Impact of Market Competition on Remanufacturing Investment

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Abstract

This study considers supply chain competition in which two symmetric manufacturers compete in both the new and remanufactured products markets. To engage in remanufacturing, the two competing manufacturers must appropriately determine their remanufacturing capability and design new products to facilitate their competition in remanufacturing. This inevitably changes the competing manufacturers' cost structure in terms of both fixed and variable costs. The problem is formulated as a two-stage game. Therein, the competing manufacturers first determine whether to invest in remanufacturing, followed by determining the production quantities of new and remanufactured products if they decide to invest in remanufacturing. Our analytical results reveal that the equilibria associated with the three scenarios in which both manufacturers invest, neither manufacturer invests, and either manufacturer invests can be conditionally achieved, depending on the fixed cost incurred in developing remanufacturing capability and the difference between marginal costs associated with new and remanufactured products. Furthermore, it is found that despite the cost structure changes, remanufacturing investment can expand the two competing manufacturers' market shares and outweigh the cannibalization effect between new and remanufactured products, resulting in higher profits. Nevertheless, the competing manufacturers may be trapped in a prisoner's dilemma when they both invest in remanufacturing operations. By comparing the environmental impact with and without remanufacturing investment, the result suggests that remanufacturing investment may not be environmentally friendly, especially when the cost difference between new and remanufactured products is significant. Finally, the subsidy policy is proven to benefit manufacturers in gaining more profits and promoting the development of the remanufacturing industry but may cause an unanticipated negative overall outcome on the environment.

Managerial relevance statement: In this study, we draw insights for manufacturers that consider investing in remanufacturing operations in a competitive setting, aiming to maximize total profit for the manufacturers. The results obtained in this study could help competitive manufacturers make remanufacturing-related decisions in the following dimensions: (1) optimal decisions when different remanufacturing investment decisions are made; (b) Nash equilibrium for the two manufacturers regarding their remanufacturing investment decisions; (c) impact of operational factors on market equilibrium; (d) environmental impact of manufacturing and remanufacturing; and (e) impact of government subsidy.

Keywords: Remanufacturing investment; closed-loop supply chain; game theory; competition

1. Introduction

The increased concerns about the environment and public health motivate many governments to enact regulations to force manufacturing firms to take significant steps on the appropriate treatment of end-of-life products [1]. In Europe, a policy named Individual Producer Responsibility (IPR) has been implemented by governments and successfully drawn the attention of the European Commission. According to IPR, each producer is responsible for the entire life-cycle of the products, and producers are encouraged to improve the design of their products to facilitate product recovery or recycling [2]. In line with the principles of IPR, many manufacturing firms are making significant progress in managing used products. For example, companies such as Sandvik and ISCAR recycle used products to create an alternative supply source of key raw materials [3]. At the business strategy level, manufacturers can use remanufacturing to defend their market share through price discrimination [4]. This is because remanufacturing restores used products to like-new or as-new conditions by recovering value from used products, replacing components, or reprocessing used parts [5-7]. A lower price is one of the remanufactured products' competitive advantages [8, 9]. As such, remanufactured products can capture sales to "low-end" customers. In addition, remanufacturing is often considered a sustainable practice that mitigates environmental burdens by using fewer virginal materials and preventing waste [10, 11].

However, some outstanding concerns have prevented manufacturers from entering the remanufacturing business. The cannibalization effect between new and remanufactured products has been widely acknowledged. When remanufactured products are introduced to the market, customers' demand for new products would be cannibalized by the existence of remanufactured products [7, 9, 12-18]. This cannibalization effect is usually the main concern for most manufacturers and prevents many from taking further steps in entering the remanufacturing business. For example, the strategy of Alpha, an equipment company that specializes in computer network equipment design, marketing, and sales, is to exclude remanufactured versions of its products for fear of market cannibalization even though its annual return volumes are worth about $800M [13]. Second, remanufacturing needs to be taken into consideration during the product design stage, which means that new products may have to be redesigned to facilitate product recovery, recycling, and remanufacturing processes. Otherwise, remanufacturing will face technical barriers. For example, remanufacturing printer cartridges often faces technical challenges if irreversible manufacturing is implemented in the product design stage [19]. iPhone 7 and iPhone 7 Plus would be disabled by Apple if home buttons and screens were replaced by unauthorized service centers [20]. Product redesign will inevitably change manufacturers' cost structure in terms of both variable and fixed costs. For example, to allow remanufacturing, additional processes may need to be added to the production process, which increases the production cost of new products [2, 14, 21, 22]. At the same time, manufacturers need to incur a one-time initial fixed investment cost to develop remanufacturing capabilities [18]. Therefore, the change in the cost structure should be considered when remanufacturing investment decisions are made, though the design for remanufacturing or product recovery has been highly encouraged by regulators for manufacturers to fulfill their IPR.

Remanufacturing investment can help manufacturers reach "low-end" customers who, in general, will not or may not be able to purchase new products because of their tight budget [9]. Remanufactured products that are offered at lower prices become perfect alternatives for those customers to satisfy their needs [23]. The market shares of manufacturers' will be naturally expanded by reaching out to these customers, resulting in a market expansion effect for those firms that invest in remanufacturing operations [14]. On the other hand, remanufacturing investment requires manufacturers to redesign their new products so that there are no technical barriers in the remanufacturing process. The redesign will inevitably change the cost structures of those manufacturers by increasing the fixed and variable costs of new products, resulting in a cost-increasing effect of remanufacturing. Furthermore, customers' demand for new products will be cannibalized by the existence of remanufactured products because some customers, especially those with a limited willingness to pay, will switch to purchasing remanufactured products instead of buying new products. The effects discussed above create critical trade-offs for manufacturers in making remanufacturing decisions. Hence, they must carefully consider when remanufacturing decisions are made, that is, whether the benefits brought by the market expansion effect can outweigh the profit loss caused by the cost-increasing effect and the cannibalization effect between new and remanufactured products.

Market competition among manufacturers is another key factor to the success of the remanufacturing business and must be considered in making an investment decision on remanufacturing. It is common that competing manufacturers also compete in the remanufacturing business. In countries such as Germany and Austria, a competitive take-back scheme is implemented. Under such a scheme, the management of used products is completely left to the discretion of individual manufacturers. Therefore, when it comes to remanufacturing investment in a competitive environment, a manufacturer not only needs to consider its operational factors but also the strategies that its competitor adopts. In the smartphone industry, Apple engages in remanufacturing operations and offers remanufactured products on its official website, whereas Huawei, Apple's main rival in the Chinese market, does not engage in remanufacturing at all [7, 18]. In the personal computer industry, both Hewlett-Packard and Dell are involved in remanufacturing operations [18, 24, 25]. The market competition induces manufacturers to adopt different remanufacturing strategies, and the diverse industry practice provides little guidance for manufacturers in making remanufacturing decisions. Therefore, it is necessary to develop a systematic approach to help manufacturers make optimal remanufacturing decisions.

This study aims to provide remanufacturing investment decision guidance for competing manufacturers. Remanufacturing investment refers to the industry practice of making proper changes in the design of new products so that they are remanufacturable [14, 21]. Hence, a manufacturer's remanufacturing investment starts at the design stage of new products and does not involve the design of remanufactured products. We consider a supply chain consisting of two symmetric manufacturers that sell perfectly substitutable new products directly to the market. The two manufacturers can engage in remanufacturing. Two remanufacturing strategies are available for the manufacturers: (a) remanufacturing some but not all available used products and (b) remanufacturing all available used products. The two manufacturers decide whether to engage in remanufacturing operations and to what extent, if they choose to engage in remanufacturing. The manufacturers develop remanufacturing capabilities and incur a one-time initial fixed cost. In addition, necessary changes must be made in the design of the new product so that there are no technical barriers during the remanufacturing phase. This change in product design usually increases the production cost of the new product. Obviously, one manufacturer's remanufacturing investment decision is affected by the other's. Therefore, the following research questions are addressed in this study:

(1) What are the two manufacturers' optimal responses when different remanufacturing strategies (i.e., remanufacture some but not all available used products, and remanufacture all available used products) are implemented under different remanufacturing investment decisions (i.e., investing in remanufacturing or not investing in remanufacturing)?
(2) What are the equilibrium outcomes for the two manufacturers concerning their remanufacturing investment decisions? Can the two manufacturers both benefit from the equilibrium outcomes? Are the equilibrium outcomes environmentally friendly for the whole society?
(3) How is the market equilibrium affected by the cannibalization effect between new and remanufactured products?
(4) What is the impact of the production cost structures on the manufacturers' remanufacturing decisions?

To encourage a remanufacturing and circular economy, some governments have implemented incentive programs promoting remanufacturing. For example, in 2009, the Chinese government released the Circular Economy Promotion Law to encourage automobile manufacturers to engage in remanufacturing [26]. In 2013, the Chinese government further selected ten automobile or engine manufacturers to implement a pilot program named "trade old for remanufactured," where customers can obtain subsidies from the government if they purchase remanufactured products from the selected manufacturers [16]. An underlying tenet of the government subsidy program is that it can lighten customers' financial burden in purchasing remanufactured products so that more customers are willing to purchase remanufactured products. This can, in turn, promote manufacturers to make a remanufacturing investment decision. However, whether manufacturers' remanufacturing investment decisions are indeed affected by government incentive programs, and the impacts of government subsidy on the whole supply chain are still unclear. To this end, we further examine how the government subsidy affects the two manufacturers' optimal responses, equilibrium outcomes, and environmental impact as well.

This study investigates a manufacturer's optimal remanufacturing capability investment decisions under market competition with and without government subsidy. Compared with the current literature on this topic, the contributions of this study lie in the following facets. First, differing from related literature (e.g., Yenipazarli [22] and Shi, et al. [14]) that examines one manufacturer's remanufacturing capability investment decision, this study considers market competition between two manufacturers where a manufacturer makes the remanufacturing investment decisions by considering its competitor's possible decisions. Different remanufacturing investment decisions often lead to different market equilibrium outcomes. Therefore, our models have distinctive features and purposes against those of Yenipazarli [22] and Shi, et al. [14]. Second, this study incorporates the innovation cost structures (i.e., one-time fixed cost and variable cost) into the analysis and examines how firms' remanufacturing investment decisions change. We show that the consideration of both fixed and variable costs can generate some interesting results that have not been discovered in previous literature. This finding is different from that of Shi, et al. [14], which only considers variable costs in remanufacturing but ignores the cost of the redesign of new products for remanufacturing. The cost structure consideration is also in contrast with that of Nie, et al. [27], which only examines fixed-cost investment in remanufacturing operations although they also study manufacturers' remanufacturing investment decisions in a competitive setting. Third, this study extends the study by Raz and Souza [3] by incorporating the coexistence of new and remanufactured products where the cannibalization effect exists between new and remanufactured products. By contrast, Raz and Souza [3] aimed to examine two competing manufacturers' recycling decision in a setting where recycling is deemed an effective alternative material supply source for a firm. As such, the two manufacturers compete in both the new and remanufactured product markets. Fourth, motivated by subsidy policies that have been popularly implemented around the world for promoting remanufacturing business, this study considers the impact of government subsidization offered to customers on the two manufacturers' remanufacturing investment decisions and the competing supply chains investigated in this paper. From this perspective, Nie, et al. [27] also studied the impact of government subsidies offered to manufacturers on their optimal responses. However, the current practice in China is that the government offers subsidies to customers who purchase remanufactured products, not manufacturers. This study adopts this policy and examines its impact on firms' decisions. The study assumes that manufacturers cannot directly benefit from the subsidy, leading to a completely different model setting and results compared to Nie, et al. [27]. Finally, this study reveals that the equilibria associated with three scenarios (i.e., both manufacturers invest, neither manufacturer invests, and either manufacturer invests) can be conditionally achieved, depending on the fixed cost incurred in developing remanufacturing capability and the difference in marginal costs associated with new and remanufactured products. We show that, when developing a remanufacturing strategy, manufacturers should be cautious to weigh the benefits from market expansion by attracting low-end customers against the loss due to the change in cost structure, as well as pay attention to customers' valuation of remanufactured products.

The rest of this paper is organized as follows. Section 2 reviews the literature that is closely related to the research topic. Section 3 presents model settings and assumptions. Section 4 shows an equilibrium analysis of two manufacturers regarding their remanufacturing investment and remanufacturing strategy decisions. The environmental impact of manufacturing and remanufacturing are presented in Section 5. Section 6 extends the main model to examine the impact of government subsidy on the two manufacturers' optimal decisions. Section 7 concludes the paper, and all proofs are provided in the Appendix (See supplemental materials for details).

2. Literature review

This study builds on three streams of research: (a) competition between new and remanufactured products, (b) technology investment decisions, and (c) market competition. The relationship between this study and the literature is discussed below to highlight the contributions of this study.

2.1. Competition between new and remanufactured products

It has been widely accepted that the existence of remanufactured products would cannibalize customers' demand for new products, among which Atasu, et al. [28], Ferguson and Souza [29], Souza [30], and Agrawal, et al. [31] can serve as an overview. Therefore, manufacturers have to form strategies to respond to the coexistence of new and remanufactured products. Oraiopoulos, et al. [24] considered a setting where the manufacturer can either eliminate the secondary market or try to embrace it by charging a relicensing fee to customers who purchase the refurbished equipment. They found that the manufacturer would embrace the existence of the refurbished equipment when the indirect benefit gained from maintaining the secondary market outweighs the profit loss of new products and vice versa. Örsdemir, et al. [5] examined how the manufacturer can use the quality of new products as a lever to compete with independent remanufacturers when new and remanufactured products compete in the same market. Although the introduction of remanufactured products decreases the profit that manufacturers can gain from selling new products, the existence of remanufactured products may be lucrative for manufacturers as a whole if proper decisions are made for new and remanufactured products [8]. In addition, remanufacturing can even act as a marketing strategy for manufacturers to reach low-end customers or green customers [12]. This motivates manufacturers to establish remanufacturing capability themselves and enter the remanufacturing market directly. Wang, et al. [9] examined whether remanufacturing should be performed in-house or outsourced if firms decided to engage in remanufacturing operations by considering the cost structure of the two strategies, quality uncertainty of the collected products, customers' valuation of remanufactured products, cannibalization between new and remanufactured products, and power structure in the channel. Timoumi, et al. [32] investigated the question of whether the manufacturer should conduct the remanufacturing activity itself or allow the retailer to remanufacture used products on its own. They found that the case where letting the retailer remanufacture used products can outperform the case where the manufacturer remanufactures itself under certain conditions in terms of profitability and supply chain efficiency. Considering the joint impact of blockchain and brand advantage, Yang, et al. [33] studied the manufacturers' decision on the marketing channel management for remanufactured products, that is, whether the manufacturer should manage the marketing of remanufactured products directly or license the marketing activity to the remanufacturer, and concluded that the manufacturer should manage the marketing of remanufactured products directly when it can endogenously determine the license fee.

Rooted in closed-loop supply chain management, this study also considers competition between new and remanufactured products and manufacturers' strategies in the remanufacturing market. However, the two competitive manufacturers adopted the remanufacturing investment strategy. More importantly, this study explicitly models the case that new products must be redesigned to facilitate remanufacturing. The redesign will increase the production costs (i.e., fixed cost and variable cost) of new products and complicate the manufacturers' investment decision on remanufacturing because of the cannibalization effect. This study is related to those of Agrawal, et al. [34] and Shi, et al. [14]. Considering market competition from third-party remanufacturers, Agrawal, et al. [34] studied when and how the manufacturer should offer a trade-in rebate to customers to achieve price discrimination and weaken competition from remanufactured products. Remanufacturing investment provides another way for manufacturers to interfere with remanufacturing operations, and this is similar to the function of the trade-in service examined in Agrawal, et al. [34]. However, the aim of remanufacturing investment is to embrace the development of remanufacturing business so that the firm can benefit from manufacturing and remanufacturing as a whole rather than weakening competition from remanufactured products. Shi, et al. [14] examined a firm's remanufacturing investment in the design of new products, focusing on the channel and department coordination within a firm. Similar to Shi, et al. [14], this study examines the remanufacturing investment from the perspective of the design of new products but extends the study of Shi, et al. [14] from a monopoly setting to a duopoly setting wherein two manufacturing firms not only compete on the market of new products but also on remanufacturing investment decisions.

2.2. Technology investment decision

In essence, firms' decision-making on whether to invest in remanufacturing operations is similar to making technology choices in the green supply chain field, given that the aim of some firms to collect used products is to comply with environmental regulations [35]. Therefore, the stream of literature that examines the impact of environmental regulations on firms' environmental innovations or green technology choice is related to this study. Kraft, et al. [36] examined whether a firm should make a replacement decision when its product contains a potentially hazardous substance. They found that the firm should always spend the effort to develop replacement substances as long as there is a threat to enact environmental regulations. Krass, et al. [37] studied how a monopolistic firm should determine its emission control technology, production quantity, and price when the regulator may enact different levels of tax, subsidy, and rebate. Drake, et al. [38] investigated how a firm should make decisions on technology choice and capacity when the regulator enacts emission tax and emission cap-and-trade regulations. Chen, et al. [39] explored a remanufacturer's decisions on quantity and collection considering the impact of both the take-back and carbon emission capacity regulations. In a competitive setting, Yenipazarli, et al. [40] used a life-cycle approach to examine environmental innovation from three perspectives, namely cost structure, advertising, and competition. Cohen, et al. [41] compared two common types of government support, namely R&D support and sales subsidies, for two competitive firms' decisions on green product design and the corresponding market competition between the two firms. Murali, et al. [42] developed a consumer-driven model to examine the impact of voluntary eco-label and mandatory regulation on two competitive firms' decisions on green product development, wherein the two firms differ in their inherent credibility. They found that when the two competitive firms adopt different strategies to communicate their unobservable environmental performance through eco-labels, the government should adopt mandatory regulation to stimulate green product development. Yang, et al. [43] considered the role of government subsidy on two firms' technology improvement decisions in a competitive setting where the new technology can expand the firms' market but will increase firms' production costs. They found that the two firms would not upgrade their technology when it is costly. They would upgrade their current technology if the market expansion effect can outweigh the cost-increasing effect.

This study borrows some modeling elements from this stream of research but differs significantly in the following dimensions. First, there is no cannibalization effect in the earlier studies on technology choice. This is because firms only sell one kind of product to the market regardless of their technology improvement decisions. Therefore, products produced by current technology or upgraded technology will not coexist in the market, and the cannibalization effect between these two kinds of products will not arise. However, in the remanufacturing investment context, new and remanufactured products will coexist in the market. The existence of remanufactured products will always cannibalize customers' demand for new products. Although similar to technology improvement, remanufacturing investment aims to adjust the design of new products so that used products are remanufacturable. At this point, Yenipazarli [22] is the exception that considers the cannibalization effect in the remanufacturing design. In addition to examining a manufacturer's remanufacturing capability investment decision, such as in Yenipazarli [22], this study considers market competition between two manufacturers where one manufacturer makes remanufacturing investment decisions by taking into account its competitor's possible decisions, and different remanufacturing investment decisions will lead to different market equilibrium outcomes. Considering the cannibalization effect, Alev, et al. [44] also studied a manufacturer's interference with the secondary market, and their main focus was to provide policy insights on how to set extended producer responsibility requirements for durable goods. Another noteworthy feature of this study is that in contrast to previous studies that only consider one kind of cost—one-time fixed cost or variable cost—in technology choice decision, this study incorporates the innovation cost structures (i.e., one-time fixed cost and variable cost) into the analysis and examines how firms' remanufacturing investment decisions change according to the cost structure. Raz, et al. [45] also examined the impact of the innovation cost structure on a firm's innovation-related decisions. However, they aimed to determine who should bear the responsibility of innovation in a supply chain.

2.3. Market competition

This study examines manufacturers' remanufacturing investment decisions in a competitive setting and relates to the literature stream investigating competition in the remanufacturing market. Atasu, et al. [12] examined the remanufacturing strategy of a manufacturer when it faces competition from a local remanufacturer and found that remanufacturing can act as an effective marketing strategy for manufacturers to deter the entry of local remanufacturers. Chen and Chen [26] identified the difference between remanufacturing and refurbishing, where the quality level of remanufactured products is higher than that of refurbished products. They examined the impact of the competition between remanufactured products and refurbished products on remanufacturing market equilibrium and the refurbisher's and remanufacturer's entry strategies. The remanufacturing authorization has been widely adopted by manufacturers to participate in remanufacturing operations. As such, competition between authorized and unauthorized remanufactured products becomes common in the remanufacturing market. Zhou, et al. [7] and Zhou, et al. [46] investigated how a manufacturer should manage its remanufacturing-related decisions, especially authorization strategy, when remanufacturing is conducted by third-party remanufacturers, and found that authorization may cause competition between authorized and unauthorized remanufactured products.

Consistent with this stream of literature, this study also considers competition in the remanufacturing market. In fact, competition not only exists in the remanufacturing market but also in the new products market if both manufacturers invest in remanufacturing design. In contrast to specifying competition in the remanufacturing market, this study investigates manufacturers' remanufacturing investment decisions for redesigning new products. The manufacturers need to incur additional costs, namely fixed cost and variable cost, to change the design of new products so that used products are remanufacturable. However, the existence of remanufactured products, on the one hand, can help the firm reach low-end customers and, thus, expand the firm's market share. On the other hand, the firm's primary business, that is, new product sales, will be cannibalized if customers have the option to purchase remanufactured products. Besides, competition between two manufacturers obviously complicates a firm's decision on remanufacturing investment. At this point, this study is related to that of Raz and Souza [3]. Raz and Souza [3] examined the impact of cost structure on two manufacturers' recycling decisions in a setting where recycling can become an effective alternative material supply source for the firm. Similar to Raz and Souza [3], this study also examines the impact of cost structure on two manufacturers' decisions in a competitive setting but considers the cannibalization effect between new and remanufactured products. As such, recycling is not aimed to provide an alternative supply source for the firm but to intensify market competition by delivering the remanufactured version of new products to the market.

To conclude, this study extends and complements existing research on closed-loop supply chain management by investigating the impact of cost structure (i.e., fixed and variable costs) caused by the redesign of new products and government subsidies offered to customers on competitive manufacturers' remanufacturing investment decisions. We not only address the manufacturers' decisions on whether to engage in remanufacturing operations but also examine the extent to which they would engage in remanufacturing. Although a portion of these questions has been addressed in the current literature for other different model settings, in this study, we use a three-stage game that captures the main issues that manufacturers might face in the remanufacturing investment process, allowing us to analyze the market equilibrium status when market expansion and cost increase effects coexist in remanufacturing operations.

3. Model settings

In this study, the considered supply chain consists of two symmetric manufacturers (e.g., Apple and Huawei), denoted by M1 and M2, directly selling perfectly substitutable new products (e.g., mobile phones) to the market. The two manufacturers' assumption is also consistent with industry practices in some countries such as Japan, where only a few consortia manufacturers exist in the country [47]. In addition to selling new products, the two manufacturers are considering whether to engage in remanufacturing and how many of the used products to remanufacture if they engage. It is important to highlight that the two manufacturers have flexible arrangements regarding whether to invest in remanufacturing operations, primarily because adhering to IPR guiding principles is more or less an industry-wide voluntary initiative in some industrial sectors.

To remanufacture used products, new products must be remanufacturable and, hence, proper changes must be made to new products' product design without changing original functions and utility. To define remanufacturing investment as manufacturers' strategies for the redesign of new products is to examine interactions between new and remanufactured products at the design stage and the following impact on manufacturers' manufacturing and remanufacturing decisions. Therefore, this study does not consider other kinds of remanufacturing investment, such as multi-brand trade-in offered by firms, as a kind of remanufacturing investment in the collection as considered by Desai, et al. [48] and remanufacturing authorization wherein manufacturers authorize other supply chain members to manage remanufacturing activity on their behalf as considered by Zou, et al. [49], Zhou, et al. [18], and Zhou, et al. [23]. This consideration is confirmed by Liu and Xiao [50] and is also in line with the principle of IPR that manufacturers are encouraged to design for recovery to facilitate the recycling or reusing of used products [2]. As such, the manufacturers must invest in remanufacturing capability so that they can make changes in the design. This will inevitably increase the production cost of new products. Following Shi, et al. [14], this study assumes that remanufacturing investment happens at the design stage of new products, and remanufacturing investment decision is made if proper changes are made to the new products. Hence, remanufacturing investment is not concerned about the design of remanufactured products and will not affect customers' perceived utility of remanufactured products. In addition, remanufacturing investment aims to make new products remanufacturable and will not change the functions of new products. As such, customers' perceived utility of new products will not be affected either.

3.1. Demand function

Customers are uniformly distributed over the interval $[0,1]$, and each customer purchases at most one product to satisfy his/her needs. The uniform distribution is for analytical tractability and has been widely used in the operations literature, such as Cao and Choi [51], Luo and Choi [52], and Zhou, et al. [23]. Customers are heterogeneous in their willingness to pay (WTP) for the product. As demonstrated by Wang, et al. [9], Shi, et al. [14], Guo, et al. [53], and Timoumi, et al. [32], customers' WTP for remanufactured products is always lower than that for new products. Therefore, customers' WTP for new products is θ and $\alpha\theta$ for remanufactured products, where $\alpha \in (0,1)$. α denotes the competitiveness of the remanufactured product and models the cannibalization effect between new and remanufactured products. The cannibalization effect between new and remanufactured products is fierce if α is large. Let p_n and p_r represent the sales price of new and remanufactured products, respectively. The net utility that a customer obtains from purchasing a new product and a remanufactured product is $u_n = \theta - p_n$ and $u_r = \alpha\theta - p_r$, respectively. Without the loss of generality, the market size is normalized to 1. Customers will purchase the product that can give them the highest utility. Hence, customers will purchase a new product if and only if $u_n \geq u_r$ and $u_n \geq 0$, and customers will purchase a remanufactured product if and only if $u_r \geq u_n$ and $u_r \geq 0$. Therefore, customers' demand for new and remanufactured products can be derived as follows through simple integral calculations.

$$d_n = 1 - \frac{p_n - p_r}{1-\alpha}, \quad d_r = \frac{p_n - p_r}{1-\alpha} - \frac{p_r}{\alpha} \tag{1}$$

where d_n and d_r represent customers' demand for new and remanufactured products, respectively.

This study assumes that the two manufacturers engage in Cournot competition and determine their production quantity of new products (and production quantity of remanufactured products if they invest in remanufacturing operations) to maximize their profit. This is because the products sold by the two manufacturers are perfectly substitutable, especially in the function of the products. Raz and Souza [3], Esenduran, et al. [54], and Zhou, et al. [7] also have similar considerations. Therefore, following Raz and Souza [3], Esenduran, et al. [54], and Zhou, et al. [7], $d_n = d_{n1} + d_{n2}$ and $d_r = d_{r1} + d_{r2}$, where d_{ni} and d_{ri} ($i = 1$ and 2) represent customers' demand for the two manufacturers' new and remanufactured products, respectively. Based on the demand functions, the inverse demand functions can be obtained as follows.

$$p_n = 1 - (d_{n1} + d_{n2}) - \alpha(d_{r1} + d_{r2}), \quad p_r = \alpha(1 - d_{n1} - d_{n2} - d_{r1} - d_{r2}). \tag{2}$$

3.2. Profit function

The two manufacturers produce new products at the cost of c_n, where $0 < c_n < 1$. Proper changes in product design are necessary to make new products remanufacturable, which increases the production cost of new products to $c_n + \Delta$, where $0 < c_n + \Delta < 1$ and $0 < \Delta < 1$. The aim of making proper changes in the design of the new product is to reduce the technical barriers that manufacturers might face in the remanufacturing process. As a result, manufacturers need to incur a higher production cost to produce new products [14, 22]. In addition, manufacturers also incur a fixed cost to build remanufacturing operations. The fixed cost usually consists of two main components: the cost of building the used product collection system and the cost of setting up the remanufacturing operation [55]. This study assumes that the total fixed cost incurred in developing remanufacturing capability is F, where $F > 0$.

Once remanufacturing operations are set up, the two manufacturers remanufacture used products at the cost of c_r. Similar to Örsdemir, et al. [5], this study assumes that the remanufacturing cost subsumes the cost of all remanufacturing-related activities, such as transportation, collection, and sorting. In practice, the remanufacturing cost highly depends on the collection process of used products and, especially, the quality of used products because the quantity and quality of used products are uncertain. For instance, Wang, et al. [9] examined the impact of the quality of used products on a firm's reverse channel design. This study, however, aims to examine two manufacturers' remanufacturing investment decisions and their interactions in the process and, hence, the remanufacturing cost is generalized and unified to c_r. In addition, the remanufacturing cost satisfies $c_n > c_r \geq 0$ as the remanufacturing process can save production cost by reusing used products and thus consuming fewer virginal materials [10, 14]. Without the loss of generality, the remanufacturing cost c_r is normalized to 0. As such, the production cost of new products, i.e., c_n, represents the cost difference between new and remanufactured products. A larger c_n indicates that remanufacturing is more cost-effective.

The two manufacturers play a two-stage game regarding their remanufacturing investment decisions.

The two manufacturers determine their remanufacturing investment decisions simultaneously in the first stage of the game. In particular, a manufacturer may choose either not to invest in or to invest in remanufacturing. The former strategy is referred to as “not investment” (or N for short), where the manufacturer does not invest in remanufacturing operations and only sells new products. The latter strategy is called “remanufacturing investment” (or R for short), where the manufacturer engages in remanufacturing operations and sells new and remanufactured products simultaneously to the market. Obviously, based on the manufacturers’ remanufacturing investment decisions in the first stage, there are four possible investment outcomes for the two manufacturers: $\{NN, RN, NR, RR\}$, where the letters represent the remanufacturing investment decisions of the two manufacturers in the first stage, respectively. Although remanufactured products sold by different manufacturers may be subject to different conditions due to different technical procedures that may be applied in the remanufacturing process even though new versions of the product are completely the same, this study assumes that remanufactured products sold by the two manufacturers are still perfectly substitutable to focus on the main research questions. This means that when Cournot competition is applied, the remanufacturing market is equally divided by the two manufacturers when both manufacturers decide to invest in remanufacturing. This assumption is reasonable in that whether the two manufacturers invest in remanufacturing or not, their primary market is still the new product market, not the remanufactured product market.

In the second stage of the game, the two manufacturers determine their production quantities of new and remanufactured products simultaneously and independently to maximize their profits. The profit function for each manufacturer is formulated as follows.

$$\Pi_{Mi} = (p_n - c_n - k\Delta)d_{ni} + kp_r d_{ri} - kF \tag{3}$$

Where k is an indicator function and equal to 1 if a manufacturer invests in remanufacturing operations and 0 otherwise. The first term in the profit function denotes the revenue from selling new products, and the production cost of new products will become $c_n + \Delta$ if remanufacturing investment decisions are made. The second and third terms represent the revenue from selling remanufactured products. Note that the constraint $0 \le d_{ri} \le d_{ni}$ should always apply if a manufacturer chooses to engage in remanufacturing operations. This is because the number of products that can be remanufactured is always smaller than the number of products that can be collected from the market [7, 18, 24]. In addition, it is assumed that the production quantity of remanufactured products is always equal to the collection quantity of used products, and all collected products can be remanufactured. This assumption is reasonable because manufacturers can always collect and remanufacture used products based on customers’ demand for remanufactured products [25, 26].

As $d_{ri} = 0$ is already considered in the “not investment” strategy, two remanufacturing strategies are available for a manufacturer that invests in remanufacturing. We define remanufacturing strategy

$R \in \{R1, R2\}$, where *R1* represents the case that the manufacturer remanufactures some but not all the used products available for collection, and *R2* denotes the case that the manufacturer remanufactures all the used product available for collection. The latter case assumes that all used products can be available for remanufacturing, which simplifies the analysis without qualitatively changing the results [56]. We also assume that all events transpire within a single period, which can be considered as the average status of the supply chain when similar products are introduced to the market repeatedly [9, 57] and similar consideration can also be found in Chen and Chen [26], Shi, et al. [14], and so on.

To evaluate the environmental performance of manufacturing and remanufacturing, let E represent the total environmental impact. This study assumes that the environmental impact of products is measured by the production quantity. In fact, many ways can be used to measure environmental impact, such as raw material used in the production process, greenhouse gas emissions, and use of water/land/air [22]. The use of production quantity is the most direct way to measure the environmental impact and is commonly used in research and industry [22, 26]. Remanufactured products have an advantage over new products in protecting the environment since they consume less raw material by reusing used products. Let β denote the relative greenness of remanufactured products, where $0 < \beta < 1$. The lower the β, the greener the remanufactured products. Hence, $E = d_{ni} + \beta d_{ri}$.

Before moving to the detailed optimal decisions of the two manufacturers, several assumptions are made to ensure that the cost difference between new and remanufactured products is within [0,1], that is, $0 < c_n < 1$, thus, avoiding trivial discussion and eliminating unrealistic cases.

Assumption 1. Customers' valuations for remanufactured products and the production cost increase of new products satisfy $\Delta < \alpha < 7 - \frac{12}{2-\Delta}$ and $0 < \Delta < \frac{1}{2}(9 - \sqrt{73})$.

Although there is no explicit assumption on a manufacturer's remanufacturing investment decision, assuming that new products are the source of remanufacturing, the manufacturing of new products is not profitable when the cost difference between new and remanufactured products is relatively high and remanufacturing is impossible when the cost difference between new and remanufactured products is relatively low. The aim of Assumption 1 is to ensure that the cost difference between new and remanufactured products is within a reasonable range so that manufacturing and remanufacturing are both applicable.

4. Manufacturers' strategies

In this section, the two manufacturers' optimal decisions regarding their remanufacturing investment decisions and remanufacturing strategies are investigated. Then, the equilibrium results between the two manufacturers are analyzed. In addition, the impact of manufacturing and remanufacturing cost structures and the cannibalization effect are analyzed. The equilibrium production quantity of the two manufacturers is investigated at the end of this section.

4.1. Optimal decisions

There are four possible outcomes for the two manufacturers concerning their remanufacturing investment decisions: neither manufacturer invests in remanufacturing (Case NN), both manufacturers invest in remanufacturing (Case RR), and one manufacturer invests in remanufacturing and the other does not (Cases RN and NR). Since the two manufacturers are completely symmetric, only strategy RN is examined, and strategy NR can be obtained symmetrically based on strategy RN. The two manufacturers' optimal decisions in the three cases are derived first, followed by an analysis of whether and when each of them will reach an equilibrium. To differentiate the three remanufacturing investment outcomes, superscripts *NN*, *RN*, and *RR* are added to the optimal decisions.

In Case NN, neither manufacturer makes remanufacturing investment decisions; hence, only new products exist in the market, and the competition between the two manufacturers is degraded to new products' competition. The two manufacturers' profit only comes from selling new products, and the two manufacturers determine their production quantity of new products to maximize their profit. Each manufacturer's profit function is formulated as follows.

$$\max_{d_{ni}} \prod_{Mi}^{NN} = (p_n - c_n)d_{ni} \tag{4}$$

In Case RR, both manufacturers invest in remanufacturing. As such, the two manufacturers incur a fixed cost to set up remanufacturing capability and change the design of the new product to make used products remanufacturable, which increases the production cost of new products. The two manufacturers' profit comes from selling both new and remanufactured products. Consequently, they need to determine their production quantities of new and remanufactured products simultaneously and independently. Each manufacturer's decision-making problem is formulated as follows.

$$\max_{d_{ni},d_{ri}} \prod_{Mi}^{RR} = (p_n - c_n - \Delta)d_{ni} + p_r d_{ri} - F \tag{5}$$

$$\text{s.t.} \quad 0 < d_{ri} \le d_{ni}$$

In Case RN, only M1 engages in remanufacturing operations. Hence, M1 changes new products' design, incurs a fixed cost for remanufacturing capability, and sells both new and remanufactured products to the market, whereas M2 does not invest in remanufacturing and only sells new products to the market. After the remanufacturing investment decisions are made, the two manufacturers determine their production quantity of new and remanufactured products to maximize their profit simultaneously and independently. The decision-making problem for the two manufacturers is formulated as follows.

$$\max_{d_{n1},d_{r1}} \prod_{M1}^{RN} = (p_n - c_n - \Delta)d_{n1} + p_r d_{r1} - F \tag{6}$$

$$\max_{d_{n2}} \prod_{M2}^{RN} = (p_n - c_n)d_{n2} \tag{7}$$

$$\text{s.t.} \quad 0 < d_{r1} \le d_{n1}$$

$$d_{n2} \geq 0$$

The concavity of these profit functions is easy to prove. Hence, based on Karush–Kuhn–Tucker (KKT) necessary conditions, the two manufacturers' optimal decisions are summarized in Proposition 1.

Proposition 1. The two manufacturers' optimal decisions in Cases NN, RR, and RN are summarized in Table 1 (See Appendix A for details), where $c_{n1}^{RR} = \frac{1-\alpha-2\Delta}{2}$, $c_{n1}^{RN} = \frac{2-\alpha(2-\Delta)-7\Delta}{5+\alpha}$, and $c_{n2}^{RN} = \frac{1+\Delta+\alpha(4-\alpha+\Delta)}{1+5\alpha}$.

Proposition 1 implies the following key insights:

(1) In Case NN when both manufacturers do not invest in remanufacturing operations, the two manufacturers' optimal production strategy is only affected by the production cost of new products. In addition, they will decrease their production quantities and correspondingly increase their sales price when the production cost is high.

(2) In Case RR when both manufacturers invest in remanufacturing operations, the two manufacturers will choose between two remanufacturing strategies (i.e., R1 and R2) depending on the cost difference between new and remanufactured products. Remanufacturing strategy R1 will be adopted by the two manufacturers when the cost difference is relatively low (i.e., $0 < c_n \leq c_{n1}^{RR}$), whereas, as the cost difference increases (i.e., $c_{n1}^{RR} < c_n < 1$), both manufacturers will adopt remanufacturing strategy R2. These indicate several important implications. First, the two manufacturers will simultaneously choose remanufacturing strategy R1 or R2, and there is no asymmetric remanufacturing strategy choice for the two manufacturers as the products sold by the two firms are perfectly substitutable. Second, the two manufacturers will remanufacture some but not all available used products when they can produce new products at a relatively low cost. However, as the cost difference between new and remanufactured products increases, the two firms will remanufacture all available used products. The adoption of remanufacturing strategy R2 is partly because of the high production cost of new products and partly because of cost saving from remanufacturing. In addition, c_{n1}^{RR} decreases with α and Δ. As such, the two manufacturers are more likely to adopt remanufacturing strategy R2 when customers' valuation of remanufactured products is high and when the remanufacturing design can greatly increase the production cost of new products.

(3) In Case RN when M1 invests in remanufacturing operations and M2 does not, there are three optimal choices available for the manufacturers. M1 will choose remanufacturing strategy R1 if $0 < c_n \leq c_{n1}^{RN}$ and remanufacturing strategy R2 as the cost difference increases (i.e., $c_{n1}^{RN} < c_n \leq c_{n2}^{RN}$). As the cost difference further increases (i.e., $c_{n2}^{RN} < c_n < 1$), M1 will still choose

(4) remanufacturing strategy R2. However, M2 will exit the market and does not even engage in new product production. Consistent with Case RR, the firm that engages in remanufacturing operations will first adopt remanufacturing strategy R1 when the cost difference between new and remanufactured products is low, and then adopt remanufacturing strategy R2 when the cost difference increases. However, the manufacturer that does not engage in remanufacturing operations will price out the market when the cost difference is relatively high. On the one hand, the high production cost prevents M2 from engaging in new-product production. On the other hand, the cost-saving from the remanufacturing motivates M1 to adopt remanufacturing strategy R2, which compensates for the high production cost of new products and helps it exist in the remanufacturing market. In addition, c_{n1}^{RN} decreases with α and Δ, while c_{n2}^{RN} decreases with α but increases with Δ. Similarly, remanufacturing strategy R2 is more likely to be adopted when customers have a high valuation of the remanufactured products and when it is more costly to change the design of new products so that used products can be remanufactured. For M2, it is more likely to exit the market when customers' valuation of the remanufactured products is high since it does not invest in remanufacturing operations. When changing the design of new products is costly, M2 is less likely to exit the market.

4.2. Equilibrium analysis

The equilibrium outcome for the two manufacturers is determined by the benefits of remanufacturing, which, in turn, are affected by the one-time fixed cost incurred in developing remanufacturing capability, the new-product production cost increase, and the sales of remanufactured products. In this subsection, we characterize how the equilibrium outcome for the two manufacturers is affected by these parameters.

Proposition 2. There exist thresholds F_1, F_2, F_3, F_4, F_5, F_6, and F_7 (detailed expressions for these thresholds are available in the Appendix) that characterize equilibrium outcome for the two manufacturers such that (1) Case RR is the unique Nash equilibrium when $F < T_1$, where $T_1 = F_4$ if $0 < c_n \le c_{n1}^{RR}$, $T_1 = F_5$ if $c_{n1}^{RN} < c_n \le c_{n1}^{RR}$, $T_1 = F_6$ if $c_{n1}^{RR} < c_n \le c_{n2}^{RN}$, and $T_1 = F_7$ if $c_{n2}^{RN} < c_n < 1$; (2) Case RN (NR) is the Nash equilibrium when $T_1 < F < T_2$, where $T_2 = F_1$ if $0 < c_n \le c_{n1}^{RN}$, $T_2 = F_2$ if $c_{n1}^{RN} < c_n \le c_{n2}^{RN}$, and $T_2 = F_3$ if $c_{n2}^{RN} < c_n < 1$; and (3) Case NN is the unique Nash equilibrium when $F > T_2$.

In real practice, the thresholds and parameter values in the expressions can be obtained based on the market conditions (via market research) and operational costs from a firm's internal data. Proposition 2 indicates that regardless of the cost difference between new and remanufactured products, both manufacturers will invest in remanufacturing operations when the fixed investment cost is relatively low. They will not invest in remanufacturing operations when the fixed investment cost is relatively high, and only one manufacturer is engaging in remanufacturing operations when the fixed cost incurred is at a medium level. However, different remanufacturing strategies will be adopted by the two manufacturers depending on the cost difference between new and remanufactured products. For example, when both manufacturers invest in remanufacturing operations (i.e., Case RR) in equilibrium, the two manufacturers should first adopt remanufacturing strategy R1 when the cost difference is relatively low (i.e., $0 < c_n \le c_{n1}^{RR}$). However, as the cost difference between new and remanufactured products increases (i.e., $c_{n1}^{RR} < c_n < 1$), the two manufacturers should remanufacture all available used products (i.e., remanufacturing strategy R2). This conclusion also applies to the scenario where only one manufacturer invests in remanufacturing operations (i.e., Case RN or NR) in equilibrium and is consistent with the results obtained in Proposition 1. For instance, M1 will adopt remanufacturing strategy R1 when $0 < c_n \le c_{n1}^{RN}$ and implement remanufacturing strategy R2 when $c_{n1}^{RN} < c_n < 1$. However, M2 will not engage in producing new products when the cost difference between new and remanufactured products is relatively high (i.e., $c_{n2}^{RN} < c_n < 1$).

After the equilibrium outcomes between the two manufacturers are obtained, we further compare the two manufacturers' profits in these cases to check whether the obtained equilibrium is in line with the manufacturers' goal of maximizing profit. In the following paragraphs, the manufacturers' profits in Cases RR and NN are compared.

Proposition 3. There exist two thresholds F_8 and F_9 (detailed expressions are available in the Appendix) that define a prisoner's dilemma with the following conditions: (i) if $T_3 < T_1$, then, a prisoner's dilemma will arise when $T_3 < F < T_1$, in which both manufacturers invest in remanufacturing operations (i.e., Case RR); (ii) if $T_3 > T_1$, then, a prisoner's dilemma will never arise when $0 < F < T_1$, where $T_3 = F_8$ if $0 < c_n \le c_{n1}^{RR}$ and $T_3 = F_9$ if $c_{n1}^{RR} < c_n < 1$ (see Appendix B for detailed discussions).

Proposition 3 implies that the two manufacturers may be trapped a prisoner's dilemma when they both make remanufacturing operation investments, especially when the cost difference between new and remanufactured products is relatively high. Remanufacturing operations affect the manufacturer that invests in remanufacturing in two ways. On the one hand, remanufactured products can help manufacturers reach price-conscious customers. Compared with new products, remanufactured products are sold at a lower price but with the same function. As such, customers with a limited budget can purchase remanufactured products to satisfy their needs. This indicates the market expansion effect of remanufacturing. On the other hand, manufacturers need to change the design of new products so that there are no technical barriers in the remanufacturing process and invest in remanufacturing capability. As such, manufacturers not only face a production cost increase of new products but also need to incur a one-time fixed cost for remanufacturing capability. This implies that remanufacturing operations can present a cost increase effect. The market expansion effect dominates the cost increase effect when the incurred fixed cost is relatively low, that is, $0 < F < T_3$. As such, the two manufacturers can earn higher profits by engaging in remanufacturing.

However, as the fixed cost increases (i.e., $T_3 < F < T_1$), the manufacturer that changes its strategy from investing to not investing in remanufacturing will be in a market share disadvantageous position, although it has a production cost advantage as it does not incur any additional remanufacturing costs. In contrast, the manufacturer that invests in remanufacturing operations will have an advantage in market expansion; hence, it will stick to the remanufacturing investment strategy. This suggests that it is optimal for each manufacturer to make the remanufacturing investment decision, and market equilibrium is stabilized at RR. However, the market expansion effect is weakened when both manufacturers engage in remanufacturing, and the market expansion effect cannot dominate the cost increase effect when the fixed cost increases, resulting in the two manufacturers' profits obtained in Case RR becoming lower than that in Case NN. Therefore, the two manufacturers will be trapped in a prisoner's dilemma when they both invest in remanufacturing.

4.3. Impact of cost structure and cannibalization effect

This subsection answers the third and fourth research questions: What is the impact of the manufacturing and remanufacturing cost structures and the cannibalization effect between new and remanufactured products on the manufacturers' remanufacturing investment decisions? The impact of key parameters on thresholds (i.e., F_1, F_2, F_3, F_4, F_5, F_6, F_7, $F_5 - F_8$, $F_6 - F_9$, and $F_7 - F_9$) that respectively characterize equilibria in Proposition 2 and prisoner's dilemma in Proposition 3 are analyzed first. Note that Proposition 3 also shows the scenarios where prisoner's dilemma may not arise; hence, these scenarios are not considered here. As a result, the impact of key parameters on the size of different equilibria regions can be obtained.

Corollary 1. The impact of Δ (the production cost increase of new products), α (which scales the cannibalization effect between new and remanufactured products), and c_n (the cost difference between new and remanufactured products) on thresholds (i.e., F_1, F_2, F_3, F_4, F_5, F_6, F_7, $F_5 - F_8$, $F_6 - F_9$, and $F_7 - F_9$) are summarized in Table 2 (See Appendix A for details).

In Table 2, the directional relationships apply to their respective range. For instance, F_1 is valid when $0 < c_n \le c_{n1}^{RN}$; hence, the directional relationships only show the monotonicity of F_1 within this range. The abbreviations used in the table are summarized as follows: (a) NA indicates not applicable; (b) U indicates unprovable; (c) M indicates mixed relationships between the parameter and threshold (i.e., can either increase or decrease); and (d) $\uparrow$ ($\downarrow$) indicates the threshold increases (decreases) with the increase of the parameter.

The results in Table 2 show how the size of each equilibrium region (denoted as a function of F) is affected by cost structure and the cannibalization effect between new and remanufactured products. The size of the region NN (i.e., neither manufacturer invests in remanufacturing operations) is determined by threshold T_2 (i.e., F_1, F_2, and F_3), the size of the region RR (i.e., both manufacturers invest in remanufacturing operations) is determined by threshold T_1 (i.e., F_4, F_5, F_6, and F_7), the size of prisoner's dilemma is determined by threshold T_3 (i.e., $F_5 - F_8$, $F_6 - F_9$, and $F_7 - F_9$); each of these is discussed below.

The size of the region NN increases as Δ increases or α decreases. In other words, $\frac{\partial T_2}{\partial \Delta} < 0$, and $\frac{\partial T_2}{\partial \alpha} > 0$. Conversely, the size of the region RR increases as Δ decreases. In other words, $\frac{\partial T_1}{\partial \Delta} < 0$. We can also numerically observe that the size of the region RR increases as α increases, and it is difficult to prove that $\frac{\partial T_1}{\partial \alpha} > 0$; as a result, the conclusion is based on the numerical observation. This indicates that the two manufacturers are more likely to invest in remanufacturing operations when customers' valuation of remanufactured products is relatively high or when the design change in new products does not significantly increase the production cost of new products. This is intuitional because (1) customers' demand for the remanufactured product would increase when customers have a high valuation of remanufactured products and (2) manufacturing new products is still profitable when the design change in new products for remanufacturing is less costly. These two reasons lead to higher profitability for manufacturers when they invest in remanufacturing operations. Therefore, even though the two manufacturers should incur additional costs to develop remanufacturing capability, the two manufacturers still prefer to invest in remanufacturing operations. Consequently, the size of the region RR will increase, whereas the size of the region NN will decrease.

The size of the regions NN and RR may either increase or decrease with the cost difference between new and remanufactured products, depending on which remanufacturing strategy is adopted by the manufacturer. When remanufacturing strategy R1 is adopted, the size of the region RR (NN) increases (decreases) with the cost difference between new and remanufactured products, and the size of the regions RR and NN may either increase or decrease with the widening cost difference between new and remanufactured products when remanufacturing strategy R2 is adopted. However, when the manufacturer that does not invest in remanufacturing exits the production of new products, the size of the region RR (NN) decreases (increases) with a widening cost difference between new and remanufactured products. As Proposition 1 shows, depending on the cost difference between new and remanufactured products, manufacturers will choose their remanufacturing strategy between R1 and R2. Manufacturers can earn more profit from remanufacturing when the cost difference between new and remanufactured products increases. The larger the cost difference, the more cost-saving remanufacturing becomes. As such, the two manufacturers are more likely to invest in remanufacturing operations, and equilibrium RR is more likely to arise. However, as the cost difference between new and remanufactured products increases further, if a manufacturer chooses to adopt remanufacturing strategy R2, the other manufacturer that does not invest in remanufacturing may exit the market. On the one hand, if the production quantity of remanufactured products needs to increase, the production quantity of new products must increase if remanufacturing strategy R2 is adopted. On the other hand, compared with remanufacturing, the manufacturing of new products may become less profitable when the cost difference between new and remanufactured products increases. As such, the size of the region RR may either increase or decrease with the cost difference between new and remanufactured products when it is at a medium level, and the size of the region RR decreases with the cost difference between new and remanufactured products when it is relatively high.

In addition, the impact of cost structure and cannibalization effect on the size of the prisoner's dilemma region is examined. The results in Table 2 imply several interesting insights. First, the size of the prisoner's dilemma region decreases as Δ increases when two manufacturers coexist in the market. In addition, Δ has no impact on the size of the prisoner's dilemma when the manufacturer that does not invest in remanufacturing operations exits the market. In other words, $\frac{\partial(F_5 - F_8)}{\partial\Delta} < 0$, and $\frac{\partial(F_6 - F_9)}{\partial\Delta} < 0$ when $0 < c_n \le c_{n2}^{RN}$. This indicates that the two manufacturers are less likely to be trapped in a prisoner's dilemma when the remanufacturing design significantly boosts the production cost of new products. This is because the two manufacturers are less likely to invest in remanufacturing operations when the change in the design is extremely costly.

Second, the size of the prisoner's dilemma region increases as α increases when remanufacturing strategy R2 is adopted. α does not have an impact on the size of the prisoner's dilemma region when remanufacturing strategy R1 is adopted or when one manufacturer exits the market. In other words, $\frac{\partial(F_5 - F_8)}{\partial\alpha} > 0$ and $\frac{\partial(F_6 - F_9)}{\partial\alpha} > 0$ when $c_{n1}^{RN} < c_n \le c_{n2}^{RN}$. When remanufacturing strategy R1 is adopted, the manufacturer only remanufactures some but not all available used products. As a result, the production quantity increases of remanufactured products do not necessarily induce the manufacturers to increase the production quantity of new products. Therefore, the increase in customers' valuation of remanufactured products does not motivate the two manufacturers to invest in remanufacturing, and the prisoner's dilemma will not arise. When one manufacturer sells both new and remanufactured products and the other manufacturer exits the market, the size of the prisoner's dilemma region is also not affected by the cannibalization effect between new and remanufactured products, even though more customers would purchase remanufactured products when customers' valuation of remanufactured products increases.

Finally, the size of the prisoner's dilemma region first increases, then continues to either increase or decrease, and finally decreases as c_n increases. In other words, $\frac{\partial(F_5 - F_8)}{\partial c_n} > 0$, $\frac{\partial(F_7 - F_9)}{\partial c_n} < 0$, while

c_n has a mixed effect on $F_7 - F_9$. The two manufacturers are more likely to invest in remanufacturing operations when the cost difference between new and remanufactured products increases as remanufacturing is more likely to become a profitable business when the cost difference is relatively high. However, a prisoner's dilemma is more likely to arise when the cost difference increases. As such, the market expansion impact caused by remanufacturing cannot dominate the cost increase effect when the cost difference is relatively high. Therefore, the two manufacturers are trapped in a prisoner's dilemma when they both invest in remanufacturing operations.

To better illustrate the results of Corollary 1, several numerical studies are conducted. Figure 1 shows the impact of α and c_n on regions for different equilibria. Thresholds T_1 and T_2 are plotted in solid lines, whereas threshold T_3 is plotted in dotted line. In addition to showing the impact of the key parameters on equilibrium results, Figure 1 uses letters in the brackets to show the manufacturing and remanufacturing strategies adopted by the manufacturer. For instance, $RN(R1, P)$ denotes the equilibrium case where one manufacturer invests in remanufacturing (R1 strategy) and the other only produces new products. Similarly, $RN(R2,U)$ also indicates that RN is the equilibrium, and one manufacturer chooses to exit the market. Since there are only symmetric remanufacturing strategies when RR arises in equilibrium, the equilibrium results are simplified as $RR(R1)$ and $RR(R2)$.

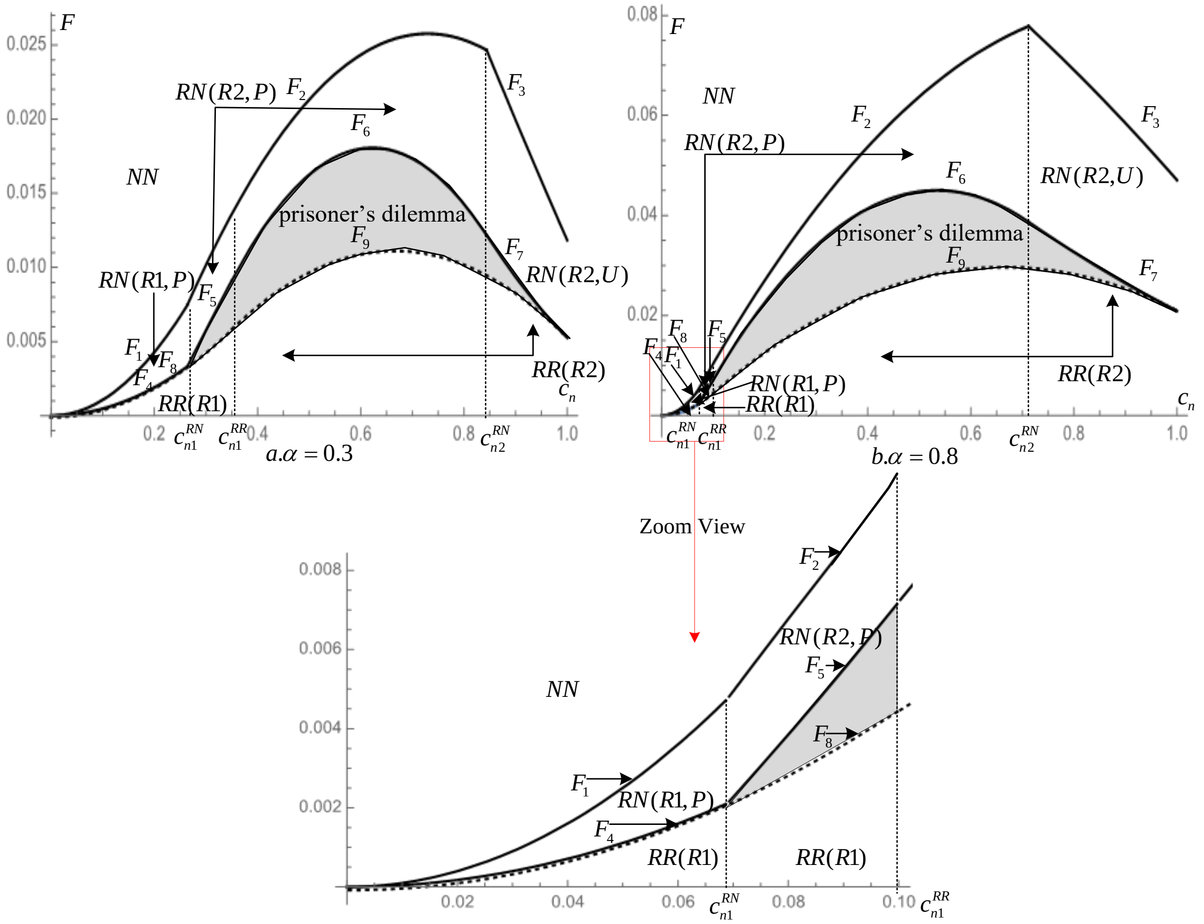

Figure 1. Impact of α and c_n on regions for different equilibria ($\Delta = 0.000001$).

In addition to verifying the results obtained in Table 2, Figure 1 also has the following insights. From Figure 1, we can see that (a) a prisoner's dilemma is more likely to arise when remanufacturing strategy R2 is adopted; (b) when the cannibalization effect between new and remanufactured products is weak (i.e., customers have a low valuation of remanufactured products), a prisoner's dilemma may not arise. The impact of Δ and c_n on regions for different equilibria is illustrated in Figure 2.

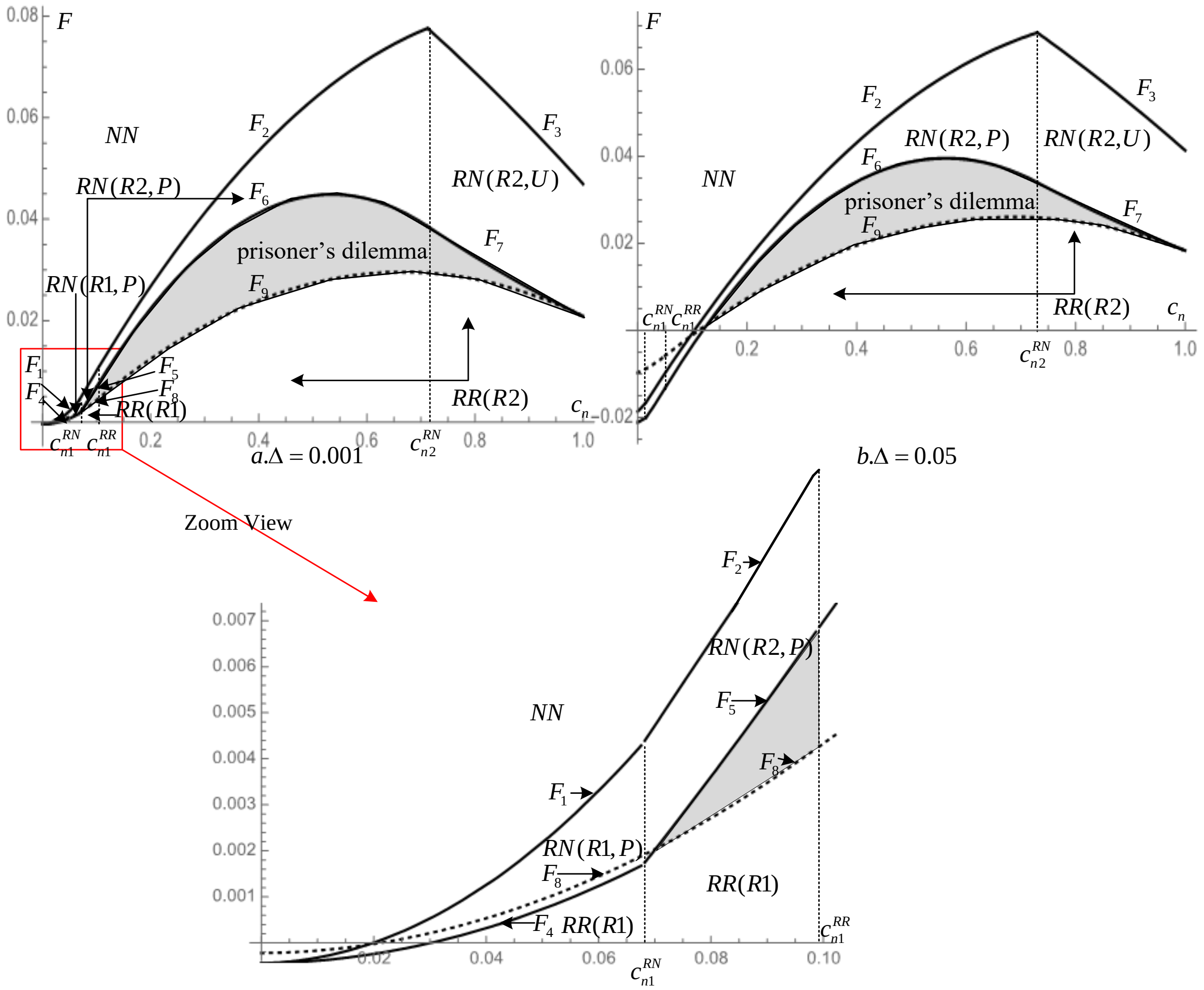

Figure 2. Impact of Δ and c_n on regions for different equilibria ($\alpha = 0.8$).

Figure 2 illustrates the results of Table 2 and shows how the regions of different equilibria are affected by the production cost increase of new products and the cost difference between new and remanufactured products. Note that in Figure 2(b), the negative part of F is also shown in the Figure for the purpose of continuity. In fact, the cost incurred in developing remanufacturing capability can never be negative. This indicates that, when the cost difference between new and remanufactured products is relatively low, neither manufacturer investing in remanufacturing operations is always the Nash equilibrium as long as the cost incurred in developing remanufacturing capability is nonnegative. Figure 2 also implies that only adopting remanufacturing strategy R1 cannot motivate the two manufacturers to invest in remanufacturing operations when the design change in new products is costly.

4.4. Equilibrium production quantity

The two manufacturers' equilibrium production quantity under different remanufacturing investment decisions is summarized in Proposition 1. This subsection examines how the equilibrium production quantity of the two manufacturers is affected by manufacturing and remanufacturing cost structures and the cannibalization effect between new and remanufactured products. The detailed results are summarized in Corollary 2.

Corollary 2. The impact of Δ (the production cost increase of new products), α (which scales the cannibalization effect between new and remanufactured products), and c_n (the cost difference between new and remanufactured products) on equilibrium production quantity of the two manufacturers under different remanufacturing investment decisions are summarized in Table 3 (See Appendix A for details).

The results in Table 3 show that, depending on the remanufacturing strategy adopted by the manufacturer, production quantities for new and remanufactured products may either increase or decrease with Δ, α, and c_n. First, when remanufacturing strategy R1 is adopted, the production quantity of new products decreases as Δ, α, and c_n increase, whereas the production quantity of remanufactured products increases as Δ, α, and c_n increase. In other words, $\frac{\partial d_{ni}}{\partial \Delta} < 0$, $\frac{\partial d_{ni}}{\partial \alpha} < 0$, $\frac{\partial d_{ni}}{\partial c_n} < 0$, $\frac{\partial d_{ri}}{\partial \Delta} > 0$, $\frac{\partial d_{ri}}{\partial \alpha} > 0$, and $\frac{\partial d_{ri}}{\partial c_n} > 0$. Surprisingly, manufacturers will increase their production quantity of remanufactured products even when the change in the design is costly for new products. Second, when remanufacturing strategy R2 is adopted, the manufacturer remanufactures all available used products, and the production quantities for new and remanufactured products decrease with Δ and c_n, whereas α has a mixed impact on production quantities for new and remanufactured products. In this situation, the increase in customers' valuation of remanufactured products does not necessarily induce the two manufacturers to increase their production quantity of remanufactured products. This is because when remanufacturing strategy R2 is adopted, manufacturers may also need to increase their production quantity for new profits if they want to increase their production quantity of remanufactured products. Finally, when RN arises in equilibrium, M2's production quantity of new products decreases with c_n and α, but increases with Δ.

In Corollary 2, the impact of key parameters on the two manufacturers' production quantity decisions is examined. It shows that the cost structure of new and remanufactured products and the cannibalization effect between new and remanufactured products can, in most scenarios, motivate both manufacturers to reduce their production quantity of new products while increasing their production quantity of remanufactured products. However, the impact of these key parameters on the two manufacturers' total production quantity is unclear, and it is difficult to derive analytical results. Next, we numerically examine how the two manufacturers' total production quantity and associated profits are affected by F and c_n. We consider two scenarios where F can be relatively high or low, that is, $F = 0.02$ and $F = 0.001$. This consideration can be considered as a joint impact of α, Δ, and c_n as F is affected by these key parameters, thus making the analysis interpretation easier. As not all equilibrium presented in Proposition 2 will arise when $F = 0.02$ and $F = 0.001$, the following figures only show the applicable scenarios in the respective region.

Figures 3 and 4 show the two manufacturers' total production quantity and the associated profits as a function of c_n when $F = 0.02$. The two figures imply that both manufacturers' total production quantity decreases as c_n increases, while the decreasing rate of M1's total production quantity is lower than that of M2 when RN becomes the equilibrium. Consequently, the two manufacturers' profit decreases when the cost difference between new and remanufactured products increases.

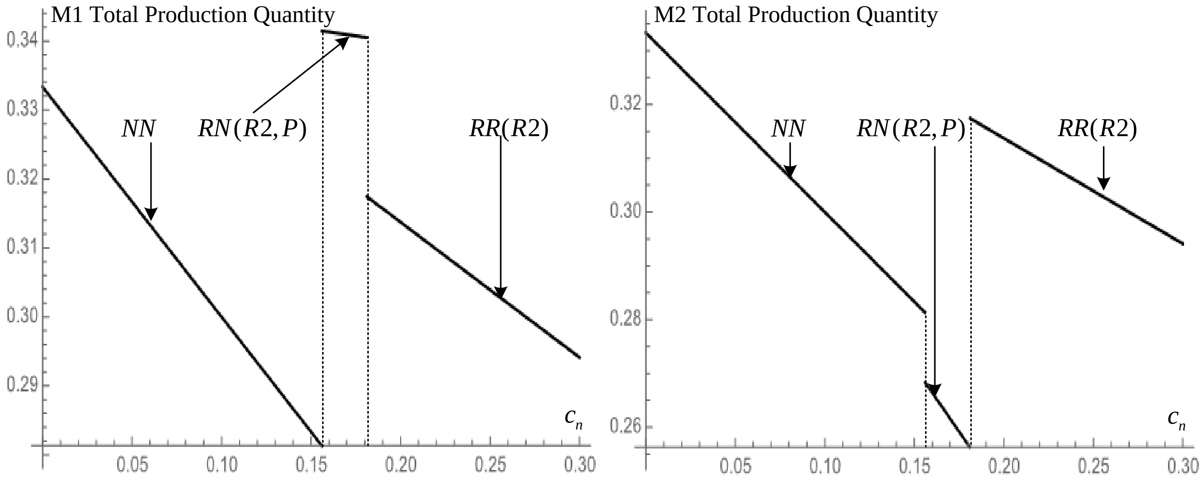

Figure 3. The two manufacturers' total production quantity as a function of c_n when $F = 0.02$.

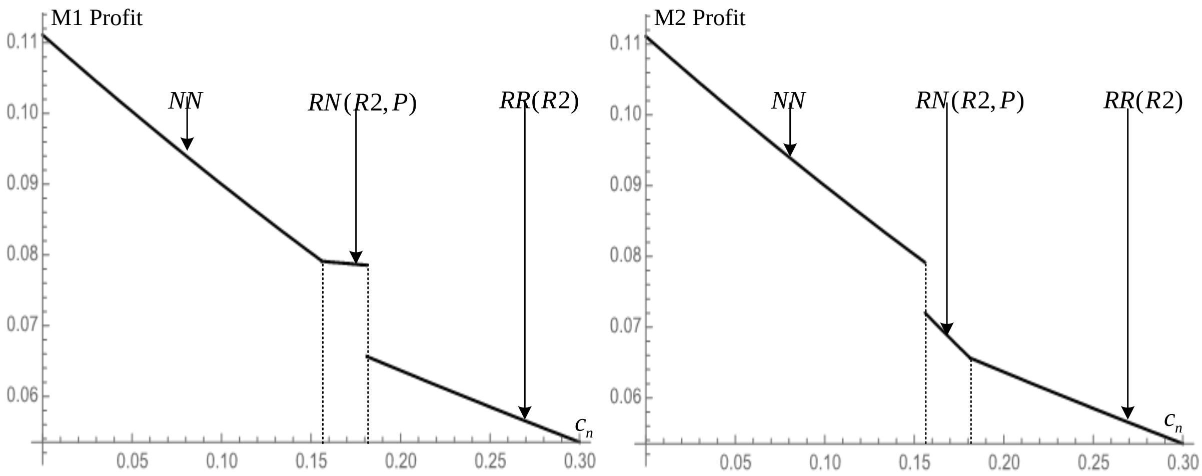

Figure 4. The two manufacturers' profit as a function of c_n when $F = 0.02$.

Figures 5 and 6 show the two manufacturers' total production quantity and the associated profits as a function of c_n when $F = 0.001$. In contrast with Figures 3 and 4, Figures 5 and 6 show that more equilibrium scenarios will appear when the cost incurred in developing remanufacturing capability is relatively low (i.e., $F = 0.001$). As such, the two manufacturers would have more equilibrium remanufacturing investment strategies. Figure 5 still shows that, in most scenarios, the two manufacturers' total production quantity decreases with the increase of c_n. However, M1's total production quantity increases with the increase of c_n when RN becomes the equilibrium, and the two manufacturers' total production quantity is not affected by c_n when RR becomes the equilibrium and when the c_n is at a medium level. This is because M1 will become more profitable when the cost difference between new and remanufactured products increases and M2 does not invest in remanufacturing operations. In equilibrium RR, the two manufacturers need to increase the production quantity of remanufactured products and reduce the production quantity of new products. As such, the change of c_n does not affect the two manufacturers' total production quantity. The overall impact on the two manufacturers' profit is that the two manufacturers' profit decreases with c_n.

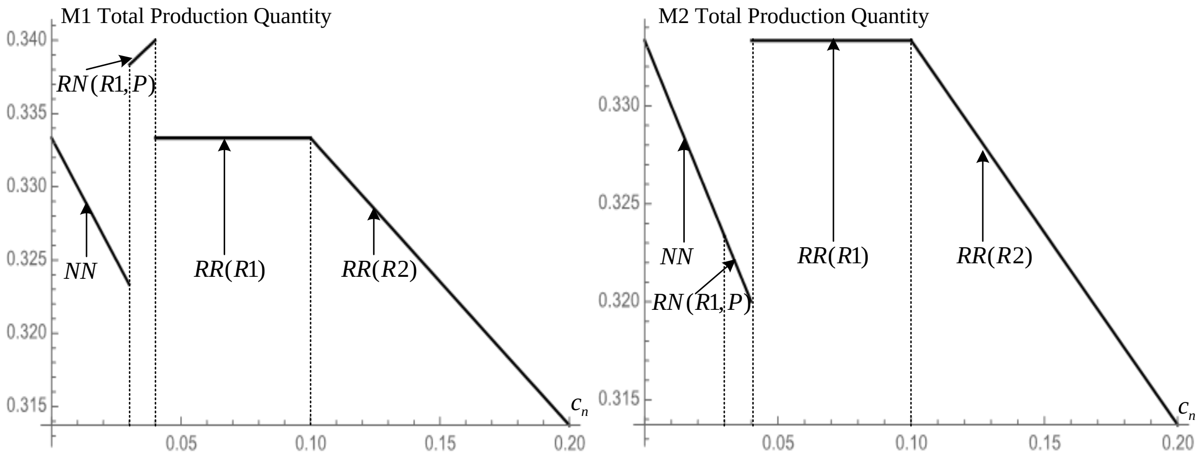

Figure 5. The two manufacturers' total production quantity as a function of c_n when $F = 0.001$.

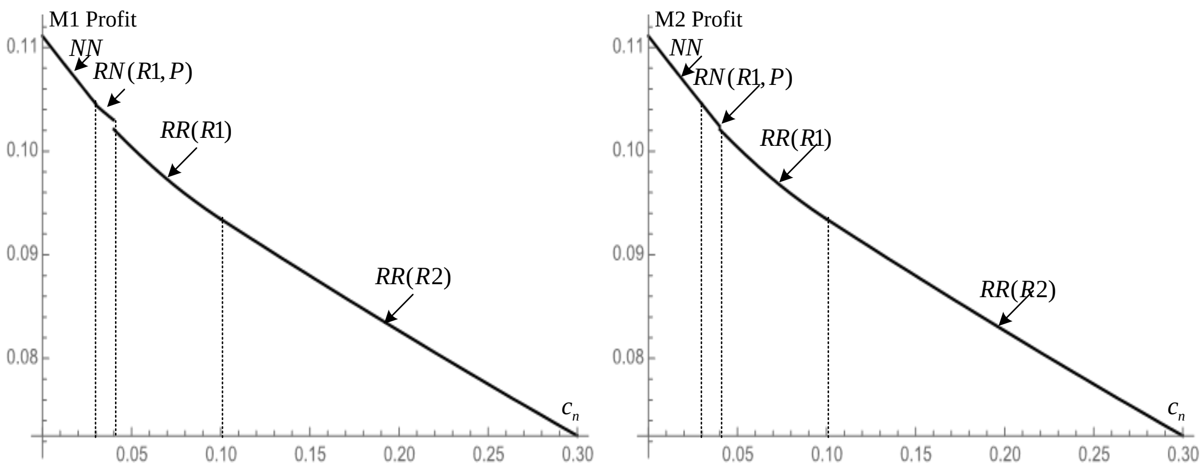

Figure 6. The two manufacturers' profit as a function of c_n when $F = 0.001$.

5. Environmental impact of manufacturing and remanufacturing

This section examines the environmental impact of manufacturing and remanufacturing and investigates whether remanufacturing can improve the environmental performance of the two manufacturers. The environmental impact of the two manufacturers in the three cases in different remanufacturing scenarios is summarized in Table 4 (See Appendix A for details). All the discussions are restricted to the range $\Delta < \alpha < 7 - \frac{12}{2-\Delta}, 0 < \Delta < \frac{1}{2}(9-\sqrt{73})$, $0 < c_n < 1$, and $0 < \beta < 1$.

Proposition 4. The environmental impact of remanufacturing operations can be discussed regarding the following two conditions:

(1) When both manufacturers investing in remanufacturing (i.e., Case RR) arise in equilibrium, two sub-conditions define the environmental impact of remanufacturing operations, such that: (i) if $0 < c_n \le c_{n1}^{RR}$, then, engaging in remanufacturing operations is not an environmentally-friendly choice when $\alpha < \beta - 2\Delta$, $\beta > 2\Delta$, and $c_n > c_{n1}$; and (ii) if $c_{n1}^{RR} < c_n < 1$, then, engaging in remanufacturing operations is not an environmentally-friendly choice when (a) $\alpha < \beta - 2\Delta$ and $\beta > 3\Delta$; or (b) $\alpha > \frac{\beta}{3}$ and $c_n > c_{n2}$, where $c_{n1} = \frac{(1-\beta)\Delta}{\beta - \alpha}$ and $c_{n2} = \frac{\alpha(2-\beta) - \beta(1-\Delta) + \Delta}{3\alpha - \beta}$.

(2) When only one manufacturer investing in remanufacturing (i.e., Case RN or Case NR) arises in equilibrium, three sub-conditions define the environmental impact of remanufacturing operations, such that the following applies: (i) If $0 < c_n \le c_{n1}^{RN}$, then, engaging in remanufacturing operations is not an environmentally-friendly choice when $\alpha < 10 + 3\beta - \frac{6(5+\beta)}{3-\Delta}$, $\beta > \frac{10\Delta}{3(1-\Delta)}$, and $c_n > c_{n3}$. (ii) If $c_{n1}^{RN} < c_n \le c_{n2}^{RN}$, then, engaging in remanufacturing operations is not an environmentally-friendly choice when (a) $\alpha > 10 + 3\beta - \frac{6(5+\beta)}{3-\Delta}$, $\beta > \frac{\Delta(13-\Delta)}{3(1-\Delta)}$, and $c_n > c_{n4}$; or (b) $\alpha < 10 + 3\beta - \frac{6(5+\beta)}{3-\Delta}$ and $\beta > \frac{\Delta(13-\Delta)}{3(1-\Delta)}$; or (c) $\beta < \frac{\Delta(13-\Delta)}{3(1-\Delta)}$ and $c_n > c_{n4}$. (iii) If $c_{n2}^{RN} < c_n < 1$, then, engaging in remanufacturing operations is always not an environmentally-friendly choice, where $c_{n3} = \frac{(4-\alpha-3\beta)\Delta}{3(\beta-\alpha)}$ and $c_{n4} = \frac{\alpha(7-3\beta) + 6(1+\beta)\Delta - \alpha^2 - 3\beta}{\alpha(13-\alpha+3\beta) - 3\beta}$.

Proposition 4 shows the environmental impact of remanufacturing under various equilibrium outcomes. This implies that, depending on some specific parameter conditions, remanufacturing operations may not be environmentally friendly even though remanufacturing itself is more environmentally friendly than manufacturing new products. From Proposition 4, we can see that customers' valuation of remanufactured products, the greenness of remanufactured products, and the cost difference between new and remanufactured products play an important role in the environmental impact of remanufacturing. Remanufacturing is harmful to the environment when the cost difference between new and remanufactured products is relatively high regardless of the levels of customers' valuation and greenness parameter of remanufactured products. This result is quite surprising in that a remanufacturing business can be highly profitable for the manufacturer that makes investment decisions when the cost difference between new and remanufactured products is relatively large. This is because, compared with new products, remanufactured products can significantly save costs for the firm when the production cost between new and remanufactured products is large. However, under such conditions, remanufacturing operations are not environmentally friendly even though they have great economic value. This indicates that environmental goals are not always in line with economic goals, and the environmental protection effect is determined by the characteristics of remanufacturing. On the one hand, manufacturers are more likely to invest in remanufacturing operations when they can produce remanufactured products at a relatively low cost. On the other hand, the number of products that can be remanufactured is strictly limited by the number of products that can be collected from the market, meaning that if the production cost for remanufactured products is low, then, manufacturers should increase their production quantity of new products so that there are more used products available for collection. As such, a negative environmental impact is caused by the production quantity increase of new and remanufactured products.

In addition, the environmental impact of remanufacturing is also heavily affected by customers' valuation and greenness parameters of remanufactured products (i.e., α and β). However, the monotonicity of the two parameters on environmental impact is difficult to analyze; hence, numerical studies are used to examine the impact of the two parameters on environmental impact. Note that the impacts of the two parameters on environmental impact are quite similar. Therefore, we set α as a constant parameter. The impact of β on environmental impact is investigated when there is no government subsidy, and the numerical results are illustrated in Figure 7. $\alpha = 0.5$ and $\Delta = 0.000001$ were used in both panels with $\beta = 0.6$ and $\beta = 0.3$ for Panels a and b, respectively. The setting of the parameters combines two scenarios that might affect the environmental impact of remanufacturing without the loss of generality. The combined two scenarios are: (a) $\alpha < \beta$, where customers' valuation of remanufactured products is low and the greenness parameter is relatively high, and (b) $\alpha > \beta$, where customers' valuation of remanufactured products is relatively high and the greenness parameter is relatively low. The shaded areas show the case in which remanufacturing is environmentally friendly.

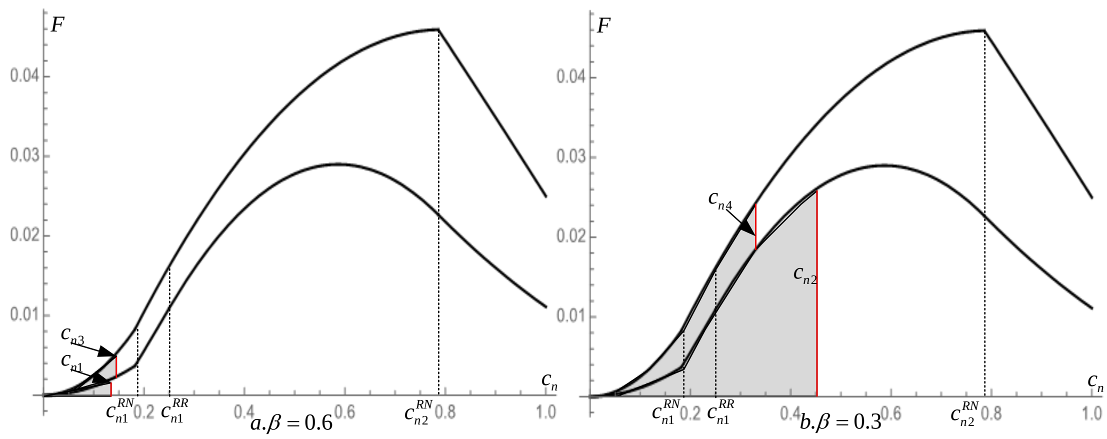

Figure 7. The impact of β on environmental impact when there is no government subsidy.

From Figure 7, we can see that the shaded area is large when β is at a low level, while as β increases, the shaded area decreases. This indicates that an environmentally-friendly outcome caused by remanufacturing operations is more likely when β is relatively low. However, as β increases, remanufacturing operations are less likely to benefit the environment. Recall that β stands for the non-greenness of remanufactured products and the smaller the β, the greener the remanufacturing. Hence, it is intuitive that remanufacturing operations are more likely to lead to an environmentally-friendly outcome when β is relatively low.

6. Extension: impact of government subsidy

In this section, we examine how the two manufacturers' optimal decisions are affected by government subsidies. For expression purposes, the superscription "S" is used in this section to denote the case where there are government subsidies. According to Cohen, et al. [41], the types of government support can be generally and broadly divided into two categories: (1) improving the "Industry Commons" and (2) providing financial incentives. The first type of government support, namely Industrial Commons, is often referred to and simplified as government R&D support, which often aims to improve the technical efficiency of the whole industry. The second type of government support, namely financial incentives, however, is often provided by the government to incentivize the development of green products in various forms, such as rebates, tax credits, and tax exemptions, and can also be offered to either customers or firms. This study assumes that the policy that the government used to support the development of remanufacturing industry is the second type, that is, financial incentives. This assumption is reasonable in that compared with R&D support, sale subsidies can better motivate firms to develop their own environmental technologies as concluded by Cohen, et al. [41]. Additionally, to be consistent with the industry practice implemented by the Chinese government, this study assumes that subsidies are provided to customers who decide to purchase remanufactured products, even though financial incentives can both be provided to firms and customers [16]. Considering different market structure conditions and the main goal of the supply chain, Yu, et al. [58] and Yu, et al. [59] concluded that subsidies offered to the manufacturer, retailer, or customer can all help maintain the whole supply chain at the optimal level under certain conditions. Hence, the assumption that the subsidy is offered to customers is consistent with the literature in the operations management field and helps this study to examine the impact of government subsidy on manufacturers' remanufacturing investment decisions and the subsequent environmental impact.

According to the Chinese government subsidy policy, customers who purchase a remanufactured product can receive a unit subsidy of s from the government. Hence, the net utility that a customer obtains from purchasing a remanufactured product is revised to $u_r^S = \alpha\theta - p_r^S + s$ after receiving the subsidy. It is still assumed that the net utility that a customer obtains from purchasing a new product remains the same and $u_n^S = \theta - p_n^S$. Similarly, based on the utility functions, customers' demand for new and remanufactured products after the subsidy policy can be derived as follows.

$$d_n^S = 1 - \frac{p_n^S - p_r^S + s}{1-\alpha}, \quad d_r^S = \frac{p_n^S - p_r^S + s}{1-\alpha} - \frac{p_r^S - s}{\alpha}. \tag{8}$$

Obviously, the subsidy offered to customers who purchase remanufactured products can decrease their demand for new products but increase customers' demand for remanufactured products. Based on the demand functions, it is easy to obtain the inverse demand functions as follows:

$$p_n^S = 1 - (d_{n1}^S + d_{n2}^S) - \alpha(d_{r1}^S + d_{r2}^S), \quad p_r^S = \alpha(1 - d_{n1}^S - d_{n2}^S - d_{r1}^S - d_{r2}^S) + s. \tag{9}$$

The subsidy does not have a direct impact on new products' sales price, but it can induce the two manufacturers to increase their sales price for remanufactured products correspondingly.

Consistent with the previous section, there are also four possible equilibrium outcomes for the two manufacturers regarding their remanufacturing investment decisions when there is a government subsidy: neither manufacturer invests in remanufacturing (Case SNN), both manufacturers invest in remanufacturing (Case SRR), and one manufacturer invests in remanufacturing and the other does not (Cases SRN and SNR). The analysis of these outcomes and equilibrium results are quite similar to that of the main model in Section 4 (no government subsidy). Therefore, the detailed analyses are placed in Appendix C, and the key results are discussed as follows.

The main results of the two manufacturers' remanufacturing operations investment decisions remain qualitatively the same. The impact of government subsidy on manufacturers' optimal responses when different remanufacturing investment decisions are made may depend on which remanufacturing strategy is adopted by the manufacturers. The two manufacturers will always increase their production quantity of remanufactured products and decrease the production quantity of new products when there are subsidies. However, the increase (decrease) in production quantity may not necessarily induce the manufacturers to adjust their pricing strategy correspondingly, and the sale price of new products is only affected by manufacturers' production quantity strategy when remanufacturing strategy R2 is adopted. This result implies that the impact of the subsidy that is offered to customers on a firm's green technology improvement decision to some extent contradicts that of the case that the subsidy is offered to the firm. Yu, et al. [58], Yu, et al. [59], and Cohen, et al. [41] found that firms rarely decrease their sale prices to pass on the savings of production cost to customers even though technological advancement decreases their production cost significantly. However, this study, indicates that firms can benefit from the government subsidy indirectly by adjusting their pricing strategies correspondingly, even though the subsidy is directly provided to customers. This shows that when the government decides to offer subsidies to customers rather than manufacturers, the subsidy policy may be profitable for the supply chain as a whole.

Furthermore, depending on the fixed cost incurred in developing remanufacturing capability, the two manufacturers' remanufacturing investment decisions will also reach an equilibrium when there are subsidies offered to customers who purchase remanufactured products. On the one hand, the subsidy policy can increase the threshold where at least one manufacturer invests in remanufacturing operations in equilibrium. On the other hand, manufacturers are more likely to adopt remanufacturing strategy R2 when the subsidy policy exists. However, the subsidy policy may not be environmentally friendly, especially when the non-greenness of remanufactured products is relatively high (see Appendix C for a detailed analysis). This result is partly different from that Cohen, et al. [41]. Cohen, et al. [41] found that government R&D support can cause unanticipated negative environmental impacts, while sales subsidies are generally beneficial to the environment. The subsidy policy considered in this study falls into the type of sales subsidy. However, in contrast to Cohen, et al. [41], this study indicates that sales subsidies can also cause unanticipated negative overall outcomes for the environment, especially when remanufactured products are not as green as expected.

7. Conclusions

7. 1. Concluding remarks and managerial implications

Whether to invest in remanufacturing operations is a strategic decision in the manufacturing and remanufacturing field as the existence of remanufactured products will seriously cannibalize customers' demand for new products and consequently affect a firm's main business. A focal manufacturer's strategic decision may affect the entire supply chain depending on the competitiveness of remanufactured products, the cost difference between new and remanufactured products, and the competitive market status between firms. In this study, we draw insights for manufacturers that consider investing in remanufacturing operations in a competitive setting, aiming to maximize profits for the manufacturers. Motivated by examples found in practice, we consider a supply chain comprising two manufacturers selling perfectly substitutable products to the market. The two manufacturers consider whether to invest in remanufacturing operations, and one manufacturer's decision is affected by the other. To make products remanufacturable, manufacturers must make changes in the new-product design, which will increase the production cost of new products. Otherwise, remanufacturing is impossible for the firm because of technical barriers. In addition to the change in product design, manufacturers should also incur a one-time fixed cost to develop remanufacturing capabilities. These considerations aim to examine whether and how the two manufacturers should invest in remanufacturing operations. There are two remanufacturing strategies available if a manufacturer makes a remanufacturing investment decision, that is, remanufacturing some but not all available used products (R1) and remanufacturing all available used products (R2). Given this construct, optimal strategies in terms of production quantity, remanufacturing investment decisions, and remanufacturing strategies are derived, and the corresponding environmental impact of different remanufacturing investment strategies is investigated. In the following paragraphs, the managerial implications of this study are further elaborated on and discussed.

Optimal decisions for the two manufacturers when different remanufacturing investment decisions are made: Depending on the cost difference between new and remanufactured products, manufacturers will adopt different remanufacturing strategies and change their remanufacturing strategy from remanufacturing some but not all available products to remanufacturing all available used products when the cost difference between new and remanufactured products increases. When both manufacturers invest in remanufacturing operations, the two manufacturers will simultaneously adopt remanufacturing strategy R1 or R2 depending on the cost difference between new and remanufactured products, and there is no asymmetric remanufacturing strategy adoption by the two manufacturers. However, when only one manufacturer invests in remanufacturing operations, the manufacturer that does not invest in remanufacturing operations may exit the market and does not even produce new products when the cost difference between new and remanufactured products is relatively high. This is because producing new products will become costly when the cost difference between new and remanufactured products is relatively high. As such, in the long term, the manufacturer that does not invest in remanufacturing operations may lose its competitiveness when only selling new products to the market. This indicates that the two manufacturers need to change not only their production quantity decisions but also their remanufacturing strategies when different remanufacturing investment decisions are made.

Nash equilibrium for the two manufacturers regarding their remanufacturing investment decisions: The manufacturer's remanufacturing operations investment decisions will reach an equilibrium depending on the fixed cost incurred by the remanufacturing capability. In each equilibrium, different remanufacturing strategies will be adopted by manufacturers depending on the cost difference between new and remanufactured products. Neither manufacturer will invest in remanufacturing operations when it is costly for them to develop remanufacturing capability. When the fixed cost incurred in developing remanufacturing capability is relatively low, both manufacturers will invest in remanufacturing operations and sell new and remanufactured simultaneously to the market. Interestingly, an asymmetric equilibrium may arise if one manufacturer invests in remanufacturing operations and the other does not when the fixed cost incurred in developing remanufacturing capability is at a medium level. However, when the fixed cost incurred in developing remanufacturing capability is at a medium level, both manufacturers may be trapped in a prisoner's dilemma when they invest in remanufacturing operations. In this situation, the market equilibrium will be stabilized at RR although the two manufacturers' profit in Case NN is strictly higher than that of RR as the market expansion effect cannot dominate the cost increase effect.

Impact of operational factors on market equilibrium: The impact of the cost structure of manufacturing and remanufacturing and the cannibalization effect between new and remanufactured products on the two manufacturers' remanufacturing investment decisions and equilibrium are also studied. We find that the remanufacturing strategy adopted by the manufacturer has a great impact on the size of the equilibria regions, the size of the prisoner's dilemma region, equilibrium production quantity, and profits. The two manufacturers should make their remanufacturing investment and remanufacturing strategy decisions flexibly depending on the cannibalization effect and cost difference between new and remanufactured products, the production cost increase of new products, and the fixed cost incurred in developing remanufacturing capability.

Environmental impact of manufacturing and remanufacturing: By comparing the environmental impact of manufacturing and remanufacturing, we find that remanufacturing operations may not be environmentally friendly, although the remanufacturing business itself is more environmentally friendly in terms of reusing existing products and materials, especially when the cost difference between new and remanufactured products is relatively high. This result is quite surprising in that, compared with new products, remanufacturing can help the manufacturer that invests in remanufacturing operations reduce production costs when the cost difference between new and remanufactured products is relatively high. However, such economic profit may not be in line with environmental protection goals as the number of products that can be remanufactured is always limited by the number of products that are available for collection. In addition, the environmental impact of remanufacturing is also affected by the greenness of remanufactured products. Intuitively, remanufacturing operations are more likely to become environmental burdens when remanufactured products are less green.

Impact of government subsidy: Consistent with industry practice, the impact of government subsidy on manufacturers' remanufacturing investment decisions is also examined. We find that the main results of the two manufacturers' remanufacturing operations investment decisions remain qualitatively the same after considering government subsidy. The impact of government subsidy on manufacturers' optimal response depends on which remanufacturing strategy is adopted by the manufacturers. The subsidy offered by the government can induce manufacturers to increase their production quantity and sales price for remanufactured products. However, the production quantity increase of remanufactured products does not necessarily make the remanufacturing business environmentally friendly.

In the decision of remanufacturing investment, the findings of this study provide managerial guidance for two competitive manufacturers in the manufacturing and remanufacturing industry. In practice, some manufacturers' remanufacturing investment decisions are consistent with the findings of the study. For instance, as mentioned in the introduction, in the smartphone industry, Apple and Huawei adopted different remanufacturing investment decisions in the Chinese market, that is, Apple invests in remanufacturing while Huawei does not invest in remanufacturing. It is noticeable that, for Apple and Huawei, customers' valuation of their remanufactured products is still high, resulting in the high remanufacturing market potential for the two firms. This indicates that the market expansion effect for these two firms is large and it might be easier to outweigh the cost-increasing effect and the cannibalization effect caused by remanufacturing investment. However, the actual remanufacturing investment equilibrium for Apple and Huawei is asymmetric equilibrium, that is, one invests while the other does not. This phenomenon might be partly because of the impact of the remanufacturing investment on the cost structure of the firm and the prisoner's dilemma. Before investing in remanufacturing, Apple had taken some measures to make it harder to remanufacture its used products [32]. For instance, Apple complicated the replacement of the battery by gluing the battery of "Retina MacBook 2015." This shows that, depending on the cost structure, Apple strategically takes some measures to change the design of new products to embrace remanufacturing. However, Huawei may not take similar measures, resulting in a change of the cost structure. This becomes an obstacle for Huawei to invest in remanufacturing operations. On the other hand, considering the large potential of the remanufacturing market, Apple and Huawei may easily be trapped in a prisoner's dilemma if both invest in remanufacturing as shown in the model results. This may also explain why Huawei does not invest in remanufacturing when it observes that Apple already invested in remanufacturing. However, note that manufacturers' actual remanufacturing investment decisions in practice are far more complex than what we consider in this study. This may be partly because the cost structure for two competitive manufacturers cannot be the same even though the products they sell to the market are perfectly substitutable. Asymmetric cost structure and manufacturers are left for future research directions; this study aims to provide a potential alternative explanation for how manufacturers should make their remanufacturing investment decisions in a competitive environment.

7. 2. Future research

Despite the key findings discussed in the above sections, this study still has some limitations that require further study. First, to focus on the manufacturer's remanufacturing investment decisions, the collection process was not considered in the model, and it was assumed that all used products can be remanufactured to the same quality. However, in practice, the quality of used products may vary and not all used products can be collected and remanufactured. The model would be more realistic if the collection process and quality of used products are taken into consideration. Second, the government's decision-making was not considered when subsidy policy is implemented, even though the impact of government policy on a firm's optimal response, market equilibrium, and environmental impact were examined. It is worth considering endogenizing government policy to determine how the government should implement its policy so that the policy can contribute to firms' sustainable development. Finally, from the perspective of the subsidy policy, we only considered the scenario where the subsidy is offered to customers who purchase remanufactured products. In fact, the subsidy may also be offered to manufacturers to offset the cost incurred in developing remanufacturing capability, which is worth studying further.

Acknowledgments

The authors declare no conflict of interest in this study.

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