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Optimal internal channel structure decision: The case of remanufacturing operations[1]

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Abstract

How manufacturing and remanufacturing functions perform in practice would relate to the supply chain system's channel structure, which can be decentralized and centralized (called "integrated"). Through building formal game theoretic models, we investigate in this paper the economic performance and environmental impact between these two internal channel structures. We find that the decentralized structure consistently improves the environment outcome by encouraging early entry into remanufacturing and full remanufacturing strategies. It proves advantageous in scenarios with polarized production costs (either low or high). Conversely, the integrated structure is optimal for manufacturers when new product production costs are moderate; however, this structure invariably entails worse environmental outcome for manufacturers. From the perspective of closed-loop supply chain systems, a triple-win outcome for the manufacturer, retailer, and remanufacturing division is unattainable because the retailer can never benefit from the manufacturer's decisions made under the decentralized structure. Nevertheless, compared to the benchmark case without remanufacturing encroachment, the manufacturer's decision to encroach into remanufacturing under both structures can have positive effects on the retailer and environment. Robustness of the main findings is checked across various extended cases, including quantity competition, changes in game sequence, customer channel preferences, and direct channel opening costs.

Keywords: Closed-loop supply chains; remanufacturing operations; manufacturer encroachment; remanufacturing division; channel structure

1. Introduction

The annual global remanufacturing market, valued at over $100 billion, plays a pivotal role in generating employment, fostering revenue growth, and delivering environmental benefits[iii].Taking the automotive sector as an example, with the remanufacturing market reaching over $60 billion in 2022 and projected to rise to over US$126 billion by 2030[iii]. These economic figures clearly reflect a broader narrative: approximately 80% of manufacturers now consider remanufacturing a strategic priority in their operations[iv]. This firmly means remanufacturing is a critical component of global industrial strategies, though traditionally, manufacturers have hesitated to encroach with remanufacturing due to concerns about cannibalization (Chua et al., 2023).

Traditionally, remanufacturing operations were integrated within manufacturing divisions, with decisions made at the firm-wide level. However, this structure often led to ambiguity regarding responsibility for new and remanufactured products, limiting operational flexibility and potentially hindering new product development.

To address these challenges, many companies have established dedicated remanufacturing divisions. For example, Caterpillar operates a specialized remanufacturing division, called Cat Reman, which works closely with Cat equipment to provide comprehensive customer support, from initial purchase through maintenance, repair, rebuilding, and overhaul[v]. The creation of the specialized remanufacturing division allows companies to delegate remanufacturing-related decisions to focused units (i.e., adopting "decentralization"), enhancing efficiency and strategic management[1].

This move towards "decentralization" is also reported in the literature. For instance, based on interviews with industry managers, Shi et al. (2020) identified conflicts between manufacturing and remanufacturing divisions following the establishment of a dedicated remanufacturing unit. When manufacturing and remanufacturing divisions set their sales prices independently, each prioritizing its own profit maximization, conflicts naturally arise. These findings highlight the growing trend of independent operations within remanufacturing divisions. While specific decision-making processes within firms remain undisclosed, available evidence suggests that companies are increasingly granting remanufacturing divisions greater autonomy[2]. This trend toward decentralized decision-making is what we called "decentralization" in this paper. This could provide a strategic pathway for firms looking to engage in remanufacturing while mitigating concerns over potential cannibalization effects associated with introducing remanufactured products. Therefore, this study seeks to determine

[1] A notable example is a job posting by Cat Reman for a product manager explicitly states responsibility for overseeing the profit and loss of the remanufacturing business, a key strategic segment at Caterpillar. This suggests that the division has been granted greater decision-making authority, even though the specific pricing process for Cat Reman remains undisclosed.

[2] For instance, while there is no publicly available confirmation that Cat Reman has full decision-making authority over remanufacturing-related decisions, a job advertisement for a Cat Reman Product Manager suggests increased autonomy. The role includes overseeing profit and loss responsibility for the Reman Business, indicating that decision-making power is shifting towards the division.

whether granting greater decision-making autonomy under decentralization to a newly established remanufacturing division is a worthwhile strategy when such a dedicated unit is formed.

Choosing the optimal internal channel structure for manufacturers engaged in encroachment poses a complex corporate policy decision. Each internal channel structure results in different economic outcomes and thereby influences operational performance, depending on whether remanufacturing-related pricing decisions are delegated to the newly established remanufacturing division. Moreover, if granted pricing authority, the remanufacturing division may or may not be incentivized to collect and remanufacture a larger volume of used products. This introduces uncertainty in the quantity of used products potentially ending up in landfills, which may elevate environmental impact for manufacturers.

As a remark, prior research on manufacturer-involved remanufacturing operations often neglected the distinct framework of a dedicated remanufacturing division. While many studies naturally focused on integrated structures when remanufacturing was lucrative for overall firm profits, the study by Shi et al. (2020) stands as an exception. They explored manufacturer decisions about channel structure, considering divisions managing new and remanufactured products separately. Their primary objective was to identify optimal marketing channels for both product categories. In contrast, this study is centered on uncovering the optimal choice of the manufacturer on internal channel structure, particularly when actively entering the remanufacturing market. Specifically, we address the following research questions: *(a) What are the optimal responses of the manufacturer, retailer, and remanufacturing division under two different internal channel structures: the integrated structure and the decentralized structure? (b) Which internal channel structure should the manufacturer adopt for remanufacturing operations, and how does this decision impact the profits of the retailer and the remanufacturing division? Additionally, will the manufacturer's choice of internal channel structure result in a win-win-win scenario for the manufacturer, retailer, and remanufacturing division? (c) Given the manufacturer's flexibility in determining the internal channel structure, will the manufacturer engage in remanufacturing encroachment? Additionally, how will the retailer be affected by the manufacturer's decision on remanufacturing encroachment?*

To address these important research questions, a supply chain model comprising of a manufacturer and a retailer is considered. In our game theoretic model, the manufacturer, contemplating entry into the remanufacturing market through a dedicated division, faces decisions under two internal channel structures: decentralized and integrated. In the decentralized structure, the remanufacturing division holds decision-making authority to maximize its profit. Conversely, in the integrated structure, the manufacturer retains control over remanufacturing decisions to maximize combined profits. Interactions with the retailer occur under a wholesale price contract, where the manufacturer sets wholesale prices for new products, and the retailer sets corresponding sales prices. The sales price of remanufactured products is determined based on the prevailing internal structure, set either by the integrated manufacturer or the remanufacturing division.

Contribution: Managing operations of new and remanufactured products in closed-loop remanufacturing systems is critical. The rise of dedicated remanufacturing divisions within manufacturing firms naturally presents challenges in choosing between integrated and decentralized structures. While both structures are prevalent in practice, existing literature lacks comprehensive guidance on “which structure manufacturers should choose” and “what corresponding implications are”. This study hence fills this gap by delineating the optimal conditions for each structure based on critical factors and examining the associated economic and environment impacts. Surprisingly, we find that the integrated structure may be preferred even with high remanufacturing costs. Additionally, the decentralized structure may offer advantages even when new product business is unprofitable, contrary to conventional wisdom. Notably, retailers do not benefit from the decentralized structure, despite its advantages for manufacturers. We also note that the profit alignment between the manufacturer and remanufacturing division holds in most scenarios, though conflicts may arise, particularly with moderate production costs. Lastly, from an environmental outcome perspective, decentralized structures consistently promote early remanufacturing adoption and full strategy implementation, despite potential impacts on retailers.

The remaining of the study is structured as follows: Section 2 comprehensively reviews the related studies to identify research gaps. Section 3 outlines the initial model settings and introduces the benchmark scenario, which does not involve remanufacturing encroachment. Section 4 delves into the core model analysis and reports key findings. To ensure the robustness of the main findings, Section 5 explores several extensions. Finally, Section 6 offers concluding remarks and presents important insights. The core proofs are provided in the Appendix, while additional proofs can be found in the Online Supplementary Materials.

2. Literature Review

This study delves into the strategic choices manufacturers make regarding their internal channel structure when entering the remanufacturing market. Our literature review focuses on two crucial dimensions.

First, there is significant interest in exploring operational performance across various domains. These include endeavors such as establishing and enacting corporate social responsibility initiatives within organizations (Cai and Choi, 2021), supply chain related environmental risk (Choi, 2016), managing complex operational systems (Choi and Chiu, 2012), and applications of big data (Choi and Lambert, 2017). This study investigates the operational performance as well as environmental outcomes in the context of new and remanufactured products, primarily focusing on the profitability of firms venturing into remanufacturing market, with a central concern being the cannibalization effect.

Extensive discussions and reviews of remanufacturing systems can be found in works such as Atasu et al. (2008) and Souza (2013). However, few studies have delved into the intricacies of the operational performance associated with internal channel structure arrangements within firms, particularly the interaction between manufacturing and remanufacturing divisions. Consequently, it has been common for remanufacturing enterprises to integrate operational aspects within the firm, leading to firm-level remanufacturing decisions. Nevertheless, emerging industry practices suggest the viability of bestowing remanufacturing decision-making authority upon a dedicated division, resulting in a decentralized channel structure. Addressing this interaction concerning initial production costs, Toktay and Wei (2011) introduced a mechanism of cost allocation to distribute the raw production costs to the remanufacturing division, aiming to harmonize the potential conflict between these divisions. Yet, their focus remained on cost allocation, without extending to examine manufacturers' decision-making regarding internal channel structure.

Notably, Shi et al. (2020)'s study stands as an exception. Their research focused on the decision between direct and indirect selling of remanufactured products, considering the internal channel structure. However, our investigation differs from theirs in several key dimensions. First, their analysis was focused on the manufacturing division's potential adaptations due to future cannibalization considerations. This excluded scenarios where firms might empower the remanufacturing division with increased autonomy to optimize divisional-level profitability. The establishment of a remanufacturing division introduces a critical choice: whether to delegate remanufacturing-related decisions to the remanufacturing division. Second, our study primarily focuses on the internal channel structure, in contrast to Shi et al. (2020), who concentrated on the choice of marketing channels for remanufactured products. This distinction allows us to examine the operational-level decision-making regarding the internal structure of firms, rather than solely considering marketing channel strategies. Furthermore, the analysis also considers the associated environmental impact, a factor not previously addressed by Shi et al. (2020).

Second, manufacturers' consideration of whether to introduce remanufactured products mirrors the extensive literature on manufacturer encroachment. Traditionally, manufacturer encroachment involves manufacturers introducing new channels, often direct or online, alongside existing distribution channels involving retailers, effectively competing with retailers in the market. Earlier studies in this domain have demonstrated that manufacturer encroachment intensifies market competition, leading retailers to resist this strategy (Ha et al., 2016). It has been proven that the retailer can also earn profit from the encroachment of the manufacturer. For example, Guan et al. (2023) discovered that a manufacturer's encroachment strategy can be beneficial for both the manufacturer and the retailer, leading to a double win outcome. Likewise, this study delves into manufacturers' endeavors to encroach by introducing remanufactured products through the creation of dedicated remanufacturing divisions, thus engaging in direct competition with retailers. To be consistent with the findings of Tang et al. (2023), our study reveals that the manufacturer's entry into remanufacturing can yield positive outcomes for the retailer, potentially resulting in a mutually beneficial scenario. However, our study delves further into the internal channel structure arrangement for the remanufacturing division, an aspect that has not been extensively explored in this literature, except for Shi et al. (2023).

Shi et al. (2023) studied manufacturer encroachment, analyzing whether a manufacturer planning to create an e-commerce division to compete with retailers should integrate or delegate operational decisions. This investigation differs from theirs in several key dimensions: First, our study focuses on manufacturer encroachment involving remanufacturing, considering customers' valuation of both new and remanufactured products. In contrast, Shi et al. (2023) primarily concentrated on customers' acceptance of different channels. Second, their investigation of internal channel structures pertained to common products, whereas our study extends the consideration to the context of new and remanufactured products, aiming to determine if general implications hold when applied to remanufactured products while still retaining a focus on the manufacturer's internal channel structure decision. When considering remanufactured products, associated impacts such as cannibalization and environmental emerge, which are not present with standard goods. Third, while their theory suggested that customer demands could be satisfied across traditional retail and direct e-channels, depending on the acceptance of the e-commerce division, which would change when remanufactured products are introduced. Customers' demand for remanufactured products is always determined by the sale of new products. Consequently, in anticipation of manufacturer encroachment through remanufacturing, the retailer can become strategic in the sale of new products as it can impact the availability of cores for remanufacturing. This strategic link is absent in Shi et al. (2023) as well as the traditional manufacturer encroachment literature, setting this study apart. Finally, this study addresses the question of whether manufacturer encroachment through remanufactured products is advisable, providing a theoretical basis for manufacturers to navigate encroachment endeavors while accommodating retailers' interests.

3. Preliminary

3.1. Model settings

In our model, we consider the interplay between a manufacturer (M) and a retailer (R). The manufacturer produces and sells new products via the retailer. At the same time, the manufacturer has the strategic option of venturing into the realm of remanufactured products through the establishment of a dedicated remanufacturing division (RD), which manages a "direct channel" that sells remanufactured products directly to customers. We thus have a closed-loop supply chain system with remanufacturing. This study specifically examines manufacturer encroachment in the remanufactured product market, rather than the new product market, meaning that only remanufactured products—not new ones—are introduced into the direct channel. Consequently, new products are sold exclusively through the retail channel, while remanufactured products are limited to the direct channel. This approach aligns with industry practices, such as Dell's strategy of offering remanufactured products only through Dell Outlet, to minimize potential cannibalization between product lines.

With the establishment of the remanufacturing division, the manufacturer must choose between two internal channel structures, namely the decentralized structure and the integrated structure. In the decentralized structure, remanufacturing decision-making authority of the price is delegated to the remanufacturing division, driven by the aim to optimize divisional profit. Conversely, the integrated structure empowers the manufacturer to retain control over remanufacturing decisions, geared towards maximizing overall profits spanning both the new and remanufacturing domains. Considering the marketing channel setup, such a configuration is possible in practical contexts. Evidence supporting this trend can be found in job postings such as that by Cat Reman, which seeks a product manager responsible for overseeing the profitability, quality performance, and overall product portfolio of remanufactured products. While specific decision-making processes may not be publicly disclosed, indications suggest that firms are granting greater decision autonomy to remanufacturing divisions. It is important to note that, regardless of the internal channel structure, the remanufacturing division is part of the manufacturer. Therefore, when comparing the two internal channel structures, the remanufacturing division's profit is considered as a part of the manufacturer's overall profit.

To focus on the remanufacturing side decision, the manufacturer and retailer engage through a wholesale price contract (Hu et al., 2016, 2018). Herein, new products are supplied to the retailer by the manufacturer at the wholesale price denoted as w_n, thereby the retailer resells new products at a retail price p_n. In the scenario of remanufacturing encroachment, the manufacturer or the remanufacturing division sets the retail price of remanufactured products at p_r. Here, p_n and p_r represent the market-clearing prices, determined with the objective of maximizing profit. Let c_n and c_r represent the production cost for new and remanufactured products respectively, where $c_n > c_r > 0$. Here, to focus on the core research questions, when we examine the manufacturers' decisions on internal channel structure, we simplify the used product collection process. Therefore, the production cost values, particularly the remanufacturing costs, represent the average production costs within the overall process, irrespective of the collection costs for used products or the method by which these products are retrieved from the market (Zhang and Zhang, 2019; Zhang et al., 2021). Furthermore, consistent with Xu et al. (2023) and Zhou et al. (2023), we assume that the costs associated with various remanufacturing activities, including collection, sorting, and transportation, are encompassed within the remanufacturing production cost. In alignment with Niu and Zou (2017), and with a focus on the repetitive introduction of similar products to the market, our analysis is conducted within a single period to capture the average dynamics of the supply chain.

Let θ denote customers' valuations for the product, which is a uniform distribution on the interval 0 and 1, i.e., $\theta \in U[0,1]$. The uniform distribution is commonly used in the related literature, such as Niu and Zou (2017) and Guo and Choi (2024), which captures heterogeneous customers' valuation for the product. Without loss of generality, the market size is normalized to 1. Moreover, at most one unit of product is purchased. In the benchmark case without remanufacturing encroachment (denoted as case B), only new products can be purchased, and customers will purchase as long as their utility is nonnegative. The net utility that customers buy one unit of a new product is $u_n^B = \theta - p_n^B$. Hence, the indifferent preference between purchasing and not purchasing the new product is $\theta = p_n^B$. Therefore, customers' demand function for new products in the benchmark case without remanufacturing encroachment is $d_n^B = 1 - p_n^B$.

In the remanufacturing encroachment case (denoted as case *E*), the manufacturer encroaches through the introduction of remanufactured products. While new and remanufactured products are respectively accessible through the retail channel and the direct channel, there is no discernible variation in valuation between these channels. Conversely, the valuation that customers assign to remanufactured products is smaller than that assigned to new products, even numerous manufacturers assert that all remanufactured items attain equivalent quality to new ones. This valuation discrepancy is exemplified by Apple's refurbished iPhone offerings, which come with new batteries, outer shells, a one-year warranty, and other benefits, yet are still valued lower by customers than new iPhones, resulting in a reduced sales price[vi]. Hence, let α be the discount factor of customers' valuation, where $0 \leq \alpha \leq 1$. The assumption of uniform customer valuation across channels deviates from studies concerning manufacturer encroachment, yet aligns with existing remanufacturing literature, as demonstrated by Shi et al. (2020). This choice aims to accentuate remanufacturing operations and ensure result comparability with other remanufacturing-oriented investigations. Following Shi et al. (2020), we assume that $\alpha > c_r$ to ensure the profitability of remanufactured products. Additionally, the cost of the manufacturer in establishing the direct channel for remanufactured product sales is normalized to 0. These two assumptions will be relaxed in the extension section, thereby confirming the robustness of the main findings.

The net utility that customers purchase a new product is $u_n^{Ej} = \theta - p_n^{Ej}$, and the net utility that customers buy one remanufactured product is $u_r^{Ej} = \alpha\theta - p_r^{Ej}$, where $j \in \{I, D\}$ indexes integrated and decentralized structures, respectively. Note that since the two channel structures are just internal arrangements of the manufacturer when remanufacturing-related decisions are made, they would not affect customers' valuation for new and remanufactured products. Hence, new products would be purchased if $u_n^{Ej} \geq u_r^{Ej}$ and $u_n^{Ej} \geq 0$, and remanufactured products would be purchased if $u_r^{Ej} \geq u_n^{Ej}$ and $u_r^{Ej} \geq 0$. Therefore, we can derive the demand functions for new and remanufactured products are $d_n^{Ej} = 1 - \frac{p_n^{Ej} - p_r^{Ej}}{1-\alpha}$ and $d_r^{Ej} = \frac{p_n^{Ej} - p_r^{Ej}}{1-\alpha} - \frac{p_r^{Ej}}{\alpha}$.

Notably, the number of available cores can be remanufactured is consistently less than those obtainable for collection. For simplicity and in line with the existing literature, such as Shi et al. (2020), we assume that the manufacturer collects used products solely based on customer demand for the product. Hence, the demand for new products is always higher than the demand for remanufactured products, i.e., $0 \leq d_r^{Ej} \leq d_n^{Ej}$. Let $S \in \{N, P, F\}$ represent the three manufacturer encroachment strategies: *N* for "no remanufacturing", *P* for "partial remanufacturing", and *F* for "full remanufacturing". In the no remanufacturing strategy, the manufacturer neither collects nor remanufactures any used products. Under the partial remanufacturing strategy, the manufacturer collects and remanufactures only a portion of the used products. In the full remanufacturing strategy, all available used products are collected and remanufactured.

These three strategies serve as metrics for assessing the environmental impact of remanufacturing. Moreover, it is worth mentioning that the “no remanufacturing” strategy, while present in the encroachment scenario, substantially diverges from the benchmark case of no encroachment. This discrepancy stems from its conditional application compared to the universal validity of the non-encroachment benchmark. In other words, despite opting for market encroachment through remanufactured products, the manufacturer might choose not to embark on remanufacturing activities given specific circumstances. In addition, the “full remanufacturing” strategy implies that all used products are collected from the market and remanufactured for resale. While this represents an idealized market scenario that may be challenging to achieve in practice, it is valuable to explore such conditions theoretically. Therefore, the "full remanufacturing" strategy is included in the analysis. The two channel structures are illustrated in Figure 1.

When determining the internal channel structure, the manufacturer evaluates both the economic performance and environmental impact of each channel arrangement. Economic performance is assessed by comparing the overall profit of each strategy, as the manufacturer’s primary objective is profit maximization. Even in a decentralized channel structure where the remanufacturing division operates independently, its profit remains an integral component of the manufacturer’s total profit when comparing different channel strategies.

In this study, environmental impact is measured by the number of products remanufactured, denoted as d_r. This approach aligns with Wang et al. (2017), who used the volume of collected used products as a proxy for environmental impact. Similarly, Timoumi et al. (2021) measured the environmental effects of remanufacturing operations using $d_n - d_r$, where $d_n - d_r$ represents the number of products that remain uncollected and ultimately end up in landfills, leading to environmental harm. A higher $d_n - d_r$ indicates a greater negative environmental impact. Thus, using d_r an indicator of environmental impact is consistent with the methodologies of Wang et al. (2017) and Timoumi et al. (2021), as it represents the number of remanufactured products. A higher volume of remanufactured products signifies a lower environmental impact, as more used products are collected and diverted from landfills[vii]. Remanufacturing mitigates environmental harm by extending product life cycles and reducing landfill waste (Chen and Chen, 2019; Esenduran et al., 2019). As a remark, using the number of remanufactured products as a measure of environmental impact provides a parsimonious yet generalizable approach. While this method does not capture the detailed manufacturing and remanufacturing processes involved in each channel strategy, it effectively quantifies the extent to which used products are diverted from landfills at this stage[3].

It is important to note that while the number of remanufactured products, i.e., d_r, can be influenced by factors like the sales prices of both the new and remanufactured products, environmental impact differs fundamentally from economic benefits. This is because the final value of d_r is determined not only by market factors, such as pricing, but also by supply-side factors, like the availability of collectable products. Additionally, economic performance accounts for both the gains and losses from the operations of new and remanufactured products, reflecting the overall profitability of each internal structure. In contrast, environmental impact pertains specifically to the process of used products ending up in landfills, which is just one dimension of remanufacturing operations within these structures.

The sequence of events is as follows: First, the manufacturer determines whether to pursue encroachment by introducing remanufactured versions of new products through the remanufacturing division. Second, once the encroachment strategy is selected, depending on whether to delegate remanufacturing-related decisions to the remanufacturing division, the manufacturer decides its internal structure. The subsequent stage involves a sequential pricing game between the manufacturer and the retailer, unfolding as follows: First, the manufacturer sets the wholesale price for new products. Subsequently, the retail price for new products is determined by the retailer. Finally, guided by their respective objectives, the retail price for remanufactured products is determined. Figure 2 depicts the whole sequence of events.

The sequence of events bears several notable features. First, the determination on remanufacturing encroachment precedes the determination of the internal structure. This is because, in contrast to the determination of the internal channel structure, the decision regarding remanufacturing encroachment requires the manufacturer to establish specialized arrangements within its product line, which is a longer-term commitment. Second, in the main analysis, we consider the case in which the new product's retail price is determined before the remanufacturer product's retail price, which allows for the remanufacturing process of encroachment even with a single period assumption. The robustness of the main results will be verified by considering a simultaneous pricing game.

With these considerations, there are three models, i.e., benchmark case without remanufacturing encroachment (model B), remanufacturing encroachment with employing the integrated structure (model *EI*), and remanufacturing encroachment with employing the decentralized structure (model *ED*). Let Π_i^j denote supply chain player i's profit under model *j*, where $i \in \{M, R, RD\}$ indexes

[3] We sincerely thank the associate editor and the reviewer for highlighting the limitations in measuring the environmental impact of our model. In practice, the environmental impact of each strategy highly depends on the specific details of the manufacturing and remanufacturing processes, such as the amount of raw materials consumed and the energy sources used in production. Given these complexities, our study adopts a simplified approach to measuring the environmental impact of each strategy, ensuring a balance between analytical tractability and practical relevance.

manufacturer, retailer, and remanufacturing division, respectively, and $j \in \{B, EI, ED\}$ indexes models *B*, *EI*, and *ED*, respectively. To enhance readability, Table 1 gives a notation table.

3.2. The benchmark case without remanufacturing

This section assesses the benchmark scenario, which lacks remanufacturing encroachment. It is important to note that in the absence of remanufactured products entering the market, all products would inevitably end up in landfills. Consequently, this scenario inherently carries significant environmental impacts. Here, the manufacturer refrains from introducing remanufactured products, leaving only new products available through the conventional retail channel. This situation is modeled as a typical Stackelberg game which the manufacturer acts as the leader. The profit function of the retailer is $\Pi_R^B = (p_n^B - w_n^B)d_n^B$. Hence, the retailer would determine the retail price of new products at $p_n^B = \frac{1+w_n^B}{2}$, with the given w_n^B. In anticipation of the pricing decision of the retailer, the wholesale price is determined by the manufacturer at $w_n^{B*} = \frac{1+c_n}{2}$ according to its profit function $\Pi_M^B = (w_n^B - c_n)d_n^B$. Hence, the optimal[viii] retail price is $p_n^{B*} = \frac{3+c_n}{4}$, customers' demand is $d_n^{B*} = \frac{1-c_n}{4}$, the profit of the retailer is $\Pi_R^{B*} = \frac{(1-c_n)^2}{16}$, and the profit of the manufacturer is $\Pi_M^{B*} = \frac{(1-c_n)^2}{8}$.

4. Equilibrium and Analysis

This section examines the manufacturer's pricing strategies when engaging in remanufacturing encroachment, considering two distinct internal channel structures: models *EI* and *ED*. Subsequently, the preference of the manufacturer between these internal structures is explored. Finally, the impact of the remanufacturing encroachment decision of the manufacturer compared to the benchmark case without remanufacturing encroachment is analyzed.

4.1. The remanufacturing encroachment case under the integrated structure: model EI

In model *EI*, remanufactured products are introduced through a dedicated division, but the manufacturer retains control over remanufacturing decisions. Supply chain players engage in the following price competition game.

In the first stage, in anticipation of the sales price of new and remanufactured products, the wholesale price charged to the retailer is set by the manufacturer to maximize the profit.

$$\max \Pi_M^{EI}(w_n^{EI}) = (w_n^{EI} - c_n)d_n^{EI} + (p_r^{EI} - c_r)d_r^{EI}.$$
$$s.t. \; 0 \le d_r^{EI} \le d_n^{EI}.$$

As outlined earlier, the constraint dictates that the quantity of cores can be remanufactured is determined by the number of cores available in the market. In the second stage, given the determined wholesale price and in anticipation of the sales price of remanufactured products, the sales price of new products is determined by the retailer to maximize its profit.

$$\max \Pi_R^{EI}(p_n^{EI}) = (p_n^{EI} - w_n^{EI})d_n^{EI}.$$

The manufacturer determines the sales price of remanufactured products such that the total profit at the whole firm level can be maximized in the last stage.

$$\max \Pi_M^{EI}(p_r^{EI}) = (w_n^{EI} - c_n)d_n^{EI} + (p_r^{EI} - c_r)d_r^{EI}.$$

Through Hessian matrix, the concavity of the problem can be proven, and all the analytical outcomes are derived and shown in the Online Supplementary Appendix. Based on the optimal results in model *EI*, the following results are obtained.

Proposition 1. *When the manufacturer employs the integrated structure (i.e., model EI), strategy N (i.e., no remanufacturing) would be selected if* $c_n \in (c_r, c_n^{EIP}]$ *, strategy P (i.e., partial remanufacturing) would be selected if* $c_n \in [c_n^{EIP} c_n^{EIF})$*, and strategy F (i.e., full remanufacturing) would be selected if* $c_n \in [c_n^{EIF}, 1)$ *, where* $c_n^{EIP} = \frac{(8-(7-\alpha)\alpha)c_r - 2(1-\alpha)\alpha}{(3-\alpha)(2-\alpha)\alpha}$ *and* $c_n^{EIF} = \frac{2(1-\alpha)^2\alpha + (8-\alpha(3+\alpha))c_r}{(5-\alpha)(2-\alpha)\alpha}$*. Moreover, the thresholds* c_n^{EIP} *and* c_n^{EIF} *increase in* c_r*,* c_n^{EIF} *decreases in* α*, while* c_n^{EIP} *may either increase (if* c_r *is low) or decrease (if* c_r *is high) in* α*.*

Proposition 1 clearly indicates that the decision of the manufacturer on remanufacturing encroachment under the integrated structure is contingent on factors such as the production costs and customers' preference of remanufactured products. When manufacturing cost is low, signifying a high profitability of new products, the manufacturer would be disinclined to engage in remanufacturing. Conversely, as the manufacturing cost rises, the manufacturer would become more inclined to introduce remanufactured products, despite the cannibalization effect. "No remanufacturing" is favored when the manufacturing cost is low. In contrast, when the manufacturing cost is high, it would be preferrable to use "full remanufacturing", while a moderate production cost encourages the manufacturer to use "partial remanufacturing". The manufacturer's decision to adjust its remanufacturing strategy based on manufacturing costs has notable environmental implications. As manufacturing costs rise, the manufacturer shifts from no remanufacturing to a full remanufacturing strategy, leading to the collection of more used products from the market. This, in turn, reduces landfill waste and improves environmental outcomes. In essence, higher manufacturing costs incentivize firms to invest more in remanufacturing, thereby diverting a greater number of products from landfills and ultimately contributing to a more sustainable environmental impact.

Note that the two thresholds, i.e., c_n^{EIP} and c_n^{EIF}, expand with c_r; and c_n^{EIF} shrinks with α. However, c_n^{EIP} may either expand or shrink with α. Intuitively, the manufacturer would be more likely to be motivated to use remanufacturing encroachment when customers' preference for remanufactured products is large and when remanufacturing cost is low. Hence, c_r expands c_n^{EIP} and c_n^{EIF}, and α shrinks c_n^{EIF}. However, c_n^{EIP} increases (decreases) in α when remanufacturing cost is low (high). c_n^{EIP} defines the condition under which remanufacturing encroachment should be adopted and hence, compared with c_n^{EIF} (which defines the condition under which "full remanufacturing" is used), its sensitivity to α also depends on c_r. This suggests that, beyond evaluating the threshold condition for selecting an appropriate remanufacturing strategy, the manufacturer should also account for the sensitivity of these thresholds once the chosen strategy is implemented.

The remanufacturing strategies identified in this study align with the established literature, such as Shi et al. (2020), but introduce a novel perspective on manufacturer encroachment. Shi et al. (2023) identified three patterns for manufacturer encroachment, assuming nonnegative customer demand and a retail price exceeding the wholesale price. In contrast, this study explores three distinct remanufacturing strategies, driven by the need to collect cores from the market and the lower perceived value of remanufactured products. Unlike Shi et al. (2023), this study considers that customer demand for remanufactured products can match that of new products in full remanufacturing scenarios. This highlights how remanufacturing encroachment can be a profitable strategy for manufacturers but poses significant losses to retailers.

4.2. The remanufacturing encroachment case under the decentralized structure: model ED

In model *ED*, decision-making of remanufacturing price is delegated to the remanufacturing division. In the first stage, the manufacturer sets the wholesale price to maximize profit. The manufacturer's payoff function is

$$\max \Pi_M^{ED}(w_n^{ED}) = (w_n^{ED} - c_n)d_n^{ED} + \Pi_{RD}^{ED}(p_r^{ED})$$
$$s.t.\ \ 0 \le d_r^{ED} \le d_n^{ED}.$$

In the second stage, with the wholesale price already set and anticipating the sales price of remanufactured products in the final stage, the retailer sets the sales price of new products to maximize its profit.

$$\max \Pi_R^{ED}(p_n^{ED}) = (p_n^{ED} - w_n^{ED})d_n^{ED}.$$

In the last stage, the remanufacturing division independently sets remanufactured product prices for its profit in the final stage. The payoff function of the remanufacturing division is

$$\Pi_{RD}^{ED}(p_r^{ED}) = (p_r^{ED} - c_r)d_r^{ED}.$$

It can be observed that in model *ED*, the manufacturer's decision in the first stage and the retailer's decision in the second stage are identical to those in model *EI*. The key difference, however, is that in the final stage, it is the remanufacturing division, not the manufacturer, that sets the sales price of the remanufactured products. Based on the equilibrium outcomes, the following results are obtained.

Proposition 2. *When the manufacturer employs the decentralized structure (i.e., model ED), strategy N (i.e., no remanufacturing) would be selected if* $c_n \in (c_r, c_n^{EDP}]$, *strategy P (i.e., partial remanufacturing) would be selected if* $c_n \in [\,c_n^{EDP},\ c_n^{EDF})$, *and strategy F (i.e., full remanufacturing) would be selected if* $c_n \in [c_n^{EDF}, 1)$, *where* $c_n^{EDP} = \frac{(8-7\alpha)c_r - 6(1-\alpha)\alpha}{(2-\alpha)\alpha}$ *and* $c_n^{EDF} = \frac{(8-3\alpha(1+\alpha))c_r - 2(1-\alpha)\alpha(1+2\alpha)}{(3-\alpha)(2-\alpha)\alpha}$. *Moreover, the thresholds* c_n^{EDP} *and* c_n^{EDF} *increase in* c_r, *and* c_n^{EDP} *may either increase (if* c_r *is low) or decrease (if* c_r *is high) in* α. *While if* α *is low,* c_n^{EDF} *is monotone decreasing in* α, *and* c_n^{EDF} *may either increase (if* c_r *is low) or decrease (if* c_r *is high) in* α *when* α *is high.*

Proposition 2 reveals that the remanufacturing encroachment strategy of the manufacturer under the decentralized mode exhibits similar patterns to those under the integrated mode. Specifically, with a low production cost, “no remanufacturing strategy” should be adopted, and “full remanufacturing” would become a preferrable choice with a high production cost, while with a moderate production cost, “partial remanufacturing” will be a preferrable choice. Furthermore, when the remanufacturing cost increases, the manufacturer would be discouraged from engaging in remanufacturing encroachment, while when customers’ preference for remanufactured products increases, the manufacturer would be incentivized to encroach with the introduction of remanufactured products. The findings regarding the decentralized structure align with those of the integrated structure, demonstrating that a high manufacturing cost is correlated with a better environmental outcome due to the adoption of remanufacturing practices.

Through the sensitivity analysis of these important thresholds, we find that as the remanufacturing cost increases, the feasible region for “no remanufacturing” expands, while the region for "partial" and "full remanufacturing" shrink. In a decentralized structure, the impact of α (remuneration factor) depends heavily on c_r. In an integrated structure, the "no remanufacturing" region grows with increasing α when c_r is low, but gets smaller when c_r is high. This contrasts with the intuitive expectation that a higher α, reflecting greater remanufacturing profitability, would lead to a smaller "no remanufacturing" region. Similarly, the "full remanufacturing" region does not consistently expand with α and may shrink depending on the cost of remanufactured products. Generally, a manufacturer might be inclined to pursue a full remanufacturing strategy if it believes the remanufactured products have strong market potential, meaning customers highly value them. However, our analysis reveals that acting solely on this intuition may not yield the optimal outcome. Even if customer demand is high, the associated remanufacturing costs might be so significant that they negate potential profits. Thus, the manufacturer must carefully balance customer valuation against remanufacturing costs when deciding on the most profitable remanufacturing strategy.

4.3. Manufacturer’s internal channel structures

This section examines the manufacturer’s decision on the two channel structures and its implications for both the retailer and remanufacturing division.

4.3.1. Internal channel decision of the manufacturer

To start with, the feasible regions under models *EI* and *ED* are compared.

Corollary 1. *Under models EI and ED, we have* $c_n^{EIP} > c_n^{EDF}$.

Corollary 1 has important implications with a neat format. It indicates that the lower (upper) bound of the feasible region of partial (not) remanufacturing under model *EI* is higher than that of the feasible region of full remanufacturing under model *ED*. This shows that in the decentralized structure, the feasible regions for all three remanufacturing encroachment strategies fall within the feasible region of "no remanufacturing" in the integrated structure. As a result, the decentralized structure leads to better environmental outcomes than the integrated structure, as it incentivizes the collection of more used products from the market. This implies that the decentralized approach promotes remanufacturing and facilitates the adoption of a comprehensive remanufacturing strategy. We illustrate the results in Figure 3.

Figure 3 depicts the feasible region divided into five parts, with the shaded areas indicating regions where the same remanufacturing strategy is adopted. In region I, both structures favor no remanufacturing, while in region V, full remanufacturing is preferred. Under the integrated structure, regions II and III consistently favor no remanufacturing, but under the decentralized structure, they encourage encroachment, with partial remanufacturing in region II and full remanufacturing in region III. In region IV, the decentralized structure favors full remanufacturing, while the integrated structure leans towards partial remanufacturing. These findings suggest that the decentralized structure tends to promote remanufacturing encroachment more than the integrated structure, resulting in better environmental outcomes. However, the optimal choice between the two structures for the manufacturer remains uncertain.

In the following, the decision of the manufacturer on the two internal channel structures is discussed by comparing its profit in each structure.

Proposition 3. *(i) When $c_n \in (c_r, c_{m1}^*) \cup (c_{m2}^*, 1)$, $\Pi_M^{EI*} < \Pi_M^{ED*}$, and $\Pi_M^{EI*} \geq \Pi_M^{ED*}$ otherwise, where $c_{m1}^* \in (c_n^{EDF}, c_n^{EIP})$ and $c_{m2}^* \in (c_n^{EIF}, 1)$. (ii) c_{m1}^* is nonmonotone in α and it increases with c_r, c_{m2}^* decreases with α and increases with c_r.*

Proposition 3 (i) indicates that the two internal channel structures each entail different levels of economic performance for the manufacturer. Specifically, the decentralized structure should be employed by the manufacturer with a high or low production cost. Otherwise, the integrated structure should be adopted. Though the decentralized structure can be an optimal choice when the production cost is polarized, the driving force behind the manufacturer's decision in those two cost conditions is different. The decentralized structure is adopted with a low production cost because, compared with the no remanufacturing encroachment strategy when the integrated structure is employed, the encroachment strategy of the manufacturer evolved from no remanufacturing to partial remanufacturing when the decentralized structure is employed. This indicates that, despite the cannibalization effect, the manufacturer can benefit from remanufacturing encroachment even though during which it is highly profitable to engage in the business of new products due to a low production cost. The implication is that, given the high profitability of the business of new products, it can be profitable for the manufacturer to adopt remanufacturing encroachment and if it is, remanufacturing-related decisions should be delegated to the remanufacturing division. The manufacturer, however, should still delegate its remanufacturing decisions to the remanufacturing division with a high production cost, while with a medium production cost, remanufacturing-related decisions should be reserved and be made at the whole firm level. Specifically, if $c_n \in (c_{m1}^*,\ c_{m2}^*)$, the manufacturer should employ the integrated decision structure; otherwise, the decentralized structure is a better choice. The manufacturer's choice between the two internal channel structures is illustrated in Figure 4.

Since $c_{m1}^* \in (c_n^{EDF}, c_n^{EIP})$ and $c_{m2}^* \in (c_n^{EIF}, 1)$, the following scenarios should be considered when discussing the manufacturer's decision on the two internal channel structures. First, if $c_n \in (c_r, c_n^{EDP})$, i.e., region I in Figure 3, pricing decision under the decentralized structure can lead to a higher profit for the manufacturer. Recall that no remanufacturing strategy would be employed in both structures in region I. However, compared with the pricing decision made when the integrated structure is employed, delegating the remanufacturing division to make remanufacturing price decision is an optimal internal arrangement for the manufacturer. Second, if $c_n \in (c_n^{EDF}, c_n^{EIF})$, namely, regions III and IV in Figure 3, the integrated structure should be employed when the production cost increases. Recall that, under model *EI*, the manufacturer should use no remanufacturing strategy in region III and use the partial remanufacturing strategy in region IV, while the full remanufacturing strategy should be used in both regions under model *ED*. This implies that even though all used products can be collected and sold to customers under the decentralized structure, such a structure is not profitable for the manufacturer. This is because the market expansion effect accompanied by remanufacturing encroachment cannot dominate the cannibalization effect even though the only difference between the two structures is the decision party. This result also implies that though remanufacturing encroachment has better economic performance, the manufacturer should make all remanufacturing-related decisions at the whole firm level. Third, if $c_n \in (c_n^{EIF}, 1)$, i.e., region V in Figure 3, the manufacturer should strategically choose between the two structures, and the integrated structure should be employed when the production cost is small. Otherwise, it should consider employing the decentralized structure. Based on the decision-making of the manufacturer over these regions, it is reasonable to conclude that the manufacturer should delegate the remanufacturing division to make remanufacturing price decision when the business of new products is highly profitable or not so profitable. Otherwise, the manufacturer should make its decisions at the whole firm level. This result may help explain why many manufacturers retain control over remanufacturing-related decisions, even when they operate a separate remanufacturing division.

Proposition 3 (ii) indicates that the threshold c_{m1}^* increases with c_r but may either increase or decrease with α. In addition, c_{m2}^* increases with c_r but decreases with α. This suggests that the manufacturer prefers an integrated structure when remanufacturing costs are high and customer preference for remanufactured products is low. Conversely, the manufacturer performs better with a decentralized structure when remanufacturing is highly profitable. This aligns with Shi et al. (2023), who found that delegating pricing decisions to the e-commerce division is advantageous when customers favor the online channel. Similarly, as remanufacturing becomes more competitive with lower costs and higher customer valuations, the manufacturer may delegate decision-making to adapt to increased competition. Therefore, our findings are consistent with the wider literature on manufacturer encroachment, demonstrating similar principles regarding new and remanufactured products. In a decentralized structure, the manufacturer has the ability to strategically reduce prices to enhance its competitive position in a more challenging market.

4.3.2. Impact of the manufacturer's internal channel decision on the retailer and remanufacturing division

After the internal channel structure is determined, its impacts on the retailer and remanufacturing division are investigated, as illustrated in Corollary 2.

Corollary 2. *(i) When the decentralized structure is employed, (a) for the retailer:* $\Pi_R^{EI*} > \Pi_R^{ED*}$*, and (b) for the remanufacturing division:* $\Pi_{RD}^{EI*} \leq \Pi_{RD}^{ED*}$*. (ii) When the integrated structure is employed, (a) for the retailer:* $\Pi_R^{EI*} > \Pi_R^{ED*}$ *if* $c_n \in (c_{m1}^*, c_n^{EIP})$*, and* $\Pi_R^{EI*} \leq \Pi_R^{ED*}$*, otherwise, and (b) for the remanufacturing division:* $\Pi_{RD}^{EI*} < \Pi_{RD}^{ED*}$ *if* $c_n \in (c_{m1}^*, c_{m3}^*)$*, and* $\Pi_{RD}^{EI*} > \Pi_{RD}^{ED*}$ *,otherwise, where* $c_{m1}^* \in (c_n^{EDF}, c_n^{EIP})$ *and* $c_{m3}^* \in (c_n^{EIP}, c_n^{EIF})$*.*

Corollary 2 implies that the employment of the integrated structure would hurt the retailer under certain conditions, while the decentralized structure is always not beneficial for the retailer. That is, the integrated structure may not always result in lower profit for the retailer, whereas the decentralized structure consistently does. Recall that the manufacturer would delegate the remanufacturing division to make remanufacturing price decision when the production cost is polarized. That is, the manufacturer is more incentivized to make the decision with employing the decentralized structure with a high or low production cost. However, the decision structure of the manufacturer is not beneficial for the retailer. This is because, with a low production cost, the manufacturer would adopt no remanufacturing strategy under the integrated structure, and during which it will not engage in remanufacturing. Hence, the decision of the manufacturer on the decentralized structure cannot be beneficial for the retailer. The manufacturer delegates the remanufacturing division to make remanufacturing price decision with a high production cost to embrace the intensified competition. However, the retailer's profit margin decreases when the production cost increases. At the same time, the demand for new products is significantly cannibalized when customers have a high preference for remanufactured products. The combination effect of those two factors makes the retailer never benefit from the decentralized structure when such structure is employed. It is worth mentioning that the adoption of the integrated structure can be profitable for both the manufacturer and retailer, leading to a win-win solution. This indicates that, regardless of the internal channel structure, the profit of the manufacturer contradicts the retailer's profit most of the time. However, there exist conditions such that the integrated structure can be a win-win solution, while the decentralized structure can never be a win-win outcome.

Next, the impact of decision of the manufacturer on the remanufacturing division is investigated. While it may be easy to assume that the decentralized structure always benefits the remanufacturing division, our findings challenge this notion. Surprisingly, the manufacturer's integrated structure can be advantageous to the remanufacturing division, but this holds true specifically with a moderate production cost. Recall that when $c_n \in (c_n^{EIP}, c_n^{EIF})$ (i.e., region IV in Figure 3), the manufacturer would use partial remanufacturing strategy under the integrated structure, while would implement the full remanufacturing strategy under the decentralized structure. The remanufacturing division's performance over the region indicates that it is better to make the decision at the division level with a low production cost, while when the production cost increases, decisions should be made at the firm level. As such, the integrated other than the decentralized structure can be beneficial to the remanufacturing division when the production cost is moderate. Furthermore, from Corollary 2, we observe that the remanufacturing division's profit consistently aligns with that of the manufacturer when the decentralized structure is in place. In contrast, with the integrated structure, there can be a profit conflict between the remanufacturing division and the manufacturer. The results are illustrated in Figure 4.

In Figure 4, the areas that it is optimal to encroach by using the decentralized structure are drawn in blue and all other areas represent the condition that the manufacturer should encroach with using the integrated structure. Moreover, the thresholds c_{m1}^*, c_{m2}^*, and c_{m3}^* respectively divide regions III, V, and IV into two sub-regions. According to the above results, regions I, II, III-I, and V-II under the decentralized structure denote a win-lose-win solution for the manufacturer, the retailer, and the remanufacturing division. Region III-II (colored yellow) shows a win-win-lose solution under the integrated structure. Region IV-I (colored green) represents a win-lose-lose solution under the integrated structure. Regions IV-II and V-I demonstrate a win-lose-win solution under the integrated structure. These findings underscore that achieving a triple win solution for the manufacturer, the retailer, and the remanufacturing division is impossible, regardless of the internal structure. The decentralized structure is consistently beneficial for the manufacturer and the remanufacturing division but would hurt the retailer. On the other hand, the integrated structure can lead to either a win-win outcome for the manufacturer and retailer or a win-lose situation for the retailer and remanufacturing division. In contrast to some manufacturer encroachment literature, like Shi et al. (2023), which suggests win-win-win outcomes, our study reveals that such harmonious outcomes cannot be attained when introducing remanufactured products. Remanufacturing encroachment, akin to setting a direct channel, differs in its dynamics compared to traditional manufacturer encroachment. Therefore, it is crucial to recognize the distinct implications of remanufacturing encroachment when making strategic decisions.

4.4. Manufacturer's encroachment pursuit

This section examines whether remanufacturing encroachment should be adopted and how the retailer's profit is affected by the manufacturer's remanufacturing encroachment decision.

4.4.1. Encroachment decision of the manufacturer

To analyse the manufacturer's encroachment decision, we compare the manufacturer's profits under the two internal channel structures with the benchmark scenario where no encroachment decision is made, as summarized in Corollary 3.

Corollary 3. *(i) Under the decentralized structure, when the manufacturer has the potential to engage in remanufacturing encroachment: (a) certain parameter configurations exist with which such encroachment can lead to a higher profit for the manufacturer when the production cost of new products is low, and (b) it is not a favorable choice for the manufacturer when the production cost of new products is high. In other words,* $\exists c_n \in (c_r, c_{m1}^*)$ *such that* $\Pi_M^{ED*} > \Pi_M^{B*}$, *and* $\forall c_n \in (c_{m2}^*, 1)$ *such that* $\Pi_M^{ED*} < \Pi_M^{B*}$. *(ii) Under the integrated structure, when the manufacturer has the potential to engage in remanufacturing encroachment, certain parameter combinations exist with which such encroachment can result in higher profits for the manufacturer. In other words,* $\exists c_n \in (c_{m1}^*, c_{m2}^*)$ *such that* $\Pi_M^{EI*} > \Pi_M^{B*}$.

Corollary 3 reveals that remanufacturing encroachment can be beneficial to the manufacturer, regardless of the internal channel structure. However, it is notable that when the production cost is high, remanufacturing encroachment becomes less viable under the decentralized structure. This result is counterintuitive as the manufacturer would be more inclined to introduce remanufactured products when it is less profitable to engage in the business of new products. The surprising aspect here is that the manufacturer opts for full remanufacturing as the preferrable strategy under both structural scenarios with a high production cost. However, in this case, remanufacturing encroachment can only offer a higher profit if the manufacturer retains control over the pricing decisions for remanufactured products. This implies that the manufacturer should not delegate the pricing decisions to the remanufacturing division if it intends to employ the full remanufacturing strategy.

The detailed analytical results highlight several notable features regarding the manufacturer's pursuit of remanufacturing encroachment. First, decisions with and without considering remanufactured products differ significantly, with the former often yielding higher profits, especially under the no remanufacturing strategy. In scenarios without remanufacturing encroachment, the absence of remanufactured products may be less advantageous for the manufacturer. Second, when customer preference for remanufactured products is low, remanufacturing encroachment can prove more beneficial for the manufacturer. This counterintuitive finding suggests that despite lower customer preference, the moderate cannibalization effect still prompts consideration of the remanufacturing encroachment strategy, highlighting its strategic importance. Third, it is always beneficial for the manufacturer to encroach with using the partial remanufacturing strategy under the integrated structure. Specifically, $\forall c_n \in (c_n^{EIP}, c_n^{EIF})$ such that $\Pi_M^{EI*} > \Pi_M^{B*}$. This indicates that the manufacturer should make its decision at the whole firm level with a moderate remanufacturing demand.

4.4.2. Impact of the manufacturer's encroachment decision on the retailer

In the following, the impact of the remanufacturing encroachment pursuit of the manufacturer on the retailer is investigated, as summarized in Corollary 4.

Corollary 4. *(i) When the manufacturer engages in remanufacturing encroachment under the decentralized structure, there are certain parameter combinations where the retailer can achieve a higher profit. In other words,* $\exists c_n \in (c_r, c_{m1}^*) \cup (c_{m2}^*, 1)$ *such that* $\Pi_R^{ED*} > \Pi_R^{B*}$. *(ii) When the manufacturer engages in remanufacturing encroachment under the integrated structure, there are certain parameter combinations with which the retailer can achieve a higher profit. In other words,* $\exists c_n \in (c_{m1}^*, c_{m2}^*)$ *such that* $\Pi_R^{EI*} > \Pi_R^{B*}$.

Corollary 4 implies that manufacturer decisions on remanufacturing encroachment, whether in a decentralized or integrated structure, can boost retailer profits, showcasing the positive effect of such encroachment. Intuitively, the existence of remanufactured products can never benefit the retailer due to the cannibalization effect, no matter which internal structure is used by the manufacturer. However, we show that this intuition is not valid despite the introduced competition. This is because, with the introduction of remanufactured products, the sales price would be decreased by the retailer to attract customers to make a purchase. This would decrease the profit margin of the retailer but increase its overall profit with the increased demand. Furthermore, it is noteworthy to mention that the retailer can make a profit from remanufacturing encroachment when the decentralized structure is employed with a high production cost, i.e., $\exists c_n \in (c_{m2}^*, 1)$ such that $\Pi_R^{ED*} > \Pi_R^{B*}$. Recall that Corollary 3, we have established that the manufacturer cannot earn profit from remanufacturing encroachment by using the decentralized structure with a high production cost. However, Corollary 4 reveals an interesting dynamic: while the manufacturer's encroachment decision cannot yield higher profits for itself in this scenario, it does improve the retailer's profitability. This seemingly contradictory result occurs because high production costs for new products push the retailer's profit margin to extremely low levels. In response, the retailer aims to increase sales with the introduced competition. Lowering the sales price of new products could attract more customers and improve the retailer's overall profit, despite intensified market competition. It is worth noting that, despite achieving a triple-win solution for the manufacturer, retailer, and remanufacturing division is impossible, the encroachment decision of the manufacturer can still increase the retailer’s profit, leading to a Pareto improvement for the retailer and manufacturer. This holds true regardless of the channel structure.

5. Extensions

5.1. Quantity competition

This sub-section extends the analysis beyond price competition to include quantity competition. Here, decision-makers determine the sales quantities instead of the sales price within each model. Under quantity competition, it is evident that the equilibrium responses of both parties in the benchmark case without remanufacturing encroachment remain consistent with those outlined in Section 3.2. Based on the analysis in the main model, the inverse demand functions can be obtained $p_n^{Ei} = 1 - d_n^{Ei} - \alpha d_r^{Ei}$ and $p_r^{Ei} = \alpha(1 - d_n^{Ei} - d_r^{Ei})$.

In quantity competition, the sequence of events remains identical as the sequence in the main model, with the only difference being that decision-makers set the sales quantity instead of the sales price. In the process, the manufacturer initiates by establishing the wholesale price, thereby the retailer deciding on the quantity of new products to sell. Subsequently, depending on the chosen internal channel structure, either the manufacturer or the remanufacturing division decides on the sales quantity of remanufactured products. In the integrated structure, remanufactured products' sales quantity is determined by the manufacturer to maximize profit from both products as follows:

$$\max \Pi_M^{QEI}\left(d_r^{QEI}\right) = \left(w_n^{QEI} - c_n\right)d_n^{QEI} + \left(p_r^{QEI} - c_r\right)d_r^{QEI}.$$

$$s.t. \, 0 \le d_r^{QEI} \le d_n^{QEI}.$$

Similarly, the optimization problem for the retailer is formulated as follows:

$$\max \Pi_R^{QEI}\left(p_n^{QEI}\right) = \left(p_n^{QEI} - w_n^{QEI}\right)d_n^{QEI}.$$

When the decentralized structure is employed, the remanufacturing division determines the sales quantity to maximize the profit of remanufacturing at the divisional level as follows:

$$\max \Pi_{RD}^{QEI}\left(d_r^{QEI}\right) = \left(p_r^{QEI} - c_r\right)d_r^{QEI}.$$

Note that "Q" has been added to the superscript to denote the extension. Backward induction is employed to address the problem and the results are summarized in Proposition 3.

Proposition 4. *In the quantity competition scenario, the following remanufacturing encroachment strategies, regardless of the internal channel structure chosen, can be optimal depending on* c_n. *That is, strategy N (i.e., no remanufacturing) would be used if* $c_n \in (c_r, c_n^{QP}]$, *strategy P (i.e., partial remanufacturing) would be used if* $c_n \in [c_n^{QP}, c_n^{QF})$, *and strategy F (i.e., full remanufacturing) would be used if* $c_n \in [c_n^{QF}, 1)$, *where* $c_n^{QP} = \left(\frac{4}{\alpha} - \frac{3}{2}\right)c_r - \frac{3}{2}(2-\alpha)$ *and* $c_n^{QF} = \frac{(8+\alpha)c_r - \alpha(2+\alpha)}{6\alpha}$. *Moreover,* $\frac{\partial c_n^{QP}}{\partial c_r} > 0$, $\frac{\partial c_n^{QF}}{\partial \alpha} < 0$, $\frac{\partial c_n^{QF}}{\partial c_r} > 0$, *and* c^{QP} *is non monotone with* α.

Proposition 4 reveals that in quantity competition, the choice between the two internal structures would not affect how the manufacturer and retailer behave. This is because the determination of remanufactured product quantities accounts for both the sales quantity and the wholesale price of new products, regardless of the decision party. This aligns with prior findings in the manufacturer encroachment and horizontal outsourcing literature, such as Shi et al. (2023). Moreover, the adoption of the partial remanufacturing strategy would be affected by customers' valuation of remanufactured products. Next, we examine the remanufacturing encroachment pursuit of the manufacturer and its impact on the retailer.

Proposition 5. *(i) For the manufacturer: (a)* $\Pi_M^{Q*} > \Pi_M^{B*}$ *when* $c_n \in (c_r, c_{m1}^{Q*}) \cup (c_n^{QP}, c_n^{QF}) \cup (c_n^{QF}, c_{m2}^{Q*})$, *and (b)* $\Pi_M^{Q*} \le \Pi_M^{B*}$ *otherwise, where* $c_{m1}^{Q*} \in (c_r, c_n^{QP})$ *and* $c_{m2}^{Q*} \in (c_n^{QF}, 1)$. *(ii) For the retailer: (a)* $\Pi_R^{Q*} > \Pi_R^{B*}$ *when* $c_n \in (?_{?1}^{?*}, ?_{?}^{??}) \cup (?_{?}^{??}, ?_{?2}^{?*}) \cup (?_{?3}^{?*}, 1)$, *and (b)* $\Pi_R^{Q*} \le \Pi_R^{B*}$ *otherwise, where* $?_{?1}^{?*} \in (c_r, c_n^{QP})$, $?_{?2}^{?*} \in (?_{?}^{??}, c_n^{QF})$, *and* $?_{?3}^{?*} \in (c_n^{QF}, 1)$.

Proposition 5 (i) reaffirms that remanufacturing encroachment can benefit the manufacturer under certain conditions, especially with the partial remanufacturing strategy. This aligns with the findings in the main analysis regarding price competition among supply chain players. The distinction lies in the choice of the internal structure when implementing the partial remanufacturing strategy under price competition. Regardless of the internal structure in quantity competition, remanufacturing some, but not all, used products can be profitable for the manufacturer.

Proposition 5 (ii), in the context of quantity competition, examines how the retailer can potentially earn profit from the remanufacturing encroachment implemented by the manufacturer. It shows that, for the retailer, each of the three remanufacturing strategies adopted by the manufacturer can be advantageous, allowing for a win-win solution. However, the benefit of the retailer is contingent on customer preferences for remanufactured products, with no advantage when customers highly value them. Production costs also play a significant role in this scenario. It is worth noting that how the retailer is affected by the encroachment decision of the manufacturer is similar to those given in Propositions 8 and 9 in Shi et al. (2023). Our results offer insights into manufacturer encroachment literature, highlighting that the applicability of general product findings to scenarios with new and remanufactured products depends on customer preferences and production costs.

5.2. Change of game sequence

This subsection extends the analysis by changing the game sequence while keeping the essential framework intact. In this scenario, both the retailer and the manufacturer (or remanufacturing division) establish the sales prices simultaneously during the final stage of the game. We add "S" to the superscript to denote the extension.

Proposition 6. *When new and remanufactured product prices are simultaneously determined, three distinct remanufacturing encroachment strategies exist regardless of the internal structure in place.(i) That is, strategy N (i.e., no remanufacturing) would be used if* $c_n \in (c_r, c_n^{SEiP}]$*, strategy P (i.e., partial remanufacturing) would be used if* $c_n \in [c_n^{SEiP}, c_n^{SEiF})$*, and strategy F (i.e., full remanufacturing) would be used if* $c_n \in [c_n^{SEiF}, 1)$*, where* $c_n^{SEIP} = \frac{(8-\alpha-\alpha^2)c_r-\alpha(2-\alpha-\alpha^2)}{6\alpha}$, $c_n^{SEIF} = \frac{\alpha(2-\alpha-\alpha^2)+(8+\alpha(3+\alpha))c_r}{2\alpha(5+\alpha)}$, $c_n^{SEDP} = \frac{(8-(9-2\alpha)\alpha)c_r-2(3-\alpha)(1-\alpha)\alpha}{(2-\alpha)\alpha}$ *and* $c_n^{SEDF} = \frac{(8-5\alpha-\alpha^2)c_r-2\alpha(1-\alpha^2)}{\alpha(6-5\alpha+\alpha^2)}$*. Furthermore,* $c_n^{SEDF} < c_n^{SEIP}$*. (ii)* $\Delta c^{EiN} < \Delta c^{SEiN}$*,* $\Delta c^{EiP} > \Delta c^{SEiP}$*, and* $\Delta c^{EiF} > \Delta c^{SEiF}$*.*

Proposition 6 highlights that, even when new and remanufactured product prices are simultaneously determined, there are three remanufacturing strategies available for the manufacturer based on costs and customer preferences. Consistently, the manufacturer is still inclined to adopt remanufacturing encroachment, particularly partial or full remanufacturing, when price decisions for remanufactured products are delegated to the remanufacturing division. Interestingly, the feasible regions for manufacturer encroachment would not expand when new and remanufactured product prices are simultaneously determined. The counterintuitive result suggests that simultaneous pricing may not necessarily be able to significantly enhance manufacturer encroachment opportunities, despite the retailer losing its first-mover advantage. Next, we examine the decision of the manufacturer on internal structures and how the other two participants would be affected by the manufacturer's decision.

Proposition 7. *(i) For the manufacturer: (a)* $\Pi_M^{SEI*} < \Pi_M^{SED*}$ *when* $c_n \in (c_r, c_{m1}^{S*}) \cup (c_{m2}^{S*}, 1)$, *and (b)* $\Pi_M^{SEI*} \geq \Pi_M^{SED*}$ *otherwise, where* $c_{m1}^{S*} \in (c_n^{SEDF}, c_n^{SEIP})$ *and* $c_{m2}^{S*} \in (c_n^{SEIF}, 1)$. *(ii) For the retailer: (a)* $\Pi_R^{SEI*} > \Pi_R^{SED*}$ *when* $c_n \in (c_r, c_{r1}^{S*}) \cup (c_{r2}^{S*}, 1)$, *and (b)* $\Pi_R^{SEI*} \leq \Pi_R^{SED*}$ *otherwise, where* $c_{r1}^{S*} \in (c_n^{SEIP}, c_n^{SEIF})$ *and* $c_{r2}^{S*} \in (c_n^{SEIF}, 1)$. *(iii) For the remanufacturing division: (a)* $\Pi_{RD}^{SEI*} < \Pi_{RD}^{SED*}$ *when* $c_n \in (c_r, c_{rd1}^{S*}) \cup (c_{rd2}^{S*}, 1)$, *and (b)* $\Pi_{RD}^{SEI*} \geq \Pi_{RD}^{SED*}$ *otherwise, where* $c_{rd1}^{S*} \in (c_n^{SEIP}, c_n^{SEIF})$ *and* $c_{rd2}^{S*} \in (c_n^{SEIF}, 1)$.

Proposition 7 reaffirms that, akin to the primary analysis, the manufacturer will opt for the decentralized structure when new products' production cost is polarized. However, when new products' production cost falls within a moderate range, the manufacturer should refrain from delegating price decision-making. In such cases, the decision-making of the price for remanufactured products should be managed at the firm level. Corollary 9 further underscores that the choice of internal structure continues to have opposing effects on the retailer and the remanufacturing division. Additionally, when concurrently determining the two sales prices, the decentralized structure still fails to benefit the retailer. Instead, the integrated structure retains the potential to yield a mutually beneficial outcome for the two parties. Despite the remanufacturing division aligning its profit with that of the manufacturer in most scenarios, a triple-win solution involving the manufacturer, retailer, and remanufacturing division remains unattainable.

Corollary 5. *(i) For the manufacturer: (a) if the decentralized structure is adopted, i.e.,* $c_n \in (c_r, c_{m1}^{S*}) \cup (c_{m2}^{S*}, 1)$, *then* $\Pi_M^{SED*} > \Pi_M^{B*}$ *when* $c_n \in (c_r, c_{m2}^{SB*}) \cup (?_?^{????}, c_{m3}^{SB*}) \cup (?_?^{????}, ?_{?4}^{??*})$, *and* $\Pi_M^{SED*} \leq \Pi_M^{B*}$ *otherwise, where* $c_{m2}^{SB*} \in (c_r, ?_?^{????})$, $c_{m3}^{SB*} \in (?_?^{????}, ?_?^{????})$, *and* $c_{m4}^{SB*} \in (?_?^{????}, c_{m1}^{S*})$, *and (b) if the integrated structure is adopted, i.e.,* $c_n \in \left(c_{m1}^{S*}, c_{m2}^{S*}\right)$, *then* $\Pi_M^{SEI*} > \Pi_M^{B*}$ *when* $c_n \in (?_{?5}^{??*}, ?_{?6}^{??*})$, *and* $\Pi_M^{SEI*} \leq \Pi_M^{B*}$ *otherwise, where* $?_{?5}^{??*} \in (c_{m1}^{S*}, ?_?^{????})$ *and* $?_{?6}^{??*} \in (?_?^{????}, 1)$. *(ii) For the retailer: (a) if the decentralized structure is adopted, i.e.,* $c_n \in (c_r, c_{m1}^{S*}) \cup (c_{m2}^{S*}, 1)$, *then* $\Pi_R^{SED*} > \Pi_R^{B*}$ *when* $c_n \in (?_{?1}^{??*}, ?_{?2}^{??*}) \cup (?_{?6}^{??*}, 1)$, *and* $\Pi_R^{SED*} \leq \Pi_R^{B*}$ *otherwise, where* $?_{?1}^{??*} \in \left(c_r, ?_?^{????}\right)$, $?_{?2}^{??*} \in (?_?^{????}, ?_?^{????})$, *and* $?_{?6}^{??*} \in (c_{m2}^{S*}, 1)$, *and (b) if the integrated structure is adopted, i.e.,* $c_n \in \left(c_{m1}^{S*}, c_{m2}^{S*}\right)$, *then* $\Pi_R^{SEI*} > \Pi_R^{B*}$ *when* $c_n \in \left(c_{m1}^{S*}, ?_{?3}^{??*}\right) \cup (?_{?4}^{??*}, ?_{?5}^{??*})$, *where* $?_{?3}^{??*} \in (c_{m1}^{S*}, ?_?^{????})$, $?_{?4}^{??*} \in (?_?^{????}, ?_?^{????})$, *and* $?_{?5}^{??*} \in (?_?^{????}, ?_{?2}^{?*})$.

Corollary 5 underscores that when the sales price of remanufactured and new products are determined simultaneously, the decision of the manufacturer to pursue remanufacturing encroachment can result in higher profits for both parties. Importantly, the adoption of remanufacturing encroachment, particularly through the partial remanufacturing strategy under the integrated structure, consistently results in increased profits for the manufacturer, even though it does not necessarily increase the profits of the retailer. These findings align with the conclusions drawn from our main analysis. However, there is one noteworthy exception. In this scenario, we demonstrate that the manufacturer can derive benefits from pursuing remanufacturing encroachment with a high production cost. This differs from our main analysis, where under the decentralized structure, the full remanufacturing strategy was shown not to benefit the manufacturer due to intensified competition, which eroded the primary profit source of the manufacturer. In this context, with the simultaneous determination of the sales prices, implementing the full remanufacturing strategy is beneficial for the manufacturer. This is because the retailer loses its first-mover advantage in the decision-making process, expanding the profitable opportunities of the manufacturer in pursuing remanufacturing encroachment.

5.3. Channel preference

In this extension, we broaden our analysis to encompass a scenario where customers assign different values to the two channels. Specifically, we consider a situation where, in contrast to the mature retail channel, customers place a lower valuation on the direct channel. Let β represent customers' valuation for the direct channel, which is smaller than customers' valuation for the retail channel, namely, $0 < \beta < 1$. As such, the net utility for customers purchasing one unit of remanufactured product is revised to $u_r^{CEj} = \alpha\beta\theta - p_r^{CEj}$, while the net utility from buying one unit of new product would not change, i.e., $u_n^{CEj} = \theta - p_n^{CEj}$. To allow for the possibility that customers' valuation for the direct channel may be larger than the valuation for the retail channel because of the convenience, β may be larger than 1 in practice. It should be noted that, even though there exists a possibility that customers may value the direct channel higher, customers' overall preference for the direct channel and remanufactured products is lower than that for new products, i.e., $0 < \alpha\beta < 1$, which is determined by the characteristic of remanufacturing. Hence, the overall results would not change even $\beta > 1$. Based on these, demand functions are: $d_n^{CEj} = 1 - \frac{p_n^{CEj} - p_r^{CEj}}{1-\alpha\beta}$ and $d_r^{CEj} = \frac{p_n^{CEj} - p_r^{CEj}}{1-\alpha\beta} - \frac{p_r^{CEj}}{\alpha\beta}$.

Accordingly, the optimal responses of supply chain players when different internal structure is employed can be obtained. Since β always appears with α, the consideration of channel preference would not change the main results dramatically and hence, its impact can be generated similarly to that of the consideration of α, and which would not change the main results qualitatively.

5.4. Channel opening cost

To engage in remanufacturing encroachment, a direct channel is employed by the manufacturer to offer remanufactured products, which may incur a non-trivial channel opening cost. In this subsection, we consider this case. Following Shi et al. (2023), the unit variable setup cost for the direct channel is assumed to be c_o. Therefore, when the integrated structure is employed, the manufacturer's optimization problem is revised to:

$$\max\Pi_M^{OEI}(p_r^{OEI}) = (w_n^{OEI} - c_n)d_n^{OEI} + (p_r^{OEI} - c_r - c_o)d_r^{OEI}.$$

When the decentralized structure is chosen, the remanufacturing division's optimization problem is revised to:

$$\max\Pi_{RD}^{OED}(p_r^{OED}) = (p_r^{OED} - c_r - c_o)d_r^{OED}.$$

All other elements of the model remain the same as those of the main analysis and hence, the equilibrium solutions and analysis can be obtained by employing the same approach.

When the manufacturer needs to incur setup costs for the opening of the direct channel, our results show that the manufacturer would be discouraged from adopting the remanufacturing encroachment strategy. Moreover, the integrated structure would be more likely to become a preferable choice for the manufacturer. Hence, it should not delegate the remanufacturing division to make pricing decision when the encroachment cost increases.

5.5. Remanufacturing target[4]

When the manufacturer considers delegating pricing decisions to the remanufacturing division, environmental impacts related to remanufacturing operations may drive this decision. To mitigate the environmental outcomes of operations, the manufacturer may impose a remanufacturing target on the division, typically in the form of collection quotas. For instance, the European Commission's WEEE Directive mandates a 45% collection rate for e-waste, with plans to increase it to 65% by 2019[ix]. Let T represent the collection target in the decentralized channel, where $0 \leq \mathrm{T} \leq 1$. If $\mathrm{T} = 0$, no collection target exists, but if $\mathrm{T} = 1$, the remanufacturing division must collect all used products from the market.

With the introduction of T, the payoff functions for the manufacturer, retailer, and remanufacturing division remain unchanged from the main analysis, but the constraint is adjusted from $0 \leq d_r \leq d_n$to $\mathrm{T} \leq d_r \leq d_n$. Here, the collection rate equals the remanufacturing rate, imposing a lower bound on d_r when optimizing the remanufacturing division's payoff.

Despite this new constraint, the qualitative outcomes of the main analysis hold. If $\mathrm{T} = 0$, the scenario reduces to the "no remanufacturing" case; if $\mathrm{T} = 1$, it aligns with the "full remanufacturing" case. For $0 < \mathrm{T} < 1$, the situation corresponds to the "partial remanufacturing" case, with the constraint determining a specific variation of this scenario. Therefore, even with a remanufacturing target, the manufacturer should base its internal channel decision on the original analysis, delegating decisions to the remanufacturing division only when costs are moderate.

6. Conclusions

6.1. Concluding remarks

This study examines manufacturer encroachment in the realm of remanufactured products, focusing

[4] We thank a reviewer for the suggestion of this part for our deeper discussion.

on the internal channel structure of the remanufacturing division. Specifically, it investigates a scenario where a manufacturer, traditionally reliant on a conventional retailer for new product distribution, extends its operations by incorporating remanufactured offerings and establishing a dedicated remanufacturing division. A crucial decision arises regarding the pricing mechanism for remanufactured products, with two approaches: entrusting pricing to the remanufacturing division (choosing "decentralized structure") or retaining control within the manufacturer's domain (selecting "integrated structure"). We analyze optimal responses, environmental outcomes, profitability implications, and impacts on the retailer and remanufacturing division under each structure. The study concludes by assessing the overall advantage of manufacturer-led remanufacturing encroachment. Rigorous analysis, including exploration of four alternative settings, is conducted to ensure the robustness of our findings. We present the core insights as follows.

When to delegate remanufacturing decision-making to the remanufacturing division: We find that production costs play a critical role in affecting the performance of the two internal channel structures. To be specific, in the primary model with price competition, our analysis suggests that delegating remanufacturing pricing to the dedicated division is optimal when new product production costs are highly polarized (i.e., either high or low). Conversely, if production costs are moderate, retaining decision-making at the manufacturer level is more suitable. In the extended model with quantity competition, the internal channel structure for remanufacturing has minimal impacts on optimal outcomes. Hence, the decentralized structure is more profitable to adopt when the production cost of new products is polarized. In contrast, the integrated structure represents an optimal option in terms of profitability. Manufacturers with a dedicated remanufacturing division should carefully evaluate the decision to delegate pricing authority to this division, as this decision influences optimal responses and ultimately impacts overall profitability.

Environmental impacts of channel structures: From an environmental standpoint, the decentralized structure consistently presents a better environmental outcome compared to the integrated structure. This is because the decentralized approach encourages manufacturers to participate in remanufacturing operations and adopt full remanufacturing strategies earlier. Thus, establishing a dedicated remanufacturing division and delegating decision-making to this division could provide a feasible solution for manufacturers to effectively manage both economic and environmental impacts, particularly when confronted with the potential cannibalization effects associated with the increased presence of remanufactured products. From an environmental perspective, the decentralized approach should be encouraged, particularly when the manufacturer's production costs are polarized.

Whether it is beneficial to encroach with the introduction of remanufactured products: Based on the analytical results, it is evident that the manufacturer should engage in remanufacturing encroachment through three distinct remanufacturing strategies, no matter which internal structure is employed. Remarkably, the manufacturer can derive benefits from pricing decisions even when considering the possibility of remanufacturing encroachment. This is true even if it includes the scenario where remanufactured products are not introduced (referred to as "no remanufacturing"). Moreover, the conclusion that the manufacturer should pursue remanufacturing encroachment is further reinforced in the context of quantity competition among supply chain players, where employing the "partial remanufacturing" strategy consistently proves advantageous. This finding aligns with the broader narrative introduced at the beginning, highlighting the increasing strategic priority placed on remanufacturing by approximately 80% of manufacturers.

Channel structure decision preference for the remanufacturing division: Intuitively, the remanufacturing division tends to favor a decentralized structure, allowing it to operate as an autonomous profit center and make independent decisions regarding remanufacturing operations. However, our analytical results reveal that the preference for channel structures within the remanufacturing division should align with the manufacturer in most cases. Specifically, when new products' production costs are moderate, decision-making integration at the firm level is recommended. Nevertheless, conflicts may arise between the manufacturer and the remanufacturing division when the optimal remanufacturing strategy is "full remanufacturing" under both channel structures, and the remanufacturing division prefers the decentralized structure despite the integrated structure is the manufacturer's preference.

Is it always harmful for the retailer when the introduced remanufactured products compete with new products: Existing studies, like Shi et al. (2020), have consistently indicated that remanufacturing can be profitable for both the manufacturer and the retailer, despite it may be associated with cannibalization effect. This finding holds true even when the manufacturer has different internal channel structures. However, our study reveals that it is always harmful for the retailer when the manufacturer makes decision under a decentralized structure. Consequently, achieving a triple-win solution becomes unattainable for the manufacturer, retailer, and remanufacturing division through remanufacturing encroachment. Nonetheless, compared to the benchmark case without remanufacturing encroachment, embracing remanufacturing still represents a Pareto improvement choice for the retailer (as both the retailer and manufacturer will be benefited or at least without any harm). This suggests that, from the retailer's perspective, rather than actively deterring the entry of remanufactured products, the retailer can also embrace the remanufacturing market and reap its benefits.

6.2. Managerial implications

The advantages of a remanufacturing business have led many manufacturers to engage in remanufacturing encroachment by establishing dedicated remanufacturing divisions. In line with trends in manufacturer encroachment, numerous manufacturers are empowering these specialized divisions with greater decision-making authority. For example, as noted by Shi et al. (2023), companies like OPPLE Lighting, New Age Beverages, and Drive DeVilbiss Healthcare have assigned increased decision-making power to their e-commerce divisions to manage online operations. Their findings show that while delegating decision-making authority can expand a manufacturer's ability to encroach, it can also intensify competition between the division and the retailer. At times, retaining decision-making at the firm level achieves a balanced solution that benefits the manufacturer, retailer, and e-commerce division alike. However, the applicability of this approach to remanufacturing encroachment remains uncertain, given that manufacturers are also establishing dedicated remanufacturing divisions, as seen in Cat Reman and the real-world cases highlighted by Shi et al. (2020). This study aims to provide managerial guidance on remanufacturing encroachment and the structuring of a dedicated remanufacturing division.

Our analysis reveals that delegating decision-making authority to the remanufacturing division can consistently help manufacturers improve environmental outcomes by encouraging early entry into remanufacturing and implementing comprehensive remanufacturing strategies. However, the decentralized structure benefits the manufacturer only when production costs are polarized. This suggests that manufacturers with a dedicated remanufacturing division should carefully consider whether to delegate pricing authority, as this decision influences optimal responses and ultimately impacts overall profitability and environmental performance. This insight aligns with the practices of Cat Reman, which grants substantial decision power to its product managers. As an experienced manufacturer with decades of specialization in remanufacturing (dating back to 1979), Cat Reman likely operates with relatively low costs compared to other industry peers, meaning that decentralized decision-making is a strategically advantageous option, both for maximizing economic profits and reducing environmental impact. This approach may not, however, suit other manufacturers, particularly those with moderate production costs.

6.3. Future Research

There are several avenues for future research. Firstly, exploring retailer encroachment, exemplified by GameStop, Amazon, and JD.com, would complement the focus on manufacturer encroachment observed in practices like Caterpillar's. Secondly, considering information asymmetry within the supply chain, a common real-world scenario, would offer a more nuanced perspective compared to the assumption of perfect information for risk analysis. Thirdly, since the condition of used products can vary in practice, it would be valuable to account for the detailed collection process of used products rather than relying on the average remanufacturing production cost. Fourthly, to focus specifically on encroachment on remanufactured products, this study assumes a simplified channel arrangement where new products are sold exclusively through the retail channel, while remanufactured products are only available in the direct channel. However, in general, manufacturers take a more complex approach by encroaching on both new and remanufactured products. In such cases, both remanufactured and new products may be introduced into the direct channel. Additionally, manufacturers might also collaborate with retailers that already distribute new products to sell remanufactured products, resulting in both product types being available in the retail channel as well. Thus, depending on the original channel arrangement for new products, remanufactured products can be distributed through both retail and direct channels, leading to more intricate channel structures. Future research could explore these more complex channel configurations to enhance understanding of the coexistence of new and remanufactured products in different market settings.

Data Availability Statement

The authors confirm that data sharing is not applicable to this article as no new data were created or analyzed in this study.

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[vii] It is important to note that this intuitive conclusion relies on the assumption that the manufacturer collects used products solely in response to customer demand. Hence, d_r represents not only the demand for remanufactured products but also the quantity of used products collected from the market.

[viii] In this paper, we use the term optimal to represent the equilibrium decisions and corresponding profits under the games.

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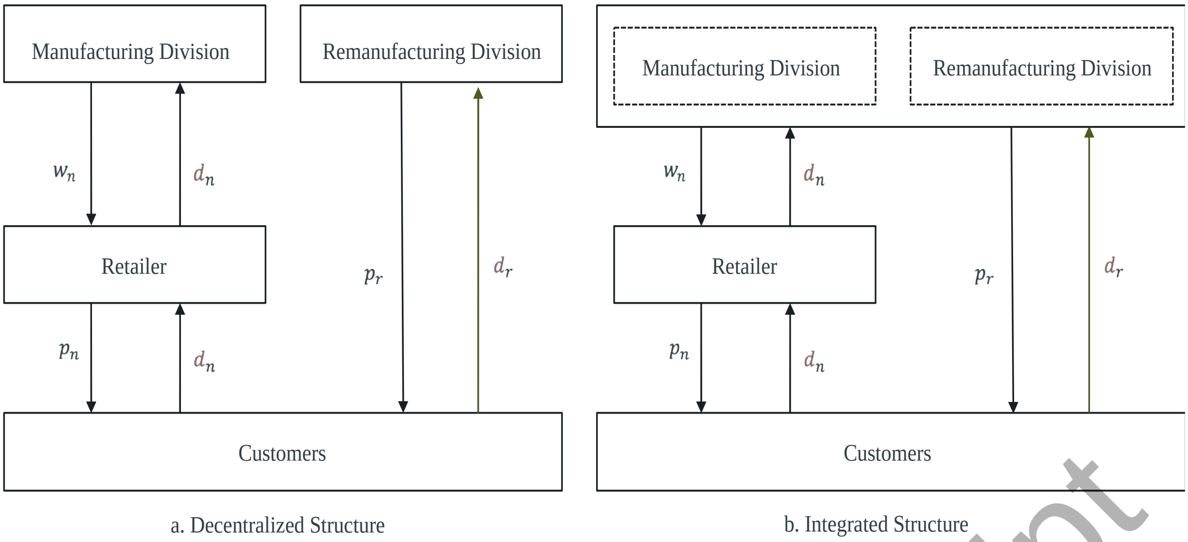

Figure 1. The two main channel structures.

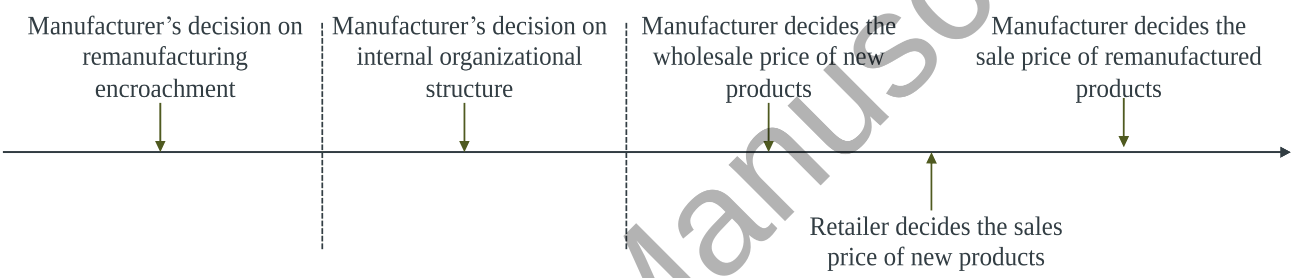

Figure 2. The sequence of the events.

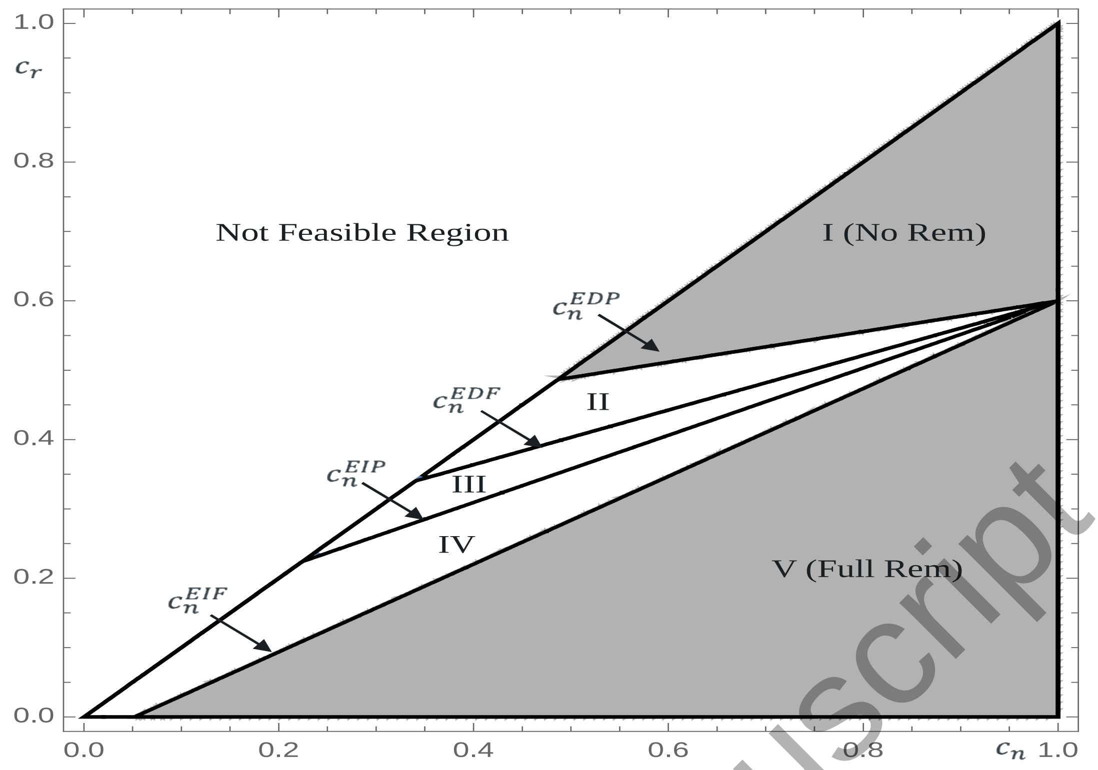

Figure 3. Feasible regions of remanufacturing encroachment strategies under models *EI* and *ED*.

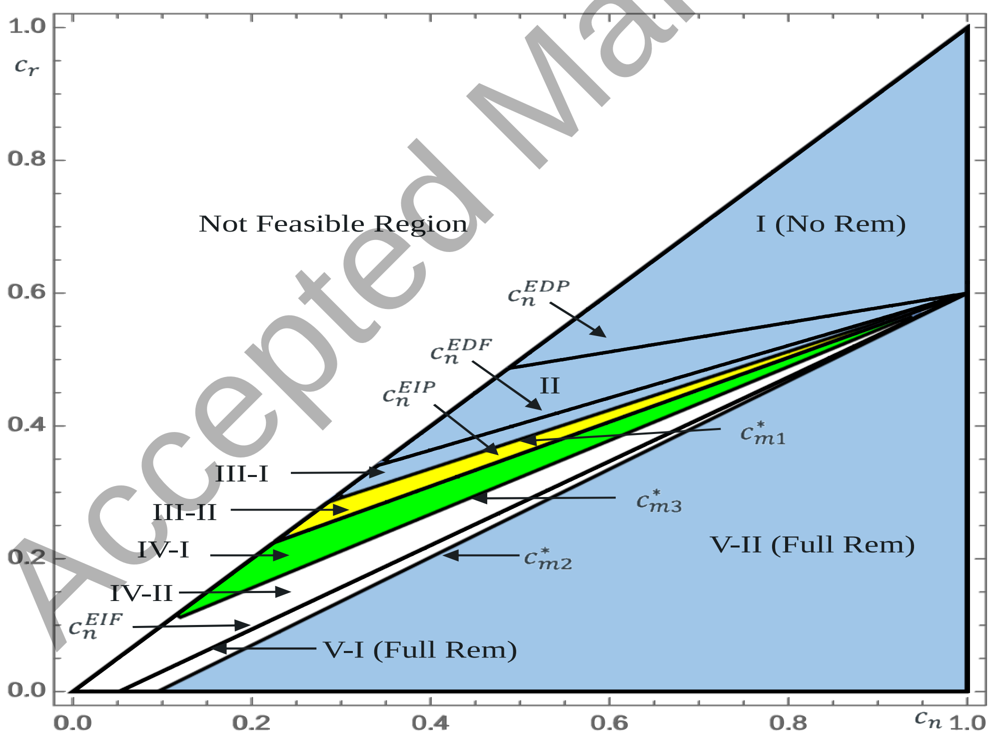

Figure 4. The manufacturer's decision between two internal structures and its impacts on the retailer and the remanufacturing division.

Table 1. A list of notations.

Notation	**Meaning**
Model B	The benchmark case without remanufacturing encroachment.
Model EI	The remanufacturing encroachment case under the integrated channel.
Model ED	The remanufacturing encroachment case under the decentralized channel.
θ	The customers' valuation for the product, which satisfies $\theta \in U[0,1]$.
α	The discount factor of customers' valuation for remanufactured products, which satisfies $0 \leq \alpha \leq 1$.
u_n/u_r	The net utility that customers can obtain when purchasing new/remanufactured products.
w_n	The wholesale price of new products.
p_n/p_r	The sales price of new/remanufactured products.
c_n/c_r	The production cost of new/remanufactured products.
d_n/d_r	The customers' demand for new/remanufactured products.
Π_M	The profit of manufacturer.
Π_R	The profit of retailer.
Π_{RD}	The profit of remanufacturing division.