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Don't Forget Your Supplier When Remanufacturing

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Don't Forget Your Supplier When Remanufacturing

A popular assumption in the current literature on remanufacturing is that the whole new product is produced by an integrated manufacturer, which is inconsistent with most industries. In this paper, we model a decentralised closed-loop supply chain consisting of a key component supplier and a non-integrated manufacturer, and demonstrate that the interaction between these players significantly impacts the economic and environmental implications of remanufacturing. In our model, the non-integrated manufacturer can purchase new components from the supplier to produce new products, and remanufacture used components to produce remanufactured products. Thus, the non-integrated manufacturer is not only a buyer but also a rival to the supplier. In a steady state period, we analyse the performances of an integrated manufacturer and the decentralised supply chain. We find that, although the integrated manufacturer always benefits from remanufacturing, the remanufacturing opportunity may constitute a lose-lose situation to the supplier and the non-integrated manufacturer, making their profits be lower than in an identical supply chain without remanufacturing. In addition, the non-integrated manufacturer may be worse off with a lower remanufacturing cost or a larger return rate of used products due to the interaction with the supplier. We further demonstrate that the government-subsidised remanufacturing in the non-integrated (integrated) manufacturer is detrimental (beneficial) to the environment.

Keywords: Supply chain management; Closed-loop supply chain; Remanufacturing; Environmental impact; Government subsidy

1. Introduction

Remanufacturing is "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). Its economic and environmental implications have gotten a lot of publicity. As a natural low-cost alternative to the traditional manufacturing, remanufacturing can play an important role in increasing profits, as shown by successful examples from many industries (Geyer et al., 2007). In addition, remanufacturing enjoys a green reputation since it reduces the disposal of used products and consumes less natural resources and energy than manufacturing all-new products (Giuntini and Gaudette, 2003). Therefore, environmental groups and governments are increasingly encouraging manufacturers to engage in remanufacturing (Hammond and Beullens, 2007; Ma et al, 2013). For instance, the Chinese Government launched a pilot programme in 2010, providing subsidies to a few selected manufacturers that had no remanufacturing experiences to develop remanufacturing technologies and build reverse logistic networks (China NDRC, 2010).

Nevertheless, most manufacturers do not choose to remanufacture their products. Such a phenomenon is explained mainly from the resource-based view: most manufacturers do not possess the infrastructure and expertise to collect used products and remanufacture them in a profitable manner (Ferguson, 2010). Even if remanufacturing is independently profitable, manufacturers may still ignore this option due to concerns about the cannibalisation of higher-margin new product sales (Atasu et al., 2010; Ferguson and Toktay, 2006). At the same time, the positive environmental profile of remanufacturing is being challenged by latest theoretical findings. Galbreth et al. (2012) shows that remanufacturing can actually increase total virgin material usage because introducing remanufactured products at a low price to the market increases the overall demand. Agrawal et al. (2012b) finds that leasing is not always greener than selling, so encouraging remanufacturing, which raises the value of off-lease product and makes leasing more profitable, may lead to heavier environmental burden.

When modelling the closed-loop supply chain, like most of the literature on remanufacturing, all above mentioned analytic studies assume that the production of the whole new product is done by an integrated manufacturer. But does the interaction on new product production make no difference to the performance of closed-loop supply chains with remanufacturing? To answer this question, in this paper, we model and investigate a decentralised closed-loop supply chain consisting of a key component supplier and a non-integrated manufacturer.

This research is motivated by the pilot programme of auto part remanufacturing in China launched by Chinese National Development and Reform Commission (Xinhuanet.com, 2008). Three auto enterprises such as China First Automobile Group are selected and supported by the government to remanufacture auto parts. However, unlike their western or Japanese counterparts, most Chinese auto manufacturers generally have no capacity to design and produce high-quality key components such as automotive engine and gearboxes. They are heavily dependent on key component suppliers. Thus, when these manufacturers engage in remanufacturing, not surprisingly, a great part of the remanufactured product will be initially produced by their suppliers. Intuitively, the remanufactured product will erode the demand for new components. With anticipation of the remanufacturing opportunity, a supplier, especially a key component supplier with the dominant channel power, can respond by strategically adjusting the new component price, which in turn influences the manufacturer's remanufacturing decision. To focus on the impact of the interaction between the key component supplier and the non-integrated manufacturer on the economic and environmental implications of remanufacturing, we consider a simple bilateral monopoly, as depicted in Figure 1. Here, in accordance with industrial practices (Fleischmann et al., 2003), we specify that the process of remanufacturing is on the level of the component rather than the whole product. The collected used products are disassembled into their constituent components, which are processed, reassembled, tested and made ready for sale as remanufactured products. In such a context, this paper seeks to provide a better understanding on the following research questions:

- If the remanufacturing cost is sufficiently low to overcome the negative impact of cannibalisation on new product sales, should the manufacturer always engage in remanufacturing?
- When engaging in remanufacturing, can the manufacturer be always better off by lowering the remanufacturing cost or enlarging the return rate of used products?
- Are the manufacturer's remanufacturing activities, especially the government-subsidised remanufacturing activities, always beneficial to the environment?

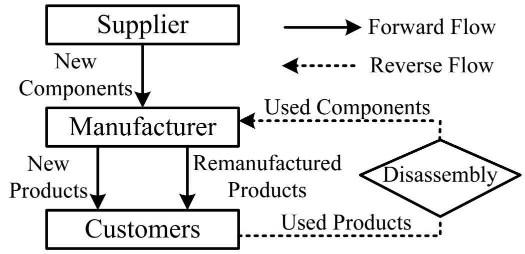


Figure 1. The decentralised closed-loop supply chain with remanufacturing

The rest of this paper is organised as follows. Section 2 reviews the literature. Section 3 introduces the assumptions and notations. Sections 4 analyses the performance of an integrated manufacturer as a benchmark. Section 5 analyses the performance of the decentralised closed-loop supply chain. Section 6 examines the environmental implications of remanufacturing. Section 7 concludes this research.

2. Relevant Literature

Our work mainly draws on and contributes to the current literature on managing closed-loop supply chains with remanufacturing. For an overview of this research field, we refer the reader to Atasu et al. (2008a) and Guide and Van Wassenhove (2009). Earlier efforts focus on optimal strategies in an integrated system with only one decision-maker. However, closed-loop supply chains generally involve many more independent players than traditional supply chains. Therefore, there has been emerging research interests in either the competitive strategy or the supply chain interaction of multiple decision-makers in the closed-loop context. However, note that these two literature streams typically assume the whole new product is produced by an integrated manufacturer.

The literature on competition in remanufacturing generally employs game theory to model pricing/production quantity decisions for an integrated manufacturer facing competition from independent remanufacturers (Ferrer and Swaminathan, 2006; Ferrer and Swaminathan, 2010; Majumder and Groenevelt, 2001). These studies conclude that the entry of independent remanufacturers is detrimental to the manufacturer, and suggest that the manufacturer should remanufacture or collect used products to pre-empt new entrants (Ferguson and Toktay, 2006). Heese et al. (2005) and Atasu et al. (2008b) analyse the profitability of remanufacturing under a direct manufacturer competition. Their results show that remanufacturing can be an effective marketing strategy that allows an integrated manufacturer to defend its market share via price discrimination. Debo et al. (2005) solves joint technology selection and pricing decisions for new and remanufactured products faced by an integrated manufacturer, and extend their model to the case of multiple competing remanufactures. They discover that new and remanufactured products may exhibit the characteristics of complementary products because remanufacturing requires used products as cores.

The impacts of interactions between supply chain partners on the performance of closed-loop supply chains are highlighted by many studies. Ostlin et al. (2008) shows that remanufacturing becomes more effective when there is a clear win-win situation for all players. Savaskan et al. (2004) explores the problem of choosing the appropriate reverse channel structure for collecting used products, Karakayali et al. (2007) and Kaya (2010) analyse decentralised collection and processing operations between a collector and a remanufacturer. In these three papers, two-part tariff contracts are designed to coordinate the channel. Bhattacharya et al. (2006) addresses the problem of determining the optimal order quantity by analysing interactions among a retailer, an integrated manufacturer, and an independent remanufacturer. In their model, new and remanufactured products are perfect substitutes, and the remanufacturer sells remanufactured products through the manufacturer. Thus, the remanufacturer actually acts as a low-cost supplier, though its production capacity is bounded by new product sales.

To the best of our knowledge, there are only two papers involving the supplier when investigating the operational performance of closed-loop supply chains. Aras et al. (2006) considers a hybrid manufacturing/remanufacturing system in which a non-integrated manufacturer purchases new components from the supplier and remanufactures used products. In their model, the manufacturer is the only decision-maker, so the interaction with the supplier is ignored. Jacobs and Subramanian (2012) examine the effects of sharing product recovery responsibility between a supplier and a non-integrated manufacturer. In their model, both virgin material and recycled material are provided by the supplier, so there is no direct competition within the supply chain. In contrast, with the opportunity to remanufacture used products, the non-integrated manufacturer in our model is a rival as well as a buyer to the supplier. Thus, this paper is the first to bridge the above two literature streams and integrate both competition concerns and supply chain partnership concerns in the closed-loop supply chain context. Although a few forward supply chain models have investigated the implications of coopetition, they do not capture the unique characteristic of the remanufacturing context: the new component and the remanufactured component can be not only substitutes but also complements, which dramatically shapes players' decisions. Their focuses are the impacts of coopetition on corporate governance or channel structure (e.g., Arya et al 2008, and Lim and Tan 2010). In contrast, we consider a static channel structure, as illustrated in Figure 1, and examine the impacts of coopetition within the forward supply chain on the player's remanufacturing strategy. Our analytic results show that the interaction between the supplier and the manufacturer is critical to the economic and environmental performances of the closed-loop supply chain.

3. Assumptions and Notations

The context of our model is illustrated in Figure 1. The key feature of our model lies in that a part of the new product (the new component) is assumed to be initially produced by the supplier, and then the manufacturer's remanufacturing activities will erode the demand for the supplier's new components. Table 1 summarises the notations. Other key assumptions are outlined and discussed below.

Table 1. Parameters and Decisions Variables

Symbol	Definition
Q	The market size
δ	The consumer value discount for remanufactured products
ϕ	The return rate factor of used products
c_n, c_r	The unit production cost of the new/remanufactured component
p_n, p_r	The new/remanufactured product price
w	The new component price
q_n, q_r	The production quantity of new/remanufactured products
Π_i	The player i's profit, $i \in \{I, S, NI\}$

ASSUMPTION 1. Remanufacturing a used component does not cost more than manufacturing a new one, i.e., $c_r \le c_n$, and c_r is constant for all remanufactured components.

As the foregoing specification, the process of remanufacturing in this paper is on the level of the component. Without loss of generality, we assume that each final product contains one component. Except for the cost to obtain a new/remanufactured component, the manufacturer's other costs to (re)assemble, test and make ready for sale as the new/remanufactured product are constant and normalised to zero. Giuntini and Gaudette (2003) affirm that remanufacturing costs 40-65% less than traditional manufacturing. Here, the difference between c_n and c_r stands for the cost advantage of remanufacturing. Fleischmann (2001) illustrates that the assumption of constant unit remanufacturing cost is a reasonable first-order approach for many cases. And, it can be easily shown that the manufacturer's incentives to remanufacture used products will be enhanced (reduced) by a remanufacturing cost with economies (diseconomies) of scale.

ASSUMPTION 2. The consumer willingness-to-pay v *of new product is heterogeneous and uniformly distributed in* $[0,Q]$. *Without loss of generality, we assume a density of* 1 *in this interval.*

Assumption 2 is widely-accepted in modelling the consumers' heterogeneity (e.g., Agrawal et al. 2012b, Ferguson and Toktay 2006). It implies that the potential market size is Q, and the upper limitation of consumer willingness-to-pay is also Q. Our model, however, unlike the literature on forward supply chain management, does not require $c_n \le Q$ to guarantee a positive production quantity. In Section 5, we will discuss the reasons why the manufacturer may keep producing new products even $Q < c_n \le Q + \phi(\delta Q - c_r)$.

ASSUMPTION 3. For each consumer, the willingness-to-pay ratio of a remanufactured product to a new one is $\delta \in (0,1)$.

Assumption 3 frames a vertical differentiation model where consumers' valuation has an agreed order, i.e. all consumers prefer a new product to a remanufactured one. Earlier studies on remanufacturing routinely assume that the consumer cannot differentiate new and remanufactured products, and have the same willingness-to-pay for them. The latest empirical evidence and experimental results, however, show remanufactured products are usually valued much lower by consumers (see Guide and Li 2010, and Agrawal et al. 2012a). According to Assumptions 2 and 3, the linear inverse demand functions for new and remanufactured products are as follows.

We refer to the reader to Ferguson and Toktay (2006) for how to derive demand functions in detail.

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

$$p_r = \delta\left(Q - q_n - q_r\right) . \tag{2}$$

ASSUMPTION 4. All decisions are considered in a steady state period: the supplier moves first to price the new component, and then the manufacturer determines the production quantity of new/remanufactured products.

One of the key features of remanufacturing is that the production quantity of remanufactured products is bounded by the quantity of used products that are available for remanufacturing. In general, only a portion, $\phi \in [0,1]$, of used products can be collected by the manufacturer. By assuming the product can be used only one period, the quantity of used products in current period is equal to the production quantity of new products in the previous period. Ferrer and Swaminathan (2006) introduce the philosophy of the steady state in managing new and remanufactured products: the players use the same policy in every period after the ramp-up in the first period in an infinite horizon setting. Thus, in this paper, for the sake of tractability, we focus on the players' decisions in a single period and assume that $q_r \le \phi q_n$. Note that, $\phi > 0$ means the manufacturer has a remanufacturing opportunity, $\phi = 0$ no remanufacturing opportunity.

ASSUMPTION 5. The production quantity of new products is used as a proxy of the supply chain's environmental performance.

Because remanufacturing a used product can eliminate its disposal impact, and consumes less natural resources and energy than manufacturing all-new products (Giuntini and Gaudette, 2003), a consensus in researchers and policy-makers is that one unit remanufactured product's life-cycle environmental impact is much smaller than one unit new product's. Without a great loss of generality, we assume that one unit remanufactured product's life-cycle environmental impact is zero, and then the supply chain's environmental performance is equal to one unit new product's life-cycle environmental impact multiplied by the production quantity of new products. Therefore, q_n can be a proxy.

ASSUMPTION 6. The effect of government subsidies is to make the manufacturer that did not remanufacture used products start remanufacturing.

When examining the environmental implication of remanufacturing, we are concerned especially about the environmental implication of the government-subsidised remanufacturing. Here, we assume that only when remanufacturing is not profitable and the manufacturer does not remanufacture used products, the government will provide the subsidies. With the subsidies, remanufacturing becomes profitable for the manufacturer, but the cost advantage of remanufacturing is still small (otherwise the government can reduce the subsidies).

In addition, we also assume that all players in our model are risk-neutral and profit seeking, and have access to the same information. The fixed investment of setting up the collection system and processing operations for remanufacturing is assumed to be insignificant. In this paper, we focus on voluntary collecting and remanufacturing. Thus, the manufacturer can collect only those used products he will remanufacture[1].

In the following analysis, subscript $i \in \{I, S, NI\}$ refers to the integrated manufacturer, the component supplier and the non-integrated manufacturer, respectively; superscripts $j \in \{I, D\}$ the integrated manufacturer and the decentralised supply chain, respectively. The players' strategic decisions are analysed under various scenarios, which are distinguished by parameters c_n, c_r and ϕ. Superscript $k \in \{A, B, C\}$ denotes the scenario under which our analysis is proceeding.

4. Integrated Manufacturer Model

In this section, we analyse the performance of an integrated manufacturer as a benchmark. An integrated manufacturer that can produce the whole new produce is equivalent to a perfectly coordinated supply chain. Its optimisation problem is

[1] How to match demand and supply for remanufacturing is a substantive and interesting issue, but beyond the scope of this paper. Please refer to Guide et al. (2003), Minner and Kiesmüller (2012), Teunter and Flapper (2011), and Xiong and Li (2012) for related research.

$$\max_{q_n, q_r} \Pi_I = \left(p_n \left(q_n, q_r \right) - c_n \right) q_n + \left(p_r \left(q_n, q_r \right) - c_r \right) q_r , \tag{3}$$

subject to $q_r \leq \phi q_n$, $q_n, q_r \geq 0$. The integrated manufacturer's optimal decisions are characterised by the following proposition. The proofs of all propositions are provided in Appendixes.

PROPOSITION 1. The integrated manufacturer's optimal production quantity decisions are:

Decision I-A, $q_n^{IA} = \left(Q - c_n\right)/2$, $q_r^{IA} = 0$, *when* $c_r \leq c_n < c_r/\delta$;

Decision I-B, $q_n^{IB} = \left[Q - c_n - \left(\delta Q - c_r\right)\right]/2\left(1-\delta\right)$, $q_r^{IB} = \left(c_n - c_r/\delta\right)/2\left(1-\delta\right)$, *when* $c_r/\delta \leq c_n \leq c_{n0}$;

Decision I-C, $q_n^{IC} = \left[Q - c_n + \phi\left(\delta Q - c_r\right)\right]/2\left(1 + 2\delta\phi + \delta\phi^2\right)$, $q_r^{IC} = \phi\left[Q - c_n + \phi\left(\delta Q - c_r\right)\right]/2\left(1 + 2\delta\phi + \delta\phi^2\right)$, *when* $c_{n0} < c_n \leq Q + \phi\left(\delta Q - c_r\right)$; *here* $c_{n0} = \left[\left(1-\delta\right)\phi Q + \left(1/\delta + \phi\right)c_r\right]/\left(1+\phi\right)$.

Intuitively, when making a production quantity decision, the integrated manufacturer examines the trade-off between the profit from remanufacturing and the cannibalisation of new product sales. When c_n is small ($c_n < c_r/\delta$), the cost savings from remanufacturing are insufficient to overcome the negative impact of cannibalisation, then the integrated manufacturer will produce only new products. In contrast, if c_n is large ($c_n > c_r/\delta$), the benefit due to market segmentation outweigh the cannibalisation, then the integrated manufacturer will produce both new and remanufactured products. And, when $c_n < c_{n0}$, the optimal production quantity of remanufactured products is less than the quantity of new products that are available for remanufacturing. As a result, only a portion of available cores will be collected and remanufactured ($q_r^{IB} < \phi q_n^{IB}$). But, when $c_n > c_{n0}$, the unconstrained optimal production quantity of remanufactured products exceeds the quantity of available cores. Consequently, all available cores will be remanufactured ($q_r^{IC} = \phi q_n^{IC}$), and then, similar to Debo et al. (2005), we say new and remanufactured products exhibit the characteristics of both complements and substitutes. By contrast, we say two products are pure substitutes when only a portion of available cores is remanufactured.

Substituting the integrated manufacturer's optimal decisions in Proposition 1 back into its optimisation problem gives the integrated manufacturer's profit (as shown in Table B1 in Appendixes). The following result characterises how this profit is shaped by the cost parameters (c_n and c_r) and return rate factor (ϕ)[2]. In all results of this paper, the signs $+$, $-$ and 0 denote an increase, decrease and no-change in equilibrium, in response to a marginal increase of the corresponding parameter, respectively.

RESULT 1. (i) The following are true:

Parameters	Π_I^{IA}	Π_I^{IB}	Π_I^{IC}
c_n	$-$	$-$	$-$
c_r	0	$-$	$-$
ϕ	0	0	$+$

(ii) $\Pi_I^{IA}\big|_{c_n=c_r/\delta} = \Pi_I^{IB}\big|_{c_n=c_r/\delta}$, $\Pi_I^{IB}\big|_{c_n=c_{n0}} = \Pi_I^{IC}\big|_{c_n=c_{n0}}$.

Result 1 reveals that the integrated manufacturer's profit is decreasing in c_n, non-increasing in c_r, and non-decreasing in ϕ. Thus, it is safe to say the integrated manufacturer always benefits from the opportunity to remanufacture used products, i.e., $\Pi_I\big|_{\phi>0} \geq \Pi_I\big|_{\phi=0}$. Like the existing literature (e.g., Atasu et al., 2010; Ferguson and Toktay, 2006), we affirm that the integrated manufacturer should engaging in remanufacturing when the remanufacturing cost is sufficiently low ($c_n > c_r/\delta$) to overcome the negative cannibalisation impact on new product sales, and then the integrated manufacturer is always better off with a lower remanufacturing cost or a larger return rate.

5. Decentralised Supply Chain Model

In this section, the performance of a decentralised supply chain consisting of a key component supplier and a non-integrated manufacturer is analysed. Firstly, we solve the

[2] It is worth noting that the separating values between different scenarios also depend on these parameters, same for Results 2, 3 and 4.

players' optimisation problems. And then we examine how the players' decisions and profits are shaped by model parameters.

5.1 Optimisation problem analysis

In the decentralised supply chain, the game between the supplier and the non-integrated manufacturer can be analysed using backward induction. By taking a given w, the non-integrated manufacturer determines q_n and q_r to maximise his profit function:

$$\max_{q_n, q_r} \Pi_{NI} = \left(p_n(q_n, q_r) - w\right) q_n + \left(p_r(q_n, q_r) - c_r\right) q_r, \quad (4)$$

subject to: $q_r \leq \phi q_n$, $q_n, q_r \geq 0$. The solutions of the non-integrated manufacturer's optimisation problem are shown in Proposition 2.

PROPOSITION 2. The non-integrated manufacturer's optimal production quantity decisions with respect to the supplier's new component price are:

Decision NI-A, $q_n^{DA} = (Q - w)/2$, $q_r^{DA} = 0$, *when* $w < c_r/\delta$;

Decision NI-B, $q_n^{DB} = \left[Q - w - (\delta Q - c_r)\right]/2(1-\delta)$, $q_r^{DB} = (w - c_r/\delta)/2(1-\delta)$, *when* $c_r/\delta \leq w \leq w_0$;

Decision NI-C, $q_n^{DC} = \left[Q - w + \phi(\delta Q - c_r)\right]/2\left(1 + 2\delta\phi + \delta\phi^2\right)$, $q_r^{DC} = \phi\left[Q - w + \phi(\delta Q - c_r)\right]/2\left(1 + 2\delta\phi + \delta\phi^2\right)$, *when* $w_0 < w \leq Q + \phi(\delta Q - c_r)$; *here,* $w_0 = \left[(1-\delta)\phi Q + (1/\delta + \phi) c_r\right]/(1+\phi)$.

When setting w, the supplier does so with anticipation that the non-integrated manufacturer will react as characterised by Proposition 2. If the supplier anticipates that the non-integrated manufacturer will take Decision NI-A, then her corresponding optimal decision is denoted as Decision S-A. The optimisation problem turns out to be:

$$\max_{w^{DA}} \Pi_S^{DA} = \left(w^{DA} - c_n\right) q_n^{DA}, \quad (5)$$

subject to: $w^{DA} < c_r/\delta$. This constraint, which is exactly the necessary condition for Decision NI-A, ensures that the non-integrated manufacturer will take Decision NI-A. By examining the non-integrated manufacturer's all possible reactions, we get the supplier's optimal new component pricing decisions, as follows.

PROPOSITION 3. The supplier's optimal new component pricing decisions with respect to the new component production cost are:

Decision S-A, $w^{DA} = (Q + c_n)/2$, *when* $c_r \le c_n < c_{n1}$;

Decision S-B-1, $w^{DB-1} = c_r/\delta$, *when* $c_{n1} \le c_n < \min\{c_{n2}, c_{n3}\}$;

Decision S-B-2, $w^{DB-2} = (Q + c_n)/2 - (\delta Q - c_r)/2$, *when* $c_{n3} \le c_n < c_{n4}$;

Decision S-C, $w^{DC} = (Q + c_n)/2 + \phi(\delta Q - c_r)/2$, *when* $\max\{c_{n2}, c_{n4}\} \le c_n \le c_{n5}$;

here, $c_{n1} = 2c_r/\delta - Q$,

$$c_{n2} = (2c_r/\delta - Q) - (Q - c_r/\delta)\left[\delta\phi(3 + 2\phi) - 2\sqrt{\delta\phi(1+\phi)(1 + 2\delta\phi + \delta\phi^2)}\right],$$

$$c_{n3} = (2/\delta - 1)c_r - (1-\delta)Q,$$

$$c_{n4} = \frac{1}{1+\phi}\left[(1-\delta)\phi Q + (1+\delta\phi)\frac{c_r}{\delta} - \left(Q - \frac{c_r}{\delta}\right)\sqrt{(1-\delta)(1+2\delta\phi+\delta\phi^2)}\right],$$

$$c_{n5} = Q + \phi(\delta Q - c_r).$$

It is worth noting that the supplier has taken the non-integrated manufacturer's optimal reaction into account when setting w. So, if the supplier's optimal decision is Decision S-k, then the non-integrated manufacturer's optimal decision must be Decision NI-k. It is worth noting that Propositions 1 and 3 reveal an interesting phenomenon: either an integrated or a non-integrated manufacturer will keep producing new products even $c_n > Q$. This is because, in our model, the manufacturer's profit comes from the sales of both new and remanufactured products. When $Q < c_n \le Q + \phi(\delta Q - c_r)$, producing new products alone is not profitable, but it can generate available cores, and then the manufacturer can make a profit by remanufacturing used (new) products; when $c_n > Q + \phi(\delta Q - c_r)$, however, the profit due to remanufacturing cannot compensate for the loss due to new product sales, and then there is no production.

5.2 Decision analysis

Based on Proposition 3, we now examine how cost parameters (c_n and c_r) and return rate factor (ϕ) shape the supplier's optimal decisions. The impacts of parameters are presented in Result 2 and illustrated in Figure 2. Note that, in Figures 2 – 6, we set $Q = 10$, $\delta = 1/2$, $\phi = 3/4$, $c_r = 4$ for (a) and $c_n = 6$ for (b).

RESULT 2. (i) The following are true:

Parameter	w^{DA}	w^{DB-1}	w^{DB-2}	w^{DC}
c_n	+	0	+	+
c_r	0	+	+	−
ϕ	0	0	0	+

(ii) $w^{DA}\Big|_{c_n=c_{r1}} = w^{DB-1}\Big|_{c_n=c_{r1}}$; $w^{DB-1}\Big|_{c_n=c_{r3}} = w^{DB-2}\Big|_{c_n=c_{r3}}$; $w^{DB}\Big|_{c_n=\max\{c_{n2},c_{n4}\}} < w^{DC}\Big|_{c_n=\max\{c_{n2},c_{n4}\}}$.

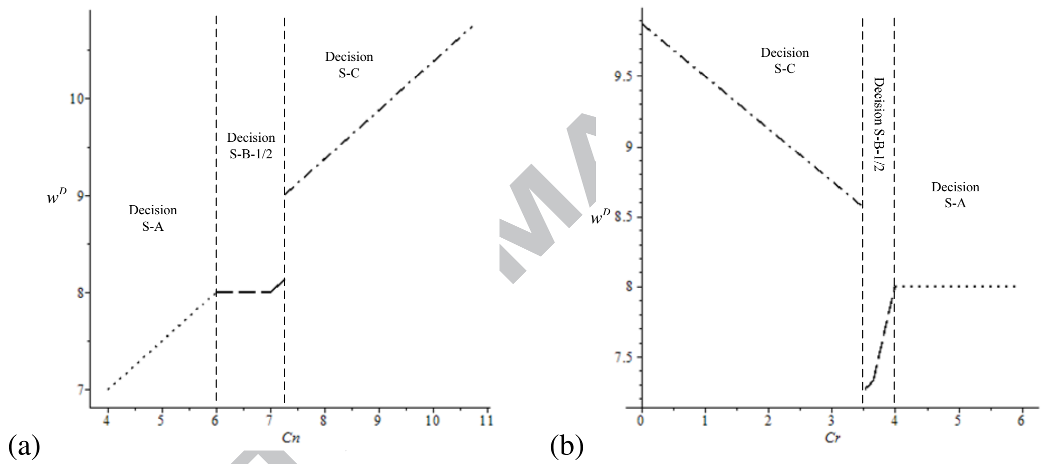


Figure 2. Optimal new component price

Firstly, Result 2 indicates that the supplier's new component price w^D is non-decreasing in c_n . Since c_n is the unit cost for the supplier to produce the new component, there should be no surprise when w^D increases in it. However, when the supplier's optimal decision is Decision S-B-1, the non-integrated manufacturer's remanufacturing business just heads into a profitable territory. Then, rather than competing with the remanufactured product in the market, a more profitable strategy for the supplier is to price in an offensive way which drives the remanufactured product out of the market. As a result, the supplier strategically does not care how costly manufacturing the new component is, but how costly remanufacturing the used component is.

Result 2 also reveals the impact of the remanufactured component unit production cost c_r on w^D: when c_r is close to c_n, w^D is independent of c_r; as c_r declines, w^D becomes at first increasing and eventually decreasing in it. The intuition for this result is as follows. According to Propositions 2 and 3, when c_n is small (the supplier's optimal decision is Decision S-A, and the non-integrated manufacturer's is Decision NI-A), the insignificant cost saving from remanufacturing cannot cover its shortage of consumer disutility. Then the non-integrated manufacturer would not remanufacture any used products, so both players do not take c_r into account when deciding their actions. When c_n is moderate (optimal decisions are Decisions S-B and NI-B), the non-integrated manufacturer will remanufacture a part of available cores ($q_r^{DB} > \phi q_n^{DB}$), then the remanufactured component is purely a substitute for the new component, so w^{DB} is increasing in c_r. When c_n is big (optimal decisions are Decisions S-C and NI-C), all available cores are remanufactured ($q_r^{DC} = \phi q_n^{DC}$), implying that the remanufactured component is purely a complement for the new product for a given ϕ, so w^{DC} is then decreasing in c_r.

A larger ϕ means a larger portion of used products are available for remanufacturing. We once naively expected to observe that w^D decreases in ϕ. However, Result 2 shows a contrasting view: w^D is always non-decreasing in ϕ. When c_n is small, it is clear that w^{DA} is independent of ϕ since the non-integrated manufacturer then produces only the new product. When c_n is moderate, although new and remanufactured products compete with each other in the market, the parameter ϕ still has no influence on the competition because only a part of available cores are remanufactured. When c_n is big, new and remanufactured products exhibit the characteristics of complements as well as substitutes. Then, for a given w^D, a bigger ϕ allows more remanufactured products enter into the market. The supplier could choose to decrease w^D to intensely compete, but the ill effect of this choice is that more used products will be available for remanufacturing, further weakening the supplier's competitive position. So, the right decision for the supplier is to increase w^D. Not only can such a strategy improve the marginal profit, but also cut down the quantity of available cores. Therefore, we observe that w^{DC} is increasing in ϕ.

Substituting the supplier's optimal new component pricing decisions in Proposition 3 back into the non-integrated manufacturer's optimal production quantity reaction with respect to w in Proposition 2 gives the non-integrated manufacturer's optimal production quantity decisions (as shown in Table B2 in Appendixes). The shape of the non-integrated manufacturer's optimal decisions is characterised by the following result and illustrated in Figures 3 and 4.

RESULT 3. (i) The following are true:

Parameter	q_n^{DA}	q_n^{DB-1}	q_n^{DB-2}	q_n^{DC}	q_r^{DA}	q_r^{DB-1}	q_r^{DB-2}	q_r^{DC}
c_n	−	0	−	−	0	0	+	−
c_r	0	−	+	−	0	0	−	−
ϕ	0	0	0	± *	0	0	0	+

*: + *if* $c_n > \left[\delta\left(1+2\phi+\delta\phi^2\right)Q+\left(1-\delta\phi^2\right)c_r\right]/2\delta(1+\phi)$; − *otherwise.*

(ii) $q_n^{DA}\big|_{c_n=c_{r1}} = q_n^{DB-1}\big|_{c_n=c_{r1}}$; $q_n^{DB-1}\big|_{c_n=c_{r3}} = q_n^{DB-2}\big|_{c_n=c_{r3}}$; $q_n^{DB}\big|_{c_n=\max\{c_{n2},c_{n4}\}} > q_n^{DC}\big|_{c_n=\max\{c_{n2},c_{n4}\}}$;

(iii) $q_r^{DA}\big|_{c_n=c_{r1}} = q_r^{DB-1}\big|_{c_n=c_{r1}}$; $q_r^{DB-1}\big|_{c_n=c_{r3}} = q_r^{DB-2}\big|_{c_n=c_{r3}}$; $q_r^{DB}\big|_{c_n=\max\{c_{n2},c_{n4}\}} < q_r^{DC}\big|_{c_n=\max\{c_{n2},c_{n4}\}}$.

Result 3 describes how model parameters shape the non-integrated manufacturer's optimal production quantity decisions. It is quite intuitive that the optimal production quantity of new (remanufactured) products is non-increasing in their own cost parameter c_n (c_r). When the manufacturer's optimal decision is Decision NI-B-1, the supplier takes an offensive pricing strategy, making the manufacturer prefer to set $q_r^{DB-1}=0$. Because w^{DB-1} is independent of c_n and increasing in c_r , q_n^{DB-1} is independent of c_n and decreasing in c_r. When the manufacturer's optimal decision is Decision NI-B-2, new and remanufactured products are pure substitutes. So the optimal production quantities of two products are increasing in each other's cost parameter. In contrast, when the manufacturer's optimal decision is Decision NI-C, for a given ϕ, new and remanufactured products are pure complements since $q_r^{DC} = \phi q_n^{DC}$. So the optimal production quantities of two products are decreasing in each other's cost parameter.

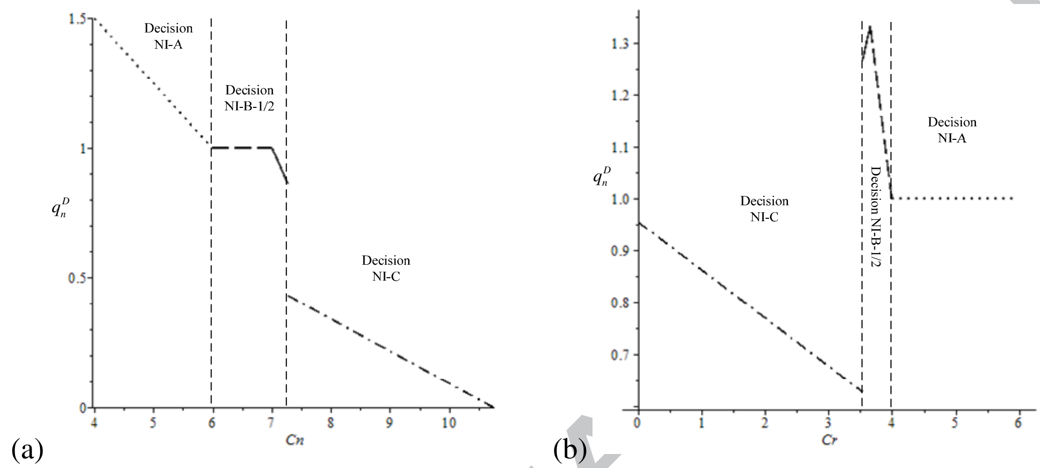


Figure 3. Optimal new product production quantity

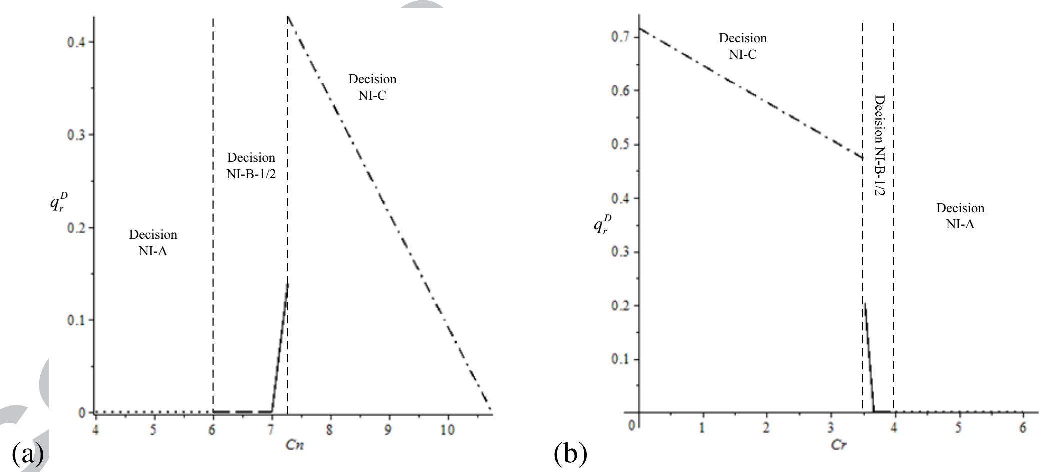


Figure 4. Optimal remanufactured product production quantity

When the manufacturer's optimal decision is Decision NI-A or Decision NI-B, then no or only a part of available cores will be remanufactured. Thus, the return rate factor ϕ has no impact on the non-integrated manufacturer's decisions. When the manufacturer's optimal decision is Decision NI-C, all available cores are remanufactured. It is very important to note that when we investigate the impact of ϕ, unlike the analysis with a given ϕ, the relationship between q_n^{DC} and q_r^{DC} should be viewed as both complements and substitutes. Intuitively, q_r^{DC} is increasing in ϕ. The effect of complementary relationship makes q_n^{DC} increase in ϕ, while the effect of substitutive relationship makes q_n^{DC} decrease in ϕ. Consequently, when $c_n > \left[\delta\left(1+2\phi+\delta\phi^2\right)Q+\left(1-\delta\phi^2\right)c_r\right]/2\delta\left(1+\phi\right)$, the complementary effect dominates, and then q_n^{DC} is increasing in ϕ; otherwise, the substitutive effect dominates, and then q_n^{DC} is decreasing in ϕ.

5.3 Profit analysis

Substituting the supplier's optimal new component pricing decisions in Proposition 3 and the non-integrated manufacturer's optimal production quantity decisions in Table B2 back into the supplier's and the manufacturer's optimisation problems gives both players' profits (as shown in Table B3 in Appendixes), illustrated in Figures 5 and 6.

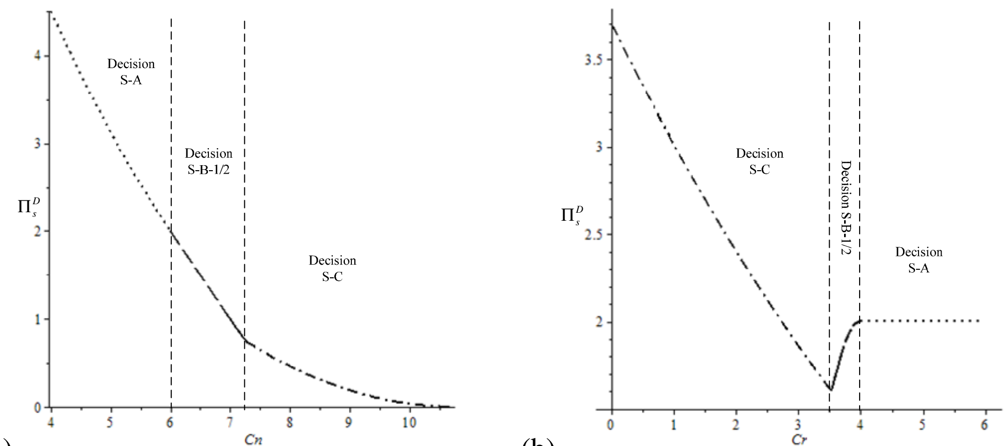
RESULT 4. (i) The following are true:

Parameter	Π_S^{DA}	Π_S^{DB-1}	Π_S^{DB-2}	Π_S^{DC}	Π_{NI}^{DA}	Π_{NI}^{DB-1}	Π_{NI}^{DB-2}	Π_{NI}^{DC}
c_n	−	−	−	−	−	0	−	−
c_r	0	+	+	−	0	−	−	−
ϕ	0	0	0	± **	0	0	0	± **

**: + *if* $c_n > \left[(1-\delta)\delta\phi Q+(1+\delta\phi)c_r\right]/\delta(1+\phi)$; − *otherwise.*

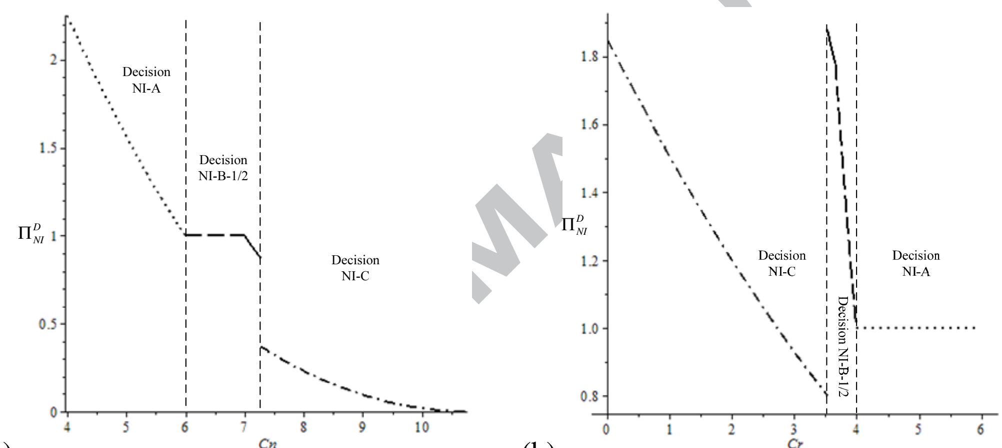
(ii) $\Pi_S^{DA}\big|_{c_n=c_{r1}} = \Pi_S^{DB-1}\big|_{c_n=c_{r1}}$; $\Pi_S^{DB-1}\big|_{c_n=c_{r3}} = \Pi_S^{DB-2}\big|_{c_n=c_{r3}}$; $\Pi_S^{DB}\big|_{c_n=\max\{c_{n2},c_{n4}\}} = \Pi_S^{DC}\big|_{c_n=\max\{c_{n2},c_{n4}\}}$;

(iii) $\Pi_{NI}^{DA}\big|_{c_n=c_{r1}} = \Pi_{NI}^{DB-1}\big|_{c_n=c_{r1}}$; $\Pi_{NI}^{DB-1}\big|_{c_n=c_{r3}} = \Pi_{NI}^{DB-2}\big|_{c_n=c_{r3}}$; $\Pi_{NI}^{DB}\big|_{c_n=\max\{c_{n2},c_{n4}\}} > \Pi_{NI}^{DC}\big|_{c_n=\max\{c_{n2},c_{n4}\}}$.



(a) (b)

Figure 5. The supplier’s profit



(a) (b)

Figure 6. The non-integrated manufacturer’s profit

Result 4 characterises players’ profits in the decentralised closed-loop supply chain. In our decentralised supply chain model, the supplier’s profit is from the sale of new components, so it is intuitive that her profit is decreasing in the new component cost parameter (c_n). And, based on our foregoing description of the relationship between new and remanufactured products, it is also easy to understand that, when remanufacturing has a significant cost advantage, as c_r declines, the supplier’s profit at first increasing and eventually decreasing in it. For the non-integrated manufacturer, his profit is from the sales of new and remanufactured products. On one hand, the optimal new component price w^D is non-decreasing in c_n ; consequently, the manufacturer’s profit is non-increasing in c_n. On the other hand, although the manufacturer's profit is non-increasing in c_r when the cost structure makes him insist on taking a certain decision, yet his profit drops rapidly once the optimal decision changes from Decision NI-B to Decision NI-C as c_r declines. This is because, the decrease of c_r will make the supplier switch to charge a much higher price for new components, as shown in Figure 2. Thus, looking at the whole picture, the non-integrated manufacturer's profit is not always non-increasing in c_r: a lower remanufacturing cost may result in a lower profit.

When it comes to the impact of return rate factor ϕ, obviously, the supplier's and the non-integrated manufacturer's profits are independent of ϕ when their optimal decisions are Decision S/NI-A or Decision S/NI-B, since then their decisions are independent of it (see Results 2 and 3). However, when the players' optimal decisions are Decision S/NI-C, both players' profits could be increasing or decreasing in ϕ contingent on the cost structure. For the non-integrated manufacturer, an increase of ϕ has two contradicting impacts on his profit. On one hand, such an increase enhances remanufactured product sales; on the other hand, it leads to a higher new component price and a smaller new product production quantity, and consequently a shrunk profit from new product sales. As a result, only if the new component cost parameter $c_n > \left[(1-\delta)\delta\phi Q + (1+\delta\phi)c_r\right]/\delta(1+\phi)$, which implicates that there is a limited profit generated by new product sales to loss, the non-integrated manufacturer's profit would increase in ϕ. For the supplier, a similar trade-off exists: the new component price is increasing in ϕ, leading to a higher marginal profit, but the production quantity of new products could be decreasing in ϕ. Thus, it also requires $c_n > \left[(1-\delta)\delta\phi Q + (1+\delta\phi)c_r\right]/\delta(1+\phi)$ to ensure the supplier's profit increasing in ϕ.

Although the integrated manufacturer is never harmed by the opportunity to remanufacture used products, Result 4 implies that, compared with the situation of no remanufacturing ($\phi = 0$), both the supplier and the non-integrated manufacturer may earn lower profits when the manufacturer has the remanufacturing opportunity ($\phi > 0$), as demonstrated by the following corollary.

COROLLARY 1. (i) When $c_r \le c_n < c_{n1}$, $\Pi_S^D\big|_{\phi>0} = \Pi_S^{DA} = \Pi_S^D\big|_{\phi=0}$, $\Pi_{NI}^D\big|_{\phi>0} = \Pi_{NI}^{DA} = \Pi_{NI}^D\big|_{\phi=0}$;

(ii) When $c_{n1} < c_n < \max\{c_{n2}, c_{n4}\}$, $\Pi_S^D\big|_{\phi>0} = \Pi_S^{DB} < \Pi_S^D\big|_{\phi=0}$, $\Pi_{NI}^D\big|_{\phi>0} = \Pi_{NI}^{DB} > \Pi_{NI}^D\big|_{\phi=0}$;

(iii) When $\max\{c_{n2}, c_{n4}\} < c_n < c_n'$, $\Pi_S^D\big|_{\phi>0} = \Pi_S^{DC} < \Pi_S^D\big|_{\phi=0}$, $\Pi_{NI}^D\big|_{\phi>0} = \Pi_{NI}^{DC} < \Pi_{NI}^D\big|_{\phi=0}$;

(iv) When $c_n' < c_n \le c_{n5}$, $\Pi_S^D\big|_{\phi>0} = \Pi_S^C > \Pi_S^D\big|_{\phi=0}$, $\Pi_{NI}^D\big|_{\phi>0} = \Pi_{NI}^{DC} > \Pi_{NI}^D\big|_{\phi=0}$; *here*

$$c_n' = \left[\delta(1+\phi)Q + c_r - (\delta Q - c_r)\sqrt{1+2\delta\phi+\delta\phi^2}\right] \Big/ \delta(2+\phi).$$

When the cost advantage of remanufacturing is insignificant ($c_r \le c_n < c_{n1}$), the non-integrated manufacturer does not remanufacture any used product. When the remanufacturing cost is sufficiently low to overcome the negative cannibalisation impact on new product sales, remanufacturing is a dominant strategy for the non-integrated manufacturer, which can deliver a win-lose, a lose-lose, or a win-win situation to the decentralised supply chain contingent on the cost advantage of remanufacturing. When the cost advantage is small ($c_{n1} < c_n < \max\{c_{n2}, c_{n4}\}$), new and remanufactured products are pure substitutes, then the supplier has to cut new component price to respond the manufacturer's remanufacturing activities. Thus, the non-integrated manufacturer can benefit from remanufactured product sales and a lower new component price, but the supplier is worse off. In contrast, when the cost advantage of remanufacturing is large ($c_n' < c_n \le c_{n5}$), new and remanufactured products are complements, then the supplier can charge a higher new component price to share the remanufacturing benefit, then both players are better off. However, when the cost advantage is moderate ($\max\{c_{n2}, c_{n4}\} < c_n < c_n'$), the remanufacturing opportunity makes both players' profits shrunk. In such a situation, for a given new component price, the manufacturer always chooses to remanufacture used products; and given the manufacturer's remanufacturing choice, the supplier strategically responds by pricing new component higher. As a result, both players' profits are then lower than in an identical supply chain without remanufacturing.

6. Environmental Implications

In this section, we analyse the environmental implications of remanufacturing.

According to Assumption 5, we use the production quantity of new products as a proxy of the supply chain's environmental performance. And, according to Assumption 6, we examine the environmental implications of government-subsidised remanufacturing by comparing the manufacturer's production quantity of new products when Decisions I/NI-A and I/NI-B are taken.

According to Proposition 1, the integrated manufacturer's optimal new product production quantity is always $\left(Q-c_n\right)/2$ when $\phi=0$. We have the following corollary.

COROLLARY 2. (i) When $c_r \le c_n < c_r/\delta$, $q_n^I\big|_{\phi>0} = q_n^{IA} = q_n^I\big|_{\phi=0}$ *;*

(ii) When $c_r/\delta < c_n \le c_{n0}$, $q_n^I\big|_{\phi>0} = q_n^{IB} < q_n^I\big|_{\phi=0}$ *;*

(iii) When $c_{n0} < c_n < \left[(1+\phi)Q + c_r/\delta\right]/(2+\phi)$, $q_n^I\big|_{\phi>0} = q_n^{IC} < q_n^I\big|_{\phi=0}$ *;*

(iv) When $\left[(1+\phi)Q + c_r/\delta\right]/(2+\phi) < c_n \le Q + \phi\left(\delta Q - c_r\right)$, $q_n^I\big|_{\phi>0} = q_n^{IC} > q_n^I\big|_{\phi=0}$ *.*

Corollary 2 indicates that the government subsidising the integrated manufacturing to remanufacture used products has a positive environmental impact. If the remanufacturing cost declines because of the government subsidy, making the integrated manufacturer's optimal decision switch from Decision I-A to Decision I-B, then less new products will be produced, which benefits the environment. However, Corollary 2 also shows that remanufacturing in the integrated manufacturer may have a negative environmental impact when new and remanufactured products exhibit the characteristics of complements. This is because, if the cost advantage of remanufacturing is large enough, i.e., $c_n > \left[(1+\phi)Q + c_r/\delta\right]/(2+\phi)$, the integrated manufacturer will strategically produce more new products to generate more available cores and exploit the benefit of remanufacturing. This finding shares a similar economic intuition behind Lee (2012), which shows that if the waste stream in a manufacturing process can be converted into a saleable by-product, the manufacturer may strategically overproduce the original product to increase the amount of waste generated.

For the non-integrated manufacturer, based on Table B2 in Appendixes, we have the following corollary.

COROLLARY 3. (i) When $c_r \le c_n < c_{n1}$, $q_n^D\big|_{\phi>0} = q_n^{DA} = q_n^D\big|_{\phi=0}$ *;*

(ii) When $c_{n1} < c_n < \max\{c_{n2}, c_{n4}\}$, $q_n^D\big|_{\phi>0} = q_n^{DB} > q_n^D\big|_{\phi=0}$ *;*

(iii) When $\max\{c_{n2}, c_{n4}\} < c_n < \left[(1+\phi)Q + c_r/\delta\right]/(2+\phi)$, $q_n^D\big|_{\phi>0} = q_n^{DC} < q_n^D\big|_{\phi=0}$;

(iv) When $\left[(1+\phi)Q + c_r/\delta\right]/(2+\phi) < c_n \le c_{n5}$, $q_n^D\big|_{\phi>0} = q_n^{DC} > q_n^D\big|_{\phi=0}$.

On one hand, similar to Corollary 2, Corollary 3 shows that, when new and remanufactured products exhibit the characteristics of complements, the non-integrated manufacturer also produces more new products, though the supplier then charges a higher new component price. On the other hand, unlike Corollary 2, Corollary 3 reveals that the government-subsidised remanufacturing in the non-integrated manufacturer has a negative environmental impact. If the remanufacturing cost declines because of the government subsidy, making the non-integrated manufacturer's optimal decision switch from Decision NI-A to Decision NI-B, then the remanufactured product is a pure substitute to the new product, and erodes the demand for the supplier's new components. Consequently, the supplier will strategically lower the new component price, making the non-integrated manufacturer be better off by producing more new products.

7. Conclusions

Closed-loop supply chain management is a hot research topic because of its sustainable profile. The current literature focuses on the interaction within the reverse supply chain or the competition between an integrated manufacturer and an independent remanufacturer. The impact of the interaction within the forward supply chain on the new/remanufactured product production is rarely studied. In this paper, we model and analyse a decentralised closed-loop supply chain with remanufacturing consisting of a key component supplier and a non-integrated manufacturer. Our analytic results show that the interaction between these two players has significant impacts on the economic and environmental implications of remanufacturing. We summarise the main findings and discuss their managerial insights as follows.

To begin with, the strategic issue for the manufacturer is whether to capitalise on remanufacturing. This research coincides with the current literature that the opportunity of remanufacturing always benefits an integrated manufacturer, which should engage in remanufacturing once the remanufacturing cost is sufficiently low to overcome the negative cannibalisation effect. But, after we consider the interaction with the key component supplier, remanufacturing may present a win-lose, a win-win, or even a lose-lose solution to the decentralised closed-loop supply chain (see Corollary 1). That is to say, the integrated manufacturer's "meat" may be the non-integrated manufacturer's "poison". This finding provides a new perspective to answer this question – why most manufacturers do not remanufacture their products even the remanufacturing business seems to be so profitable. A key component supplier's strategic responses significantly change the non-integrated manufacturer's incentives. When remanufacturing forms a lose-lose solution, which may be further exaggerated by the competition from independent remanufacturers, the supplier and the manufacturer should eliminate the remanufacturing opportunity. So, designing products to prevent remanufacturing in practice does not come as a surprise (see Agrawal et al., 2012a).

Secondly, the tactical issues in remanufacturing are whether to reduce the remanufacturing cost and enlarge the return rate of used products. No existing literature says no to this question, many papers in technology management and industrial engineering contribute to deliver a lower remanufacturing cost or a larger return rate (see Srivastava, 2007 for a review). But, our analysis shows that, although the conventional view works in the case of an integrated manufacturer, the non-integrated manufacturer may be worse off with a lower remanufacturing cost or a larger return rate because of the interaction with the component supplier (see Result 4). This finding highlights the importance of examining the key component supplier's responses before the non-integrated manufacturer carries out the incremental cost-reducing innovation for remanufacturing or improve the efficiency of reverse logistics network.

Lastly, we outline the environmental implications of remanufacturing, especially the government-subsidised remanufacturing. Even if the life-cycle environmental impact of remanufactured products is assumed to be zero, remanufacturing cannot always deliver a positive effect to the environment. When new and remanufactured products exhibit the characteristics of complements, both the integrated and non-integrated manufacturers will strategically produce more new products, increasing the consumption of natural resources and energy and aggravating the environmental burden. When two products are pure substitutes, the integrated manufacturer will produce less new products, but the non-integrated manufacturer will still produce more new product. Thus, a simple subsidy policy encouraging the non-integrated manufacturer that did not remanufacture used product to launch a remanufacturing project will be detrimental to the environment. In order to deliver a sustainable solution via remanufacturing, the government could deliberate on sharing the subsidies across the closed-loop supply chain, as suggested by Mitra and Webster (2008).

Although this research points out the potential negative effect of remanufacturing on the environmental and economic performances of the decentralised supply chain, we do not seek to discourage remanufacturing. On the contrary, this research systemically rediscovers the complexity of closed-loop supply chains with remanufacturing, which requires much more effort than we thought to deliver a greener and more profitable solution. A simple policy to spur more remanufacturing activities may be detrimental to both the environment and the industry.

In closing this paper, we discuss its limitations and highlight possible avenues for future research[3]. Firstly, our model focuses on a decentralised closed-loop supply chain where the supplier enjoys a dominant channel power and can move first by pricing the new component to share the non-integrated manufacture's remanufacturing profits. While this is consistent with a number of industries such as auto part remanufacturing in China, there are also many cases where this assumption does not hold. We speculate that a powerful non-integrated manufacturer may simply propose a different type of contract to seize all remanufacturing profits, and operates like an integrated manufacturer. Even if being not so powerful to seize all remanufacturing profits, the non-integrated manufacturer can strategically decentralise its manufacturing and remanufacturing operations to obtain a greater profit (see Zhou et al. 2012). Secondly, our model considers only short term decisions like pricing and production quantity. A simple two-part tariff contract can be used to coordinate such a decentralised closed-loop supply chain (see Karakayali et al. 2007, Kaya 2010, and Savaskan et al. 2004). Our model can be extended to incorporated long term decisions like design for product recovery (e.g., Wu, 2012). Then the supplier seems to face an interesting paradox: producing better components with a higher level of remanufacturability, but losing more business since those components can be remanufactured more often. In this case, how to coordinate the decentralised supply chain is worth a great effort. Lastly, like most literature on closed-loop supply chain management, our analytic results heavily depend on the price-response function in

[3] We highly appreciate two anonymous reviewers' comments and suggestions in identifying limitations and future research directions of this paper.

Equations (1) and (2). Although this demand function is backed by some empirical and experimental evidences, Ovchinnikov (2011) finds that the fiction of consumers who switch from new to remanufactured product has an inverted-U shape with respect to the remanufactured product price. Thus, a fruitful direction of future research is to conduct more empirical and experimental study to understand the underlying consumer behaviour, and examine the sensitivity or robustness of our results.

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Appendixes

See the "Supplementary material".

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Highlights

- We model a closed-loop supply chain in which the manufacturer can remanufacture used products.
- The interaction with the supplier significantly impacts the performance of remanufacturing.
- The remanufacturing opportunity can form a lose-lose situation, making the players' profits shrunk.
- The manufacturer may be worse off with a lower remanufacturing cost or a larger return rate.
- The remanufacturing may be detrimental to the environment.