**Rent, sell, and remanufacture: The manufacturer’s choice when remanufacturing can be outsourced**

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**Abstract**

Manufacturers have increasingly started offering rental options for the products they sell. Renting products offers an opportunity: segmenting consumers. However, this also raises a challenge: what to do with the returned products? One solution is to remanufacture these products and then rent or resell them. Subsequently, should remanufacturing be outsourced to a third-party firm that can remanufacture at a lower cost? Here, we use a multi-period setting and examine the optimal decisions for different selling and renting constellations. Importantly, we allow the manufacturing costs of the sales and rental products to differ, as they seem to be critical in determining the manufacturer’s renting and selling decisions and remanufacturing strategies. For example, under integrated (i.e. in-house) remanufacturing, when the new rental product’s manufacturing cost is sufficiently high, no remanufacturing happens. Under both remanufacturing strategies—integrated and outsourced—the manufacturer does not rent new products in the second period if the manufacturing costs of the sales and rental products are identical. If the rental product’s manufacturing cost is either sufficiently low or high, then integrated remanufacturing is more profitable; when this manufacturing cost is within a moderate range, the manufacturer outsources remanufacturing to an independent remanufacturer. Surprisingly, in some situations, the production quantity of the new sales product may even increase with its manufacturing cost. This is because the manufacturer may extract an even higher margin compared with the new rental product. Finally, we also consider several extensions such as uncertainty regarding the quality of the returned goods, simultaneous selling and renting of remanufactured goods, and longer horizons and the product’s life cycle.

**Keywords:** supply chain management, remanufacturing, rent, pricing, outsourcing strategy

# Introduction

Remanufacturing activities are an increasingly important mechanism to avoid resource wastage, increase environmental protection, and reduce manufacturing costs. According to Guide and Van Wassenhove (2001), for a remanufacturer operating a recoverable product system, returned used products serve as the basic input. Remanufacturing has been widely and successfully applied in some industries. Some well-known manufacturers, such as GE Transportation, Kodak, Hewlett-Packard (HP), Canon, and Xerox, have remanufactured products. In the United States, recent estimates for remanufactured product sales exceed $100 billion per year, with consumer markets representing approximately $10 billion worth of sales per year (Abbey et al., 2015).

Manufacturers usually face a strategic choice when they consider remanufacturing. On the one hand, some firms outsource their remanufacturing activities to independent remanufacturers and earn an additional profit from the returned products (Orsdemir et al., 2014). Independent remanufacturers possess specialised technologies and dedicated facilities for remanufacturing; therefore, they usually have a lower remanufacturing cost (Majumder and Groenevelt, 2001). For example, Caterpillar Remanufacturing, as a preferred supplier, provides remanufacturing products and services for Land Rover (Zou et al., 2016). On the other hand, other firms choose to remanufacture in-house (integrated remanufacturing) or discard the returns to block independent remanufacturers and prevent cannibalisation (Ferguson and Toktay, 2006; Abbey et al., 2015).

Remanufacturing can be easily implemented in environments where the firm rents the products and hence controls the flow of used products. Indeed, integration of remanufacturing and renting operations has been applied in reality. For instance, Caterpillar’s earnings from product leasing and services account for more than 60% of its global sales. Xerox’s remanufacturing facility relies, among others, on returns from trade-ins and off-lease products, which has generated cost savings of several hundred million dollars each year (Fishbein et al., 2000). Moreover, Shi and Jo Min (2014) note that Xerox leases photocopiers to Staples, which provides copying services to its customers. Another example is Interface Inc., a carpet manufacturer, which provides the Evergreen Lease to reduce the environmental impact of its operations (Olivia and Quinn, 2003). These examples also demonstrate that some consumers prefer to rent (remanufactured) products.

Many consumers may not need to keep a product for an extended period; instead, rental options can address this short-term need. Moreover, rentals can relieve consumers from the need to maintain the product as it deteriorates over time. Accordingly, renting products allows a convenient interplay with consumers and facilitates demand segmentation. Additionally, the manufacturer can keep the residual value of the product at the end of the rental period. These rented products—once collected by the manufacturer or independent remanufacturer and after undergoing some remanufacturing process—can be rented again to a new group of consumers.

Importantly, selling and renting products offer different benefits to consumers. The former endows consumers with the product’s entire life benefit, while the latter gives consumers only the period pro-rated benefit. As such, offering rental services coupled with remanufacturing of those products can bestow the firm with a mechanism to segment demand and yield higher profits. However, product variety can lead to cannibalisation, whereby the remanufactured product steals demand from the new products. Hence, it is necessary to investigate how to trade-off between the positive (demand segmentation) and negative (product cannibalisation) effects of product variety.

Here, we analyse the manufacturer’s renting or selling decisions for new and remanufactured products and investigate the minimum quality decisions of the collected products under integrated and outsourced remanufacturing strategies. Specifically, we address the following important research questions: (1) What is the manufacturer’s selling or renting strategy when the rental units can be collected and remanufactured? Can the manufacturer benefit by offering a return option for the sold units so that they can be remanufactured as well? (2) How do identical or differentiated manufacturing costs for the sales and rental products impact the manufacturer’s decisions? (3) Can outsourcing the remanufacturing of the collected units benefit the manufacturer?

We consider a two-period model and study the market segmentation, whereby consumers benefit differently from the different product types they buy or rent. In the first period, the consumers can only buy or rent new products. At the end of the first period, the rental products are collected by the manufacturer or the third-party firm to be remanufactured either by the firm itself or by the third-party remanufacturer. Thus, in the second period, the product portfolio may increase to also include the remanufactured products—for rent or purchase. A critical factor in our analysis is the manufacturing cost of the different product types—those for rental and sale. Firms may recognise that their products serve different audiences; hence, these products may be associated with different production costs.

The main contributions of this study are as follows. First, to the best of our knowledge, this is the first study to establish rent-or-sell decisions coupled with remanufacturing strategies in a unified two-period model. Second, we investigate the cooperative and competitive relationships between a manufacturer and an independent remanufacturer under a remanufacturing outsourcing environment. Third, in one of the extensions of our model, we incorporate the quality uncertainty of the used product.

We obtain some key findings. We find that the manufacturing costs of sales and rental products are critical in determining the manufacturer’s product offering decisions (rental or sales) and remanufacturing strategies. Regarding the choice of product offering, our results suggest that under an integrated remanufacturing strategy, when the rental product’s manufacturing cost is sufficiently high, the manufacturer should focus solely on producing the new sales product (i.e. abandon the rental product and the remanufacturing activities). Regarding the strategy’s implementation, we also find that the manufacturer is not always better off with integrated remanufacturing: If the rental product’s manufacturing cost is relatively high, the manufacturer will be worse off with integrated remanufacturing. When the manufacturing costs of the rental and sales products are identical, a moderate manufacturing cost can induce more profit with an outsourced remanufacturing strategy. These findings have important implications for manufacturers who strategically decide whether to sell or rent their products and how to execute remanufacturing. Furthermore, it is crucial to understand consumers’ preferences and design the product portfolio accordingly.

Moreover, from the view of implementing a remanufacturing strategy, this study provides some results that differ from the existing literature. For example, Oraiopoulos et al. (2012) find that when consumers’ willingness to pay (WTP) for the remanufactured product is sufficiently low, there is no secondary market, even at zero relicensing fees. Meanwhile, we find that only when the rental’s product manufacturing is sufficiently high, the manufacturer stops remanufacturing—both integrated and outsourced. Moreover, if the rental product’s manufacturing cost is low such that remanufacturing is allowed, and simultaneously, the sales product’s manufacturing cost becomes high, the manufacturer would induce the remanufacturer into entering the market by offering a free licensing fee. Wang et al. (2017) find that the retailer’s remanufacturing strategy depends on the variable cost of remanufacturing: when this cost is sufficiently high, the retailer decides to outsource remanufacturing. However, we argue that the remanufacturing strategy is impacted by the differential manufacturing costs between new sales and rental products.

The remainder of this paper is organised as follows. Section 2 undertakes the literature review, Section 3 describes the modelling framework, and Section 4 analyses the manufacturer’s remanufacturing strategy. Further, Section 5 extends our model to account for the following: the quality risk of the used products (subsection 5.1); consumers who rent in period 1 and return in period 2 (subsection 5.2); consumers who return their purchased new product (subsection 5.3); the option of selling the remanufactured products (subsection 5.4); a longer horizon and the product’s life cycle (subsection 5.5); the linked production costs of both types of products (subsection 5.6). Finally, Section 6 concludes the study and outlines future research directions.

# Literature review

Our study is related to two streams of literature: selling and rental decisions of durable products and remanufacturing in closed-loop supply chains.

# Selling and renting durable products

Durable products have been extensively examined in the literature, where one major focus is on how the used products are handled at the end of a period. Several studies focus on secondary markets as a mechanism for trading the used products. Shulman and Coughlan (2007) examine the manufacturer’s channel contract with the retailer and the sales and profit effects of a retailer-operated secondary market.Jiang et al. (2017) investigate the impact of a peer-to-peer marketplace on supply chain decisions while assuming the used products can be traded between consumers through this marketplace. Namely, consumers who bought the products in the first period can sell them to other consumers who wish to buy them in the second period. However, these studies do not focus on the remanufacturing cost savings and the impact of the quality uncertainty of the used product on the remanufacturing activities.

Some studies examine diverse considerations relating to rental decisions of the durable product (e.g. [Bhaskaran](https://pubsonline.informs.org/action/doSearch?text1=Bhaskaran%2C+Sreekumar+R&field1=Contrib) and [Gilbert](https://pubsonline.informs.org/action/doSearch?text1=Gilbert%2C+Stephen+M&field1=Contrib), 2009; Xiong et al., 2012; Agrawal et al., 2012; Li and Xu, 2015; Yu et al., 2018). [Bhaskaran](https://pubsonline.informs.org/action/doSearch?text1=Bhaskaran%2C+Sreekumar+R&field1=Contrib) and [Gilbert](https://pubsonline.informs.org/action/doSearch?text1=Gilbert%2C+Stephen+M&field1=Contrib) (2009) consider a manufacturer who sells or leases the durable product through independent dealers. The authors find that when the competition level among dealers is high, manufacturers would be willing to lease the product to their dealers. Further, Xiong et al. (2012) consider a different perspective whereby the downstream dealer may sell or rent the product in a multiple period setting, while the upstream manufacturer may encroach and adopt a dual-channel strategy to discipline the downstream dealer. Moreover, Jia et al. (2018) investigate the combined effects of different price discrimination strategies and software upgrades on the monopolist’s profit under selling and leasing models. Furthermore, using a single-period model, Yu et al. (2018) consider the quality difference between the rented and sold products, investigate the firm’s optimal pricing problem for per-use rental services and sales, and numerically illustrate the impact of vertical differentiation on profitability. However, these studies only focus on the firm’s decision and do not involve any remanufacturing activities. Nevertheless, in our study, a market is segmented by consumers’ choices: buy/rent a new product and buy/rent a remanufactured one. Additionally, we discuss whether the manufacturer undertakes integrated remanufacturing of the product or outsources this to an independent remanufacturer.

Finally, several studies have investigated renting decisions in the context of remanufacturing. From a real options perspective, Shi and Jo Min (2013) consider a manufacturer who rents a product to a service provider and analyse the manufacturer’s remanufacturing decisions. While considering consumers’ preferences, Agrawal et al. (2012) separately examine the manufacturer’s selling and leasing choices where consumers buy either a new or used product. Conversely, our study combines the manufacturer’s rental or sales decisions for new and remanufactured products in a unified two-period model. Meanwhile, Aras et al. (2011) consider a firm’s optimal pricing strategy when the firm rents the new products but sells the remanufactured product to consumers; the authors perceive that the manufacturer cannot benefit from renting the remanufactured product. Contrary to this viewpoint, one of our results suggests that when the manufacturing cost is high, the manufacturer should concentrate on selling the new product and renting the remanufactured one.

# Remanufacturing in closed-loop supply chains

Govindan et al. (2015) provide a comprehensive review of the extensive literature on closed-loop supply chains, indicating that outsourcing and authorising remanufacturing is an important topic. In outsourced situations, the manufacturer and independent remanufacturer both compete and cooperate. On the one hand, the manufacturer can sell some of the used products to the remanufacturer for additional profits. On the other hand, the remanufactured products produced by the remanufacturer cannibalise the manufacturer’s new product market and compete for market share. For example, Oraiopoulos et al. (2012) study an original equipment manufacturer’s optimal strategies on whether to permit a third-party entrant to sell refurbished products through a secondary market while controlling the relicensing fee. Hong et al. (2017) extend the work of Oraiopoulos et al. (2012) by considering two different relicensing patterns: fixed fee relicensing and royalty relicensing. Further, Orsdemir et al. (2014) and Zou et al. (2016) study the case where remanufacturing is performed by a third-party remanufacturer. Moreover, Majumder and Groenevelt (2001), Wu (2012), and Bulmus et al. (2014) focus on competition in the remanufacturing supply chain. Wu and Zhou (2019) consider a supplier who sells the same component to one manufacturer and one independent remanufacturer. The authors investigate the effect of a buyer-specific/uniform pricing strategy on the closed-loop supply chain. Additionally, to avoid cannibalisation, Li et al. (2019) propose selling the remanufactured products in the secondary markets. Finally, Li et al. (2018) discuss the conditions under which product quality improvement helps remanufacturing.

Several studies investigate a manufacturer/remanufacturer’s remanufacturing strategy when the yield rate of the returned product is uncertain (e.g. Mukhopadhyay and Ma, 2009; Teunter and Flapper, 2011; Cai et al., 2014; Guo and Ya, 2015; He, 2015; Li et al., 2015). This kind of uncertainty affects the pricing decisions and profits of supply chain members (Souza, 2013). However, these studies neglect the segmentation of demand. Using a single period model, Atasu and Souza (2013) analyse the impact of three forms of recovery (quality recovery, profitable recovery, and costly recovery) on quality choice, whereas Wang et al. (2017) investigate a retailer’s reverse channel strategy (outsourcing or integration). The latter focuses on the role of variable remanufacturing costs and how the balance of power drives the retailer’s remanufacturing strategy.

Further, El Saadany et al. (2013) assume that the used product can be recovered a finite number of times and examine a production and recovery inventory system for a single product. Their findings suggest that as the number of times an item is recovered increases, the percentage of available used units that are recoverable plateaus. Notably, the authors consider that the market demand is constant. Conversely, as in our study, the market is segmented given the consumers’ preferences, and the rental/sales quantities are impacted by the manufacturing costs for both the new rental and new sales products.

Different from these existing studies, our work is novel—we consider an endogenous remanufacturing rate, which is decided by the ratio between the quantity of the remanufactured and new rental products. This is closer to the actual situation.

Despite the extensive coverage of remanufacturing decisions covered by this stream of literature, it does not involve the remanufacturer’s rental services, which is becoming increasingly common in practice. With rental services, the manufacturer receives the products at the end of the rental period and can use them again. Remanufacturing is required frequently to ensure that these products can be offered to the consumers again.

# Model

We investigate two remanufacturing strategies: integrated and outsourced. When the manufacturer opts for the integrated approach, it centralises the activities—it sells and rents the units, manages the collection and remanufacturing aspects, and rents the remanufactured units. When the manufacturer outsources remanufacturing, it lets an independent remanufacturer handle the collection, remanufacturing, and rental of those remanufactured units.

We consider a two-period model, where the manufacturer can sell and rent new units to consumers in both periods. At the end of period 1, the manufacturer—or the remanufacturer—collects all rented (used) products from consumers, and decides how many units to remanufacture. The remanufactured units are rented out again in period 2, whereas the remaining units are discarded. Therefore, given their different qualities, in period 2, the new and the remanufactured products are sold at different prices. Let and  denote the selling and renting price, respectively, in period , with , of the new/remanufactured product *i*, with . Similarly, let  and  denote the demand quantities for the products when they are sold and rented, respectively.

We assume that the remanufactured product can be rented in period 2 at a price . Note that in Section 5.2, we relax this assumption and allow the remanufactured to be sold as well. The sales product’s manufacturing cost is , whereas the rental product’s manufacturing cost is *d*. This is in line with Yu et al. (2018), who state that the quality of products offered in rental services is usually different from that of those for sale. In some scenarios, the rental product’s manufacturing cost is equal or lower (). For instance, the manufacturing cost and configurations of sharing cars are lower than that of the private cars while satisfying renter requirements. Moreover, following the consumer’s principle ‘Don’t be gentle, it’s a rental’, the car manufacturer would choose to reduce the standard of the rental car’s equipment. However, in other scenarios, the rented product’s manufacturing cost may be higher (), as is the case for Fuji-Xerox printers (Yu et al., 2018). In our setting, we limit our attention to the former case. We assume that the remanufacturing cost for the integrated manufacturer, , is such that .

Consumers can either buy or rent the products or not use them at all. We assume that the consumer’s WTP for the new product is , which is uniformly distributed over [0, 1]. According to Wang et al. (2017), consumers perceive the quality of the remanufactured product to be lower than that of the new one. Hence, consumers’ WTP for the remanufactured product is discounted by a factor of , where , resulting in a WTP of . We assume that the product is durable—it retains a value beyond a single period. Specifically, at the end of one period of use, the product still retains a fraction ** of its value, **. Thus, consumers who purchase the product receive the entire utility from the product even if they buy in period 2; however, those who rent the product for one period only enjoy a fraction  of the product’s valuation. Accordingly, in period 2, consumers are willing to pay  for renting a new product and  for renting a remanufactured product.

In period 1, if consumers’ utility from buying a new product, , is larger than the utility from renting it, , they buy it as long as the utility is positive. Otherwise, they rent it, unless this utility is negative, in which case they do not buy or rent during this period. The consumer who is indifferent between buying and renting has a valuation of , and the consumer who is indifferent between renting and not using the product at all has a valuation . Thus, the demand for purchasing the new product is , and that for renting the new product is . At the end of period 1, the rented products are collected from consumers, remanufactured, and rented to consumers once again in period 2.

In period 2, a new cohort of consumers enters the market. They face three choices: buy a new product, rent a new product, or rent a remanufactured product. The consumer’s utilities are as follows: if they buy the new product, they obtain a utility ; if they rent a new one, they obtain a utility ; if they rent a remanufactured one, they obtain a utility , where . Therefore, we obtain the indifferent consumers and derive the demand. Specifically, the demand for purchasing the new product is , that for renting the new product is , and that for renting the remanufactured product is .

Notice that the quantity of remanufactured products that can be rented in period 2, , is constrained by the quantity of rental units from period 1, , as only a fraction of the rented units in period 1 will be collected for refurbishing in period 2. Thus, we impose the condition . The inverse demand functions in the first period are  and . In the second period, they are given by, , and.

In this game, the manufacturer is the Stackelberg leader, and the remanufacturer is the follower. The sequence of events is as follows. The manufacturer decides whether to undertake integrated remanufacturing or outsource this to an independent remanufacturer. If the manufacturer undertakes integrated remanufacturing, they decide the production quantity required for the new sales units as  and the new rental units as  in period 1. At the end of period 1, the manufacturer takes back all rented products. In period 2, the manufacturer sets the production quantity for the new sales units as , that for the new rental units as , and that for the remanufactured units to be rented as . If the manufacturer chooses to outsource the remanufacturing activities, they set  and  in period 1. Later, in period 2, the manufacturer decides  and  and sets the outsourcing fee  for the used products paid by the third-party remanufacturer. Subsequently, the remanufacturer decides the remanufactured quantity to be rented, . This outsourcing fee *w* can be perceived as a licensing fee (see Oriopulous et al., 2012) because the remanufacturer is required to pay the manufacturer to access these products and ultimately sell or rent them.

To guarantee a positive profit, we require that the rental price exceeds the corresponding cost—, , and . Here, we limit our attention to scenarios where the remanufacturing cost is sufficiently low (). Namely, we assume that the remanufacturing cost is less than the discounted cost of producing the rental product (). This is a mild assumption and a considerably reasonable one, as if the remanufacturing cost is high, no refurbishing will occur.

***Assumption 1.***

An overview of the model parameters and decision variables is provided in Table 1. We denote the superscript I and O for integrating and outsourcing, respectively, and only use them when necessary.

**Table 1.** Model parameters and decision variables

|  |  |
| --- | --- |
| *Model parameters* |  |
|  | Manufacturing cost for the new rental product |
|  | Manufacturing cost for the new sales product |
|  | Remanufacturing cost for the integrated manufacturer |
|  | Consumer’s WTP for the new product |
|  | Consumer’s valuation discounting for the remanufactured product, |
|  | Product’s remaining value at the end of a period |
| *Decision variables* |  |
|  | Selling price for the new product in period *t*, |
|  | Rental price for the new product in period *t*, |
|  | Rental price for the remanufactured one in period 2 |
|  | Sales quantity of the new product in period *t*, |
|  | Rental quantity of the new product in period *t*, |
|  | Rental quantity of the remanufactured product in period 2 |
|  | Manufacturer’s outsourcing fee under the outsourcing strategy |

# Manufacturer’s remanufacturing strategy

We examine the manufacturer’s two remanufacturing strategies—integrated (Section 4.1) and outsourcing (Section 4.2)—and compare the two (Section 4.3).

# Integrated remanufacturing

Under integrated remanufacturing, the manufacturer produces the new product and collects the used ones from consumers and refurbishes them. Solving backwards, the manufacturer’s profit in period 2 is as follows:



In period 1, the manufacturer’s profit is given by the following:



We distinguish between two scenarios: when the rental product’s manufacturing cost is strictly less than the new product’s manufacturing cost, ; when these two costs are identical, .

# The case where

Let , , , and . Further, let denote the value of *c* that solves . Subsequently, we have the following result.

***Proposition 1.*** *Consider a manufacturer with integrated remanufacturing with . No rental, and hence, no remanufacturing takes place if* . *All rental products are remanufactured if* *. Finally, only partial remanufacturing takes place if* *.*

Under the manufacturer’s different remanufacturing scenarios in Proposition 1, the manufacturer makes the following sales and rental decisions.

***Result 1****. Regarding sales and rental: (i) No new products are sold in either of the two periods (**) if* *; (ii) All types of products are offered if*  *and* *; (iii) There are no new sales in the two periods, and no new rental products are offered in period 2 if*  and ; *(iv) There are no new rental products in period 2 if* *; (v) No rentals take place if* *. The complete sales and rental expressions are provided in Table 2.*



Figure 1. Sales and rental quantities as a function of *c* and *d*, with , , and .

Figure 1 illustrates the strategies as a function of varying *c* (*x*-axis) and *d* (*y*-axis) values, which corresponds with Table 2. It also reflects that the boundary values , , and  are increasing in .

Table 2 summarises the various ranges and the corresponding quantities from Proposition 1 and Result 1. It provides the following insights. First, when the new sales product’s manufacturing cost, *c*, is increasing, its quantity decreases, but that for the new rental product in both periods increase. Second, when the new rental product’s manufacturing cost, *d*, increases, the incentive to rent a new product diminishes, whereas that to rent the remanufactured one increases. Third, as the remanufacturing cost  rises, the quantity of the new rental (remanufactured) product increases in period 2. Finally, when the consumer’s WTP for the remanufactured product  is higher, more new sales product are sold, but fewer new products are rented in period 2. Additionally, for the remanufactured rental ones, the quantity is also impacted by the new rental product’s manufacturing cost . When  is sufficiently low (), the quantity of the remanufactured rental product increases. However, when  is high (), the quantity decreases in .

Consequently, we have the following implications. If the new rental product’s manufacturing cost is not so high (), the manufacturer can always benefit from conducting the remanufacturing activity. Meanwhile, when the manufacturing cost is sufficiently low (), it is better for the manufacturer to rent rather than sell in both periods. Finally, when the manufacturing cost becomes high (), the manufacturer should give up renting the new product in period 2.

**Table 2.** Sales volumes in each of the ranges when 

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Range |  |  |  |  |  |
| 1 (i) | and | 0 |  | 0 |  |  |
| 1 (ii) | and |  |  |  |  |  |
| 1 (iii) | and |  |  |  | 0 |  |
| 1 (iv) | and |  | 0 |  | 0 | 0 |
| 2 (i) | and | 0 |  | 0 |  |  |
| 2 (ii) | and | 0 |  | 0 | 0 |  |
| 2 (iii) | and |  |  |  | 0 |  |
| 2 (iv) | and |  | 0 |  | 0 | 0 |

Here,, , and . Furthermore, is the value of *c* that solves . For convenience of expression, let .

# The case where

*Letand . Subsequently , we have the following result.*

***Corollary 1.*** *Consider a manufacturer with integrated remanufacturing with . No rentals, and hence, no remanufacturing takes place if* ; *all rental products are remanufactured if*  *or* ; *only partial remanufacturing happens when*  *or* *.*

Under the manufacturer’s different remanufacturing scenarios in Corollary 1, the manufacturer has the following sales and rental decision results.

***Result 2****. When , the manufacturer does not rent the new products in period 2.* (*i) If* , *the manufacturer only sells the new product in both periods. (ii) If* *, the manufacturer sells new products in two periods, rents new ones in period 1, and rents remanufactured ones in period 2. (iii) If* *, the manufacturer sells new products in period 2 and rents in both periods (the new product in period 1 and the remanufactured one in period 2). The complete sales and rental expressions are listed in Table 3.*

The intuition is as follows. The relative cost advantage of the new rental product, which served as an instrument for facilitating market segmentation, diminishes. Accordingly, the profit gain from this product deteriorates; ultimately, the manufacturer stops renting the new product in period 2 and may only offer the remanufactured units. This has some managerial implications: when the manufacturing costs for the new sales and rental products are identical, the manufacturer should concentrate on selling the new product and renting the remanufactured one. Notice that this insight differs from that of Aras et al. (2011), who consider a manufacturer who offers its products to its customers only in either of the two ways: renting a new product and selling the remanufactured version of this product. Thus, these authors do not offer a rental option for the remanufactured product. Our findings are supported by some industrial examples, such as LIANDO Building Templates, which is a company based in China. This company offers its products to its customers in three different ways: selling new templates, renting new templates, and renting remanufactured ones. Owing to the low renting cost associated with the remanufactured templates, there is a greater need for renting these remanufactured building templates in the market. Thus, in practice, LIANDO mainly rents remanufactured building templates. Another classical example is Xerox’s printing machines. Fuji Xerox offers products containing remanufactured components in its rental service business.

Table 3 illustrates that when , the quantity of new products sold in period 1, , increases with the manufacturing cost *c*, which is a counter-intuitive result. This is because of the incremental decrease of the new rental product’s quantity as *c* increases. Thus, the manufacturer would produce more new sales products to gain profits.

Meanwhile, more remanufactured products are rented as the manufacturing cost *c* increases, while fewer new products are rented in period 1 as *c* increases. To some extent, this reveals that an increasing manufacturing cost improves the remanufacturing rate ().

|  |  |
| --- | --- |
|  |  |
| 1. The ranges of values with | 1. The ranges of values with |

Figure 2. The ranges of values of *c* and  when . The parameters are  and  and 0.2.

**Table 3**. Sales quantities in each of the ranges when 

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Cases | Range |  |  |  |  |
| 1 (i) |  |  |  |  |  |
| 1 (ii) |  |  |  |  |  |
| 1 (iii) |  |  | 0 |  | 0 |
| 2 (i) |  | 0 |  |  |  |
| 2 (ii) |  | 0 |  |  |  |

Here, ** is the boundary value of **. We see is *independent of c*r. When cr is sufficiently small, *.* For convenience of expression, let .

# Outsourcing to an independent remanufacturer to remanufacture the collected products

We assume that a manufacturer only sells or rents the new products in two periods. At the end of period 1, the manufacturer collects the used products. An independent remanufacturer pays an outsourcing fee (transfer price)  to the manufacturer for each remanufactured unit, remanufactures some (or all) units, and ultimately rents them for . To reflect the independent remanufacturer’s remanufacturing cost advantage over the manufacturer, we assume that the remanufacturer’s cost is zero, as in the study of Wu and Zhou (2019).

In this case, the manufacturer lets the remanufacturer to remanufacture and directly compete with the manufacturer as the remanufacturer can rent the remanufactured products. This is an important distinction. However, the manufacturer can control the flow of remanufactured products by adjusting .

In period 2, the manufacturer’s profit becomes the following:



.

The remanufacturer’s profit is as follows:

.

In this Stackelberg game model, we solve the optimal decisions by backward induction.

# The case where

Let ** and **. Subsequently, we have the following results.

***Proposition 2.*** *Consider a supply chain with outsourced remanufacturing with . (1) When  and , in period 1,  and , and in period 2, , , , and .*

*(2) When  and , the optimal decisions are as follows: , , , , , and .*

Note that the value of  was defined in Section . From Proposition 2, we have the following implications. When the new sales product’s manufacturing cost *c* is sufficiently high, the manufacturer will not sell new products at all in both periods and will only rent them out. This case is suitable, for example, in the renting business of high-end cameras in the film industry. In this market, these high-end cameras are considerably expensive, and the filming crew requires the cameras only for a short period. Moreover, the manufacturer offers the remanufacturer the returned products for free (). This reveals that under some conditions, the entry of a competitor (remanufacturer) enhances supply chain’s profits. Thus, the manufacturer induces the remanufacturer into entering the market by offering a free licensing fee (setting  to 0).

Additionally, we find that the optimal outsourcing fee  is independent of the manufacturing costs *c* and *d* in each of the two ranges.

# The case where

For a special case , we obtain Corollary 2.

***Corollary 2.*** *In the decentralised supply chain with  and* *, (1) when , the optimal decisions are as follows: , , , and . In period 1,  and . (2) When , the optimal decisions are as follows: , , , ,, and , where* *, and  and  are the same as before.*

Corollary 2 implies that when the manufacturing costs for selling and renting the new product are same (), in period 2, the manufacturer would sell but not rent the new product. This result is different from Proposition 2.

# Comparison of the results under the two remanufacturing strategies

Here, we compare the quantity decisions and profits under the two remanufacturing strategies: integrated and outsourced.

# Comparing the quantity decisions

Comparing the quantities under outsourced remanufacturing (Proposition 2) with that under integrated remanufacturing (Proposition 1), we derive Corollary 3.

***Corollary 3.*** *When , (i) fewer units are remanufactured under the outsourcing strategy than under the integrated strategy. Further, (ii) if the remanufacturing cost under integrated remanufacturing strategy  is lower than the boundary value , the rental quantity of the new products under integrated remanufacturing is smaller than that under outsourced remanufacturing.*

Corollary 3 implies when is small and ** is sufficiently low, outsourcing may lead to less remanufacturing while increasing the rentals of new ones. This also indicates that when the new rental product’s manufacturing cost is low, outsourcing remanufacturing is disadvantageous under the competition status.

Additionally, when the new rental product’s manufacturing cost  is sufficiently low, the quantity of new rental products under the two scenarios is impacted by the remanufacturing cost .

# Comparing the profits

We compare the manufacturer’s profit under the two scenarios to show the conditions under which the manufacturer will choose to open up the market for remanufacturing. In Appendix B, we provide some explanations on when the manufacturer should conduct remanufacturing. Owing to the complex expressions of decisions and profits in two scenarios, we employ numerical examples to illustrate how the new rental product’s manufacturing, *d*, impacts the manufacturer’s remanufacturing decisions (i.e. profits).

**4.3.2.1 The case where ****

To compare the profits under the integrated producing strategy (Section 4.3.1) with that under the outsourcing strategy, consider the following two panels in Figure 3.

|  |  |
| --- | --- |
|  |  |
| a. The manufacturer’s profit with | b. The manufacturer’s profit with |

Figure 3. The impact of *d* on the manufacturer’s profits (). The parameters are , , , and  or 0.5 (to reflect the cases where and , respectively).

The boundary value for opening up the remanufacturing activity is impacted by the parameters , , and .

From Figure 3, we have several insights:

***Observation 1.*** *Under both remanufacturing strategies, the manufacturer’s profit decreases with the new rental product’s manufacturing cost, d, because an increase in d heavily decreases this product’s production quantity and its ability to segment the demand.*

***Observation 2.*** *When the new rental product’s manufacturing cost, d, is sufficiently high, the manufacturer outsources the remanufacturing activities. However, when d is sufficiently low, the manufacturer undertakes integrated remanufacturing. According to Observation 1, the manufacturer loses from renting the new product and only wins some profits from concentrating on selling it. Thus, giving up rentals implies giving up remanufacturing. However, when d is small, segmenting the demand induces remanufacturing of some or all products.*

**4.3.2.2 The case where ****

To compare the manufacturer’s profits under the two remanufacturing strategies, we plot Figure 4.

|  |  |
| --- | --- |
|  |  |
| a. Manufacturer’s profit in *c* with  and | b. Manufacturer’s profit in *c* withand |

Figure 4. Manufacturer’s profit varies in *c* when . The parameters are , , and  and 0.3, correspondingly satisfying  and , respectively.

Figure 4 reveals that the manufacturer has some similar behaviour in two cases:  and . When the manufacturing cost *c* is larger than  and lower than a boundary value (), the manufacturer chooses to outsource the remanufacturing to a third-party remanufacturer. Otherwise, when the manufacturing cost *c* is sufficiently low () or sufficiently high (), the manufacturer makes more profit from integrated remanufacturing. It is because a lower manufacturing cost *c* can help the integrated manufacturer control all production activities and gain a high margin profit from both the sale and rental products. Moreover, when *c* is sufficiently high, the integrated manufacturer would only focus on the new sales product and cease all rental and remanufacturing activities.

# Extensions

We consider four extensions. In subsection 5.1, we consider the quality risk of the used products. In subsection 5.2, we consider consumers who rent in period 1 and return in period 2. Further, in subsection 5.3, we investigate the scenario where consumers who purchased the new product in period 1 are allowed to return their product. Moreover, in subsection 5.4, we let the remanufactured products to be sold in period 2 as well. In subsection 5.5, we extend our view to a longer horizon and consider the product’s life cycle. Finally, we consider that the production costs of both types of products are linked.

# Accounting for quality risk of the returned used products

In this extended model, we assume that the quality of the used product is uncertain—product usage by consumers during the first period is uncertain; hence, the remanufacturing cost of the different collected units is also uncertain. As discussed in Section 3, the remanufactured product has a lower quality than that of the new one. However, the remanufacturer needs to set a minimum quality level for the collected product that can be used for remanufacturing.

In Wang et al.’s study (2017), the decision of whether to remanufacture a used item depends on the item’s quality, . We assume that  is a random variable distributed over  with a density function and cumulative distribution function .

The remanufacturing rate is, where  is the minimum quality of the collected product required for remanufacturing. This is a decision variable. Subsequently, the remanufactured amount is . As the collected units have different qualities, we assume the unit remanufacturing cost to be a linear decreasing function of the quality of the used product, , where  is the remanufacturing cost when the used product has a quality .

We first discuss the relationship between the remanufactured quantity  and the demand for the remanufactured product  in the second period. Here, we require , such that the remanufactured amount can satisfy the consumer’s demand for the remanufactured product.

***Proposition******3.*** *Assume* *follows an increasing failure rate (IFR) distribution, where F () is strictly increasing in .  satisfies the following equation:*

.

To obtain some analytical results, as a special case, we assume that  is uniformly distributed over [0, 1]. The total remanufacturing cost is then a function of  such that . Next, we consider the quality decision under integrated remanufacturing (subsection ) and outsourced remanufacturing (subsection ).

# Quality decision of the used product under integrated remanufacturing

Considering the used product’s quality, we derive the following conclusions:

***Proposition 4.*** *Consider an integrated remanufacturing with .*

*(1) When , (i) if , the minimum quality level of the collected product is* ; *(ii) if ,* *; (iii) if , *.

*(2) When , (i) if , the minimum quality level of the collected product is* *; (ii) if , ; (iii) if , .*

From Proposition 4, we know that when the new rental product’s manufacturing cost, , is sufficiently low (), the quality level of the used product is strictly positive. This means that only some of the used products from period 1 are refurbished in period 2, and a 100% remanufacturing rate cannot be achieved. Additionally, the minimum quality level of the used product  increases with the remanufacturing cost coefficient  but decreases with the consumer’s WTP for the remanufactured product . However, when the new rental product’s manufacturing cost, , is sufficiently high (), the quality level of the used product is set at 0, implying a 100% remanufacturing rate and a perfect use of resources. This is because the higher cost for the new rental product induces higher demands for the remanufactured product so that the minimum quality level of the collected product decreases.

We analyse the impact of quality uncertainty of the used products on the remanufacturing cost, order quantities, and profits.

***Observation 3****. The remanufacturing cost  increases with the consumer’s WTP for the remanufactured product . Additionally, with an increasing , the remanufacturing cost decreases.*

This result is counter-intuitive. This occurs because the remanufacturing rate  dramatically decreases with .

***Observation 4****. Considering the quality uncertainty of the used product, the manufacturer’s profit first increases and then decreases with the consumer’s WTP for the remanufactured product .*

Note that Observation 4 provides an insight different from the previous results, where the manufacturer’s profit monotonously decreases in .

 

|  |  |
| --- | --- |
| a. Different remanufacturing cost  values | b. Different remanufacturing cost values |

Figure 5. The manufacturer’s profits as a function of . The parameters are , , and .

When there is no difference between the manufacturing cost of the sales and rental products, , the minimum quality level of the collected product  is given as follows.

***Corollary 4.*** *Consider an integrated remanufacturing strategy with .*

*(1) When , (i) if , ; (ii) if , .*

*(2) When , (i) if , ; (ii) if , .*

This shows that when the new product’s manufacturing cost, *c*, is sufficiently high (), the quality level of the used product needs to be larger than some strictly positive . However, when the new product’s manufacturing cost is low (), the threshold quality level of the used product drops to 0, and we achieve a 100% remanufacturing rate.

# Quality decision of the used product under outsourcing remanufacturing strategy

When the manufacturer outsources remanufacturing, the minimum quality level of the used products  is as follows.

***Proposition******5.*** *Consider an outsourcing remanufacturing strategy with .*

*(1) When  and , the minimum quality level of the collected products is .*

*(2) When  and , the minimum quality level of the collected products is .*

Proposition 5 reflects that when the manufacturer outsources remanufacturing with **, when the new product’s manufacturing cost *c* is smaller,  decreases in  and increases in *c*. When *c* is larger,  is independent of *c*.

For the special case where , we have Corollary 5.

***Corollary 5.*** *Consider an outsourcing remanufacturing strategy with .*

*(1) When , the minimum quality level of the collected products is .*

*(2) When , the minimum value of is .*

Contrary to Proposition 4, Corollary 5 shows that when the manufacturer outsources remanufacturing with , the minimum quality level of the collected products  decreases with the new product’s manufacturing cost *c*.

# Considering consumers who rent in period 1 and return in period 2

In this extended model, we consider consumers who rent in period 1 and return in period 2 to possibly rent the new product again. We examine how the existence of these consumers impacts the manufacturer’s optimal decisions.

We consider two cases based on whether the amount of used product is sufficient or insufficient for the second period (i.e. whether  or , respectively).

**5.2.1** **The used product is sufficient** **()**.

**Table** 4. The optimal values in the basic and extended models, where the parameters are , and .

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Decision variables |  |  |  |  |  |  |
| Basic model | 0 | 0.625 | 0 | 0.1875 | 0.2344 | 0.1535 |
| Extended model with | 0.391 | 0.028 | 0.3864 | 0.028 | 0.0075 | 0.3204 |

Compared with the optimal decisions in the basic model, we find that when consumers who rent the new product in period 1 return in period 2, a significant proportion of them choose to buy the new product, while fewer consumers rent both the new and remanufactured products. Consequently, the manufacturer earns more profit. Thus, the manufacturer should transfer the focus of activities from leasing to selling.

**5.2.2 The used product is not sufficient ()**

**Table** **5**. The optimal values in the basic and extended models, where the parameters are , and .

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Decision variables |  |  |  |  |  |  |
| Basic model | 0.1042 | 0.3472 | 0.1458 | 0 | 0.3472 | 0.158 |
| Extended model () | 0.1971 | 0.1261 | 0.1365 | 0.1261 | 0.1261 | 0.137 |

Table 5 shows that leasing the new product in both periods reduces the manufacturer’s profits. In the basic model, the manufacturer’s optimal decision is giving up leasing the new product in period 2. This is because the manufacturer can earn more profit from renting the remanufactured product than renting the new product. However, in this model, continuous leasing of the new product restrains the rental quantity of the remanufactured product.

**5.3 Allowing consumers who purchased the new product in period 1 to return it**

In practice, some consumers may also be willing to return the products they purchased at the end of period 1 for different reasons (e.g. the consumer’s environmental consciousness, or the product cannot fulfill the consumer’s needs any more in the following periods). We call this ‘consumer returns’. Thus, if the proportion of these consumers is , the quantity of consumer returns will be . Subsequently, the remanufactured quantity should be smaller than . Further, the new constraint, , should be inserted into the previous/basic model from Section 4.1. In the following, we examine how the parameter  impacts the optimal decisions. Here, we also introduce a buyback price *b*, and let , , , , , and . Subsequently, we derive the following results:

(1) Allowing consumer returns enlarges the collected units available for remanufacturing, which raises the boundary value .

(2) Refer to Table 2. When , we only need to replace with . Obviously, with  increasing,  and  decrease, and the total profit reduces. This is because the remanufactured quantity in period 2, , is independent of  and . Although accepting these consumer returns increases the returned quantities, the remanufacturing rate cannot be improved. Therefore, it rather increases the manufacturer’s cost burden; consequently, the profit decreases.

When , the rental quantity in period 1, , first decreases and then increases with . The sales quantities in both periods 1 and 2 decrease with . The remanufactured quantity in period 2, , increases with . Consequently, the manufacturer’s profit decreases with both  and ; the manufacturer will obtain the maximum profit at  and . This means that permitting consumer returns cannot make the manufacturer earn more profit even if .

# 5.4 Remanufactured product can be sold in period 2

Thus far, we have assumed that the remanufactured units can only be rented during period 2. Here, we relax this assumption: the manufacturer or remanufacturer can rent and sell the remanufactured product in period 2.

In period 1, the demand functions are as before. That is, the demand for purchasing the new product is , and that for renting the new product is . Correspondingly, the inverse demand functions in the first period are  and , respectively.

In period 2, as a new cohort of consumers enters the market, they face four choices: buy a new product, rent a new product, buy a remanufactured product, or rent a remanufactured product. The consumer’s utilities are as follows: to buy the new product, ; to rent a new product, ; to buy a remanufactured product, ; to rent a remanufactured product, , where .

Therefore, the demand for purchasing the new product is , that for renting the new product is , that for purchasing the remanufactured product is , and that for renting the remanufactured product is .

These lead to the following inverse demand functions in the second period: , , , and , respectively.

When the remanufacturing cost  is low, there is little room for differentiation between renting and selling the remanufactured product. Thus, we assume that the remanufacturing cost for selling and renting is equal to *cr* (Agrawal et al., 2012).

Under the manufacturer’s integrated remanufacturing strategy, the manufacturer produces the new product and collects and remanufactures the used product by itself at the end of the first period. In period 2, the manufacturer’s profit under the centralised scenario becomes the following:

.

In period 1, the manufacturer’s profit expression is the same as before:



.

Notice that the quantity of remanufactured products in period 2, , is constrained by the amounts of rental products from period 1, . Thus, we impose . Obviously, when the manufacturer’s remanufacturing cost for selling and renting the product is identical, the manufacturer does not rent the remanufactured product, .

Solving backwards, we obtain the manufacturer’s selling or renting decisions as a function of *c* and *d*. Here, letting , we only highlight the following interesting results.

***Proposition 6.*** *When remanufactured products can be sold, if* *, the manufacturer undertakes remanufacturing (sells the remanufactured products)*. *Moreover*, *if* *, the manufacturer partially remanufactures; if* *, the manufacturer fully remanufactures.*

Comparing Propositions 1 and 6, notice that the conditions for the manufacturer’s remanufacturing decisions are similar. This shows that our research results are robust.

Next, we evaluate the influence of the change in the consumer’s decision sequence. We consider that consumers prefer buying the remanufactured product than renting the new product. That is, the consumer’s preference is to buy new, buy remanufactured, rent new, and rent the remanufactured. Accordingly, the consumer’s utilities are as follows:, , , and , respectively.

Subsequently, the inverse demand functions are as follows:

,

,

, and

.

Inserting the above inverse demand functions into the manufacturer’s profit function in Section 5.2, we can solve the manufacturer’s optimal decisions. Next, under the condition of , the optimal decisions are derived: ,,, and .

The decision results are intuitive. When the sales price for the remanufactured product, , is higher than the leasing price for the new product, , but the remanufacturing cost, *cr*, is much less than the new rental product’s manufacturing cost, *d*, the manufacturer obviously gains more profit from selling the remanufactured product. Therefore, the manufacturer gives up renting the new product in period 2. There is a similar reason for giving up renting the remanufactured product. This result is different from that of Aras et al. (2011), who assume that the remanufactured product can only be leased. From the perspective of consumer preference, it is wiser for the manufacturer to sell the remanufactured product.

# 5.5 Longer horizons and the product’s life cycle

Next, we consider a three-period model. The rental remanufactured products in period 3 are collected from the rented new products and remanufactured products in period 2. Here, similar to EI Saadany et al. (2013), we introduce a parameter, which denotes the proportion of the collected/used units that can be used for remanufacturing for the next period. This also means that the returned products cannot be remanufactured infinitely. In period 3, the quantity of the sales remanufactured product cannot be more than . That is, .

Consumers still have three choices: buy new, rent new, or rent remanufactured. The demand function is same as that in period 2. Solving backwards, we have the following process.



In period 2, the manufacturer’s profit is as follows:



In period 1, the manufacturer’s profit is given by the following:



Let . When  (), the demand for remanufactured products can be satisfied. In period 3, the optimal sales/rented quantities are the same as that in period 2. Here, notice that . This means that the boundary for renting the remanufactured products decreases, and more consumers would like to choose the remanufactured product. When  (), the demand for remanufactured products cannot be satisfied. Subsequently, the optimal sales/rented quantities may be changed. Let  and insert it into the above profit function . Next, the optimal decisions can be obtained (see the appendix). In this subsection, we focus on the latter scenario.

From the decision results, we find that both the sales quantities for the new product in periods 2 and 3 are zero, . This shows that selling the new product means losing the market advantage. To obtain some insights, we use some examples to illustrate the change of optimal selling, renting, and remanufacturing decisions with the increase in the operations periods and how parameter  impacts the optimal decisions.

Referring to Table 2, we illustrate the following three cases: (a) and ; (b)  and , then ; (c) , then .

 

(a) a=0.5, e=0.8, cr=0.1, c=0.3, d=0.15; (b) a=0.5; e=0.8; cr=0.1; c=0.4; d=0.15;

;  ; 



(c) a=0.5; e=0.8; cr=0.15; c=0.4; d=0.25;

; 

Figure 6. The quantities in a three-period model.

From the above figures, we have the following observations:

(1) With an increasing number of periods, there are more used products that can be used for remanufacturing, which helps satisfy the demand from more consumers interested in remanufactured products (). Therefore, the manufacturer should pay more attention on the remanufacturing activity.

(2) As the parameter  increases, the quantity of rented remanufactured product in period 2, , first increases and then decreases.

**5.6 Production costs of both types of products are linked**

Even if the new products destined to be sold and rented differ in some features, they may still share some product commonality, such as certain components. Consequently, they may be produced on the same equipment. Considering this, it may make sense to assume that the production costs of both types of products may be linked. Similar to Li et al. (2018), we let  and , where , and reflect the degree of product differentiation among the three types of products (the new sales product, the new rental product, and the remanufactured product, respectively). Simultaneously replacing  with  and  with in Table 2, we obtain the optimal decisions under the new expression of manufacturing cost. Subsequently, if *c* remains constant and  increases, the new rental product’s manufacturing cost  increases. For example, let and  vary from 0 to 0.5, which is equivalent to letting *d* vary from 0 to 0.2. Thus, as both *d* and *c* are exogenous parameters, the new cost expressions do not change the properties of the optimal decisions.

# Conclusions

Remanufacturing strategies become increasingly important in theoretical research and industrial practice. Our study fills an important gap by combining both the manufacturer’s rental or sales decisions for new and remanufactured products in a unified two-period model, considering a competitive and cooperative relationship between the manufacturer and the remanufacturer and incorporating quality uncertainty of used products. We find that the manufacturing costs of the rental and sales products critically impact the manufacturer’s renting or selling decisions. When the new rental product’s manufacturing cost is sufficiently high, the manufacturer will not rent the new product. When this manufacturing cost is even higher, outsourced remanufacturing can be more beneficial for the manufacturer than integrated remanufacturing.

Our results can provide some managerial suggestions for the firms that face renting or selling and remanufacturing decisions. Specifically, we briefly discuss some key results. The manufacturer can offer different products and apply different remanufacturing strategies based on the relative manufacturing costs of sales and rental products. When the new rental and sales products have different manufacturing costs, and the rental product’s manufacturing cost is relatively high, then the manufacturer should outsource remanufacturing to an independent remanufacturer. However, when the rental and sales products have identical manufacturing costs, the manufacturer should undertake integrated remanufacturing if the manufacturing cost is either sufficiently low or sufficiently high; otherwise, outsourcing is preferable. Additionally, considering the quality uncertainty of the used product, the remanufacturing cost under integrated remanufacturing will increase with the consumer’s WTP for the remanufactured product. Subsequently, the manufacturer’s profit would first increase and then decrease. This is different from the results under an exogenous remanufacturing cost.

Our study has some limitations. First, in our model, there is one manufacturer and one remanufacturer, and we assume that they handle all processes such as producing, collecting, and selling the products by themselves. However, in practice, the collection channels may be diverse, such as a third-party collection. Therefore, multiple supply chain members can be considered. Second, our insight that returning used products reduces the manufacturer’s profit may disagree with some practical observations. For instance, mobile phone providers lure customers to return their phones so that their customers can purchase instead a newer model (new or remanufactured). This is, indeed, a lucrative segment of consumers that our model does not fully address. One could be the manufacturer’s incentive to shorten the duration of time that consumers hold on to their products, which can be explored in future research along with the concept of trade-in programmes and their impact on the manufacturer’s selling or renting strategy. Last but not least, government regulation is considerably important in guiding firms’ production planning. If governments introduce a positive policy (e.g., reducing the firm’s tax cost or increasing the subsidy) for remanufacturing activities, then the firm may have a greater motivation to put more efforts on remanufacturing. Hence, future research can incorporate the government’s subsidy for remanufacturing and consider its effect on the manufacturer’s strategic decisions.

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# Appendix A: Proofs

**Proof of Proposition 1:** For , its first order conditions with respect to , , and , respectively, are as follows:

,

, and

.

First, only if , the optimal values of  , , and  exist by simultaneously solving the above three equations.

The condition () means that the renting quantity in period 1 can satisfy the demand for the remanufactured product in period 2 (). If , then the renting quantity in period 1 cannot satisfy the demand for the remanufactured product in period 2 (). Subsequently, we consider a binding problem and replace  with  in the profit function . In period 2, the manufacturer decides  and . Furthermore, in period 1, they decide  and .

Therefore, the optimisation problem of the manufacturer in period 2, , has the following constraints:  and .

The above problem can be changed into the following:



Subsequently, we derive the optimal decision: .

Inserting  into ,  is a function of . Subsequently, we consider the optimisation of the profit function of period 1 as follows:

. 

**Proof of Corollary 1:** When , the optimal values exist if .

It is always .First, we check the following decisions:

, ,, and , .

Subsequently, we need to check the range of the existence of optimal values. Letting , we have . Furthermore, letting , we have . Comparing the two boundary values, we find that . Therefore, when , we have and .

Additionally, when , we have , and  and . Furthermore, when , we have  and .

(1) When , we have , and  and . Subsequently, the optimal quantity decisions are .

(2) When , we have  and . We also check the size relationship between  and . If , the remanufacturing cost  is sufficiently low, and the optimal quantity decisions are , , , , and . In this case, .

If , then . We consider the binding problem, and and . 

**Proof of Proposition 2:** In this decentralised system, we only consider the decisions under . That is, the renting price for the new *d* is lower than a boundary value , (), where  is the solution of . As if , we need to substitute  for  in the expression , and then the remanufacturer will not make any decision. In other words, there is a larger demand for the remanufactured product in the market; therefore, manufacturers will maximise their market share and let  (). The remainder is the same as that in the centralised case.

In this Stackelberg game, we solve the optimal decisions by backward induction. In period 2, we first solve the equation  and then obtain the reaction function . Inserting  into  and solving the equations , , and , we obtain the optimal decisions: , , , and .

That is, , , , and . In period 1, and .

Using a similar way to Proposition 1, we observe these optimal solutions and determine their size relationship. Subsequently, we conclude Proposition 2. 

**Proof of Proposition 3:**

In Section 5, we assume that  follows an increasing failure rate (IFR) distribution, where *F*() is strictly increasing in . The remanufacturing rate is, where  is the minimum quality of the collected product required for remanufacturing.

The remanufacturing cost is , and the expected remanufacturing cost can be expressed as . Therefore, the quality level of the used product impacts the remanufacturing rate and cost.

The minimum quality level of the collected product satisfies the following relationship: .

From Table 2,  is independent of , and . Subsequently, the expected remanufactured quantity can be computed as follows:



Thus, satisfies the following equation:

. 

**Proof of Proposition** **4:**

When follows a uniform distribution in [0, 1], we have  and . Thus, the minimum quality of the collected product satisfies . The expected remanufacturing cost  can be expressed as . From Table 2, we have . Subsequently, the expected remanufactured quantity , and  is independent of . Therefore, satisfies the equation: .

Solving the above equation, we obtain the minimum quality of the used product . 

**Proof ofCorollary 4:** Combining with Table 3, the minimum quality of the used product satisfies the following equation: .

Solving the above equation, we obtain the minimum quality of the used product . 

**Proof of Proposition 6:** In Section 5.2, (1) when , simultaneously solving the following four equations,, , , and , we derive the following decisions:

, , , and .

Notably, these optimal values exist if , and the remanufacturing cost  needs to satisfy the following: .

Subsequently, the remanufactured quantity for renting —the manufacturer should not rent the remanufactured product. Consequently, in period 2,

, , and .

In period 1, and .

(2) When , the maximum quantity for selling the remanufactured product  is equal to .

The following solving process is similar to Proposition 1. 

**Section 5.4:** The consumer’s decision sequence changes.

When the sale quantities for the remanufactured in period 2, , is larger than the rental quantities in period 1, , that is, , the manufacturer’s optimal decisions are as follows: ,

, and

. 

**Section 5.5:** Let , which is the solution obtained by solving the equation . When , the quantity of the sales remanufactured product  in period 3 is smaller than the maximum collected quantities at the end of period 2, . Therefore, the demand for remanufactured products in period 3 can be satisfied. Subsequently, the optimal sales/rented quantities in period 3 are the same as that in period 2.

However, when , the demand for remanufactured products cannot be satisfied, and the optimal sales/rented quantities may be changed. Let  and insert it into the above profit function . Subsequently, we discuss the optimal decisions under the following three cases.

(a) When , if , the optimal decisions in the three periods are as follows:

，, ,, , and

. In period 1, and .

(b) When , if ,

, , and .

(c) When , if ,

,

, and

. 

# Appendix B: Should the manufacturer undertake remanufacturing?

**A case: No remanufacturing**

When the manufacturer only produces the new product and does not remanufacture, the optimal decisions become as follows:

 and .

The manufacturer’s profit is as follows:

.

In the centralised scenario, the boundary value  is . Let  and 0.5, respectively. Subsequently, we compare the profits under integrated producing with no remanufacturing using two figures.

**(1) The case d < c**

|  |  |
| --- | --- |
|  |  |
| a. The manufacturer’s profit () | b. The manufacturer’s profit () |

Figure b1. The impact of *d* on the manufacturer’s profit ()

From Figure b1, we find that when the new rental product’s manufacturing cost is sufficiently low, the manufacturer will not undertake remanufacturing.

**(2) The case d = c**

|  |  |
| --- | --- |
|  |  |
| a. The manufacturer’s profit () | b. The manufacturer’s profit () |

Figure b2. The impact of *c* on the manufacturer’s profit ()

Figure b2 shows that when the manufacturing cost for selling/renting the new product is sufficiently low, the manufacturer will not undertake remanufacture. However, if the manufacturing cost for selling/renting the new product is sufficiently high, the manufacturer will benefit from remanufacturing.

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