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Highlights

- The variable remanufacturing cost can be reduced via process innovation.
- Remanufacturing in general requires stepwise innovation.
- Decentralisation of decision-making may cause overinvestment in process innovation.
- The overinvestment issue is always beneficial to the environment.

Managing a Closed-loop Supply Chain with Process Innovation for Remanufacturing

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ABSTRACT: Remanufacturing is an opportunity to deliver all-round sustainability benefits when products are designed accordingly. In this paper, we focus on the link between remanufacturing and the opportunity to lower the variable remanufacturing cost via process innovation. Specifically, we analyse how the opportunity is utilized in a supply chain consisting of a manufacturer and a retailer. Only the manufacturer may undertake process innovation, while remanufacturing as such could be done by either the manufacturer or the retailer. We find that although the traditional manufacturing process accepts incremental improvement, remanufacturing in general requires stepwise innovation; thus, the optimal strategy of managing process innovation in a forward supply chain does not directly apply to manage process innovation for remanufacturing in a closed-loop supply chain. Our analytical results also show that a decentralised supply chain could be more likely to take up remanufacturing than an integrated supply chain, especially when the process innovation cost is sufficiently high. Consequently, inefficiency resulting from decentralisation of decision-making in the closed-loop supply chain may cause not only underinvestment but also overinvestment in process innovation for remanufacturing. Finally, through an extensive numerical analysis, we find that this overinvestment always reduces the environmental impact in terms of the overall production quantity, even if the decision-making process does not explicitly consider any environmental aspect.

KEYWORDS: supply chain management; closed-loop supply chain; remanufacturing; process innovation; environmental performance

1. Introduction

Remanufacturing presents a golden opportunity to deliver a sustainable future. It reduces the disposal of end-of-use products and consumes less natural resources and energy than manufacturing all-new products (Giuntini and Gaudette 2003, Atasu et al. 2008, Agrawal et al. 2016). However, the full social, environmental and economic benefits of remanufacturing cannot be realised unless design for remanufacturing becomes an integral part of the product development process (Seitz and Peattie 2004). It is also widely agreed that economic considerations must be at the forefront of design for remanufacturing because there is little sense in improving remanufacturability if it will render the product not cost effective (Linton 2008).

Some manufacturers who are very good at manufacturing cannot operate the remanufacturing business in a profitable manner; e.g., *Ford* purchased several automotive salvage yards and parts recycling companies to levy the potential economic benefit associated with end-of-use vehicle processing. But, because of its inexperience in the specialised sector, *Ford* had to abandon the business and redirect resources to auto making (Karakayali et al. 2007).

The pioneers who greatly succeed in the remanufacturing sector usually make huge investments in new product design to lower the remanufacturing cost (Zhu et al. 2014, Genc and De Giovanni 2018). *Fuji Xerox* shows that the cost saving from photocopier remanufacturing is significantly increased because of one intentioned design for disassembly (Kerr and Ryan 2001); *Bosch* has developed an inexpensive chip for its power tools and household appliances to facilitate the assessment of the quality of components harvested from collected used products (Toffel 2004, Robotis et al. 2012). In fact, many other design concepts are appropriate to lower the remanufacturing cost, see Hatcher et al. (2011) for a review. These approaches have various aspects in common: they require a substantial upfront R&D investment; they can lower the unit production cost of remanufactured products, but do not necessarily change the unit production cost of new products significantly; and to what extent the remanufacturing cost can be lowered depends on the R&D level. In this paper, we refer to these approaches as **Process Innovation for Remanufacturing (PIR)**.

Our primary objective in this paper is to develop a general understanding of the operational strategy to manage PIR in a closed-loop supply chain; we are particularly interested in the following question:

- *Why do some manufacturers make huge investments in PIR, while many others invest zero?*

To investigate this issue, we at first consider an integrated supply chain model to derive the global optimal solution for PIR. Interestingly, we find that the optimal PIR strategy is usually an **all-or-nothing** strategy; in other words, the supply chain should invest aggressively to realise the maximum unit cost saving from remanufacturing, or totally give up remanufacturing. The driving force behind this result lies in that the optimal production quantity of remanufactured products is zero unless the cost saving from remanufacturing is high enough. If the investment on PIR cannot guarantee a minimum cost reduction necessary to take up remanufacturing at all, then it is optimal for the supply chain to produce new products only. Contrary to that, it is worth noting that with opportunities to lower the variable manufacturing cost, the supply chain does not require a threshold to trigger the new product production, and then a small incremental improvement is acceptable, i.e., the supply chain always invests in process innovation for manufacturing. Therefore, we obtain an important implication: traditional innovation strategies in the literature may not be applicable to manage PIR in the closed-loop supply chain.

Closed-loop supply chains routinely involve more decision-makers than forward supply chains (Guide and Van Wassenhove 2009). When the benefits of innovation are shared by others in the supply chain, the innovator has no incentive to invest at the global optimal level. The underinvestment problem has been well documented in the literature as the consequence of decentralised decision-making in the forward supply chain (Amaldoss and Rapoport 2005, Terwiesch and Xu 2008, Ge et al. 2014). Yet, as we have mentioned above, the closed-loop supply chain context for PIR decisions is very different. Thus, we are interested in answering the following question:

- *What are the consequences of decentralised decision-making on the manufacturer's PIR strategy?*

In many cases, it is the manufacturer who physically engages in remanufacturing and one of our model variants will capture that situation; e.g., as a world class manufacturer of heavy machinery, *Caterpillar* runs several remanufacturing programs by itself (Zhou et al. 2013). However, some manufacturers are incapable to remanufacture in a profitable manner, or they are reluctant to remanufacture because of concerns about cannibalisation of the new product sales; consequently, the remanufacturing opportunity is captured by someone else. Thus, we consider a second model variant in which the downstream player, i.e., the retailer, may operate the remanufacturing business. Retailer-remanufacturing is not uncommon in practice, especially in the industry of heavy machinery. Not all western manufacturers are capable to establish remanufacturing factories in China, like what *Caterpillar* did. Consequently, some local retailers such as SEVALO Construction Machinery Group have collected the used products and operated the remanufacturing business, see Yi et al. (2016) for details.

In a closed-loop supply chain with manufacturer-remanufacturing, we confirm the existence of the underinvestment issue. As for a closed-loop supply chain with retailer-remanufacturing, conventional wisdom might suggest the manufacturer invests nothing in PIR because of the cannibalisation concern. But, our analysis demonstrates an **overinvestment** problem resulting from decentralisation of decision-making: the manufacturer invests over the global optimal level in PIR under certain conditions. The economic intuition behind this finding is interpreted as follows. In a decentralised setting, even if the manufacturer invests nothing in PIR, the retailer may engage in remanufacturing; and then the manufacturer could be better off by investing in PIR to induce the retailer to remanufacture as many units as possible (note that, the remanufactured product quantity is bound by the new product quantity) and charging the retailer a higher new product wholesale price.

Note that in practice we also observe a lot of cases in which remanufacturing is operated by a third-party remanufacturer, but these cases are uninteresting from a PIR perspective. Competing with an independent remanufacturer, as demonstrated by the literature, e.g., Majumder and Groenevelt (2001), Ferguson and Toktay (2006), and Örsdemir et al. (2014), the manufacturer has no incentive to lower the remanufacturing cost, and hence invests zero for PIR.

The remainder of this paper is organised as follows. The next section reviews the relevant literature. Section 3 presents the model. Section 4 characterises the optimal PIR strategies. Section 5 conducts a comparison between model variants to highlight the economic and environmental consequences of decentralised decision-making. Section 6 concludes the paper. All mathematical proofs are provided in the online Appendix A.

2. Relevant literature

This study builds on and contributes to two research streams: (1) the literature on closed-loop supply chain management, and (2) the literature on innovation and new product development management. The first stream typically ignores the possibility of PIR to lower the variable remanufacturing cost by defaulting the cost to be exogenous, and the second stream mainly focuses on innovation relating to demand enhancement or cost reduction of the new product. To the best of our knowledge, this paper makes the first attempt to bridge these two streams and investigates the optimal PIR strategy in a decentralised closed-loop supply chain. In what follows, we provide an overview of the relevant literature and clarify our contributions.

Managing closed-loop supply chains with remanufacturing has been an active area of research in recent years; we refer the reader to Souza (2013), Govindan et al. (2015), and Diallo et al. (2017) for a thorough discussion. This research stream usually assumes that remanufacturing is a low-cost alternative of all-new manufacturing, and uses the cost saving from remanufacturing to characterize the optimal remanufacturing strategy; see, e.g., Ferrer and Swaminathan (2006), De Giovanni and Zaccour (2014), and Han et al. (2017). However, the variable remanufacturing cost in these existing studies is assumed to be exogenous. Our contribution to this stream is straightforward; that is, our model takes PIR into consideration by allowing the manufacturer to invest in process innovation to lower the variable remanufacturing cost. Our analysis characterizes the relationship between the optimal PIR level and the optimal remanufacturing strategy. For the closed-loop supply chain, if the optimal PIR level is zero, then the optimal strategy is not to remanufacture; otherwise, the optimal strategy is to remanufacture as many units as possible. This result differs from the standard structure under the exogenous remanufacturing cost assumption, where as a third option, partial remanufacturing might be optimal.

A growing amount of studies pay attention to innovation and new product development in a forward supply chain; see, e.g., Kim and Netessine (2013), Arya et al. (2015), and Du et al. (2016). As these papers do not consider remanufacturing, it is unclear whether the optimal innovation strategies derived in these papers can be apply to the closed-loop setting. Thus, we expand this research stream to closed-loop supply chains with remanufacturing. More importantly, our work makes a substantial contribution by demonstrating that the optimal strategy of managing process innovation for manufacturing in forward supply chains does no directly apply in that the remanufacturing context is fundamentally different; specifically, the traditional manufacturing process accepts small incremental improvements, but remanufacturing in general requires stepwise innovation that can significantly lower the variable remanufacturing cost.

A few papers consider the decisions on remanufacturing and innovation together. Debo et al. (2005) is, to the best of our knowledge, the first to analyse product technology selection in the remanufacturing context. Their model characterises whether to produce a remanufacturable product. Özdemir et al. (2012) examine the manufacturer's remanufacturing decisions in a legislative disposal fee environment. Wu (2012) considers the competition between a manufacturer and a remanufacturer and investigates the manufacturer's strategic dilemma when determining the degree of disassemblability. Similarly, Subramanian et al. (2013) extend the classic component commonality decision to consider remanufacturing operated by either the manufacturer or the remanufacturer. The investment in component commonality can be viewed as an investment in lowering the remanufacturing cost. Their analysis identifies the conditions in which the commonality decision may be reversed due to remanufacturing. Atasu and Souza (2013) and Li et al. (2018) study the impact of remanufacturing on product design, specifically new product quality. They find that remanufacturing induces the monopolist to provider higher quality new products.

These most relevant papers investigate PIR in a monopoly setting or under a competition between the manufacturer and third-party remanufacturers. Our work contributes to that literature by putting the PIR issue into a real supply chain context and revealing the consequences of decentralised decision-making on the manufacturer's PIR strategy. Interestingly, we find that the manufacturer might invest over the global optimal level in PIR in the decentralised closed-loop supply chain with retailer-remanufacturing.

3. The model

In this study, we consider a closed-loop supply chain consisting of two firms: a manufacturer and a retailer. The manufacturer who produces new products has opportunities to lower the variable cost of remanufacturing via process innovation, such as design for disassembly. The retailer orders new products from the manufacturer and sells them to final customers. Remanufacturing of end-of-use products is performed by either the manufacturer or the retailer, but not both, one explanation for which could be the high fixed cost of setting up the collection and remanufacturing operations.

To avoid the distraction of initial and terminal time-period effect, following the literature on remanufacturing, e.g., Ovchinnikov (2011), Subramanian et al. (2013), and Wu and Zhou (2016), we focus our analysis on a steady state, which implies that players use the identical strategies in every period after a ramp-up in the first period.

3.1 Model variants and notation

We consider three different variants within the closed-loop supply chain, see Figure 1 for illustration.

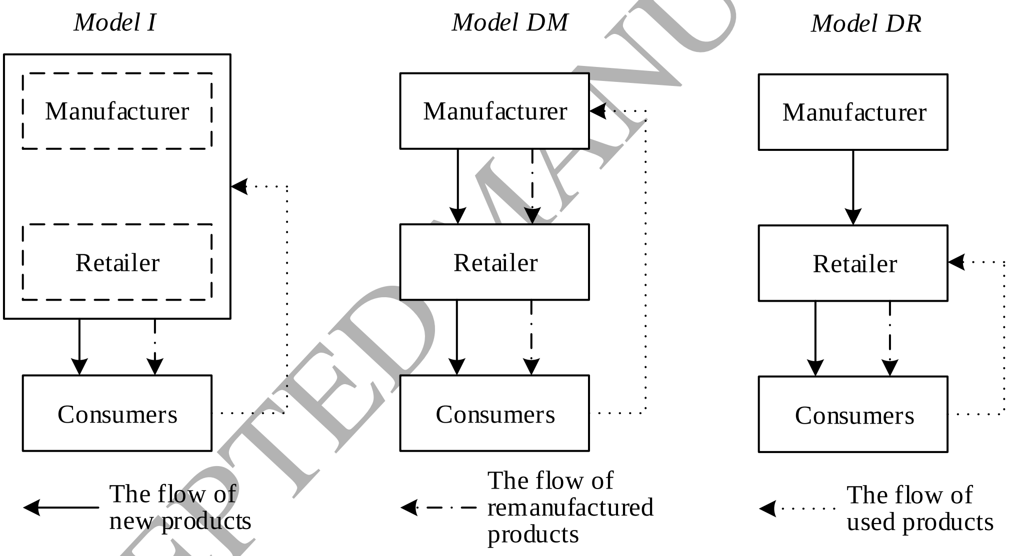

Figure 1. Three variants within the closed-loop supply chain

As a benchmark case, an integrated supply chain model (Model I) is first analysed, where all decisions are centrally coordinated. This will provide us with the supply chain optimal decisions.

Next, our focus will be on the managerial implications of decentralised decision-making; particularly, we would like to examine the structural influence of who (the manufacturer or the retailer) undertakes the remanufacturing task on the optimal PIR level. Thus, in the second variant, we consider a decentralised supply chain model with the manufacturer remanufacturing used products (Model DM). The timeline of decision-making is as follows: the manufacturer moves first by deciding on the optimal process innovation level and the wholesale prices of the new and remanufactured products; and then the retailer decides the quantities.

In the third variant, we consider a decentralised supply chain with the retailer remanufacturing used products (Model DR). The timeline of decision-making is as follows: the manufacturer firstly decides the optimal innovation level and the wholesale price of the new product, and then the retailer decides the quantities of the new and remanufactured products.

In the following analysis, subscript $i \in \{I, M, R\}$ refers to the integrated supply chain, the manufacturer, and the retailer, respectively; superscript $j \in \{I, DM, DR\}$ denotes the integrated supply chain model, as well as the decentralised supply chain models with the manufacturer remanufacturing and the retailer remanufacturing, respectively. Table 1 summarises the notations.

Table 1. Notations

Symbol	Definition
Parameters	
$c_n \in (0,1)$	Variable cost of the new product
$c_r \in (0, c_n]$	Variable cost of the remanufactured product
$r \in (0, c_n)$	Maximal unit cost saving from remanufacturing via process innovation
$k \in (0, +\infty)$	Investment cost parameter of process innovation in a steady-state period
$\delta \in (0,1]$	Consumer value discount for the remanufactured product
Decision and auxiliary variables	
$\theta \in [0,1]$	Level of process innovation
$p_n / p_r \in [0,1]$	Market clearing price of the new/remanufactured product
$w_n / w_r \in [0,1]$	Wholesale price of the new/remanufactured product
$q_n / q_r \in [0,1]$	Quantity of the new/remanufactured product
$\Pi_i^j \in [0, +\infty)$	Player i 's profit, $i \in \{I, M, R\}$, $j \in \{I, DM, DR\}$

3.2 Cost structure and supply of remanufacturable cores

The literature on remanufacturing typically assumes that remanufacturing of one used product does not cost more than manufacturing of one new product, e.g., Savaskan et al. (2004), Ovchinnikov et al. (2014), and Hong et al. (2017). We follow this assumption; in addition, we consider the manufacturer's opportunities to reduce the variable remanufacturing cost, and hence in this study

$$c_r = c_n - r\theta , \tag{1}$$

where $0 \le r \le c_n$, $0 \le \theta \le 1$. The parameter r measures the maximum amount of cost reduction that can be attained via process innovation. It is restricted by the current level of science and technology, i.e., the variable remanufacturing cost cannot be less than $c_n - r$ regardless of how much the manufacturer invests. Equation (1) implies that remanufacturing has no cost advantage in the absence of investments on process innovation, i.e., $c_r = c_n$ when $\theta = 0$. Note that this assumption is not critical and relaxing it, i.e., c_r is lower than c_n, does not qualitatively change our main results.

The manufacturer's upfront investment is a function of the process innovation level and modelled as $k\theta^2$. The investment is convex with respect to θ, which is often attributed to diminishing returns from R&D expenditures (Gilbert and Cvsa 2003, Pun 2014, Wu and Zhou 2017).

Without loss of generality, the retailer's variable selling cost is assumed to be constant and normalized to 0.

Remanufacturing is possible only if new products have been used and become cores for remanufacturing. We assume that the product can be remanufactured at most once (Ferrer and Swaminathan 2010, Li et al. 2012, Jin et al. 2017). Thus, the remanufactured product quantity in the current period is constrained by the new product quantity in the previous period, which is equal to the new product quantity in the current period; i.e., we have the constraint $q_r \le q_n$ in a steady-state period.

We recognise that in practice not all used products can be collected and remanufactured (i.e., in practice $q_r \le \phi q_n$ with $\phi < 1$). Yet, in assuming $\phi = 1$ we again follow the literature, e.g., Zhou et al. (2013), Agrawal et al. (2016), and Saha et al.

(2016). This assumption significantly simplifies the analysis and does not change any of the qualitative insights.

3.3 Inverse demand functions

Remanufacturing cannibalises sales of the new product. However, empirical evidence and experimental results show that consumers usually value the remanufactured product less than the new one (Guide and Li 2010, Agrawal et al. 2015, Wu and Zhou 2016). In this paper, we follow the extant literature, e.g. Ferguson and Toktay (2006), Örsdemir et al. (2014), and Wang et al. (2017), and assume that consumers' willingness-to-pay for the new product is heterogeneous and uniformly distributed in the interval $\left[0,1\right]$ with the density of 1, and each consumer's willingness-to-pay for the remanufactured product is a fraction δ of that for the new one. Each consumer buys at most one unit of the new/remanufactured product. Furthermore, both new and remanufactured products can be used for one period (that is, one period is defined as the product life duration). Hence in every period all consumers have to make their purchase decisions, thereby keeping the total market size constant.

The consumer heterogeneity assumption, together with the uniform distribution, give rise to the linear inverse demand functions which facilitate analytical tractability of the model. As mentioned above, the consumer's purchasing decision assumption controls the market size and thereby also reflects the steady-state nature of our model.

Summarizing, our model builds on previous literature by using the following inverse demand functions

$$p_n = 1 - q_n - \delta q_r , \tag{2}$$

$$p_r = \delta\left(1 - q_n - q_r\right) . \tag{3}$$

3.4 Optimization models for decision making

As mentioned above, in Model I all decisions are centrally coordinated, yielding the supply chain optimal decisions. The associated optimisation problem is

$$\max_{\theta, q_n, q_r} \Pi_I^I = \left(p_n - c_n\right) q_n + \left(p_r - \left(c_n - r\theta\right)\right) q_r - k\theta^2 , \tag{4}$$

subject to $0 \le \theta \le 1$, $q_n \ge q_r \ge 0$.

Conversely, in Model DM, where the manufacturer remanufactures the used products the manufacturer's optimisation problem is

$$\max_{\theta, w_n, w_r} \Pi_M^{DM} = \left(w_n - c_n\right) q_n + \left(w_r - \left(c_n - r\theta\right)\right) q_r - k\theta^2 \text{, subject to } 0 \le \theta \le 1. \quad (5)$$

The retailer's optimisation problem is

$$\max_{q_n, q_r} \Pi_R^{DM} = \left(p_n - w_n\right) q_n + \left(p_r - w_r\right) q_r \text{, subject to } q_n \ge q_r \ge 0. \quad (6)$$

Finally, in Model DR the manufacturer's optimisation problem is

$$\max_{\theta, w_n} \Pi_M^{DR} = \left(w_n - c_n\right) q_n - k\theta^2 \text{, subject to } 0 \le \theta \le 1. \quad (7)$$

The retailer's optimisation problem is

$$\max_{q_n, q_r} \Pi_R^{DR} = \left(p_n - w_n\right) q_n + \left(p_r - \left(c_n - r\theta\right)\right) q_r \text{, subject to } q_n \ge q_r \ge 0. \quad (8)$$

4. The analysis

Our analysis is based on the solutions of these models through backward induction. Thus, we first obtain the optimal quantities q_n and q_r as a function of θ and the wholesale price(s). Then, we derive the optimal PIR level as well as the optimal wholesale price(s).

To start out, let us first consider the effect of PIR on the optimal quantity responses. The following lemma highlights a very general result for Models I and DM.

LEMMA 1. In the integrated supply chain or the decentralised supply chain with manufacturer-remanufacturing, the optimal PIR strategy and the optimal quantity responses are linked in the following way:

1) If it is optimal not to carry out PIR, i.e., $\theta^* = 0$*, then it is optimal not to remanufacture, i.e.,* $q_r^* = 0$*;*

2) If it is optimal to carry out PIR, i.e., $\theta^* > 0$*, then it is optimal to remanufacture as many units as possible, i.e.,* $q_r^* = q_n$.

This all-or-nothing result differs from the standard structure under exogenous remanufacturing costs, where as a third option, partial remanufacturing is possible. The economic intuition behind our differing result lies in the fact that in our model the variable remanufacturing cost is endogenous. Without investment, i.e., $\theta = 0$, there is no cost saving from remanufacturing, and given consumers' reduced willingness-to-pay for the remanufactured product, intuitively, there should be no remanufacturing in the integrated model.[1]

In the decentralised supply chain model with manufacturer-remanufacturing, the intuition is similar. Any positive investment in process innovation $\theta > 0$ yields a cost saving from remanufacturing. Now assume that the manufacturer chooses wholesale prices for the new and remanufactured products that induce the retailer not to order all available remanufactured products. Because cost savings will not be fully realised when not all used products are remanufactured, we can say that a portion of investment is wasted. Consequently, the manufacturer could improve its economic performance by cutting down on the investment. This in turn reduces cost savings from remanufacturing, leading to a smaller optimal order quantity of the remanufactured product and more unrealised cost savings. Therefore, a strategy with non-zero investment in which not all used products are remanufactured is always a suboptimal strategy compared to the strategy without investment.

We can now turn to our main results concerning the optimal process innovation level. Propositions 1 and 2 provide the structural insights into PIR for models I, DM, and DR, respectively.

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[1] For our setting with $c_r = c_n$, it is clear that zero investment cannot lead to remanufacturing in the integrated model since there are no cost benefits and remanufactured products can only be sold at a lower price. We note however that our result holds even for $c_r < c_n$, unless c_r is too low. When c_r gets too low, the associated initial cost advantage of remanufacturing over new production gives rise to remanufacturing even there is no (additional) process investment, i.e. $\theta = 0$.

PROPOSITION 1. *The optimal PIR strategy in an integrated supply chain or a decentralised supply chain with manufacturer-remanufacturing is given by one of two possible structures ($X = 4$ for Model I and $X = 8$ for Model DM):*

(1) If $\delta > \frac{1+\sqrt{17}}{8}(\approx 0.64)$, $\frac{1-\sqrt{1-\frac{4\delta(1-\delta)}{3\delta-1}}}{2} < c_n < \frac{1+\sqrt{1-\frac{4\delta(1-\delta)}{3\delta-1}}}{2}$*, and* $r > \frac{(1-\delta)(\delta+2c_n-3c_n^2)}{1+\delta-2c_n}$*, the optimal PIR strategy follows a tri-fold structure: (i)* $\theta^{I*} = 0$*, if* $k \geq \frac{r^2(1-c_n)^2}{X(1-\delta)(\delta+2c_n-3c_n^2)}$*; (ii)* $\theta^{I*} = \frac{r(1+\delta-2c_n)}{Xk(1+3\delta)-r^2}$*, if* $\frac{r^2+r(1+\delta-2c_n)}{X(1+3\delta)} \leq k < \frac{r^2(1-c_n)^2}{X(1-\delta)(\delta+2c_n-3c_n^2)}$*; (iii)* $\theta^{I*} = 1$*, otherwise.*

(2) Otherwise, the optimal PIR strategy is an all-or-nothing strategy: (i) $\theta^{I*} = 0$*, if* $k \geq \frac{(1+\delta-2c_n+r)^2}{X(1+3\delta)} - \frac{(1-c_n)^2}{X}$*; (ii)* $\theta^{I*} = 1$*, otherwise.*

It is demonstrated that in the integrated supply chain, the optimal PIR level is decreasing in the investment cost parameter k; specifically, if k is sufficiently high, the optimal strategy is to invest nothing. Although this result seems to be in line with intuition, it significantly differs from the optimal strategy of managing process innovation for manufacturing in a traditional supply chain.

As shown in Appendix B, with opportunities to lower the variable manufacturing cost, the traditional supply chain always invests in process innovation regardless of the value of the investment cost parameter; i.e., the optimal process innovation level might be sufficiently low, but it is always greater than 0. In this case, we say the traditional manufacturing process accepts incremental improvement.

In contrast, a small incremental improvement in the remanufacturing cost efficiency is valueless to the closed-loop supply chain; i.e., the optimal PIR level is either sufficiently high or 0. In this case, we say the remanufacturing process requires stepwise innovation that can significantly lower the variable remanufacturing cost. This is because, unlike in the case of process innovation for manufacturing, there is a minimum remanufacturing cost reduction necessary to induce the closed-loop supply chain to take up remanufacturing at all; if the variable cost reduction is below a threshold, the closed-loop supply chain will never remanufacture, and then any investment would be wasted. Consequently, the integrated supply chain does not invest in PIR, and produces the new product only.

Observe that the strategy for Model DM is structurally identical to the strategy for Model I. The intuition behind the strategy is also similar.

PROPOSITION 2. *The optimal PIR strategy in a decentralised supply chain with retailer-remanufacturing depends on the relationship between* c_n *and* δ *in the following way:*

(1) When $c_n < \delta/2$*, the optimal PIR strategy is given by one of three possible structures:*

(1.1) if $(1-\delta)(1+3\delta)-(1+\delta-2c_n)^2 \le 0$*, it is never optimal for the manufacturer not to invest and the PIR strategy follows a two-fold structure: (i)* $\theta^{\mathrm{D}R*} = \dfrac{r(1+\delta-2c_n)}{8k(1+3\delta)-r^2}$*, if* $k \ge \dfrac{r^2+r(1+\delta-2c_n)}{8(1+3\delta)}$*; (ii)* $\theta^{\mathrm{D}R*}=1$*, otherwise;*

(1.2) otherwise, and if $r > \dfrac{(1-\delta)(1+3\delta)-(\delta+2c_n-3c_n{}^2)}{1+\delta-2c_n}$*, the optimal PIR strategy follows a tri-fold structure: (i)* $\theta^{\mathrm{D}R*}=0$*, if* $k \ge \dfrac{r^2(1-\delta)}{8\left((1-\delta)(1+3\delta)-(\delta+2c_n-3c_n{}^2)\right)}$*; (ii)* $\theta^{\mathrm{D}R*} = \dfrac{r(1+\delta-2c_n)}{8k(1+3\delta)-r^2}$*, if* $\dfrac{r^2+r(1+\delta-2c_n)}{8(1+3\delta)} \le k < \dfrac{r^2(1-\delta)}{8\left((1-\delta)(1+3\delta)-(\delta+2c_n-3c_n{}^2)\right)}$*; (iii)* $\theta^{\mathrm{D}R*}=1$*, otherwise;*

(1.3) otherwise, the optimal PIR strategy is an all-or-nothing strategy: (i) $\theta^{\mathrm{D}R*}=0$*, if* $k \ge \dfrac{(1+\delta-2c_n+r)^2}{8(1+3\delta)} - \dfrac{1-\delta}{8}$*; (ii)* $\theta^{\mathrm{D}R*}=1$*, otherwise.*

(2) When $\delta/2 \le c_n < \delta/(2-\delta)$*, the optimal PIR strategy is structurally identical to above:*

(2.1) if $4(\delta-c_n)(1-\delta)(1+3\delta)-\delta^2(1+\delta-2c_n)^2 \le 0$*, it is never optimal for the manufacturer not to invest and the PIR strategy follows a two-fold structure: (i)* $\theta^{\mathrm{D}R*} = \dfrac{r(1+\delta-2c_n)}{8k(1+3\delta)-r^2}$*, if* $k \ge \dfrac{r^2+r(1+\delta-2c_n)}{8(1+3\delta)}$*; (ii)* $\theta^{\mathrm{D}R*}=1$*, otherwise;*

(2.2) otherwise, and if $r > \dfrac{(1+\delta-2c_n)\left(4(\delta-c_n)(1-\delta)(1+3\delta)-\delta^2(1+\delta-2c_n)^2\right)}{\delta^2(1+\delta-2c_n)^2-4(1-c_n)(\delta-c_n)(1-\delta)(1+3\delta)}$*, the optimal PIR strategy follows a tri-fold structure: (i)* $\theta^{\mathrm{D}R*}=0$*, if* $k \ge \dfrac{r^2 c_n(1-\delta)(\delta-c_n)}{2\left(4(\delta-c_n)(1-\delta)(1+3\delta)-\delta^2(1+\delta-2c_n)^2\right)}$*; (ii)* $\theta^{\mathrm{D}R*}=\dfrac{r(1+\delta-2c_n)}{8k(1+3\delta)-r^2}$*, if* $\dfrac{r^2+r(1+\delta-2c_n)}{8(1+3\delta)} \le k < \dfrac{r^2 c_n(1-\delta)(\delta-c_n)}{2\left(4(\delta-c_n)(1-\delta)(1+3\delta)-\delta^2(1+\delta-2c_n)^2\right)}$*; (iii)* $\theta^{\mathrm{D}R*}=1$*, otherwise;*

(2.3) otherwise, the optimal PIR strategy is an all-or-nothing strategy: (i) $\theta^{\mathrm{D}R*}=0$*, if* $k \ge \dfrac{(1+\delta-2c_n+r)^2}{8(1+3\delta)}-\dfrac{c_n(1-\delta)(\delta-c_n)}{2\delta^2}$*; (ii)* $\theta^{\mathrm{D}R*}=1$*, otherwise.*

(3) When $c_n \ge \delta/(2-\delta)$*, the optimal PIR strategy in Model DR is identical to the strategy in Model DM.*

Note that in Model DR the strategy is structurally very different from the strategies in Models I and DM, when $c_n < \delta/(2-\delta)$. First, when $c_n < \delta/2$ the retailer will remanufacture even if the manufacturer does not invest in PIR. Second, when δ is high (precisely, when $\delta \ge 2/3$ and $c_n < \delta/2$) the manufacturer will always invest in PIR regardless of the values of the investment cost parameter k and the magnitude of the possible reduction r, see the case (A) of Proposition 2 (1).

The intuition behind this result hinges on the interrelation of the demand-side and the supply-side link between the new and remanufactured products. Specifically, the wholesale price of the new product will be always higher than their variable manufacturing cost, while the variable remanufacturing cost is less than or equal to the variable manufacturing cost. Thus, the retailer has an incentive to offer the remanufactured product even when $\theta = 0$. In addition, to generate more used products available for remanufacturing, the retailer then also has an incentive to order more new products. When c_n is small relative to δ, the price-sensitivity of demand for the new product – driven by the (low) cannibalisation effect between the new and remanufactured products – is small, and the manufacturer will strategically price the new product higher to share the remanufacturing benefit.

On the other hand, the manufacturer will not invest in PIR and at the same time set a wholesale price for the new product that induces the retailer not to remanufacture. Thus, anticipating that the retailer may remanufacture anyways, it may be even better for the manufacturer to attempt to obtain a larger share of the remanufacturing benefit. By investing in remanufacturing cost reduction, the manufacturer can try to induce the retailer to remanufacture all available used products. When demand for the remanufactured product is high, the supply constraint on the availability of used products reduces the pressure on the wholesale price for the new product. Consequently, the increased wholesale price of the new product more than covers the investment in PIR.

5. Comparison and discussion

In this section, we firstly compare the optimal PIR levels in the integrated supply chain model and the decentralised supply chain model to highlight inefficiencies resulting from the decentralisation of decision-making. Next, we are also interested in how the optimal PIR level and the profits are shaped by key modelling parameters. Finally, we discuss the environmental implications of PIR. Note that, due to the complexity in mathematics, some results cannot be ascertained analytically, but could only be verified numerically.

5.1 Comparison of optimal PIR levels

The underinvestment issue as inefficiency resulting from the decentralisation of decision-making has been widely studied in the literature on traditional supply chain models, see, e.g., Bhaskaran and Krishnan (2009), Huang et al. (2016), and Pun and Ghamat (2016). In line with intuition, in the decentralised supply chain with manufacturer-remanufacturing, the benefit of the manufacturer's investment in PIR will be partly shared by the retailer through the wholesale prices of the new and remanufactured products. Such a free-riding problem leads the manufacturer to underinvest, relative to the first-best solution.

Interestingly, for the decentralised supply chain with retailer-remanufacturing, both over- and underinvestment may occur, depending on the specific parameter constellation. Due to the various possible cases, it is difficult to provide a closed-form solution describing all possible outcomes. The following proposition characterises the general insights into the overinvestment issue.

PROPOSITION 3. *Compared with the first-best PIR level in the integrated supply chain,*

(1) in the decentralised supply chain with manufacturer-remanufacturing there is never overinvestment, and the manufacturer underinvests in PIR under certain conditions (detailed in the proof);

(2) in the decentralised supply chain with retailer-remanufacturing the manufacturer may overinvest, specifically, (i) overinvestment can only occur when $\theta^{I*}=0$*, (ii) when* $(1-\delta)(1+3\delta)-(1+\delta-2c_n)^2\le 0$ *and* $r\le(1-c_n)\sqrt{1+3\delta}-(1+\delta-2c_n)$*, overinvestment always occurs regardless of the value of* k.

This result is intriguing because it implies that the manufacturer would incentivise the retailer to remanufacture, when the first-best strategy in an integrated supply chain is not to do so. Moreover, it basically highlights that the manufacturer may be able to share any cost of PIR with the retailer through the wholesale price of the new product. The manufacturer anticipates that the retailer, to maximise its own profit, remanufactures even if the manufacturer makes no investment; additionally, the supply of the remanufactured products is constrained by the availability of used products resulting from earlier new product sales. Based on these two observations, the manufacturer capitalises on the resulting reduced price-sensitivity of demand for the new product and amortises the investment through an increase in the wholesale price. Therefore, inefficiency resulting from the decentralisation of decision-making may lie in the manufacturer's incentive to overinvest in PIR in the closed-loop supply chain with retailer-remanufacturing.

We also perform a numerical analysis to show the scale of over- and underinvestment issues. The parameter values we have chosen cover a broad range of possible outcomes. The domain of parameters c_n, r, and δ is $[0,1]$. We consider values $\{0.1, 0.2, ..., 0.8, 0.9\}$, subject to $r\le c_n$. Finally, the domain of value k is $[0,\infty)$. After some initial sensitivity tests, we chose to vary k between $\{0.001, 0.006, ..., 0.046, 0.051\}$ to ensure that not only trivial extreme scenarios (in which $\theta=0$ or $\theta=1$) exist. Overall, these parameter settings give rise to 4455 scenarios.

Table 2 reveals that on an aggregate level the underinvestment issue is much more pronounced than the overinvestment issue in both decentralised models. Underinvestment occurs in around 13% of the scenarios, while overinvestment occurs in around 5% of the cases in Model DR. Moreover, in the underinvestment scenarios the average investment is $\theta^{I*} = 0.95$ in Model I, while in both decentralised models we observe $\theta^{\mathrm{DM*/DR*}} = 0.11$. On the other hand, in the overinvestment scenarios the average investment by the manufacturer is $\theta^{\mathrm{DR*}} = 0.32$ in Model DR, while, as shown in Proposition 4, then there is no investment in Model I.

Table 2. The scale of over- and underinvestment issues

	Model I	**Model DM**	**Model DR**
$\theta^* = 0$	3367	3815	3592
$0 < \theta^* < 1$	99	110	318
$\theta^* = 1$	989	530	545
$\theta^{\mathrm{DM*/DR*}} < \theta^{\mathrm{I*}}$	N/A	558	561
$\theta^{\mathrm{DM*/DR*}} > \theta^{\mathrm{I*}}$	N/A	0	218

5.2 Sensitivity with respect to key parameters

The impact of key modelling parameters on the optimal PIR level and the profits are also revealed by the numerical analysis. We observe mostly the expected result that θ^* is non-increasing in c_n and k, and non-decreasing in r. For δ the result hinges on the remanufacturing decision. With δ increasing, the optimal PIR level may switch from no remanufacturing (and consequently $\theta^* = 0$) to full remanufacturing with $\theta^* > 0$. Once that happens, a further increase in δ may reduce the optimal solution, reflecting the increased willingness-to-pay and therefore the lower price pressure on the remanufactured product. Figure 1 exemplifies this result for Models I and DR. it also shows both the under- and overinvestment issues arising in Model DR.

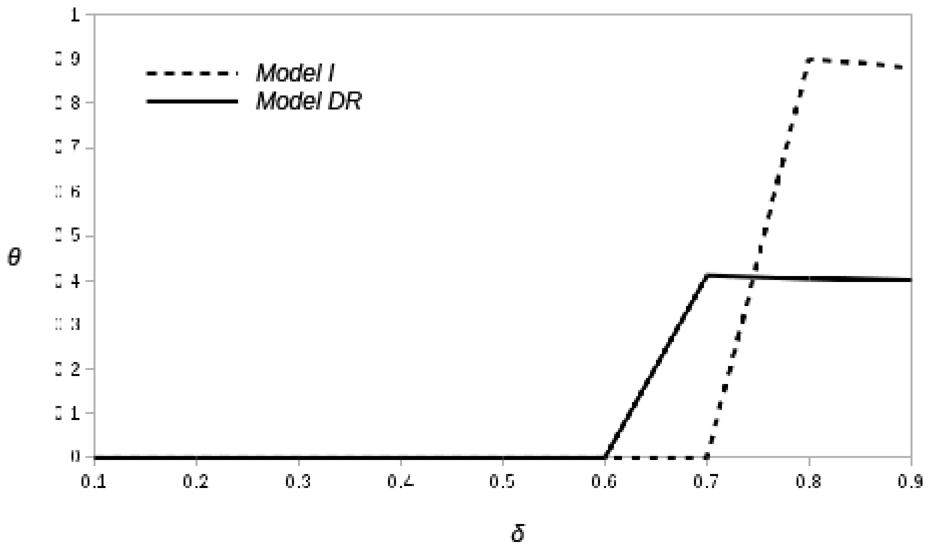

Figure 1. Sensitivity of θ^* w.r.t. δ ($c_n = 0.3$, $r = 0.3$, $k = 0.036$)

Looking at the sensitivity of the profits, as summarised in Table 3, we observe that in Model I the expected trends arise. However, in both decentralised models the only clear-cut tendency remaining is the manufacturer's profit falling in c_n. All other relationships can point in either direction. These results highlight the complexity of the decision situation in the decentralised supply chain in general. Let us just briefly discuss two specific aspects. First, in Model DR the retailer's profit may be increasing in the investment cost parameter of PIR, k. When k is small enough, the manufacturer's optimal strategy is to invest in PIR and increase the wholesale price of the new product anticipating that all available used products will be remanufactured; otherwise, the manufacturer's optimal strategy is to make no investment and price the new product lower. Consequently, if k is large enough, although the unit remanufacturing cost is higher, the retailer can obtain a greater profit due to a lower new product wholesale price.

Table 3. The results of sensitivity analysis

	Sensitivity of $\Pi_I / \Pi_M / \Pi_R$ w.r.t.		
	Model I	**Model DM**	**Model DR**
c_n	-/na/na	±/-/±	±/-/±
r	+/na/na	±/±/±	±/±/±

δ	+/na/na	±/±/±	±/±/±
k	-/na/na	±/±/±	±/±/±

Second, in Model DR the retailer’s profit may be decreasing in the consumer value discount for the remanufactured product, δ. If δ is small enough, the manufacturer makes no investment in PIR and the retailer remanufactures nothing; otherwise, the manufacturer always invests in PIR and the retailer remanufactures all available used products. This result in fact implies that the remanufacturing opportunity may form a lose-lose situation to the manufacturer and the retailer, which has been demonstrated in Xiong et al. (2013). The intuition is that, if c_n is low and δ is large enough, as mentioned before, the retailer will remanufacture even if there is no PIR. Anticipating that, the manufacturer will strategically make an investment and price the new product higher to share the remanufacturing benefit. However, the higher new product wholesale price will lead to a lower production quantity of the new product and undermine the remanufacturing benefit. Consequently, both the manufacturer and the retailer may be worse off.

5.3 Environmental impacts

Let us finally consider the impacts of PIR on the environment. Following the literature, e.g., Galbreth et al. (2013), Yan et al. (2015), and Xiong et al. (2016), we use the overall production quantity $\mathrm{E} = q_n + \gamma q_r$ as a proxy for the environmental effect, where $\gamma \leq 1$ reflects the potentially lower negative impact on the environment due to collecting and reusing end-of-use products. Note that, PIR could be of help for the environment because cost savings are usually linked with the reduction of carbon emissions and resource consumption (Porter and Linde 1995). Therefore, in this paper, we assume that the cost reduction induced by θ has a one-to-one relationship with the reduction of environmental impacts, i.e., investing θ in remanufacturing cost reduction, reduces the environmental impact of the remanufactured product by θ as well, yielding $\gamma = 1 - \theta$. Table 4 summarises the aggregate results. The two columns provide the following information: the first column counts the number of scenarios in which the weighted production quantity is smaller under decentralisation. For example, from Table 2 we know that there are 218 scenarios where there is overinvestment in Model DR. The associated entry in the last row of Table 4 tells us that in all of those 218 scenarios (i.e., 100%) the weighted production quantity is smaller in Model DR than in Model I. The second column examines the average change in the weighted production quantity overall. So, in the first line in Table 4, the value of 2.80% refers to the average reduction in the weighted production quantity when $\theta^{j*} < \theta^{I*}$.

Table 4. Environmental impacts under different CLSC structures

		The probability of $\mathrm{E}^I > \mathrm{E}^j$	$\frac{\mathrm{E}^I - \mathrm{E}^j}{\mathrm{E}^I} \cdot 100\%$
$j = DM$	**When** $\theta^{j*} < \theta^{I*}$	51.79%	2.80%
	When $\theta^{j*} = \theta^{I*}$	13.60%	6.80%
$j = DR$	**When** $\theta^{j*} < \theta^{I*}$	69.16%	16.92%
	When $\theta^{j*} = \theta^{I*}$	23.88%	10.40%
	When $\theta^{j*} > \theta^{I*}$	100%	54.62%

Because of the well-known effect of double marginalisation, a decentralised supply chain always charges a higher price and sells a smaller quantity than an integrated supply chain. However, from Table 4 we observe that in a closed-loop supply chain, the decentralised decision-making does not always lead to a smaller quantity, e.g., in Model DM when $\theta^{j*} < \theta^{I*}$, there is only 51.79% of scenarios in which the weighted production quantity is reduced. This result seems counterintuitive at first, yet it highlights an important structural insight. The mix between new and remanufactured products offered may be different; specifically, the decentralised supply chain may offer more new products and less remanufactured products (due to the underinvestment issue). Thus, in those scenarios decentralisation forms another loss-loss situation. Not only do profits decline, but the environmental impact is also worsened.

Second, observe that whenever the manufacturer overinvests in Model DR, overall environmental impact is always reduced, i.e., when $\theta^{j*} > \theta^{I*}$, in 100% of scenarios the weighted production quantity is reduced; in addition, the average reduction is significantly higher, i.e., 54.62% in this case, while it is at most 16.92% in other cases. Thus, the overinvestment issue, while inefficient from an economic perspective, benefits the environmental aspect quite drastically.

6. Conclusions

Managing closed-loop supply chains with remanufacturing is a hot research topic because of its sustainable profile. In order to explore its full environmental and economic benefits, this study investigates PIR in a decentralised supply chain. In our model, remanufacturing can be conducted by either the manufacturer or the retailer, and the manufacturer has opportunities to lower the variable remanufacturing cost via process innovation.

Our key findings generate the following implications for different stakeholders.

(1) Implications for the manufacturer. In general, traditional process innovation for manufacturing accepts small incremental improvements in that cost savings in the manufacturing process, no matter how small they are, can improve the profit margin; consequently the manufacturer should seize every single opportunity to lower the new production cost. Conversely, stepwise innovation is required to significantly lower the variable remanufacturing cost and make remanufacturing viable at all. That is to say, not all cost-reduction opportunities in the remanufacturing process are valuable. The manufacturer should forgo some opportunities that cannot reduce the variable remanufacturing cost beyond the threshold required to make it a profitable option.

If investing in PIR is profitable, the manufacturer should carefully choose the optimal PIR level, which depends heavily on who carries out remanufacturing. Intuitively, the global optimal PIR level is achieved if the closed-loop supply chain is fully coordinated. Otherwise, the manufacturer should invest less than the global optimal level when remanufacturing is performed by itself and might invest over the global optimal level when the retailer operates the remanufacturing business.

(2) Implications for the retailer. In many industries, especially the industry of heavy machinery, it is difficult for global manufacturers to carry out the remanufacturing operation around the world, while local retailers benefit from their proximity to customers and may perform the remanufacturing task. If remanufacturing has no cost advantage, the manufacturer does never remanufacture; however, the retailer can strategically use remanufacturing to compete with the new product and hence

induce the manufacturer to lower the wholesale price. That is to say, retailers could be more proactive to capitalize on remanufacturing.

Given the retailer starts up remanufacturing, the manufacturer might invest in PIR even if the global optimal strategy is not to invest. As a consequence, the variable remanufacturing cost is reduced and then the retailer can benefit more from remanufacturing.

(3) Implications for the government. The remanufacturing sector is usually supported by the government because of its sustainable profile. Our study compares manufacturer-remanufacturing and retailer-remanufacturing and finds that retailer-remanufacturing has the following advantages. First, it is easier to be triggered since the retailer would like to remanufacture even if remanufacturing has no cost efficiency; second, the manufacturer might invest over the global optimal PIR level in the case of retailer-remanufacturing; finally, the overinvestment issue, though inefficient from a supply chain’s profitability point of view, always leads to a reduced virgin material consumption even without explicit consideration of the environmental aspects in the decision-making process. Therefore, the government should give priority to retailer-remanufacturing when making policies to develop the remanufacturing sector.

Summarising, our results have shown the potential benefits of PIR, but also the caveats to avoid under decentralised decision-making and potentially conflicting economic and environmental key performance indicators. Future research will have to consider the relationship between remanufacturing and product innovation to aid understanding the long-term implications of remanufacturing on new product introductions. A prime example of an associated open research question concerns the planned obsolescence debate, where the environmental benefits of prolonged usage periods seem to be in conflict with the environmental benefits of new product introductions featuring a lower per-unit footprint.

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Appendices

See the online supplementary material.

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