanufacturing even if remanufacturing a used component costs more than manufacturing a new one. The economic intuition behind this finding is explained as follows. The supplier measures the cost savings from remanufacturing by comparing c_r and c_n, thus, she may remanufacture used components only if $c_r < c_n$. By contrast, the manufacturer measures the cost savings by comparing c_r and w_n. A profit seeking supplier must set $w_n \ge c_n$. Thus, it may be profitable for the manufacturer to remanufacture used components if $c_n < c_r < w_n$.

Next, we can rewrite Propositions 2 and 3 using the consumer value discount for the remanufactured product δ as the separating parameter. Thus, following from Corollaries 1 and 2, and letting $c_r = c_2^M$ ($c_r = c_1^S$), we have $\delta = \left(1+c_n+c_r \pm \sqrt{B}\right)/2$ ($\delta = c_r/c_n$), $B = 1+2c_n+2c_nc_r+{c_n}^2-6c_r+{c_r}^2$. The impact of δ on the decision of whether to remanufacture is followed.

Corollary 3. In the model of manufacturer-remanufacturing, there exists two threshold values $\delta_1^M = \left(1+c_n+c_r-\sqrt{B}\right)/2$ and $\delta_2^M = \left(1+c_n+c_r+\sqrt{B}\right)/2$ such that the manufacturer should engage in remanufacturing if $\delta_1^M < \delta < \delta_2^M$; the threshold value $\delta_2^M < 1$ if $c_r > c_n$.

Corollary 4. In the model of supplier-remanufacturing, there exists a threshold value $\delta_1^S = c_r/c_n$ such that the supplier should engage in remanufacturing if $\delta > \delta_1^S$; the threshold value $\delta_1^S > 1$ if $c_r > c_n$.

Corollaries 3 and 4 show that in both models, the impact of δ on the decision of whether to remanufacture is monotone if $c_r \le c_n$, i.e., the higher the value of δ is, the more likely the remanufacturer is to engage in remanufacturing. But, if $c_r > c_n$, although the supplier should not remanufacture any used component, the impact of δ on the manufacturer's decision of remanufacturing is non-monotone, i.e., as the value of δ increases, at first, the manufacturer is more likely to engage in remanufacturing, but eventually, the manufacturer is more likely to forgo remanufacturing.

This finding is striking because it challenges the generally accepted notion that consumers' low willingness-to-pay for the remanufactured product is a major barrier for remanufacturing (Liu et al., 2009, Atasu et al., 2010, Abbey et al., 2015). In order to understand the counterintuitive finding, let's revisit the interaction between the supplier and the manufacturer in the model of manufacturer-remanufacturing where remanufacturing is profitable if the consumer value discount for the remanufactured product is not low enough and the remanufactured component will cannibalize the supplier's new component sales. If the value of δ is moderate, the potential cannibalization problem is not serious, and then the supplier is better off by accommodating remanufacturing, e.g., pricing the new component at $w_{2-2}^M = (1+c_m-\delta+c_r)/2$; however, if the value of δ is high, and then the supplier is better off by changing her strategy to successfully thwart remanufacturing, e.g., pricing the new component at $w_{2-1}^M = c_r/\delta$. As a result, taking the supplier's strategic behavior into account, the manufacturer's decision on whether to remanufacture may switch from engaging in to forgoing as the increasing of δ.

4.2. Who is the "right" remanufacturer?

In this subsection, we identify the "right" remanufacturer from different stakeholder perspectives. Following from Propositions 2 and 3, we have six scenarios to examine the desirability of manufacturer-remanufacturing and supplier-remanufacturing, as shown in Table 4 and illustrated in Fig. 3. Here, we list only the

Table 2
The profit expressions in the model of manufacturer-remanufacturing.

	$c_r \le c_3^M$	$c_3^M < c_r \le c_2^M$	$c_2^M < c_r \le c_1^M$	$c_r > c_1^M$
Π_S^M	$\frac{(1-c_n-c_r+\delta)^2}{8(1+3\delta)}$	$\frac{(1-c_n+c_r-\delta)^2}{8(1-\delta)}$	$\frac{(\delta-c_r)(c_r-\delta c_n)}{2\delta^2}$	$\frac{(1-c_n)^2}{8}$
Π_M^M	$\frac{(1-c_n-c_r+\delta)^2}{16(1+3\delta)}$	$\frac{X}{16\delta(1-\delta)}$	$\frac{(\delta-c_r)^2}{4\delta^2}$	$\frac{(1-c_n)^2}{16}$

$X = \delta{c_n}^2 - 2\delta(1+c_r-\delta)c_n + (4-3\delta){c_r}^2 - 6\delta(1-\delta)c_r + \delta + 2\delta^2 - 3\delta^3$.

Table 3
The profit expressions in the model of supplier-remanufacturing.

	$c_r < c_2^S$	$c_2^S \le c_r \le c_1^S$	$c_r > c_1^S$
Π_S^S	$\frac{(1-c_n-c_r+\delta)^2}{8(1+3\delta)}$	$\frac{Y}{8\delta(1-\delta)}$	$\frac{(1-c_n)^2}{8}$
Π_M^S	$\frac{(1-c_n-c_r+\delta)^2}{16(1+3\delta)}$	$\frac{Y}{16\delta(1-\delta)}$	$\frac{(1-c_n)^2}{16}$

$Y = \delta{c_n}^2 - 2\delta(1+c_r-\delta)c_n + {c_r}^2 + \delta - \delta^2$.

Table 4
These six scenarios of comparison.

Scenario	Condition	w_n^M	$\{w_n^S, w_r^S\}$
1	$c_r > c_1^M$	w_{n1}^M	$\{w_{n1}^S, w_{r1}^S\}$
2	$c_2^M < c_r \le c_1^M$	w_{2-1}^M	$\{w_{n1}^S, w_{r1}^S\}$
3	$c_3^M < c_r \le c_2^M$	w_{2-2}^M	$\{w_{n1}^S, w_{r1}^S\}$
4	$c_1^S < c_r \le c_3^M$	w_{n3}^M	$\{w_{n1}^S, w_{r1}^S\}$
5	$c_2^S \le c_r \le c_1^S$	w_{n3}^M	$\{w_{n2}^S, w_{r2}^S\}$
6	$c_r < c_2^S$	w_{n3}^M	$\{w_{n3}^S, w_{r3}^S\}$

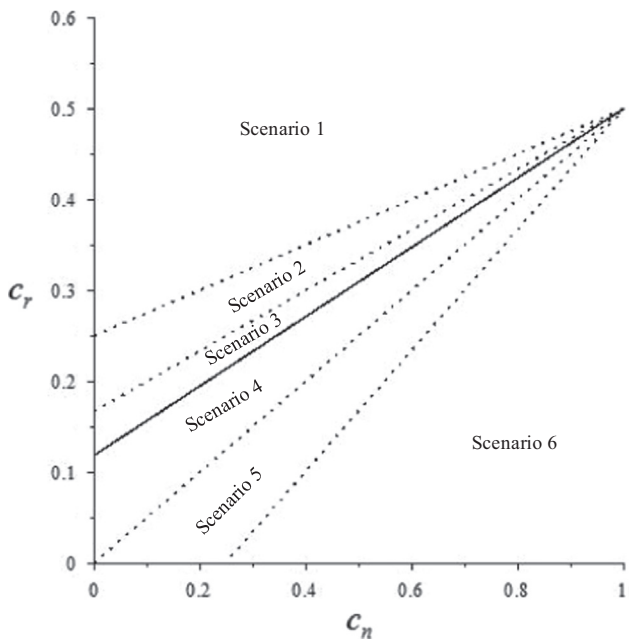

Fig. 3. The illustration of these six scenarios.

supplier's optimal decision in each scenario. As said before, if the supplier's optimal decision is w_{nk}^M or $\{w_{nk}^S, w_{rk}^S\}$, then the manufacturer's optimal response must be $\{q_{nk}^i, q_{rk}^i\}$. It is worth noting that, the solid line in Fig. 3 refers to $c_r = c_3^M$, which separates the manufacturer's, the consumers' and the environment's preferences to manufacturer-remanufacturing and supplier-remanufacturing, as demonstrated by the following Propositions.

In line with intuition, if the remanufacturing cost is sufficiently low $c_r < c_2^S$ or sufficiently high $c_r > c_1^M$, all used products or no used product will be remanufactured in both models, and then manufacturer-remanufacturing and supplier-remanufacturing are equivalent from the perspective of all stakeholders (as shown in Proofs of Propositions 4–7). Thus, in what follows, we focus on the scenarios under the condition $c_2^S \le c_r \le c_1^M$, i.e., Scenarios 2–5.

From the perspective of the manufacturer, we identify the "right" remanufacturer as the firm who makes the manufacturer obtain a higher profit. Thus, by comparing the manufacturer's profits in models of manufacturer-remanufacturing and supplier-remanufacturing, we have the following proposition.

Proposition 4. From the perspective of the manufacturer, manufacturer-remanufacturing is preferred if $c_r > c_3^M$; otherwise, supplier-remanufacturing is preferred.

Following from Eqs. (4) and (6), letting the supplier remanufacture, the manufacturer's cost to obtain a unit remanufactured component will change from c_r to w_r; in addition, a profit seeking supplier must price w_r higher than c_r. Well, why does the manufacturer still benefit from supplier-remanufacturing if the remanufacturing cost is low enough? The economic intuition behind Proposition 4 lies in that, if $c_r \le c_3^M$, remanufacturing is so profitable that the manufacturer is willing to remanufacture all used products, and then new and remanufactured products exhibit the characteristics of complements (Debo et al., 2005, Xiong et al., 2013). Therefore, the supplier can appropriate the remanufacturing benefit by pricing the new component higher, which leads to a smaller optimal production quantity of new and remanufactured products and consequently, makes manufacturer-remanufacturing less attractive for the manufacturer. By contrast, with supplier-remanufacturing, although the cost to obtain a unit remanufactured component is higher, the manufacturer can obtain a lower wholesale price for the new component, e.g., $w_{n3}^M > w_{n2}^S$. So supplier-remanufacturing is more desirable for the manufacturer if the remanufacturing cost is low enough.

Similarly, from the perspective of the supplier, the "right" remanufacturer is identified as follows.

Proposition 5. From the perspective of the supplier, supplier-remanufacturing is always preferred over manufacturer-remanufacturing.

Proposition 5 shows that manufacturer-remanufacturing is always detrimental to the supplier. The economic intuition behind this result is straightforward. On one hand, if $c_r > c_3^M$, the remanufactured component is a substitute for the new component, then manufacture-remanufacturing will cannibalize the sales of the new component and hurt the supplier. On the other hand, if $c_r \le c_3^M$, with manufacturer-remanufacturing, the profit seeking supplier will strategically price the new component higher and the profit seeking manufacturer will strategically produce fewer new products, which forms a loss–loss situation. As a result, manufacturer-remanufacturing is never preferred by the supplier.

From the perspective of the consumers, we identify the "right" remanufacturer as the firm who makes consumers obtain a greater surplus. Based on our linear inverse demand functions, consumer's surplus is calculated as

$$v_k^i = \frac{1}{2}\left(1 - p_{nk}^i\right) q_{nk}^i + \frac{1}{2}\left(\delta - p_{rk}^i\right) q_{rk}^i \tag{7}$$

Comparing the consumers' surpluses in models of manufacturer-remanufacturing and supplier-remanufacturing gives the following proposition.

Proposition 6. From the perspective of the consumers, manufacturer-remanufacturing is preferred if $c_r > c_3^M$; otherwise, supplier-remanufacturing is preferred.

Following from Propositions 4 and 6, it is revealed that consumers have the same preference as the manufacturer. This is because, on one hand, if $c_r > c_3^M$, the manufacturer will engage in remanufacturing, but the supplier will not, and then remanufacturing drives down the new product price and provides a low-price alternative to the consumers who cannot afford the new product, so manufacturer-remanufacturing is more preferable; on the other hand, if $c_r \le c_3^M$, as said before, manufacturer-remanufacturing results in a higher new product price and consequently a lower production quantity, which reduce the consumers' surplus, and then supplier-remanufacturing is naturally more preferable.

It is worth noting that, we use the weighted production quantity $q_n + \phi q_r$ as a proxy of the closed-loop supply chain's environmental performance. From the perspective of the environment, the "right" remanufacturer is identified as the firm whose remanufacturing business leads to less impact on the environment, i.e., a fewer weighted production quantity $q_n + \phi q_r$.

Proposition 7. From the perspective of the environment, if $c_r > c_3^M$, supplier-remanufacturing is preferred regardless of the value of ϕ; if $c_r \le c_3^M$, supplier-remanufacturing is preferred if ϕ is

large enough, otherwise, manufacturer-remanufacturing is preferred.

It is worth noting that, if $c_r > c_3^M$, the profit seeking supplier does not remanufacture used products. However, Proposition 7 reveals that supplier-remanufacturing is then preferred from the perspective of the environment. The economic intuition has been discussed by Xiong et al. (2013). Even with $\phi = 0$, although remanufacturing cannibalizes the sales of the new product, the profit seeking supplier will strategically lower the new component price, e.g., $w_{2-2}^M < w_{n1}^S$, making the manufacturer better off by producing more new products, so remanufacturing is then detrimental to the environment. On the other hand, if $c_r \le c_3^M$, in the model of manufacturer-remanufacturing, fewer new products will be produced; however, all used products will be remanufactured. Therefore, manufacturer-remanufacturing leads to fewer new products but more remanufactured products compared with supplier-remanufacturing. Intuitively, the desirability of manufacturer-remanufacturing and supplier-remanufacturing depends on the value of ϕ.

5. Conclusions

In this paper, motivated by the pilot program of auto part remanufacturing in China, we analyze the performance of manufacturer-remanufacturing and supplier-remanufacturing, and examine their desirability from different stakeholder perspectives. Most of our modeling elements are widely used in the literature, but a main deviation lies in the unit remanufacturing cost is allowed to be higher than the unit manufacturing cost, which is motivated by the fact that not all manufacturers and suppliers have the infrastructure and expertize to remanufacture cost-efficiently.

Our analytical result confirms that both the manufacturer and the supplier are more likely to engage in remanufacturing as the decreasing of the unit remanufacturing cost. However, a less-intuitive finding is that the manufacturer (and only the manufacturer) may engage in remanufacturing even if remanufacturing a used component is costlier than manufacturing a new one. This finding implies that manufacturers could start up remanufacturing even if its technology is not sophisticated, which is consistent with our observation of the development of remanufacturing in many industries where high-profile manufacturers like Boeing, Caterpillar, General Electric, IBM, Kodak, Volkswagen and Xerox initiate a business model in which remanufacturing is an integral part.

We also find that if remanufacturing costs less, both the manufacturer and the supplier are more likely to engage in remanufacturing as a marginal increase in consumer willingness-to-pay for the remanufactured product; in contrast, if remanufacturing costs more, the manufacturer may forgo remanufacturing due to a marginal increase in consumer willingness-to-pay for the remanufactured product. Furthermore, it is demonstrated that supplier-remanufacturing is a dominant strategy for both the manufacturer and the supplier if the remanufacturing cost is low enough.

These findings delineate a clear trajectory to guide the development of remanufacturing from a business perspective. At the early stage when the remanufacturing technology is unsophisticated, i.e., remanufacturing has a cost disadvantage, manufacturers should pioneer, and then the direction to promote remanufacturing is to invest in process innovation and lower the remanufacturing cost. As the remanufacturing technology becomes more sophisticated, i.e., remanufacturing enjoys a cost advantage, suppliers should be encouraged to engage in remanufacturing, and then tactics such as consumer education could be adopted to increase consumer willingness-to-pay for the remanufactured product and accelerate the development of remanufacturing.

This paper also examines the desirability of manufacturer-remanufacturing and supplier-remanufacturing from the perspective of the consumers and the environment, which may guide consumer groups and environmental organizations to lobby. As Xiong et al. (2013) commented, a simple governmental policy to spur more remanufacturing activities may be detrimental to both the industry and the environment. Given the tensions between different stakeholder perspectives, the government has to make a tradeoff and deliberate on the policy to take the full advantage of remanufacturing for a sustainable future.

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Appendices

Proof of Proposition 1

In the model of manufacturer-remanufacturing, the Lagrangean and the KKT optimality conditions for the manufacturer's optimization problem are

$$L = (p_n(q_n^M, q_r^M) - w_n)q_n^M + (p_r(q_n^M, q_r^M) - c_r)q_r^M + \lambda_1 q_r^M - \lambda_2(q_r^M - q_n^M), \tag{A1}$$

$$\partial L/\partial q_n^M = 1 - 2q_n^M - 2\delta q_r^M - w_n + \lambda_2 = 0, \tag{A2}$$

$$\partial L/\partial q_r^M = -\delta(q_n^M + q_r^M) + \delta(1 - q_n^M - q_r^M) - c_r + \lambda_1 - \lambda_2 = 0, \tag{A3}$$

$$\lambda_1 q_r^M = \lambda_2(q_r^M - q_n^M) = 0, \tag{A4}$$

$$q_n^M \ge q_r^M \ge 0. \tag{A5}$$

Because the multipliers λ_1 and λ_2 can be either zero or positive, we have four scenarios to examine.

Scenario 1 with $\lambda_1 > 0$ and $\lambda_2 = 0$: we have $q_{r1}^M = 0$ according to the optimality condition (A4); substituting $\lambda_2 = 0$ and $q_{r1}^M = 0$ back into Eqs. (A2) and (A3) gives $q_{n1}^M = (1 - w_n)/2$ and $\lambda_1 = c_r - \delta w_n$; here, $\lambda_1 > 0$ requires $w_n < c_r/\delta$.

Scenario 2 with $\lambda_1 = 0$ and $\lambda_2 = 0$: by solving simultaneous Eqs. (A2) and (A3), we have $q_{n2}^M = (1 - w_n - \delta + c_r)/2(1-\delta)$ and $q_{r2}^M = (\delta w_n - c_r)/2\delta(1-\delta)$; the optimality condition (A5) requires $c_r/\delta \le w_n \le \left(c_r + \delta c_r + \delta - \delta^2\right)/2\delta$.

Scenario 3 with $\lambda_1 = 0$ and $\lambda_2 > 0$: similar to Scenario 1, we have $q_{n3}^M = q_{r3}^M = (1 - w_n + \delta - c_r)/2(1+3\delta)$ and $\lambda_2 = \left(2\delta w_n + \delta^2 - \delta - c_r - \delta c_r\right)/(1+3\delta)$, which requires $w_n > \left(c_r + \delta c_r + \delta - \delta^2\right)/2\delta$.

Scenario 4 with $\lambda_1 > 0$ and $\lambda_2 > 0$: according to the optimality condition (A4), we have $q_{n4}^M = q_{r4}^M = 0$, which is trivial and discarded.

Proof of Proposition 2

Scenario M1. We assume that in this scenario the supplier behaves to let the manufacturer chooses $\{q_{n1}^M, q_{r1}^M\}$. Thus, her

optimization problem is

$$\max_{w_n^M} \quad \Pi_{S1}^M = (w_n^M - c_n) q_{n1}^M, \tag{A6}$$

subject to $w_n^M < c_r/\delta$, which guarantees that the manufacturer will respond by choosing $\{q_{n1}^M, q_{r1}^M\}$, see Proposition 1. It is easy to get the unconstrained optimal solution $w_{n1}^M = (1+c_n)/2$, which is the optimal wholesale price if $c_r > \delta(1+c_n)/2$ according to the constraint $w_n^M < c_r/\delta$. If $c_r \le \delta(1+c_n)/2$, then the optimal wholesale price in this case is infinitely closed to c_r/δ, which is dominated by $w_{2-1}^M = c_r/\delta$ (we get this solution in the next case).

Scenario M2. In this scenario, we assume that the supplier behaves to let the manufacturer chooses $\{q_{n2}^M, q_{r2}^M\}$. The optimization problem is

$$\max_{w_n^M} \quad \Pi_{S2}^M = (w_n^M - c_n) q_{n2}^M, \tag{A7}$$

subject to $c_r/\delta \le w_n^M \le \left(c_r + \delta c_r + \delta - \delta^2\right)/2\delta$. Similar to the proof of Proposition 1, we have the optimal wholesale price

(1) $w_{n2-1}^M = c_r/\delta$, if $c_r > \delta(1+c_n-\delta)/(2-\delta)$;
(2) $w_{n2-2}^M = (1+c_n-\delta+c_r)/2$, if $\delta c_n \le c_r \le \delta(1+c_n-\delta)/(2-\delta)$;
(3) $w_{n2-3}^M = \left(c_r + \delta c_r + \delta - \delta^2\right)/2\delta$, if $c_r < \delta c_n$.

Scenario M3. In this scenario, we assume that the supplier behaves to let the manufacturer chooses $\{q_{n3}^M, q_{r3}^M\}$. The optimization problem is

$$\max_{w_n^M} \quad \Pi_{S3}^M = (w_n^M - c_n) q_{n3}^M, \tag{A8}$$

subject to $w_n^M > \left(c_r + \delta c_r + \delta - \delta^2\right)/2\delta$, and then similar to Case M1, the optimal wholesale price is $w_{n3}^M = (1+\delta+c_n-c_r)/2$ if $c_r < \delta(c_n+2\delta)/(1+2\delta)$.

Next, we are to identify the optimal wholesale price on the whole parameter space. With $\delta \ge 1/2$, it is easy to prove that $\delta(c_n+2\delta)/(1+2\delta) \ge \delta(1+c_n)/2 > \delta(1+c_n-\delta)/(2-\delta) > \delta c_n$. Thus, if $c_r > \delta(1+c_n)/2$, the supplier has two possible solutions: (1) w_{n1}^M and letting the manufacturer chooses $\{q_{n1}^M, q_{r1}^M\}$, and (2) w_{n2-1}^M and letting the manufacturer chooses $\{q_{n2}^M, q_{r2}^M\}$. Solving for $\Pi_{S1}^M(w_{n1}^M, q_{n1}^M, q_{r1}^M) > \Pi_{S2}^M(w_{n2-1}^M, q_{n2}^M, q_{r2}^M)$, we get $c_r > \delta(1+c_n)/2$. Thus, in this situation, the wholesale price w_{n1}^M is a dominant strategy for the supplier. Similarly, it can be demonstrated that from the perspective of the supplier, w_{n1}^M is preferred over w_{n3}^M if $\delta(1+c_n)/2 < c_r < \delta(c_n+2\delta)/(1+2\delta)$; w_{n2-1}^M is preferred over w_{n3}^M if $\delta(1+c_n-\delta)/(2-\delta) < c_r \le \delta(1+c_n)/2$; w_{n3}^M is preferred over w_{n2-3}^M if $c_r < \delta c_n$.

If $\delta c_n < c_r \le \delta(1+c_n-\delta)/(2-\delta)$, two possible solutions are: (1) w_{n2-2}^M and letting the manufacturer chooses $\{q_{n2}^M, q_{r2}^M\}$, and (2) w_{n3}^M and letting the manufacturer chooses $\{q_{n3}^M, q_{r3}^M\}$. Let $\Delta^M = \Pi_{S2}^M(w_{n2-2}^M, q_{n2}^M, q_{r2}^M) - \Pi_{S3}^M(w_{n3}^M, q_{n3}^M, q_{r3}^M)$, we have $\partial\Delta^M/\partial c_r > 0$, $\Delta^M(c_r = \delta c_n) = -(\delta(1-c_n))^2/2(1+3\delta) < 0$, and $\Delta^M(c_r = \delta(1+c_n-\delta)/(2-\delta)) = (2-3\delta)\delta(1-c_n)^2/2(1+3\delta)(2-\delta)^2$. In this scenario, if $\delta \ge 2/3$, $\Delta^M(c_r = \delta(1+c_n-\delta)/(2-\delta)) \le 0$, thus w_{n3}^M is always preferred over w_{n2-2}^M; if $1/2 \le \delta < 2/3$, $\Delta^M(c_r = \delta(1+c_n-\delta)/(2-\delta)) > 0$, and then there exists c_3^M (its expression can be found in Proposition 2) such that w_{n3}^M is preferred if $\delta c_n < c_r < c_3^M$, otherwise, w_{n2-2}^M is preferred.

The Scenario with $\delta < 1/2$ is a simplification of that with $1/2 \le \delta < 2/3$. With $1/3 \le \delta < 1/2$, we can skip the comparison of w_{n1}^M and w_{n3}^M, and with $\delta < 1/3$, we can further skip the comparison of w_{n2-1}^M and w_{n3}^M. The results are all the same in the Scenario with $1/2 \le \delta < 2/3$.

Combining the above analysis and comparison gives the supplier's optimal wholesale price of the new component in the model of manufacturer-remanufacturing.

Proof of Proposition 3

Scenario S1. In this scenario, we assume that the supplier behaves to let the manufacturer chooses $\{q_{n1}^S, q_{r1}^S\}$. The optimization problem is

$$\max_{w_n^S, w_r^S} \quad \Pi_{S1}^S = (w_n^S - c_n) q_{n1}^S + (w_r^S - c_r) q_{r1}^S, \tag{A9}$$

subject to $w_n^S < w_r^S/\delta$. It is easy to get that the unconstrained solution is $w_{n1}^S = (1+c_n)/2$, which is the optimal wholesale price of the new component if $w_{r1}^S > \delta w_{n1}^S$. Because Π_{S1}^S is independent in w_r^S, we do not care about the exact value of w_{r1}^S. As we will get in the next case, with $\{w_{n2-1}^S, w_{r2-1}^S\}$, we have $q_{r2}^S = q_{r1}^S = 0$. Thus, the solutions, $\{w_{n1}^S, w_{r1}^S\}$ and $\{w_{n2-1}^S, w_{r2-1}^S\}$, are equivalent.

Scenario S2. In this scenario, we assume that the supplier behaves to let the manufacturer chooses $\{q_{n2}^S, q_{r2}^S\}$. The optimization problem is

$$\max_{w_n^S, w_r^S} \quad \Pi_{S2}^S = (w_n^S - c_n) q_{n2}^S + (w_r^S - c_r) q_{r2}^S, \tag{A10}$$

subject to $w_r^S/\delta \le w_n^S \le \left(w_r^S + \delta w_r^S + \delta - \delta^2\right)/2\delta$. Similar to the Proof of Proposition 1, we have the optimal wholesale prices of new and remanufactured components

(1) $w_{n2-1}^S = (1+c_n)/2$, $w_{r2-1}^S = \delta(1+c_n)/2$, if $c_r > \delta c_n$;
(2) $w_{n2-2}^S = (1+c_n)/2$, $w_{r2-2}^S = (\delta+c_r)/2$, if $\delta(2c_n+\delta-1)/(1+\delta) \le c_r \le \delta c_n$;
(3) $w_{n2-3}^S = \left(1+4\delta-\delta^2+(1+\delta)(c_n+c_r)\right)/2(1+3\delta)$,
$w_{r2-3}^S = \delta(2\delta+c_n+c_r)/(1+3\delta)$, if $c_r < \delta(2c_n+\delta-1)/(1+\delta)$.

Scenario S3. In this scenario, we assume that the supplier behaves to let the manufacturer chooses $\{q_{n3}^S, q_{r3}^S\}$. The optimization problem is

$$\max_{w_n^S, w_r^S} \quad \Pi_{S3}^S = (w_n^S - c_n) q_{n3}^S + (w_r^S - c_r) q_{r3}^S, \tag{A11}$$

subject to $w_n^S > \left(w_r^S + \delta w_r^S + \delta - \delta^2\right)/2\delta$. Because of $q_{n3}^S = q_{r3}^S$, the optimization problem can be rewritten as

$$\max_{w_n^S, w_r^S} \quad \Pi_{S3}^S = (w_n^S + w_r^S - c_n - c_r) q_{n3}^S. \tag{A12}$$

Clearly, Π_{S3}^S is concave in the sum of w_n^S and w_r^S. We have the unconstrained solutions satisfy $w_{n3}^S + w_{r3}^S = (1+\delta+c_n+c_r)/2$. Without loss of generality, we set $w_{r3}^S = w_{r2-3}^S$, the unconstrained relationship $w_{n3}^S + w_{r3}^S = (1+\delta+c_n+c_r)/2$ requires $w_{n3}^S = w_{n2-3}^S$, and the constraint $w_n^S > \left(w_r^S + \delta w_r^S + \delta - \delta^2\right)/2\delta$ requires w_{n3}^S is infinitely closed to w_{n2-3}^S. Thus, we say that the solutions, $\{w_{n3}^S, w_{r3}^S\}$ and $\{w_{n2-3}^S, w_{r2-3}^S\}$, are equivalent.

Combining the above analysis and comparison gives the supplier's optimal wholesale prices of new and remanufactured components in the model of supplier-remanufacturing.

Proof of Proposition 4

Clearly, we have six scenarios to compare the manufacturer's profits. We define $\Delta_{Ml} = \Pi_M^M - \Pi_M^S$ in scenario l.

In Scenario 1 with $c_r > c_1^M$, $\Delta_{M1} = 0$.

In Scenario 2 with $c_2^M < c_r \le c_1^M$, $\partial^2\Delta_{M2}/\partial c_r{}^2 = 1/2\delta^2 > 0$, letting $\partial\Delta_{M2}/\partial c_r = 0$, we have $c_r = \delta$, that is to say, Δ_{M2} reaches its global minimum at $c_r = \delta$. In addition, the condition of this scenario implies $c_2^M < c_1^M < \delta$. Thus, we have $\Delta_{M2} \ge \Delta_{M2}(c_r = c_1^M) = 0$.

In Scenario 3 with $c_3^M < c_r \le c_2^M$, similar to Scenario 2, we have $\Delta_{M3} > 0$.

In Scenario 4 with $c_1^S < c_r \le c_3^M$, $\partial^2\Delta_{M4}/\partial c_r{}^2 = 1/8(1+3\delta) > 0$, in addition, the condition of this scenario implies $c_1^S < c_3^M < c_2^M$. We have $\Delta_{M4}(c_r = c_2^M) = -\delta(1-\delta)(8-3\delta)(1-c_n)^2/16(1+3\delta)(2-\delta)^2 < 0$, and $\Delta_{M4}(c_r = c_1^S) = -\delta(1-\delta)(1-c_n)^2/16(1+3\delta) < 0$. Thus, $\Delta_{M4} < 0$.

In Scenario 5 with $c_2^S \le c_r \le c_1^S$, $\Delta_{M5} = -(\delta + c_r + \delta c_r - 2\delta c_n - \delta^2)^2/16\delta(1+3\delta)(1-\delta) \le 0$.

In Scenario 6 with $c_r < c_2^S$, $\Delta_{M6} = 0$.

Combining these results in all six scenarios gives Proposition 4.

Proof of Proposition 5

Similarly, we define $\Delta_{Sl} = \Pi_S^M - \Pi_S^S$ in scenario l.

In Scenario 1 with $c_r > c_1^M$, $\Delta_{S1} = 0$.

In Scenario 2 with $c_2^M < c_r \le c_1^M$, $\Delta_{S2} = -(\delta + \delta c_n - 2c_r)^2/8\delta < 0$.

In Scenario 3 with $c_3^M < c_r \le c_2^M$, $\partial^2\Delta_{S3}/\partial c_r{}^2 = 1/8(1-\delta) > 0$, letting $\partial\Delta_{S3}/\partial c_r = 0$, we have $c_r = \delta + c_n - 1$, that is to say, Δ_{S3} reaches its global minimum at $c_r = \delta + c_n - 1$. In addition, the condition of this scenario implies $\delta + c_n - 1 < c_3^M < c_2^M$. Thus, Δ_{S3} is increasing in c_r. We have $\Delta_{S3} \le \Delta_{S3}(c_r = c_2^M) = -(1-c_n)^2\delta^2/8(2-\delta)^2 < 0$.

In Scenario 4 with $c_1^S < c_r \le c_3^M$, similar to Scenario 3, we have $\Delta_{S4} < 0$.

In Scenario 5 with $c_2^S \le c_r \le c_1^S$, $\Delta_{S5} = -(\delta + c_r + \delta c_r - 2\delta c_n - \delta^2)^2/8\delta(1+3\delta)(1-\delta) < 0$.

In Scenario 6 with $c_r < c_2^S$, $\Delta_{S6} = 0$.

Combining these results in all six scenarios gives Proposition 5.

Proof of Proposition 6

Similarly, we define $\Delta_{\upsilon l} = \upsilon^M - \upsilon^S$ in scenario l.

In Scenario 1 with $c_r > c_1^M$, $\Delta_{\upsilon 1} = 0$.

In Scenario 2 with $c_2^M < c_r \le c_1^M$, $\partial^2\Delta_{\upsilon 2}/\partial c_r{}^2 = 1/4\delta^2 > 0$, letting $\partial\Delta_{\upsilon 2}/\partial c_r = 0$, we have $c_r = c_1^M$, that is to say, Δ_{S3} reaches its global minimum at $c_r = c_1^M$. We have $\Delta_{\upsilon 2} \ge \Delta_{\upsilon 2}(c_r = c_1^M) = 0$.

In Scenario 3 with $c_3^M < c_r \le c_2^M$, $\partial^2\Delta_{\upsilon 3}/\partial c_r{}^2 = -(8-6\delta)/32\delta(1-\delta) < 0$, letting $\partial\Delta_{\upsilon 3}/\partial c_r = 0$, we have $c_r = (3 + c_n - 3\delta)\delta/(4-3\delta)$, that is to say, $\Delta_{\upsilon 3}$ reaches its global maximum at $c_r = (3 + c_n - 3\delta)\delta/(4-3\delta)$. In addition, the condition of this scenario implies $c_1^S < c_3^M < c_2^M < (3 + c_n - 3\delta)\delta/(4-3\delta)$. Thus, $\Delta_{\upsilon 3}$ is increasing in c_r. We have $\Delta_{\upsilon 3} > \Delta_{S3}(c_r = c_1^S) = 3\delta(1-c_n)^2/32 > 0$.

In Scenario 4 with $c_1^S < c_r \le c_3^M$, similar to Scenario 3, we have $\Delta_{\upsilon 4} < 0$.

In Scenario 5 with $c_2^S \le c_r \le c_1^S$, $\Delta_{\upsilon 5} = -(\delta + c_r + \delta c_r - 2\delta c_n - \delta^2)^2/32\delta(1+3\delta)(1-\delta) < 0$.

In Scenario 6 with $c_r < c_2^S$, $\Delta_{\upsilon 6} = 0$.

Combining these results in all six scenarios gives Proposition 6.

Proof of Proposition 7

Similarly, we define $\Delta_{El} = E^M - E^S$ in scenario l.

In Scenario 1 with $c_r > c_1^M$, $\Delta_{E1} = 0$.

In Scenario 2 with $c_2^M < c_r \le c_1^M$, $\Delta_{E2} = (\delta + \delta c_n - 2c_r)/4\delta$, clearly, Δ_{E2} is decreasing in c_r. Thus, we have $\Delta_{E2} \ge \Delta_{E2}(c_r = c_1^M) = 0$.

In Scenario 3 with $c_3^M < c_r \le c_2^M$, $\partial\Delta_{E3}/\partial\phi > 0$. Thus, $\Delta_{E3} \ge \Delta_{E3}(\phi = 0) = (c_r - \delta c_n)/4(1-\delta)$. In addition, the condition of this scenario implies $c_1^S < c_3^M < c_2^M$. Thus, $\Delta_{E3} > \Delta_{E3}(c_r = c_1^S) = 0$.

In Scenario 4 with $c_1^S < c_r \le c_3^M$, $\Delta_{E4}(\phi = 0, c_r = c_1^S) = -\delta(1-c_n)/2(1+3\delta) < 0$ and $\Delta_{E4}(\phi = 1, c_r = c_1^S) = (1-\delta)(1-c_n)/4(1+3\delta) > 0$. Thus, in this scenario, there must exist a threshold value (letting $\Delta_{E4} = 0$, we have) $\phi = \phi' = (2\delta + c_r - 3\delta c_n)/(1 - c_n + \delta - c_r)$ such that if $\phi > \phi'$, $\Delta_{E4} > 0$; otherwise, $\Delta_{E4} \le 0$.

In Scenario 5 with $c_2^S \le c_r \le c_1^S$, similar to Scenario 4, there exists a threshold value $\phi = \phi'' = 2\delta/(1+\delta)$ such that if $\phi > \phi''$, $\Delta_{E5} > 0$; otherwise, $\Delta_{E5} \le 0$.

In Scenario 6 with $c_r < c_2^S$, $\Delta_{E6} = 0$.

Combining these results in all six scenarios gives Proposition 7.

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