



New Product Production, Remanufacturing, and Coopetition Strategies in Closed-Loop Supply Chains: The Role of Spillover Effects and Policy Interventions

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Fabrication de produits neufs, remanufacturation et stratégies de coopétition dans les chaînes d'approvisionnement en boucle fermée : le rôle des effets de débordement et des interventions politiques

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Abstract

Closed-loop supply chains (CLSCs) enable firms to remanufacture used products and reintegrate recovered materials into production processes, thereby generating substantial environmental, economic, and social benefits. Motivated by these benefits and mounting regulatory pressures, both original equipment manufacturers (OEMs) and independent remanufacturers — including third-party remanufacturers (TPRs) and multinational remanufacturers (MNRs) — are increasingly engaging in CLSCs. These firms participate either directly by managing end-of-life products or indirectly through cooperative agreements. However, factors such as spillover effects, environmental regulations, and market competition jointly reshape firms' cost structures and influence consumer demand. These dynamics, in turn, complicate firms' decision-making regarding new product production, remanufacturing, and coopetition. Understanding how firms make such decisions under the influence of spillover effects and policy interventions is crucial for advancing academic knowledge and supporting more effective decision-making at the firm level. Against this backdrop, this dissertation adopts an article-based structure. It comprises three interrelated studies that examine firms' decisions on new product production, remanufacturing strategies, and coopetition in CLSC contexts.

The **first study** investigates a remanufacturing system consisting of an OEM (he) and a TPR (she). The TPR remanufactures used products originally produced by the OEM, either independently or in authorization cooperation with the OEM. She may also produce and sell new products that compete with both her remanufactured goods and the OEM's new products. In such a system, knowledge spillovers from the OEM to the TPR — both general and innovation-related — are inevitable. This study examines how these spillovers influence both firms' production and coopetition strategies. The results highlight: (i) the conditions under which the TPR engages in remanufacturing and/or new product production; (ii) when remanufacturing authorization is mutually beneficial compared to pure competition; and (iii) the

OEM's optimal decision on the unit authorization fee. The **second study** explores interactions between an OEM and a TPR under two environmental policies: emission taxes and waste management regulations. In this setting, the OEM can either pay waste management taxes or outsource used product management to the TPR. The TPR recovers value from these used products by remanufacturing them or recovering materials from them; she may also produce new products using recovered materials. This study analyzes how environmental policies affect the OEM's outsourcing decisions and the TPR's recovery and new product production strategies. It identifies the conditions under which: i) the TPR chooses remanufacturing and/or new product production, ii) the OEM outsources used product management, and iii) new product introduction by the TPR encourages the OEM to outsource used product management. The **third study** focuses on a cross-border supply chain involving a local OEM and an MNR (she). The OEM produces new products and may engage in remanufacturing, while the MNR competes either by exporting remanufactured products or establishing a local remanufacturing center. Technology spillovers occur when the MNR localizes remanufacturing and the OEM engages in remanufacturing. This study aims to figure out how governmental policies — such as environmental taxes, tariffs, and remanufacturing incentives — and technology spillovers influence the OEM's remanufacturing decisions and the MNR's choice of remanufacturing location. Additionally, it explores how factors (e.g., technology spillovers) affect policy design. Collectively, these three studies provide valuable managerial insights for firms' decision-making in new product production, remanufacturing, and coopetition. They also offer policymakers guidance to formulate regulations that promote sustainable industrial practices.

Keywords: closed-loop supply chains, knowledge spillovers, policy interventions, coopetition, remanufacturing, new product production

Résumé

Les chaînes d'approvisionnement en boucle fermée (Closed-Loop Supply Chains, CLSCs) permettent aux entreprises de remanufacturer des produits usagés et de réintégrer les matériaux récupérés dans les processus de production, générant ainsi d'importants bénéfices environnementaux, économiques et sociaux. Motivés par ces avantages et par une pression réglementaire croissante, tant les fabricants d'équipements d'origine (Original Equipment Manufacturers, OEMs) que les remanufacturiers indépendants — y compris les remanufacturiers tiers (Third-Party Remanufacturers, TPRs) et les remanufacturiers multinationaux (Multinational Remanufacturers, MNRs) — participent de plus en plus aux CLSCs. Ces entreprises interviennent soit directement, en gérant les produits en fin de vie, soit indirectement, par le biais d'accords de coopération. Toutefois, les effets d'externalité technologique, les réglementations environnementales et la concurrence sur le marché modifient conjointement les structures de coûts des entreprises et influencent la demande des consommateurs. Ces dynamiques complexifient les décisions relatives à la production de nouveaux produits, à la remanufacturation et à la stratégie de coopération. Comprendre comment les entreprises prennent ces décisions sous l'influence d'effets d'externalité et d'interventions politiques est essentiel pour faire progresser les connaissances académiques et soutenir des prises de décision plus efficaces à l'échelle organisationnelle.

Dans ce contexte, cette thèse adopte une structure par articles. Elle comprend trois études interconnectées qui analysent les décisions des entreprises en matière de production de nouveaux produits, de stratégies de remanufacturation et de coopération dans des contextes de CLSC.

La première étude examine un système de remanufacturation composé d'un OEM (il) et d'un TPR (elle). Le TPR remanufacture des produits usagés initialement fabriqués par l'OEM, soit de manière indépendante, soit dans le cadre d'un accord

d'autorisation. Elle peut également produire et vendre de nouveaux produits en concurrence avec ses propres produits remanufacturés et ceux de l'OEM. Dans un tel système, des externalités de connaissances — générales et liées à l'innovation — de l'OEM vers le TPR sont inévitables. Cette étude analyse l'impact de ces externalités sur les stratégies de production et de coopération des deux entreprises. Elle met en évidence : (i) les conditions dans lesquelles le TPR choisit de remanufacturer et/ou de produire de nouveaux produits; (ii) les situations où une autorisation de remanufacturation est mutuellement bénéfique par rapport à une concurrence pure; et (iii) la décision optimale de l'OEM concernant le tarif unitaire d'autorisation.

La deuxième étude explore les interactions entre un OEM et un TPR dans un cadre réglementaire comportant deux instruments environnementaux : la taxe sur les émissions et les réglementations sur la gestion des déchets. L'OEM peut soit s'acquitter de la taxe de gestion des déchets, soit externaliser cette gestion au TPR. Le TPR valorise les produits usagés en les remanufacturant ou en récupérant leurs matériaux, et peut aussi produire de nouveaux produits à partir de ces matériaux récupérés. Cette étude examine l'influence des politiques environnementales sur les décisions d'externalisation de l'OEM et les stratégies de valorisation du TPR. Elle identifie les conditions dans lesquelles : (i) le TPR choisit la remanufacturation et/ou la production de nouveaux produits; (ii) l'OEM externalise la gestion des produits usagés; et (iii) l'introduction de nouveaux produits par le TPR incite l'OEM à externaliser cette gestion.

La troisième étude porte sur une chaîne d'approvisionnement transfrontalière impliquant un OEM local et un MNR (elle). L'OEM fabrique de nouveaux produits et peut aussi pratiquer la remanufacturation, tandis que le MNR entre en concurrence soit en exportant des produits remanufacturés, soit en implantant un centre local de remanufacturation. Des externalités technologiques surviennent lorsque le MNR localise sa remanufacturation et que l'OEM s'y engage également. Cette étude examine comment les politiques gouvernementales — telles que les taxes environnementales, les droits de douane et les incitations à la remanufacturation —

ainsi que les externalités technologiques influencent les décisions de remanufacturation de l'OEM et le choix de localisation du MNR. Elle explore également les implications de ces facteurs sur la conception des politiques publiques.

Collectivement, ces trois études offrent des éclairages managériaux précieux sur les décisions des entreprises en matière de production, de remanufacturation et de coopération. Elles apportent également des recommandations utiles aux décideurs politiques pour élaborer des réglementations favorisant des pratiques industrielles durables.

Mots-clés: chaînes d'approvisionnement en boucle fermée, externalités de connaissances, interventions politiques, coopération, remanufacturation, production de nouveaux produits

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1. Introduction

This dissertation adopts an article-based format and consists of three interrelated but self-contained academic studies. All three studies examine firm-level decisions in a closed-loop supply chain (CLSC) by focusing on the competitive and/or cooperative interactions between original equipment manufacturers (OEMs) and independent remanufacturers including third-party remanufacturers (TPRs) and multinational remanufacturers (MNRs). While each study has a distinct decision-making scenario, they address a common research theme: how firms make production, remanufacturing, and coopetition decisions in the presence of spillover effects and policy interventions. In this regard, the three studies share a consistent theoretical foundation and a similar industry background. This chapter presents the background underpinning the dissertation, explains the interactions between OEMs and independent remanufacturers, and highlights the decision-making challenges. It then introduces the research objectives and questions of each study, followed by the structure of this dissertation.

1.1 Background

In recent years, the accelerating pace of mass production, rapid technological advancement, and the shortening of product lifecycles have significantly intensified the consumption of raw materials and energy ([Elliott and Shanshan, 2008](#); [Ramli and Munisamy, 2015](#)). This trend has resulted in substantial resource depletion and increasing greenhouse gas emissions. According to the Global Resources Outlook 2024, global material extraction increased from 30.9 billion tons in 1970 to 95.1 billion tons in 2020, while greenhouse gas emissions doubled over the same period ([UNEP, 2024](#)). In parallel, waste generated from production processes (e.g., industrial byproducts and residues) and the disposal of end-of-life products pollutes the air, water, and soil, thereby accelerating resource exhaustion and global warming ([Plambeck and Wang, 2009](#); [Liu et al., 2017](#)). Research by [Shafiee and Topal \(2009\)](#) further underscores the urgency of this issue and estimates that if fossil fuel consumption continues at 2006 rates, global oil and natural gas reserves will be depleted within approximately 40 and 70 years, respectively.

CLSCs have emerged as a key strategy for promoting sustainable production and resource conservation in response to these environmental challenges. CLSCs are designed to recover value from used products through activities such as remanufacturing and recovering materials. Among used product management approaches, remanufacturing can effectively recover residual value by restoring used products to nearly new condition ([Atasu et al., 2008](#)). Real-world data from CAT Reman highlights the substantial advantages of remanufacturing. For example, compared to new production, remanufacturing a used cylinder head reduces greenhouse gas emissions by 61%, water usage by 93%, and energy consumption by 86%. It also improves workplace safety by 82% and reduces the amount of material required and landfill space used by more than 99%¹. In addition to remanufacturing, recovering raw materials from used products and reusing the recovered materials further enhance resource efficiency and minimize waste. More specifically, integrating recovered materials into new product production allows manufacturers to reduce their reliance on virgin resources, minimize environmental impact, and contribute to a more circular economy. For instance, the U.S. Environmental Protection Agency (EPA) estimates that increasing the recycling rate from 30% in 2000 to 35% could reduce greenhouse gas emissions by an additional 10 million metric tons of carbon equivalent compared to landfilling².

The development of CLSCs has been facilitated by both policy-driven and market-driven forces. Governments worldwide have implemented a range of policy interventions to promote remanufacturing and material recovery. For instance, the Swedish Environmental Protection Agency mandates that OEMs must pay for waste collection. Similarly, the Belgian government requires that at least 95% of end-of-life vehicles be properly disposed of, either by recovering components or materials ([Soo et al., 2017](#)). Additionally, the European Commission has established extended producer responsibility (EPR) policies that hold manufacturers accountable for the entire lifecycle of their products. These policies stimulate firms to reduce emissions and promote the reuse and recovery of used products. Moreover, the U.S. has implemented initiatives aimed at encouraging remanufacturing. For example, the

¹ https://www.cat.com/en_US/products/new/parts/remman.html

² <https://archive.epa.gov/epawaste/nonhaz/municipal/web/pdf/climfold.pdf>

EPA has developed certification programs that ensure remanufactured products meet strict quality and safety standards ([Atasu and Subramanian, 2012](#); [Huang et al., 2019b](#)). In addition to the above regulatory initiatives aimed at encouraging OEMs' sustainable practices, some regulators have taken measures to attract foreign direct investment (FDI) from multinational independent remanufacturers to strengthen their domestic circular economy. For instance, the German government has offered a range of incentives to encourage foreign investors to engage in the remanufacturing or repurposing of used lithium batteries³; the Indian government has provided subsidies for the remanufacturing of electronic products to stimulate the sector and attract investment⁴. In addition to policy interventions, shifting consumer preferences have also played a crucial role in promoting remanufacturing. At the same time, consumers' growing preference for affordable and sustainable products has boosted the market for remanufactured products ([Atasu et al., 2008](#)).

Motivated by regulatory pressures, consumer preferences, and economic benefits, firms are increasingly engaging in CLSC practices such as remanufacturing and material recovery. Traditional OEMs (e.g., Xerox, Apple) have integrated remanufacturing into their operations ([Savaskan et al., 2004](#); [Zhao et al., 2021](#)). Meanwhile, remanufacturing offers distinct advantages in cost and time savings ([Gutowski et al., 2011](#)). As a result, many independent remanufacturers — including TPRs and MNRs — have emerged over the past decades ([Örsemir et al., 2014c](#); [Zou et al., 2016](#)). More specifically, some TPRs have established production facilities domestically (e.g., Sankaku⁵), while others have built remanufacturing centers across multiple regions (e.g., Caterpillar). In summary, both OEMs and independent remanufacturers (TPRs or MNRs) participate in CLSCs by offering new and/or remanufactured products within the same markets. Each type of firm has distinct competitive advantages: OEMs possess advantages in new product production, backed by a strong brand reputation and accumulated knowledge in innovation and manufacturing, while TPRs are

³ <https://www.gtai.de/en/invest/industries/environmental-technologies/battery-recycling-market-opportunities-in-germany-995330#toc-anchor--3>

⁴ <https://www.livemint.com/Politics/JnYd4X6aCHFl8h7jEVMJ3L/Govt-extends-capital-subsidy-to-electronic-products-to-boost.html>

⁵ http://www.sankaku.com.cn/en_gsjs.asp

typically more specialized in remanufacturing.

The coexistence of OEMs and independent remanufacturers in CLSCs has introduced complex dynamics of interaction. On the one hand, the substitutability of their products leads to market competition. On the other hand, the complementarity of their capabilities fosters cooperation (such as remanufacturing authorization and used product management outsourcing) and leads to potential knowledge spillovers between OEMs and independent remanufacturers. Accordingly, this dissertation considers interactions between firms involving competition, cooperation, and knowledge spillovers. These interactions, shaped by market forces and policy interventions, require firms to make strategic trade-offs in managing new product production, remanufacturing, and coopetition.

1.2 Interactions between OEMs and independent remanufacturers

This section delves deeper into the interactions between OEMs and independent remanufacturers, focusing on the mechanisms and implications of competition, cooperation, knowledge spillovers, and technology spillovers.

1.2.1 Competition and cooperation

Competition between OEMs' new and/or remanufactured products and TPRs' remanufactured products is a widely observed phenomenon. OEMs typically focus on new product production; some also engage in remanufacturing. TPRs collect used products originally produced by OEMs and remanufacture them. Consequently, TPRs' remanufactured products compete directly with OEMs' new and remanufactured products for market share. Existing studies have extensively examined OEMs' and TPRs' decisions regarding new product production and remanufacturing. They investigate the impact of factors such as government policies, product quality, and consumer behavior on firms' decision-making (Krass et al., 2013; Bulmus et al., 2014; Örsdemir et al., 2014b).

It is noteworthy that in practice, beyond their traditional focus on remanufacturing, many TPRs (e.g., LKQ, Sankaku) have increasingly engaging in new product production. For example, LKQ Corporation, which began by specializing in recycling and remanufacturing used auto parts, gradually expanded into new product production as it gained manufacturing

expertise. Today, LKQ is not only a leading provider of remanufactured auto parts but also aftermarket parts, which are new components not produced by OEMs⁶. This entry of TPRs into new product production challenges the traditional roles of OEMs and adds further complexity to the competitive landscape (Xue et al., 2021).

Despite their competitive interactions, OEMs and TPRs also collaborate through mechanisms such as outsourcing and authorizing remanufacturing agreements. For example, Land Rover outsourced its remanufacturing service to Caterpillar in 2005 (Qin et al., 2023). Apple and Foxconn reached a remanufacturing authorization agreement in 2015, granting the latter proprietary rights to remanufacture end-of-life iPhones and remarket them in the Chinese market (Zou et al., 2016). In such cooperative contexts, OEMs can focus on innovation while TPRs contribute to sustainable practices and cost savings. These dual interactions — where firms both compete and collaborate simultaneously — are defined as coopetition (Chen et al., 2019b).

1.2.2 Knowledge and technology spillovers

In remanufacturing systems, the similarity between OEMs and TPRs (or MNRs), often reflected in shared design, functionality, and technical specifications, facilitates knowledge spillovers between the firms. Additionally, their cooperative arrangements further enhance these spillovers. These spillovers occur through various channels and play a critical role in enhancing both firms' production capabilities and efficiency.

First, OEMs' general knowledge naturally diffuses to the TPRs during remanufacturing (Letmathe and Rößler, 2019). When TPRs disassemble and analyze OEM products, they gain insight into product design, component specifications, functionality, and quality standards. This hands-on exposure enables TPRs to absorb a broad range of production-related knowledge including general product insights, manufacturing techniques, detailed component specifications, and testing procedures. Such knowledge spillovers not only refine TPRs' remanufacturing processes but also pave the way for expanding their operations into new product production. In other words, after accumulating valuable manufacturing experience

⁶ <https://www.lkqcorp.com/>

through remanufacturing, TPRs acquire the ability to produce new products.

Second, innovation-related knowledge — often tacit and not easily absorbed through observation — may spill over to TPRs during formal cooperation with OEMs. When OEMs grant TPRs remanufacturing authorization, they work to ensure that the remanufactured products meet their strict specifications and quality standards. This process requires OEMs to share proprietary innovation knowledge with TPRs ([Harhoff et al., 2003](#); [Bogers, 2011](#)), leading to further spillovers of their knowledge. Often, the knowledge shared with TPRs is related to product and production innovation, which cannot be directly acquired or used by TPRs without OEMs' guidance ([Bagchi and Mukherjee, 2014](#)). This form of knowledge transfer is referred to as innovation spillovers. Such spillovers enable TPRs to produce high-quality remanufactured products at lower costs. They also create opportunities for TPRs to enhance the innovativeness of their new products, should they engage in new product production ([Hu et al., 2020](#)).

Finally, when MNRs establish local remanufacturing centers in domestic markets, their knowledge (e.g., remanufacturing technology, efficient processes) can spill over to local OEMs operating in the domestic market. This spillover occurs through several channels, such as shared supplier networks, structured knowledge diffusion, labor mobility, and imitation by local firms ([Kohpaiboon, 2006](#); [Crespo and Fontoura, 2007](#); [Han et al., 2014](#)). For example, local OEMs may adopt MNRs' advanced quality control systems to streamline their own remanufacturing processes, while the movement of skilled labor helps transfer critical expertise. By leveraging these spillovers, local OEMs can benefit from enhanced infrastructure, improved workforce skills, and shared technical know-how, ultimately boosting their remanufacturing efficiency and reducing production costs ([Kohpaiboon, 2006](#)).

1.3 Decision-making problems and challenges

In the above discussion, we detailed the interactions between OEMs and independent remanufacturers (i.e., TPRs and MNRs) in terms of competition, cooperation, and knowledge/technology spillovers. Although these interactions can yield benefits such as improved resource efficiency, greater consumer choice, and enhanced technological learning

for CLSCs, they also lead to several complex decision-making problems for both OEMs and independent remanufacturers (TPRs or MNRs). Specifically, OEMs need to decide whether or not to engage in remanufacturing and/or to cooperate with TPRs. TPRs must determine whether or not to engage in new product production and/or cooperate with OEMs. MNRs need to choose between exporting remanufactured products to domestic markets and establishing local remanufacturing centers in those markets. These decisions are far from straightforward, as they are shaped by a set of interrelated factors discussed below.

The risk of market cannibalization — where one product type erodes the market for another — poses a fundamental strategic dilemma for both OEMs and independent remanufacturers (Guide and Li, 2010; Hu et al., 2021). For OEMs, offering remanufactured products or cooperating with TPRs through remanufacturing authorization can create new revenue streams such as sales of remanufactured products and remanufacturing authorization fees. However, remanufactured products — whether produced in-house or by TPRs/MNRs — may cannibalize the sales of their new products. In response to this potential cannibalization, OEMs may be forced to lower the selling price or reduce the production volume of their new products. This, in turn, can lead to a decrease in their profit margins for new products. As a result, OEMs face a trade-off between pursuing an additional revenue stream through direct or indirect involvement in remanufacturing and maintaining the profit of their new products.

For independent remanufacturers, producing their own-branded new products generates an additional revenue stream. However, it also creates internal market cannibalization and further intensifies external competition. Internally, their own-branded new products compete with their remanufactured offerings, which can reduce the demand for and profit of remanufactured products. Externally, new product introduction by the independent remanufacturers escalates the rivalry with OEMs. This intensified competition can discourage OEMs from engaging in cooperative arrangements, such as remanufacturing authorization or used product management outsourcing. Thus, independent remanufacturers face a strategic trade-off: whether to remain focused on remanufacturing and maintain cooperation with OEMs, or to pursue higher profits through new product production at the risk of reduced cooperation and heightened competition.

Knowledge/technology spillovers add additional complexity to the decision-making of OEMs and independent remanufacturers (i.e., TPRs or MNRs) by increasing the risk of market cannibalization (Fan et al., 2020; Qian et al., 2024). In cases where OEMs do not engage in remanufacturing but authorize TPRs to remanufacture, the resulting innovation-related knowledge spillovers help TPRs enhance the innovativeness of their new products (as mentioned in Section 1.2.2). This results in an increase in consumers' willingness to pay (WTP) for TPRs' new products. The increase in consumers' WTP may elevate the risk of TPRs' new products cannibalizing the market share of OEMs' new products and their own remanufactured products, resulting in reduced profits for both parties. Therefore, for OEMs, when determining whether or not to authorize remanufacturing and deciding authorization fees, they must balance the revenue from cooperation against the risks of strengthening competitors: TPRs. For TPRs, when deciding whether or not to engage in new product production, they must weigh the benefits of new product production against the revenue losses of remanufactured products caused by internal market cannibalization. However, because the effects of knowledge spillovers are often uncertain and hard to measure in advance, it is difficult for OEMs and TPRs to quantify their revenue loss.

A similar dilemma arises in the relationship between MNRs and local OEMs. When MNRs establish local remanufacturing centers in domestic markets and local OEMs engage in remanufacturing, the resulting technology spillovers reduce local OEMs' remanufacturing costs (as mentioned in Section 1.2.2). The decrease in local OEMs' remanufacturing costs enhances the competitive advantage of their remanufactured products. This, in turn, increases the risk that local OEMs' remanufactured products cannibalize the market share of their own new products and MNRs' remanufactured products. Consequently, for local OEMs, when determining whether or not to engage in remanufacturing, they must weigh the trade-off between remanufacturing profits and the potential loss in new product revenue. For MNRs, when determining whether or not to establish local remanufacturing centers in domestic markets, they should balance the cost savings from local production against the risk of being cannibalized by strengthened local competitors: local OEMs. Similarly, the unpredictable nature of technology spillovers makes it difficult for firms to accurately assess

cannibalization risks. As a result, understanding the mechanisms and consequences of knowledge spillovers is crucial for firms as they navigate the dual pressures of competition and collaboration in CLSCs.

In addition to internal dynamics, external policy interventions (e.g., environmental taxes, tariffs, remanufacturing incentives) play a vital role in shaping strategic decision-making of OEMs and TPRs/MNRs in CLSCs. Policies not only change firms' cost structures but also reshape market dynamics by affecting profit margins and competitive positioning between OEMs and independent remanufacturers (i.e., TPRs or MNRs), thereby introducing additional complexity into firms' decision-making. For OEMs, although the risks of market cannibalization and knowledge spillovers may discourage engagement in remanufacturing, stricter environmental regulations can increase the pressure to participate — either directly or through partnerships with TPRs. For TPRs, environmental taxes may promote remanufacturing and recovered material reuse, but they also introduce uncertainty regarding competitive dynamics. For MNRs, tariffs and local remanufacturing incentives encourage the establishment of local remanufacturing centers, but the effectiveness of such policies in offsetting their revenue losses caused by technology spillovers remains uncertain. In summary, policy interventions further complicate firms' ability to evaluate the trade-offs involved, challenging decision-making in CLSCs.

1.4 Research objectives and questions

Given these decision-making challenges arising from multiple factors (i.e., market competition, knowledge and technology spillovers, and policy interventions), this dissertation aims to explore how these factors influence firms' operations in CLSCs. In particular, it focuses on understanding the impact of knowledge and technology spillovers and policy interventions on the production, remanufacturing, and coopetition decisions of OEMs and independent remanufacturers (TPRs or MNRs). To achieve this aim, this dissertation presents three interrelated studies that collectively provide a comprehensive investigation of strategic decision-making in CLSCs. [Figure 1.1](#) illustrates the overall research objective and how each study contributes to addressing it.

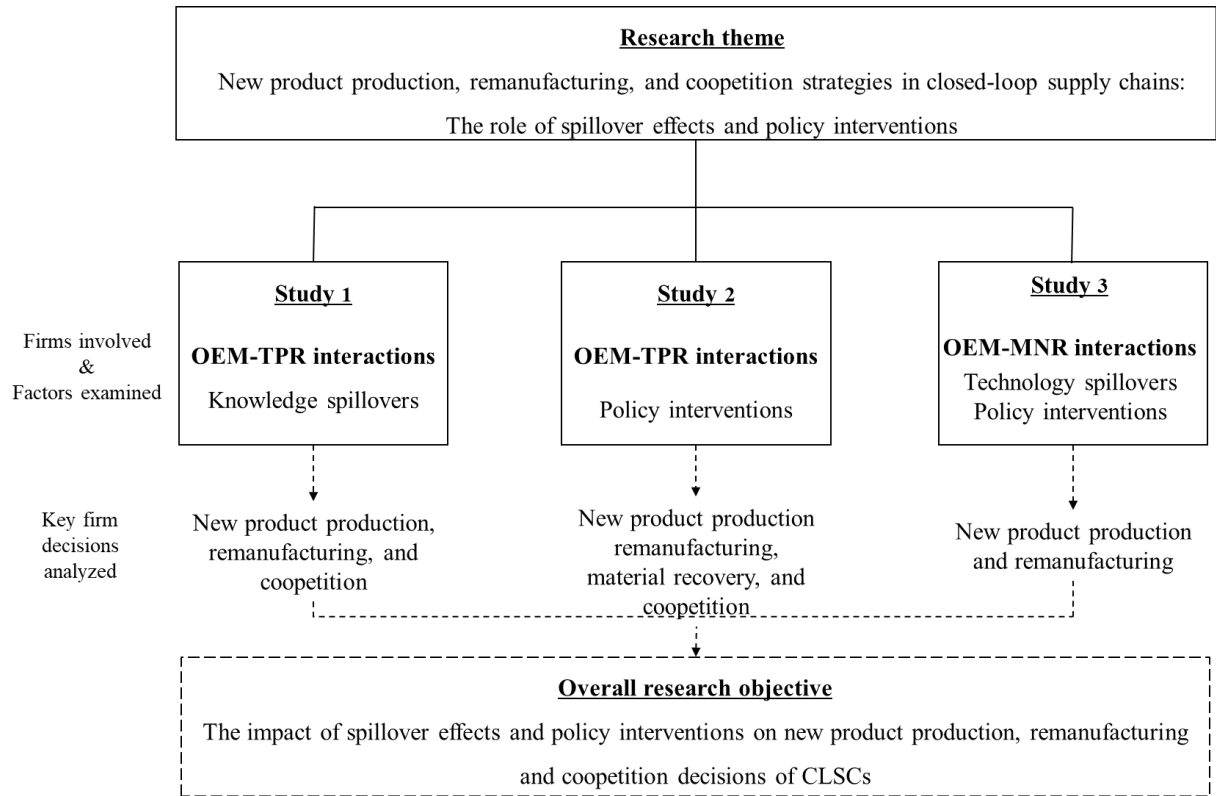


Figure 1.1. Overall and study-specific research objectives

The first study investigates production and coopetition strategies in a remanufacturing system where knowledge spillovers significantly influence firms' strategic decisions. In the remanufacturing system considered, a TPR (she) can either remanufacture used products from an OEM (he) without authorization (competition scenario) or with the OEM's authorization (coopetition scenario), while the OEM focuses on new product production. The study identifies two types of knowledge spillovers: (i) general spillovers, which arise during the remanufacturing process; and (ii) innovation spillovers, which occur when the OEM grants the TPR remanufacturing authorization. General knowledge spillovers enable the TPR to engage in new product production, while innovation spillovers help the TPR improve her new and remanufactured products. Given the complexities of decision-making introduced by knowledge spillovers and market competition (as discussed in Section 1.3), the objective of this study is to examine how these factors influence the two firms' decisions on new product production, remanufacturing, and coopetition. Specifically, it focuses on the following research questions:

- Under what circumstances do general knowledge spillovers drive a TPR to engage in new product production or cease remanufacturing?
- How do innovation spillovers influence the TPR's production strategy?
- Under what circumstances does coopetition become a win-win situation for both the OEM and the TPR?

Building on the first study, which highlights the evolving role of the TPR in new product production, the second study examines how environmental policies — emission taxes and waste management regulations — shape firms' decisions on used product management and production strategies in CLSCs. In the CLSC considered, the OEM can either pay waste management taxes for products he produces or outsource used product management to the TPR. The TPR recovers value from these used products by remanufacturing them and/or recovering materials; she also reuses recovered materials to produce new products. Since both the OEM and TPR sell products in the same market, their offerings can cannibalize each other's market share. Due to the decision-making challenges caused by factors including environmental policies and market competition (as discussed in Section 1.3), it is difficult for the two firms to make the following decisions: (i) the OEM's decision on whether or not to outsource used product management; (ii) the TPR's decisions on used product recovery strategies and whether or not to reuse recovered materials to produce new products. To provide decision-making support, this study aims to investigate the interactions between the OEM and the TPR. Specifically, it addresses the following research questions:

- When does the OEM outsource used product management to the TPR?
- What are the TPR's used product recovery strategies?
- When does the TPR produce new products?
- How does the introduction of the TPR's new products influence the OEM's outsourcing strategy?

As remanufacturing increasingly involves international participants, the third study extends the analysis to a global supply chain context and examines how policy interventions and technology spillovers influence firms' remanufacturing strategies. The supply chain under consideration includes a local OEM (he) and an MNR (she). The local OEM, based in

the domestic market, focuses on new product production and considers entering the remanufacturing market in response to environmental taxes on new products and remanufacturing incentives. The MNR evaluates two market entry strategies: exporting remanufactured products to the domestic market, incurring tariffs, or establishing a local remanufacturing center, which would make her eligible for remanufacturing incentives. Technology spillovers occur when the MNR establishes a local remanufacturing center and when the local OEM engages in remanufacturing. As discussed in Section 1.3, the two firms face decision-making challenges arising from the conflicting incentives⁷ and their decision-making interdependencies — both shaped by policy interventions, technology spillovers, and market conditions. These factors not only complicate firms' decision-making but also create difficulties for policymakers in designing effective policies to promote remanufacturing. To support decision-making for both firms and policymakers, this study investigates the OEM's remanufacturing decisions and the MNR's location strategies under different policy interventions including environmental taxes, tariffs, and remanufacturing incentives. Specifically, it addresses the following research questions:

- Should the OEM engage in remanufacturing given government policies, technology spillovers, and competition from the MNR's products?
- Under what conditions should the MNR establish local remanufacturing centers instead of exporting remanufactured products?
- How should governments design policies to promote remanufacturing while ensuring a level playing field between the OEM and the MNR?

Together, these three studies form an integrated research framework that examines how firms in CLSCs make decisions regarding production, remanufacturing, and competition in the presence of knowledge and technology spillovers, market competition, and policy interventions. This integrated approach enhances theoretical understanding of strategic interactions in CLSCs and offers practical guidance for industry practitioners and

⁷ For example, when an MNR establishes a local remanufacturing center, it may benefit from cost savings and government incentives. However, it also faces the risk of intensified competition due to potential technology spillovers to local OEMs. This trade-off exemplifies the conflicting incentives that firms often face.

policymakers. Despite extensive research on remanufacturing, an important gap remains: few studies account for knowledge and technology spillovers in firm-level decision-making, and the strategic implications of TPRs' engagement in new product production are relatively unexplored. This dissertation bridges this gap by developing an integrated analytical framework that captures the decision-making problems of OEMs and independent remanufacturers (TPRs or MNRs). It contributes to the literature by revealing how firms balance spillover-driven interactions and policy-induced trade-offs in CLSCs.

1.5 Dissertation structure

This dissertation is structured into six chapters. Following the introduction, **Chapter 2** reviews the relevant literature across three thematic streams: manufacturing and remanufacturing decisions in CLSCs, competition and cooperation in remanufacturing systems, and knowledge and technology spillovers in operations management. **Chapter 3** presents the first study. It examines how spillover effects and market conditions jointly influence production and competition strategies in a remanufacturing system involving an OEM and a TPR. **Chapter 4** introduces the second study, which investigates the role of environmental policies — such as emission taxes and waste management regulations — in shaping the OEM's outsourcing strategy for used product management and the TPR's strategies for product recovery and new product production. **Chapter 5** features the third study. This study shifts the focus to a global supply chain context and investigates how technology spillovers from MNRs and government policy interventions influence the remanufacturing decisions of OEMs and the location choices of MNRs. It also addresses policy design problems faced by regulators. Finally, **Chapter 6** concludes the dissertation by summarizing key findings, discussing their theoretical and managerial implications, and offering directions for future research.

2. Literature review

This chapter reviews the existing studies from three streams: manufacturing and remanufacturing decisions in CLSCs, competition and cooperation in remanufacturing systems, and knowledge and technology spillovers in operations management.

2.1 Manufacturing and remanufacturing decisions in CLSCs

CLSCs integrate forward activities, such as manufacturing and distribution of new products, with reverse logistics processes, including used product returns, recycling, remanufacturing, and disposal (Guide et al., 2003). Among these activities, remanufacturing — restoring used products to like-new condition — offers significant benefits by enhancing resource efficiency, reducing environmental impacts, and generating economic value (Ferrer, 2001). However, as remanufactured products frequently compete directly with new products, firms face challenges in deciding whether to prioritize manufacturing or engage in remanufacturing (Atasu, 2010). These challenges, driven by the competitive interplay between new and remanufactured products, have motivated researchers to examine extensively firms' manufacturing and remanufacturing decisions in CLSCs.

Numerous studies have identified barriers that discourage OEMs from engaging in remanufacturing. A primary concern discouraging OEMs from remanufacturing is the cannibalization risk that remanufactured products pose to new product sales, as stressed by Atasu (2010). Similarly, Guide and Van Wassenhove (2009) argue that although remanufacturing offers potential advantages, firms may still be reluctant to engage in it due to the complexities associated with related activities such as product collection, disassembly, and reprocessing. In addition to these economic and operational concerns, consumer perception also plays a critical role. Zhou et al. (2021c) examine how educating consumers about the benefits of remanufacturing affects OEMs' strategic decisions. Their findings reveal that while consumers' WTP for remanufactured products may increase, the OEM might still strategically opt out of remanufacturing to safeguard new product sales from cannibalization. Moreover, product-specific factors — particularly limited product quality and remanufacturability — have also been recognized as key obstacles to remanufacturing

(Örsdemir et al., 2014; Schäfer et al., 2020; Qin et al., 2023).

While many studies highlight the challenges of remanufacturing, other researchers emphasize that remanufacturing offers substantial economic benefits, which can serve as strong incentives for OEMs to engage in it. For instance, [Savaskan et al. \(2004\)](#) and [Ferguson and Toktay \(2006\)](#) emphasize that the potential cost savings associated with remanufacturing are critical drivers for firms to adopt remanufacturing. [Debo et al. \(2005\)](#) demonstrate that remanufacturing yields higher profit than new product production when the relative cost advantage of remanufacturing over new product manufacturing is high and consumer depreciation of remanufactured products is minimal. Apart from cost advantages and consumer behaviors, market dynamics and operational constraints have also drawn scholarly attention. [Nadar et al. \(2021\)](#) incorporate product diffusion speed and the availability and timing of product returns into their analysis. Their results reveal that the OEM should partially satisfy the demand for remanufactured products when diffusion rates are high, remanufacturing margins are significant, and demand for remanufactured products is limited. [Souza \(2013\)](#) reviews the existing studies and summarizes that firms' remanufacturing decisions are shaped by cost structures, consumer behavior, operational constraints (e.g., capacity limitations, return timing), and regulatory frameworks.

Several researchers have examined TPRs' remanufacturing decisions when competing with OEMs. [Ferguson and Toktay \(2006\)](#) consider a competitive setting in which both the OEM and the TPR can engage in remanufacturing. Their results indicate that although the OEM may not make a profit from remanufacturing, the TPR can benefit from remanufacturing the OEM's used products when consumers' relative WTP for remanufactured products compared to new products is high. Under a similar supply chain setting, [Wu \(2012\)](#) shows that the TPR's remanufacturing quantity is constrained by the collection quantity when the OEM's product cost is high. [Xue et al. \(2021\)](#) explore the conditions under which the low-end firm should remanufacture used products originally produced by a high-end firm. Their results suggest that the low-end firm should engage in remanufacturing when the remanufacturing cost is low.

In addition to firm-specific and market-driven factors, government regulations also

significantly affect firms' manufacturing and remanufacturing decisions within CLSCs. These regulations include take-back legislation ([Pazoki and Samarghandi, 2020](#); [Wang et al., 2021](#)), environmental taxes ([Ding et al., 2020](#); [Zhang et al., 2020](#)), EPR ([Atasu and Subramanian, 2012](#); [Yi et al., 2021](#)), and remanufacturing subsidies ([Li et al., 2018](#); [Zhang et al., 2020](#)).

[Esenduran et al. \(2015\)](#) point out that take-back legislation mandates manufacturers to manage the end-of-life treatment of their products, thereby directly incentivizing firms to adopt remanufacturing and increasing remanufacturing quantity. [Pazoki and Samarghandi \(2020\)](#) examine the impact of take-back legislation on firms' strategic choice between adopting remanufacturing and investing in eco-design. Their results indicate that under take-back regulations, a high eco-design cost motivates the OEM to engage in remanufacturing. [Atasu and Subramanian \(2012\)](#) stress that EPR policies extend OEMs' obligations by requiring them to manage end-of-life products and redesign products to facilitate remanufacturing and recycling. Under the EPR-based take-back legislation, [Huang et al. \(2019\)](#) analyze firms' design strategies and find that stricter recycling or collection targets may paradoxically reduce recyclability or durability, as firms attempt to minimize compliance costs. [Krass et al. \(2013\)](#) point out that environmental taxes, such as emission taxes and waste disposal fees, increase the cost of conventional manufacturing, thus encouraging firms to adopt remanufacturing. [Niu et al. \(2022\)](#) examine an OEM's decision-making regarding the use of remanufactured components or new components in producing new products. Their results indicate that when the OEM's brand premium is limited and the environmental tax is high, remanufactured components are preferred. [Li et al. \(2024\)](#) consider a cross-border supply chain and study the impact of carbon tariffs on the OEM's manufacturing and remanufacturing decisions. Their findings reveal that high carbon taxes lead to an increased remanufacturing quantity and a reduced production quantity of new products. [Zhang et al. \(2020\)](#) emphasize that subsidies specifically targeted at remanufacturing can effectively lower operational costs and enhance the profitability of remanufacturing operations. [Sun and Liu \(2023\)](#) study the impact of remanufacturing subsidy on promoting remanufacturing output. The findings reveal that subsidizing the OEM is more effective than subsidizing the TPR. [Han et al. \(2017\)](#) show that high product remanufacturability and government subsidies

jointly incentivize firms to implement trade-old-for-remanufactured programs, thereby encouraging firms to increase remanufacturing quantity.

2.2 Competition and cooperation in remanufacturing systems

In remanufacturing systems, the relationship between OEMs and TPRs is complex. On the one hand, TPRs compete with OEMs' new products by capturing market share through lower-priced remanufactured products, potentially cannibalizing the OEMs' new product sales. On the other hand, OEMs may choose to cooperate with TPRs through remanufacturing licensing, outsourcing, or authorization to retain control over remanufacturing activities while benefiting from TPRs' remanufacturing activities (Guide and Li, 2010; Fang et al., 2020). The competition and/or cooperation relationship between OEMs and TPRs has become a critical theme in remanufacturing research. Several studies (Guide and Li, 2010; Hu et al., 2021) argue that TPRs' remanufacturing activities may harm OEMs' profits because remanufactured products cannibalize demand for OEMs' new products.

However, other researchers, such as Wu and Zhou (2016), Jin et al. (2017), and Fang et al. (2020), revisit this view and identify conditions under which TPR competition can be beneficial to OEMs. Wu and Zhou (2016) analyze how different OEM-TPR competition structures affect the profits of two competing OEMs. Their results reveal that both OEMs earn higher profits when multiple TPRs enter the market than when a single TPR does. Jin et al. (2017) examine how TPR entry benefits the OEM when he purchases new components from a supplier. The findings show that TPR entry induces the supplier to decrease the wholesale price, thereby offsetting the OEM's revenue loss caused by competition from remanufactured products. Fang et al. (2020) refer to the phenomenon where the presence of remanufactured products alters consumer valuation of new products as the contrast effect. Their study suggests that TPR entry can increase the OEM's profit by reinforcing the premium positioning of new products.

Facing competition from TPRs, OEMs have developed various strategic responses aimed at mitigating negative impacts and maintaining their market position. One stream of research emphasizes defensive strategies such as adjusting production or pricing decisions.

Majumder and Groenevelt (2001) show that OEMs can reduce the availability of used products (cores) in the market by lowering their new product production quantity. Ferguson and Toktay (2006) suggest that the OEM can reclaim lost market share caused by competition from the TPR's remanufactured products by entering the remanufacturing market themselves. Conversely, Chen and Chen (2019) argue that this strategy is only effective if the OEM enjoys a substantial cost advantage in remanufacturing. In terms of adjusting pricing, Xue et al. (2021) examine the OEM's reactions to the encroachment from the low-end firms' remanufactured products. Their results indicate that the OEM can mitigate market share loss caused by competition from the TPR's remanufactured products by lowering the selling price of his new products; Xu et al. (2021) investigate the interaction between an OEM and a TPR in remanufacturing. The findings suggest that when the production cost of new components is moderate and the TPR can make profit from remanufacturing, motivating the TPR to engage in remanufacturing by strategically lowering the price of the new component can benefit the OEM. Moreover, authors such as Chen and Chang (2013) and Hong et al. (2019) show that instead of simply decreasing prices, OEMs can better respond to TPR competition by dynamically adjusting new and remanufactured product prices based on market conditions. Beyond pricing and production adjustments, design-oriented and resource-based strategies also play a role. Studies have shown that OEMs can implement take-back programs (Zhao et al., 2021), increase product disassembly complexity (Wu, 2012), or reduce component commonality (Subramanian et al., 2013) to raise TPRs' remanufacturing costs and weaken their competitive position.

Unlike the above studies that emphasize defensive strategies, a growing body of literature suggests that OEMs can benefit from cooperating with TPRs in remanufacturing. Jin et al. (2022) highlight that OEMs can implement cooperation strategies to increase their profits despite direct competition from TPRs; (Yang et al., 2022; Zhou et al., 2024) point out that TPRs can benefit from collaborating with OEMs by leveraging the OEMs' brand premium, advanced technology, and established market presence. In other words, under certain conditions, OEMs and TPRs can achieve mutual benefits even within a competitive environment. As a result, researchers have examined various cooperative forms between

OEMs and TPRs, including remanufacturing authorization (Zou et al., 2016; Zhou et al., 2021b; Jin et al., 2022), remanufacturing outsourcing (Zou et al., 2016; Li et al., 2023; Lin et al., 2024), co-branding strategies (Hong and Zhang, 2019; Li et al., 2019), and supply chain partnerships (Zhao and Zhu, 2015; Yang et al., 2022). Among these, remanufacturing outsourcing and authorization agreements have received the most attention in literature due to their practical relevance and strategic complexity. Remanufacturing authorization involves OEMs granting TPRs the legal right to remanufacture their products under contractual agreements that often include quality standards and licensing fees. It allows TPRs to capitalize on OEM brand recognition and improve consumer acceptance (Zou et al., 2016; Zhou et al., 2021a; Zhou et al., 2021b). Remanufacturing outsourcing involves OEMs subcontracting remanufacturing operations to TPRs while retaining control over product branding, pricing, and sales channels. This approach enables OEMs to take advantage of TPRs' technical expertise, specialized remanufacturing capabilities, and cost efficiencies without directly engaging in remanufacturing operations (Li et al., 2023; Lin et al., 2024).

Existing literature has extensively analyzed firms' strategic choices between pure competition and cooperation through remanufacturing authorization or outsourcing. Zhu et al. (2023) explore the impact of the TPR's advantage on OEM' remanufacturing outsourcing decisions. The results show that the OEM should outsource remanufacturing when the TPR has either cost advantage or quality advantage. Zhou et al. (2021b) investigate the conditions under which the OEM should authorize remanufacturing to his contract manufacturer. The findings reveal that the OEM should authorize his contract manufacturer when he can decide the authorization fee. Qin et al. (2023) examine the impact of quality uncertainty on the OEM's selection of remanufacturing modes including integrated remanufacturing, outsourcing, and authorization. Jin et al. (2022) consider a scenario in which an OEM authorizes both remanufacturing and the sale of new products to a TPR. While the above studies focus on OEMs' coopetition strategies, some researchers also explore TPRs' strategic choices. For instance, Zou et al. (2016) study the TPR's preference between remanufacturing authorization and outsourcing. Yang et al. (2022) examine whether a TPR should sell remanufactured products independently or through the OEM-controlled channel, which

incurs an authorization fee and adopts blockchain technology to enhance consumers' perceived quality of remanufactured products.

Beyond firm-level strategic considerations, governmental policies also play a critical role in shaping OEM-TPR interactions. [Esenduran et al. \(2017\)](#) analyze the effects of take-back regulation on remanufacturing levels for the OEM and the TPR. [Li et al. \(2018\)](#) consider a remanufacturing system consisting of an OEM, a recycler, and a TPR, examining how subsidy and tax policy influence their decision-making. Under carbon emission quota policy, [Mao et al. \(2023\)](#) explore the interactions in a three-level supply chain comprising an OEM, a TPR, and a retailer. Their findings indicate that carbon emission quota policy motivates the TPR to improve the quality of remanufactured products. [Zhang et al. \(2024b\)](#) study the role of cap-and-trade policies on OEM-TPR competition. Their results show that these policies prevent firms from reaching the remanufacturing authorization cooperation. [Li et al. \(2023\)](#) examine how environment tax and tariff affect the OEM's remanufacturing outsourcing decisions. Their results reveal that high trade barriers stimulate the OEM to outsource remanufacturing.

2.3 Knowledge and technology spillovers in operations management

Knowledge — broadly includes innovation, technology, managerial practices, and other forms of organizational know-how — is widely recognized as a critical resource for fostering innovation and sustaining competitive advantage ([Ornaghi, 2006](#)). Extensive research has underscored its essential role in enhancing firm performance. For example, [Harlow \(2008\)](#) stresses that knowledge is central to economic growth; [Cohen and Klepper \(1992\)](#) show that a firm's knowledge capital is positively associated with its product innovation outcomes; [Ornaghi \(2006\)](#) demonstrates that knowledge accumulation significantly boosts innovative output and enables the diffusion of best practices across firms. Beyond firm boundaries, knowledge may also generate unintended externalities, known as knowledge spillovers. [Fershtman and Gandal \(2011\)](#) argue that knowledge spillovers are a primary channel through which firms gain access to external knowledge. Similarly, [Audretsch and Keilbach \(2007\)](#) and [Ning and Babich \(2018\)](#) note that such spillovers occur when a firm's proprietary knowledge — often unprotected or difficult to contain — spreads to other organizations or supply chain

actors. To conclude, knowledge not only delivers internal benefits but also acts as a catalyst for broader innovation diffusion in competitive environments.

From an operations management perspective, knowledge spillovers often occur among firms operating at the same level, whether they are competitors or complementary partners (Awasthy et al., 2022; Xia et al., 2023; Kadeer and Mengzhe, 2024). They can also take place among upstream and downstream partners within the supply chain (Yoon, 2016). Knowledge spillovers can occur through non-cooperative channels, such as observation, imitation, employee mobility, and FDI (Meyer, 2004; Du et al., 2012; Ning and Babich, 2018; Eapen et al., 2019). They can also take place through cooperative channels, including outsourcing partnerships (Hu et al., 2020; Liu et al., 2025), shared supplier relationships (Agrawal et al., 2016; Veldman et al., 2023), and other cooperation arrangements (Yang et al., 2023). The effects of knowledge spillovers are typically measured by their influence on consumer-perceived value and firm cost structures. Alan et al. (2019) and Nire and Matsubayashi (2024) demonstrate that spillovers related to advertising and brand management directly enhance consumer-perceived value; Hu et al. (2020) argue that innovation spillovers improve product quality, further strengthening market perception. Meanwhile, authors such as Buckley et al. (2007), Du et al. (2012) and Han et al. (2014) point out that the diffusion of advanced technology and production expertise contributes to cost reductions and improved operational efficiency. These impacts in turn affect firms' strategic decisions and long-term performance. Therefore, a growing number of studies have examined how spillovers shape firm behavior in areas such as investment, collaboration, and research and development (R&D) management.

Technological spillovers, particularly those arising from R&D activities, have received considerable attention in operations management. Niu and Shen (2022) investigate how bilateral investments in uncertain process innovation influence competing OEMs under knowledge spillovers. They identify a wide range of outcomes (i.e., lose-lose, lose-win, win-lose, and win-win) from mutual gains to zero-sum results. Muthulingam and Agrawal (2016) explore conditions under which knowledge spillovers occur through shared suppliers. Agrawal et al. (2016) reveal that spillover effects between competitors generate significant impact on firms' decision to invest in shared suppliers. Wang et al. (2014) find that spillovers

among competing manufacturers sharing a supplier may discourage investments in supplier reliability. Similarly, [Yang et al. \(2024\)](#) demonstrate that knowledge spillovers reduce OEMs' incentives to invest in R&D when sourcing identical parts from the same supplier. In contrast, [Veldman et al. \(2023\)](#) suggest that spillover from generic supplier development is an investment opportunity instead of a threat for OEMs. [Xia et al. \(2023\)](#) analyze how spillovers influence two competing OEMs' decisions on investment in a shared supplier's environmental quality under spillovers and demand uncertainty. Their findings show that high spillovers and varying risk aversion lead to diverse investment outcomes — from no investment to bilateral efforts — while greater uncertainty or environmental sensitivity boosts investment motivation.

Beyond the direct impact of R&D spillovers on firm-level performance, several studies extend the discussion to industry-wide and macroeconomic implications, particularly under the influence of environmental policies and government interventions. [Kadeer and Mengzhe \(2024\)](#) emphasize that enhancing technology spillovers benefits both manufacturers and overall market competition. [Eichner and Kollenbach \(2022\)](#) examine how technological spillovers within international environmental agreements influence R&D investments in clean technologies. Their findings reveal that although spillovers encourage R&D through free-riding benefits, they can also erode private returns and discourage innovation. [Hu et al. \(2023\)](#) similarly argue that increased R&D spillovers expand access to innovation resources and advocate for government subsidies to stimulate R&D efforts.

Unlike the above studies on spillovers among competitors, some research shifts toward examining knowledge spillovers between supply chain partners. For instance, [Yoon \(2016\)](#) investigates the impact of spillovers from the OEM's investment in reducing production costs on a retailer's profit. The findings suggest that spillover effects benefit retailers when product differentiation between the OEM and retailer is moderate. [Chen et al. \(2019\)](#) examine a two-echelon supply chain consisting of an OEM and a retailer and explore how technological spillovers influence coopetition strategies and green R&D investment decisions. Their results show that stronger spillovers encourage both firms to invest more in green R&D. [Hu et al. \(2020\)](#) examine how technical and non-technical innovation spillovers shape an innovator's

decision to outsource manufacturing to a rival contract manufacturer (CM). The results reveal that both types of spillovers can benefit the innovator because: technical innovation spillovers — occurring solely through outsourcing — can delay the CM’s new product launch, while non-technical innovation spillovers — occurring via both outsourcing and market channels — force the CM to share innovation uncertainties. [Awasthy et al. \(2022\)](#) examine how firms respond to technology spillovers from green initiatives across markets. Their findings show that spillovers can encourage competitors to increase greening efforts and the selling prices of their products. [Cao et al. \(2023\)](#) explore how spillovers of ESG (environmental, social, and governance) among buyers affect competing buyers’ cooperation in supplier due diligence. The results indicate that low spillovers encourage a fairness-neutral strong buyer to cooperate.

Other scholars explore brand and advertising spillovers⁸ as strategic forms of knowledge diffusion and study their influence on firms’ decision-making. [Wu et al. \(2022\)](#) analyze how brand spillovers — where a weak-brand retailer discloses its shared contract manufacturer with a strong-brand manufacturer — affect firms’ performance. The findings show that this spillover may lead the strong OEM to prefer direct selling to reselling or dual-channel strategies. [Yang et al. \(2023\)](#) investigate demand spillovers in live-streamed remanufacturing scenarios and indicate that positive spillovers favor e-retailer–KOL cooperation, while negative spillovers can be mitigated via pricing. [Qian et al. \(2024\)](#) examine how advertising spillovers from new products to remanufactured products influence digital advertising efforts of OEMs and e-retailers. The results reveal that high spillover reduces their digital advertising intensity. [Nire and Matsubayashi \(2024\)](#) explore forward and reciprocal spillovers across product generations, showing that only certain spillover types encourage branded firms to enter new markets.

Some studies further incorporate government interventions into spillover dynamics. [Chen and Fan \(2025\)](#) analyze how spillovers and government subsidies jointly affect competing logistics firms’ R&D strategies. Their results demonstrate that high spillovers

⁸ Brand spillover refers to brand reputation transfers between products or firms. Advertising spillover refers to promotion of one product boosts another. They can be seen as knowledge spillover — encompassing innovation and managerial know-how—when they involve strategic knowledge diffusion.

deter investment, while low spillovers foster technology convergence. Under cap-and-trade regulations, [Zhang et al. \(2024a\)](#) study the influence of technology spillovers on OEMs' performance and find that spillovers lead to lower profits and reduced emissions when carbon prices are high. [Fan et al. \(2020\)](#) examine a global supply chain consisting of a domestic OEM and an imported OEM and investigate the impact of technology spillover on the effectiveness of government subsidies and tariff policies. The findings highlight that technology spillovers can enhance the effectiveness of domestic subsidy and tariff policies when the spillover intensity is high.

2.4 Summary

The existing literature has thoroughly examined firms' manufacturing and remanufacturing decisions in CLSCs, the interactions between OEMs and independent manufacturers (TPRs or MNRs), and the role of knowledge and technology spillovers in operations management.

Research on the first stream focuses on OEMs' trade-offs between new product production and remanufacturing, as well as TPRs' remanufacturing decisions. These decisions are shaped by factors such as government regulations, cost structures, and consumer preferences. The second stream investigates interactions between OEMs and manufacturers, highlighting both competitive and cooperative dynamics. In competitive settings, OEMs adopt strategies such as pricing and production adjustments, take-back programs, increased complexity of product disassembly, and reduced component commonality to mitigate cannibalization from remanufactured products. In cooperative settings, strategies such as remanufacturing outsourcing, authorization, and co-branding have been shown to increase the profits of both OEMs and TPRs. The third stream emphasizes the role of knowledge and technology spillovers in influencing firms' operational decisions. By affecting cost structures and perceived product value, such spillovers shape decisions related to product quality, investment, and cooperation.

While these three streams offer valuable insights into firm behavior in CLSCs, several important gaps remain unaddressed. First, most existing studies focus solely on TPRs'

remanufacturing activities and overlook their decisions related to material recovery, reuse of recovered components, and entry into new product markets. Second, although the effects of knowledge and technology spillovers have been widely studied in supply chain contexts, their influence on remanufacturing systems — particularly in shaping TPRs' new product strategies and MNRs' decisions to engage in remanufacturing — remains insufficiently explored. Third, although some research considers firms' cross-border strategies, limited attention has been paid to how policy interventions affect MNRs' remanufacturing decisions within global supply chains.

To address these gaps, this dissertation conducts three interrelated studies to examine how market conditions, knowledge spillovers, and policy interventions influence the decisions of OEMs and independent remanufacturers (TPRs or MNRs). Specifically, the first study investigates how knowledge spillovers affect OEMs' production and remanufacturing authorization decisions and TPRs' new product production decisions. The second study examines how environmental policies impact OEMs' decisions on outsourcing used product management and TPRs' strategies for product recovery and new product production. The third study explores how technology spillovers from MNRs, along with government policies, influence the remanufacturing decisions of both OEMs and MNRs. On top of the existing literature, this dissertation provides a comprehensive framework for understanding how spillover effects and policy interventions shape firms' new product production, remanufacturing, and coopetition strategies in CLSCs.

3. Study 1: Production and coopetition strategies in remanufacturing involving knowledge spillovers

This study explores production and coopetition strategies in remanufacturing systems, considering the impact of knowledge spillovers. In the remanufacturing system addressed in this study, a third-party remanufacturer (TPR, she) can potentially remanufacture used products initially produced by an original equipment manufacturer (OEM, he), either in cooperation with his (coopetition scenario) or on her own (competition scenario). Meanwhile, the TPR may also produce and sell her own-branded new products in the same market as the OEM's products and her own remanufactured products. Regarding this, TPR's new product cannibalizes her and OEM's market shares. The OEM's general and innovation knowledge spillovers to the TPR are unavoidable in the remanufacturing system described above. In examining how knowledge spillovers influence the two firms' production strategies and decisions, we develop analytical models describing competition and coopetition scenarios. Our results highlight the conditions under which the TPR engages in new product production and ceases remanufacturing in competition or coopetition. Additionally, although innovation knowledge spillover motivates the TPR to engage in new product production and weakens the OEM's competitiveness, both firms can be better off compared to the competition scenario. Moreover, we point out that coopetition improves consumer surplus and the environment under certain conditions.

3.1 Introduction

Remanufacturing is restoring used products to a like-new condition through quality recovery, which involves replacing or reprocessing components ([Atasu et al., 2008](#); [Atasu and Souza, 2013](#)). It can significantly extend the service lives of both used components and their embodied material. [Ferrer and Swaminathan \(2006\)](#) point out that reusing used products expedites product development. Consequently, compared to new product creation, remanufacturing has distinct advantages in terms of cost and time savings ([Atasu et al., 2008](#)). Regarding this, it is an attractive option for firms to quickly enter an existing market by offering high-quality yet low-price alternatives to new products. As a result, many TPRs have emerged to carry out remanufacturing in the past decades⁹.

In many industries in practice, third-party remanufacturers (TPRs) dominate remanufacturing, and they have become a competitive threat to original equipment manufacturers (OEMs) by selling substitute products in their market ([Örsdemir et al., 2014](#)). In the automobile industry in Europe, some well-known TPRs are LKQ, BORG Automotive, and Carwood, and the OEMs competing with them in the same markets are Ford, Bosch, and Peugeot¹⁰. In China, the TPRs are Hand in Hand Recovery Auto Parts, Yuchai remanufacturing industry, Sankaku (Xia-men) Auto Parts Company Ltd, and so on. Their competing OEMs include Geely Auto and Caterpillar (China), which sell gearboxes or diesel engines in the same market¹¹. In other industries, for example, Foxconn competes with Apple in the Chinese smartphone market ([Engadget, 2015](#)).

TPRs collect used products initially produced by OEMs and remanufacture them through processes including but not limited to disassembly, cleaning, sorting, inspection, reconditioning, replenishment, and reassembly ([Savaskan et al., 2004](#); [King et al., 2006](#)). During remanufacturing, TPRs have opportunities to analyze OEMs' products to understand

⁹ In most cases, TPRs do not require OEMs' authorization to carry out remanufacturing, especially when there is no infringement of intellectual property or brand rights. Industry examples show that many TPRs produce and sell remanufactured products without authorization from OEMs (Liu et al., 2018).

¹⁰ <https://www.lkqcorp.com/>; <https://borgautomotive-reman.com/>; <https://carwood.co.uk/>

¹¹ <https://www.crracelve.com/>; <http://www.yuchaie.com/>; <http://www.sankaku.com.cn/>; <https://global.geely.com/>

design, component specifications, functionalities, and quality standards (He et al., 2020). Such analysis allows TPRs to acquire some of OEMs' general knowledge, including product information, production techniques, component specifications, and testing knowledge. Thus, a spillover of OEMs' general knowledge naturally occurs in remanufacturing processes (Figure 3.1). In this study, we refer to this as a *general knowledge spillover*.

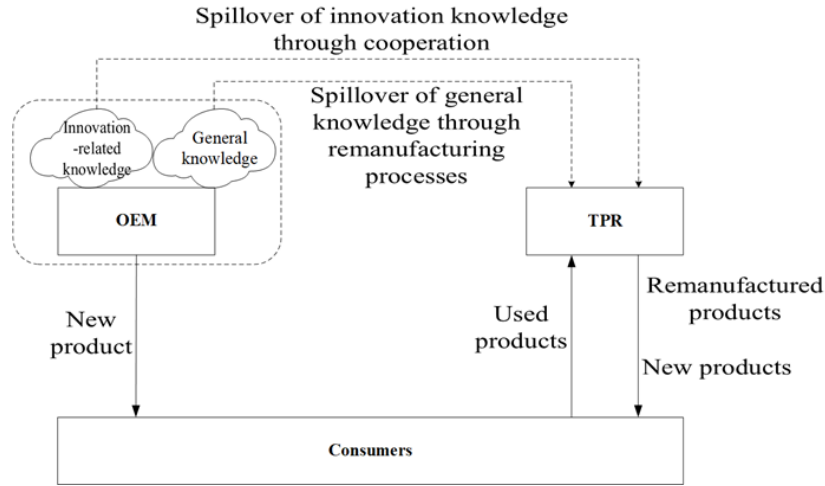


Figure 3.1. Knowledge spillovers from an OEM to a TPR

General knowledge spillover opens a new avenue for TPRs: the possibility of expanding their operations to include own-branded new product (hereafter new product) production¹². That is, after accumulating experience through remanufacturing, TPRs could produce new products to be sold in the same market as their remanufactured versions, thus potentially cannibalizing the latter's market share. Similarly, their remanufactured and new products can also cannibalize the market share of OEMs' new products. For example, LKQ (the TPR mentioned above) sells remanufactured auto parts and aftermarket parts (i.e., new auto parts under her own brand) in competition with Ford (the OEM) in the American market. Similarly, Foxconn sells both remanufactured iPhones (as mentioned above) and new smartphones in competition with Apple¹³.

In response to the market share cannibalization, OEMs have adopted various strategies to mitigate the profit losses resulting from the encroachment of TPRs. Among all,

¹² For TPRs that lack the capability to manufacture new core components, they can purchase them and use them together with non-core components to assemble final products, as shown in practice (Niu et al., 2024).

¹³ <https://www.foxconn.com/en-us>

remanufacturing cooperation with authorization (referred to simply as cooperation, hereafter) is common in practice. Under the cooperation, an OEM grants a TPR the permission to remanufacture used products and sell remanufactured products that bear remanufacturing-authorized labels. Meanwhile, the TPR pays the OEM a remanufacturing authorization fee (authorization fee, hereafter). In practice, the total authorization fees include i) a fixed fee and ii) a variable fee, which depends on the quantity of remanufactured products sold by the TPR (Zhou et al., 2021a, b). For example, Ford authorized LKQ to sell remanufactured parts for all Ford models in the United States. In return, in addition to the fixed authorization fee, LKQ paid Ford a royalty for each such part sold during the term of the agreement (Zhou et al., 2021a). Moreover, the OEM strives to make TPR's remanufactured products meet his specifications and quality standards and maintain consistency in performance and safety. In doing so, the OEM must share some of his knowledge with the TPR (Harhoff et al., 2003; Bogers, 2011). Such sharing leads to further spillovers of his knowledge.

In many cases, the knowledge shared with the TPR is related to product and production innovation and cannot be directly acquired or used by the TPR without the OEM's guidance (Bagchi and Mukherjee, 2014). This innovation-related knowledge spillover is called an *innovation spillover* in this study (Figure 2.1). With this spillover, if the TPR decides to engage in new product production, she can enhance the innovativeness of her new products, thus weakening the competitiveness of OEM's products (Hu et al., 2020).

The potential market cannibalization mentioned earlier makes it very difficult for the TPR to optimally decide whether to produce new products and the production quantities of new and/or remanufactured products (Guide and Li, 2010). The potentially rise in costs due to the authorization fees that the TPR must pay to the OEM exacerbates the TPR's decision-making. Likewise, facing the risk of losing market shares due to the reduced competitiveness of his products, the OEM encounters challenges when making decisions, such as whether to grant remanufacturing authorization to the TPR and how many products to produce if remanufacturing cooperation takes place. Although making the above decisions is paramount for both firms, effective solutions have not been discussed in practice or literature (Liu et al., 2018; Zhou et al., 2021a, b).

In addition to our understanding of knowledge spillovers and their general impact on firms' decision-making difficulties, our motivation stems from a deep insight into the complex decision activities and interactions in practice. In an example of a real remanufacturing system¹⁴, initially, a TPR remanufactured the used alternators originally produced by an OEM. Later, the TPR was able to produce new alternators thanks to OEM's general knowledge acquired during remanufacturing. She also received the remanufacturing authorization proposed by the OEM. Despite the benefits the TPR received, including the improved image of her remanufactured alternators thanks to the remanufacturing-authorized labels and the enhanced innovation level of her alternators, the TPR experienced enormous difficulties when making production strategies and decisions at different stages, such as whether or not to produce new alternators, accept or not OEM's remanufacturing authorization, how many new and/or remanufactured alternators to produce, and when to produce new and/or remanufactured alternators.

Several obstacles contributed to the decision-making difficulties. First, it was tough for the TPR to quantify the potential profit loss due to market cannibalization and the potential revenue generated from selling new alternators. [Atasu et al. \(2008\)](#) recognize this problem and stress that because of the lack of guidance, managers in practice struggled to make remanufacturing decisions to avoid cannibalization. Second, the increased costs associated with the authorization fees presented another hurdle complicating TPR's decision-making, as they interacted with TPR's production strategies and decisions. In other words, the increased costs were both the input and the results of the TPR's strategies and decisions. More specifically, the TPR needed the total costs, including the total authorization fees, to determine, e.g., production quantities of remanufactured alternators. In the meantime, the TPR could only calculate the total authorization fees owed to the OEM with the production quantities of remanufactured alternators.

Moreover, it was not straightforward for the OEM to decide i) to offer the TPR the remanufacturing authorization, ii) the values of fixed and unit authorization fees, and iii) the

¹⁴ <http://www.sankaku.com.cn/>

production quantities of his alternators. There are several reasons for the OEM's decision-making difficulty. Without a quantitative solution, the OEM could not determine the potential market loss resulting from the reduced competitiveness of his alternators (knowledge spillovers reduce OEM's competitiveness, as mentioned earlier). Nor could the OEM quantify the potential market loss even though he indulged in remanufacturing cooperation to mitigate the risk of losing his market share. Similarly, while the OEM profited from the total authorization fees paid by the TPR, he could not determine the optimal fixed and unit authorization fees because of the lack of quantitative solutions. To conclude, general knowledge and innovation spillovers significantly increase decision-making complexities for TPRs and OEMs, thus affecting their decision-making.

This study, thus, examines how OEMs and TPRs can optimize their production strategies and coopetition decisions considering spillovers. Despite their realism and importance, a very few studies include spillovers in addressing a firm's decision-making in remanufacturing. Additionally, remanufacturing models presented in these studies ([e.g., Ferguson and Toktay, 2006; Guide and Li, 2010](#)) overlook the impact of innovation spillover on consumer-perceived values of OEMs' and TPRs' new products. Consequently, the available studies do not provide a clear understanding of how innovation spillover affects firms' production and coopetition strategies in remanufacturing contexts.

To unveil production and coopetition decision-making in remanufacturing systems, we focus on the below research questions: i) Under what circumstances does general knowledge spillover drive a TPR to engage in new product production or cease remanufacturing? ii) How does innovation spillover influence the TPR's production strategy? iii) Under what circumstances does coopetition become a win-win situation for both the OEM and the TPR?

To answer our research questions, we consider a two-period duopoly market consisting of an OEM and a TPR. In period 1, the TPR carries out remanufacturing, with or without authorization from the OEM. In period 2, the TPR may engage in new product production, with or without continuing remanufacturing. In both periods, various products from the two parties compete. Additionally, the TPR may cooperate with the OEM, thus benefiting from innovation spillover and improving the quality of her products. We thus have two scenarios

— competition and coopetition — for which we develop two game models to study the decision-making of the two parties.

The rest of this paper is organized as follows. Section 3.2 reviews the relevant literature. We describe the problem context and the model setting in Section 3.3. Section 3.4 develops the competition and coopetition scenarios, formulates the problem and the game equilibria, derives the OEM’s optimal decision on the unit authorization fee, and solves some numerical examples. We conclude the paper in Section 3.5 and highlight potential avenues for future research.

3.2 Literature review

We classify the relevant literature into two streams: competition and coopetition in remanufacturing systems and the spillover effect in firms. Our review also discusses the distinctions between the existing research and our study.

3.2.1 Competition and coopetition in remanufacturing systems

In examining competition within remanufacturing systems, the existing literature focuses on collection competition involving used products ([Wu, 2015](#); [Kleber et al., 2020](#); [Hong et al., 2023](#)) and sales competition between new and remanufactured products ([Mitra and Webster, 2008](#); [Wu, 2012, 2013](#); [Li et al., 2024](#)). Because our study involves sales competition in remanufacturing systems, we review this part of relevant literature.

The extant literature explores sales competition in remanufacturing systems from two perspectives: i) sales competition between new and remanufactured products produced by a monopolist OEM and ii) sales competition between an OEM’s new and remanufactured products and TPRs’ remanufactured products. On the one hand, [Guide and Li \(2010\)](#), [Li et al. \(2024\)](#), [Zhang et al. \(2021\)](#), and others have extensively discussed the potential impact of remanufactured products cannibalizing the market share of OEMs’ new products. On the other hand, although remanufactured products compete with OEMs’ new products in the same markets, some authors discuss the motivations for OEMs to engage in remanufacturing. For example, [Ferguson and Toktay \(2006\)](#) investigate the sales competition between new and remanufactured products produced by an OEM. They highlight that remanufacturing can be

an effective marketing strategy for the OEM to defend his market share through differentiated pricing. [Ferrer and Swaminathan \(2006\)](#) conduct a similar study and obtain the same result. As [Atasu et al. \(2008\)](#) point out, introducing remanufactured products is a significant marketing opportunity for the OEM when there is a green consumer segment. In a recent study, assuming all consumers are environmentally conscious, [Hong et al. \(2020\)](#) demonstrate that consumers' environmental consciousness and government subsidies can effectively incentivize an OEM to increase remanufacturing efforts.

[Pazoki and Samarghandi \(2020\)](#) highlight that remanufacturing becomes a favorable choice for OEMs when eco-design is costly. They conclude this after examining the impact of take-back regulation on the OEM's choice between eco-design and remanufacturing. Since remanufacturing could cannibalize OEMs' market shares, [Majumder and Groenevelt \(2001\)](#), [Wei and Zhao \(2014\)](#), [Xue et al. \(2021\)](#), and others address the sales competition between OEMs' products and TPRs' remanufactured products. [Chen and Chen \(2019\)](#) include an OEM, a TPR, and a refurbishing firm and investigate the impact of sales competition on the OEM's performance. [Sun et al. \(2024\)](#) explore the influence of several factors, such as asymmetric demand, the TPR's cost efficiency, and consumers' willingness to pay (WTP) for remanufactured products, on the OEM's and the TPR's performance. These studies show that OEMs naturally discourage external parties' attempts to recover, refurbish, or remanufacture their used products in fear of losing their market shares.

Nevertheless, [Jin et al. \(2022\)](#) argue that OEMs should not discourage TPRs from entering the market because preventing TPRs' entry could cause OEMs to miss out on benefits from remanufacturing. Authors highlight that OEMs can implement coopetition strategies to increase their profits when facing sales competition from TPRs. These strategies include channel cooperation ([Yang et al., 2022](#)), remanufacturing outsourcing ([Qin et al., 2023](#)), remanufacturing cooperation with authorization ([Zhou et al., 2021a](#); [Huang et al., 2024](#)), and so on. Additionally, [Zhou et al. \(2022\)](#) demonstrate that establishing a coopetition relationship with the OEM benefits the TPR. Per their results, compared to the competition scenario, coopetition offers a win-win scenario to both the OEM and the TPR under certain conditions. Unlike some earlier studies where the TPR's cost information is known to the

OEM, [Huang et al. \(2019\)](#) examine a scenario in which the TPR's cost information is private. Their findings suggest that sharing the cost information with the OEM can increase the profits of both firms. While the above literature considers competition or coopetition between new products and remanufactured counterparts, [Xue et al. \(2021\)](#) analyze competition between TPRs' and OEMs' new products. However, unlike the above literature, [Xue et al. \(2021\)](#) do not factor in the TPR to have any remanufacturing experience or expertise in producing new products. Instead, she enters the OEM's market by exploring the conditions under which she should remanufacture his used products.

To conclude, most existing studies consider only the case where a TPR uses remanufacturing experience and expertise in remanufacturing used products but not in new product production. They also do not include knowledge spillovers when examining the conditions for TPRs to engage in remanufacturing. In contrast, we consider general knowledge spillovers inducing the TPR to remanufacture used products and innovation spillovers possibly leading him to produce new products. In the latter case, the sales competition analyzed in this paper also includes new products she sells. Specifically, we aim to uncover the conditions under which she will engage in new product production and/or remanufacturing and understand the impact of knowledge spillovers on TPRs' strategies and decisions.

3.2.2 Spillovers in firms

The second stream of literature deals with the effect of spillovers in firms. Spillovers can be classified into two types: vertical and horizontal. Vertical spillovers refer to the transfer of knowledge or information between upstream and downstream partners in supply chains, whilst horizontal spillovers transfer knowledge or information between competitors. Our paper considers both spillover types because when the OEM and the TPR compete, knowledge spills horizontally, and when they cooperate, it spills vertically.

An early work that explores the impact of vertical knowledge spillover on firms' research and development (R&D) efforts is due to [Griliches \(1979\)](#). Later, many authors examine how vertical spillovers of firms' R&D knowledge affect the performance of supply

chains. [Ge et al. \(2014\)](#) examine a supply chain including an upstream firm and a downstream firm where both firms invest in R&D to reduce production costs. [Chen et al. \(2019\)](#) examine a supply chain consisting of an OEM and a retailer where both firms invest in green R&D to reduce carbon emissions. Although these studies address different supply chain decisions, their results suggest that higher knowledge spillovers lead to higher profits for the partners. Related more closely to our work, [Qian et al. \(2024\)](#) investigate the impact of advertising spillover on the OEM's advertising decision in a remanufacturing system. Their results show that when the substitutability between new and remanufactured products is relatively high, a high advertising spillover encourages the OEM to invest in additional advertising efforts.

Regarding the literature on horizontal knowledge spillovers in supply chains, [Hu et al. \(2020\)](#) investigate the impact of innovation spillovers on the innovator's manufacturing outsourcing strategy. Based on the results, the authors highlight the conditions under which strategic innovation spillovers benefit the innovator. [Shen et al. \(2020\)](#) reveal that spillover of green technology between competitors leads to improved product greenness. [Bernstein et al. \(2009\)](#) claim that the spillover of an OEM's marketing activities benefits the retailer, the OEM, and the OEM's competitor. In examining a supply chain comprising a supplier and two competing OEMs where both OEMs invest in cost-reduction R&D, [Yang et al. \(2024\)](#) highlight that the spillover effect may prevent OEMs from investing in R&D. Based on this insight, they design a cost-sharing contract to coordinate the supply chain. After examining the impact of a retailer's service spillover on the decision timing preference, [Xue et al. \(2020\)](#) demonstrate that a high spillover intensity encourages an OEM to become a decision follower. Additionally, [Hsieh and Lathifah \(2024\)](#) explore how the spillover effect of blockchain technology impacts the dual-channel supply chain. Their findings indicate that the spillover effect enhances supply chain performance only when the supply chain is coordinated. Studies also consider spillovers of firms' other expertise and knowledge, such as brands and channels. For example, [Zhou et al. \(2019\)](#) and [Wu et al. \(2022a\)](#) examine how brand spillovers affect supply chain performance. [Zhou and Cai \(2019\)](#) conclude that OEMs benefit from the retailers' spillover of in-store promotion knowledge and expertise. [Wu et al. \(2022a\)](#) show

that retailers can implement a brand spillover strategy by introducing a well-known brand to their sales channels, hoping to enhance their private brand power. Additionally, some authors consider the spillover effect between online and offline sales channels and obtain corresponding results. For example, [Zhen et al. \(2022\)](#) point out that when the channel competition is moderate, the retailers' willingness to use a third-party platform increases as the spillover effect increases.

In summary, most of the available studies consider knowledge spillovers from the perspective of supply chains and highlight their positive impact on supply chain performance. However, in the context of remanufacturing, how spillovers influence firms' decision-making — particularly the TPR's decisions regarding new product production — and how these decisions impact firms' performance remain largely unexplored, excluding ([Qian et al., 2024](#)) discussed earlier. Our study, thus, is aimed at addressing these issues, in hope of offering guidance for firms to optimize their production and remanufacturing decisions.

3.3 Model setup

3.3.1 Problem description

We consider a duopoly where an OEM and a TPR compete in two periods. In period 1, the OEM produces an innovative product (M), and the TPR collects used M to produce remanufactured products (R). The OEM can influence the TPR's remanufacturing quantity decisions by capitalizing on his authorization strategy. In practice, examples from various industries show that both authorized and unauthorized remanufacturing may exist in the market ([Liu et al., 2018](#)). Accordingly, the TPR can decide to remanufacture with or without the OEM's authorization. If two firms fail to achieve remanufacturing authorization, they proceed with pure competition (competition scenario); otherwise, they simultaneously engage in competition and cooperation (coopetition scenario). At the end of period 1, the TPR accumulates enough experience to produce her new product (S). Note: The TPR does not need authorization to produce S. S is assumed to be inferior to M in terms of innovation. Innovation spillovers in the coopetition scenario enable the TPR to enhance S's innovation level. In period 2, the TPR decides whether to produce a new product and to continue

remanufacturing. In the meantime, the OEM keeps selling M, competing with TPR's products. Thus, in period 2, the TPR has four possible production strategy options: i) E: exiting the market, ii) R: continuing remanufacturing, iii) SR: producing new and remanufactured products, and iv) S: producing new products only.

To explore how knowledge spillovers impact the TPR's production strategies and when coopetition benefits both firms, we develop two 2-period models: Model U and Model A (details to appear later). Model U describes the competition scenario without remanufacturing authorization. Its solution reveals the impact of OEM's general knowledge spillover on TPR's production strategies and decisions. Model A describes the coopetition scenario where the TPR remanufactures under OEM's authorization. Its solution sheds light on the influence of innovation spillovers on two firms' decision-making. [Table 3.1](#) provides the notation.

Table 3.1.Parameters and decision variables

Notation	
Parameters	
V	Consumers' WTP for OEM's product, M
θ	The discount rate of consumers' WTP for S (or UR) relative to M (or AR), $0 < \theta < 1$
λ	Degree of innovation spillover, $0 \leq \lambda \leq 1$
δ	The discount rate of consumers' WTP for remanufactured products, $0 < \delta < 1$
c_M, c_S	Unit production costs of M and S, respectively.
c_R	The unit remanufacturing cost of R with or without remanufacturing authorization
β	Ratio c_R/c_M
γ	Ratio c_S/c_M
τ	Ratio δ/β , remanufactured products' cost-to-value ratio
p_{Mn}^i, p_{Rn}^i	Unit selling prices of M and R in Model i and period n
p_S	The unit selling price of S
F	Fixed authorization fee
π_j^i	Player j 's profit in Model i when TPR chooses strategy ST
CS_{ST}^i	Consumer surplus in Model i when TPR chooses strategy ST
EI_{ST}^i	Total negative environmental impact in Model i when TPR chooses strategy ST
Decision variables	
q_{Mn}^i, q_{Rn}^i	Production quantities of M and R in Model i and period n
q_S^i	Production quantity of S in Model i
f	Unit authorization fee

* $n \in \{1,2\}, i \in \{U,A\}, j \in \{\text{OEM}, \text{TPR}\}, ST \in \{E, R, SR, S\}$.

3.3.2 Price function

A consumer decides to purchase a product based on the utility that s/he derives from purchasing. The utility is determined by a consumer's WTP for a product and the product's selling price. In keeping with Ferrer (2001) and Zhou et al. (2021a), we assume that consumers are heterogeneous in their WTP: V for M . V is distributed in the interval $[0, 1]$. According to the literature (Majumder and Groenevelt, 2001; Ferrer and Swaminathan, 2006), every consumer's WTP for a remanufactured product is a fraction δ ($0 < \delta < 1$) of their WTP for a new product. Both practice and literature have shown that consumers perceive authorized remanufactured products (AR) to have superior quality assurance and stronger brand equity compared to unauthorized remanufactured products (UR) (Shi et al., 2020; Zhou et al., 2021a). As a result, consumers perceive a higher value for AR over UR. Similarly, S is perceived as a low-end product compared to M (Xue et al., 2021). Accordingly, consumers' preference for S and UR is the fraction θ ($0 < \theta < 1$) of that for M and AR, respectively. For simplicity, we assume the lifetime of each product is one period. Accordingly, no one buys more than one product during each period.

Each consumer makes his/her purchasing decision by maximizing utility. In Model U, consumer utilities for M and UR in period 1 are formulated as $U_{M1}^U = V - p_{M1}^U$ and $U_{R1}^U = \theta\delta V - p_{R1}^U$, respectively. In maximizing utility, each consumer decides to i) buy M , ii) buy UR, or iii) buy nothing. A consumer buys M if $U_{M1}^U > U_{R1}^U$ and $U_{M1}^U > 0$, i.e., $\frac{p_{M1}^U - p_{R1}^U}{1 - \delta\theta} \leq V < 1$. A consumer buys UR if $U_{R1}^U > U_{M1}^U$ and $U_{R1}^U > 0$, i.e., $\frac{p_{R1}^U}{\delta\theta} \leq V < \frac{p_{M1}^U - p_{R1}^U}{1 - \delta\theta}$. The consumer does not buy any product if $V < \frac{p_{R1}^U}{\delta\theta}$. Similarly, consumer utilities for M , S , and UR in period 2 are $U_{M2}^U = V - p_{M2}^U$, $U_S^U = \theta V - p_S^U$, and $U_{R2}^U = \theta\delta V - p_{R2}^U$, respectively.

In Model A, we use λ ($\lambda \in [0, 1]$) to denote the degree of innovation spillovers, interpreted as the TPR's ability to absorb the OEM's innovation spillovers. Thanks to innovation spillovers, the consumers' WTP for S can be denoted as $\theta + (1 - \theta)\lambda$, as in (Wu et al., 2022b). Intuitively, $\lambda = 0$ indicates no innovation spillovers, while $\lambda = 1$ indicates S and M having the same innovation level. In most business practices, $\lambda < 1$, which highlights that OEM's innovation cannot be completely imitated. Considering consumer preference and

innovation spillovers, we develop utility functions in Model A. First, in coopetition, consumer utilities for M and AR in period 1 are formulated as $U_{M1}^A = V - p_{M1}^A$ and $U_{R1}^A = \delta V - p_{R1}^A$, respectively. Consumer utilities for M, S, and AR in period 2 are formulated as $U_{M2}^A = V - p_{M2}^A$, $U_S^A = ((1 - \theta)\lambda + \theta)V - p_S^A$, and $U_{R2}^A = \delta V - p_{R2}^A$, respectively.

For analytical simplicity, we assume that consumers' WTP for S is higher than for AR, i.e., $\theta \geq \delta$. The selling prices (i.e., the inverse demand functions) for M and AR/UR in two periods and for S in period 2 are presented in Table 3.2.

Table 3.2. Demand and price functions in Model U and A

Model	Period	Selling price
U	1	$p_{M1}^U = 1 - q_{M1}^U - \delta\theta q_{R1}^U$
		$p_{R1}^U = \delta\theta(1 - q_{M1}^U - q_{R1}^U)$
	2	$p_{M2}^U = 1 - q_{M2}^U - \theta(\delta q_{R2}^U + q_S^U)$
		$p_S^U = \theta(1 - q_{M2}^U - \delta q_{R2}^U - q_S^U)$
		$p_{R2}^U = \delta\theta(1 - q_{M2}^U - q_{R2}^U - q_S^U)$
A	1	$p_{M1}^A = 1 - q_{M1}^A - \delta q_{R1}^A$
		$p_{R1}^A = \delta(1 - q_{M1}^A - q_{R1}^A)$
	2	$p_{M2}^A = 1 - q_{M2}^A - \delta q_{R2}^A - (\theta + (1 - \theta)\lambda)q_S^A$
		$p_S^A = \theta + (1 - \theta)\lambda - \delta q_{R2}^A - (\theta + (1 - \theta)\lambda)(q_{M2}^A + q_S^A)$
		$p_{R2}^A = \delta(1 - q_{M2}^A - q_{R2}^A - q_S^A)$

3.3.3 Cost structure

Being consistent with the literature (Ferrer, 2001; Savaskan et al., 2004; Örsdemir et al., 2014), the unit remanufacturing cost: c_R is a proportion — β ($0 < \beta < 1$) — of the OEM's unit production cost: c_M . Additionally, by following practice (Xue et al., 2021), we assume that the unit production cost of S: c_S is lower than c_M , and it is a proportion — γ ($0 < \gamma < 1$) — of c_M . For analytical simplicity, let $c_M = c$ (a constant) and obtain $c_S = \gamma c_M = \gamma c$ and $c_R = \beta c_M = \beta c$. Since consumers prefer new products over remanufactured ones, they only purchase remanufactured products if the prices are lower than these of new products. If c_S is lower than c_R , the remanufactured product becomes uncompetitive, leading to zero demand. Therefore, the TPR always discontinues remanufacturing in period 2. To avoid this situation, we assume c_S to be higher than c_R , i.e., $0 < \beta < \gamma < 1$. Further, a lower β/γ means the TPR's remanufacturing/production cost is low. As stressed by Besanko et al. (2001), firms

incurring low costs can benefit from reduced or lower prices of their products. Consequently, in competition, if β or γ is too low, no one buys M, leading to non-positive demand for M. To avoid this trivial case, we assume that compared to c_M , c_R and c_S are moderate, i.e., $\beta > \beta^{U*}$ and $\gamma > \gamma^{U*}$. Additionally, our study does not focus on collection decisions which have been widely examined in literature (e.g., [Kushwaha et al., 2022](#); [Zhang et al., 2021](#); [Hong et al., 2023](#)). Thus, for analysis simplicity, by following some studies (e.g., [Huang et al., 2019](#); [Shen et al., 2020](#); [Li et al., 2024](#)), we normalize collection and other costs (such as the TPR's learning costs) to be zero.

3.3.4 Consumer surplus and environmental impact

Based on the definition in ([Hitt and Brynjolfsson, 1996](#); [Zhu et al., 2020](#)), we formulate consumer surplus below.

$$\begin{aligned}
 CS_{ST}^i = & \int_{p\{U_{M1}^i=U_{R1}^i\}}^1 U_{M1}^i(p_{M1}^*, p_{R1}^*) dV + \int_{p\{U_{R1}^i=0\}}^{p\{U_{M1}^i=U_{R1}^i\}} U_{R1}^i(p_{M1}^*, p_{R1}^*) dV \\
 & \int_{p\{U_{M2}^i=U_S^i\}}^1 U_{M2}^i(p_{M2}^*, p_S^*, p_{R2}^*) dV + \int_{p\{U_S^i=U_{R2}^i\}}^{p\{U_{M2}^i=U_S^i\}} U_S^i(p_{M2}^*, p_S^*, p_{R2}^*) dV \\
 & + \int_{p\{U_{R2}^i=0\}}^{p\{U_S^i=U_{R2}^i\}} U_S^i(p_{M2}^*, p_S^*, p_{R2}^*) dV
 \end{aligned} \tag{3-1}$$

Consistent with the literature ([Ding et al., 2020](#)), we use carbon emissions, e_n and e_r , to measure the unit environmental impact of new and remanufactured products, respectively. Thus, the total environmental impact of the remanufacturing system is calculated as

$$EL_{ST}^i = (q_{M1}^{i*} + q_{M2}^{i*} + q_S^{i*})e_n + (q_{R1}^{i*} + q_{R2}^{i*})e_r. \tag{3-2}$$

3.4 Models, results analysis, and managerial implications

Assume M has been in the market for a long time, and the OEM's brand is well known. Consequently, the TPR can collect enough end-of-life M from the market. The remanufacturing quantities in two periods are, thus, not constrained by the corresponding production quantities of new products in the previous periods. We further assume that the quality of all used products is good enough to be remanufactured but can be remanufactured only once.

3.4.1 Competition scenario

In this scenario, the OEM sells M during two periods. The TPR remanufactures the OEM's used products in period 1. In period 2, she determines her production strategy based on four options: E, R, SR, and S. The OEM and the TPR compete by offering M, R, and S. Their profits are formulated as follows:

$$\begin{aligned}
 \max \pi_{OEM}^U &= (p_{M1}^U - c)q_{M1}^U + (p_{M2}^U - c)q_{M2}^U \\
 \max \pi_{TPR}^U &= (p_S^U - \gamma c)q_S^U + (p_{R1}^U - \beta c)q_{R1}^U + (p_{R2}^U - \beta c)q_{R2}^U \\
 \text{s. t. } &q_{M1}^U > 0, q_{M2}^U > 0, q_{R1}^U \geq 0, q_{R2}^U \geq 0, q_S^U \geq 0
 \end{aligned} \tag{3-3}$$

The two firms' decision sequences are as follows. In period 1, the OEM decides the production quantity of M: q_{M1}^U . Simultaneously, the TPR decides whether to enter the market and how much to remanufacture. In period 2, the OEM determines the production quantity of M: q_{M2}^U , while the TPR determines the production quantities of both S and UR: q_S^U and q_{R2}^U . We first present the two firms' optimal production decisions for period 1 by deriving Proposition A-1. See the proof in [Appendix A-1](#).

Proposition A-1. *Given $\beta > \beta^{U*}$, there is a threshold τ^{R*} such that:*

- i) *When $\tau \leq \tau^{R*}$, the TPR does not enter the market in period 1. The corresponding production quantities for the OEM and the TPR are $q_{M1}^{U*} = \frac{1-c}{2}$ and $q_{R1}^{U*} = 0$, respectively;*
- ii) *When $\tau > \tau^{R*}$, the TPR enters the market in period 1. The corresponding production quantities for the OEM and the TPR are $q_{M1}^{U*} = 1 + \frac{2-c(-2+\beta)}{-4+\delta\theta}$ and $q_{R1}^{U*} = \frac{2c\beta-(1+c)\delta\theta}{\delta\theta(-4+\delta\theta)}$, respectively,*

where $\tau^{R*} = 2c/((1+c)\theta)$ and $\beta^{U*} = (-2 + 2c + \delta\theta)/c$.

In Proposition A-1, the precondition: $\beta > \beta^{U*}$ guarantees the inequalities: $q_{M1}^{U*} \geq 0$. In other words, to ensure a non-negative market demand for M in period 1, c_R cannot be excessively lower than c_M . This is explainable. With the decrease in the unit remanufacturing cost, the TPR takes the initiative to lower the selling price of UR to gain more market share. Consequently, to maintain the market share, the OEM passively reduces the selling price of M. The degree of price reduction for M resulting from the unit reduction in β is larger than

that for UR (i.e., $\partial p_{M1}/\partial \beta < \partial p_{R1}/\partial \beta$). Although it decreases in the TPR's selling price, the market demand for M increases in the OEM's selling price, according to (Hausman et al., 1994). Thus, the OEM's production quantity decreases along with the decrease in β . That is, q_{M1}^{U*} increases in β . Therefore, when β is lower than β^{U*} , q_{M1}^{U*} is negative. Additionally, $\beta > \beta^{U*}$ implies that, in practice, when the OEM faces potential market cannibalization, she needs to reduce her production cost to maintain her market share.

As shown in Proposition A-1, the remanufactured product's cost-to-value ratio: τ is paramount for the TPR to decide whether to remanufacture used products in period 1. When τ is low, the TPR does not enter the market. Conversely, when τ is high, she enters the market. Thus, if the TPR wants to survive in the competition with the OEM, she should decrease the remanufacturing cost or improve consumers' WTP for the remanufactured products. The implication is that, in practice, remanufacturing is profitable if either the cost reduction from remanufacturing or the consumers' WTP for remanufactured products is high enough. This observation is consistent with the literature (Atasu et al., 2008).

Given $\tau > \tau^{R*}$, we optimally solve the two firms' decisions in period 2 based on the Karush-Kuhn-Tucker conditions: $q_{R2}^U \geq 0$ and $q_S^U \geq 0$. The equilibria and the corresponding firm-level profits are provided in Table A.1 (See the table and the proof in Appendix A-2).

Based on the results, we highlight that if the TPR enters the market in period 1, she does not exit in period 2. Thus, the TPR's optimal production strategy in period 2 is one of the three: R, SR, and S. We present the TPR's production strategies in different situations in Proposition A-2 below. See the proof in Appendix A-2.

Proposition A-2. *Given $\tau > \tau^{R*}$, $\beta > \beta^{U*}$, and $\gamma > \gamma^{U*}$, there are two thresholds $\hat{\gamma}_1^U$ and $\hat{\gamma}_2^U$ such that:*

- i) *If $\gamma \geq \hat{\gamma}_1^U$, the TPR's production strategy is R, i.e., she only engages in remanufacturing in period 2.*
- ii) *If $\hat{\gamma}_2^U \leq \gamma < \hat{\gamma}_1^U$, the TPR's production strategy is SR, i.e., she engages in both remanufacturing and new product production in period 2.*

iii) If $\gamma < \hat{\gamma}_2^U$, the TPR's production strategy is S, i.e., she only produces new products in period 2.

Note that $\hat{\gamma}_1^U$ and $\hat{\gamma}_2^U$ increase in β .

As indicated in Proposition A-2, when the remanufacturing efficiency is not too low (i.e., $\tau > \tau^{R*}$), the TPR's production strategies depend on γ . The TPR does not produce S when γ is relatively high, i.e., $\gamma \geq \hat{\gamma}_1^U$ (see Part i)), as shown in Figure 3.2. (Note: Figure 3.2 is developed using $c = 1/2$, $\theta = 3/5$, and $\delta = 1/2$.) However, when γ is relatively low, i.e., $\gamma < \hat{\gamma}_2^U$ (Part iii)), the TPR engages in new product production and ceases remanufacturing. This is understandable because producing S may cannibalize the market share of both M and R. The TPR's decisions about producing S and ceasing remanufacturing are contingent on her profits. The TPR produces S if the profit from selling S can compensate for the potential loss resulting from the reduced demand for R; otherwise, she does not introduce S. To summarize, a high γ discourages the TPR from engaging in new product production; however, it induces the TPR to carry out remanufacturing. At last, when γ is moderate, i.e., $\hat{\gamma}_2^U \leq \gamma < \hat{\gamma}_1^U$ (Part ii)), the TPR produces new products and engages in remanufacturing, thus pursuing the optimal production strategy of SR (see Figure 3.2). The TPR can meet diverse consumer needs with SR by employing product differentiation pricing. Accordingly, strategy SR allows the TPR to maximize profits when γ is moderate. Moreover, as shown in the proposition, with the increase of the remanufacturing cost (i.e., β), the TPR's willingness to engage in new product production increases, and her willingness to remanufacture decreases (see Figure 3.2).

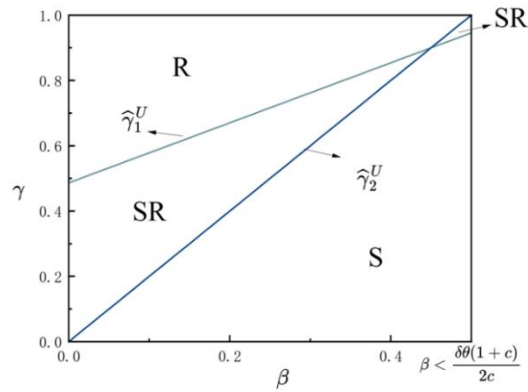


Figure 3.2. The TPR's production strategies in competition scenario

This proposition suggests that, in practice, if production costs for TPRs' new product are

moderate, they should employ strategic pricing to effectively position both new and remanufactured products in the market, thereby enhancing overall profitability. Otherwise, they should focus exclusively on remanufacturing when production costs for new products are high and focus on new product production when they are low. Additionally, although TPRs can benefit from offering a diverse range of products due to the general knowledge spillover, they should be mindful of competitive responses from OEMs; for instance, OEMs may not permit them to engage in remanufacturing without authorization.

In addition, we examine if involving the TPR in the remanufacturing system benefits consumers and the environment. We first derive the remanufacturing system's consumer surplus and total carbon emissions under different production strategies in Corollary A.1 (See this Corollary in [Appendix A-3](#)). Subsequently, we obtain Corollary A-1 and Corollary A-2 in which we compare consumer surplus/environmental impacts in situations involving or not the TPR. The proofs are straightforward and, thus, omitted.

Corollary A-1. *Given $\tau > \tau^{R*}$, $\beta > \beta^{U*}$, and $\gamma > \gamma^{U*}$, regardless of the TPR's production strategies, the TPR's entry into the market results in an increase in consumer surplus compared to the scenario without the TPR, as shown below.*

- i) *When the TPR's strategy is R, $CS_R^U > CS_E^U$;*
- ii) *When the TPR's strategy is SR, $CS_{SR}^U > CS_E^U$; and*
- iii) *When the TPR's strategy is S, $CS_S^U > CS_E^U$.*

As highlighted in Corollary A-1, the TPR's entry into the market leads to an increase in consumer surplus, regardless of the TPR's production strategies. This result can be attributed to two main factors. First, the entry of the TPR prevents the concentration of market power in the hands of the OEM. The ensuing competition among M, S, and R drives the OEM to reduce the selling price of M. As a result, the gap between consumers' maximum WTP and the actual market price increases. Second, S and R, the lower-priced M alternatives, attract more consumers with a lower WTP. That, in turn, increases the total product demand. The total consumer surplus increases as the demand and price decrease.

Corollary A-2. *Given $\tau > \tau^{R*}$, $\beta > \beta^{U*}$ and $\gamma > \gamma^{U*}$, compare the environmental impacts in*

the competition scenario and the scenario without the TPR, and obtain the results below.

- i) When the TPR's production strategy is R, if $e_r \leq \frac{\delta\theta e_n}{2}$, $EI_R^U \leq EI_E^U$; otherwise, $EI_R^U > EI_E^U$;
- ii) When the TPR's production strategy is SR, if $e_r \leq \hat{e}_r^{EI}$, $EI_{SR}^U \leq EI_E^U$; otherwise, $EI_{SR}^U > EI_E^U$;
- iii) When the TPR's production strategy is S, $EI_S^U > EI_E^U$.

As shown in Corollary A-2, when the carbon emissions of a remanufactured product are low enough, the entry of the TPR reduces total carbon emissions if and only if the TPR continues remanufacturing in period 2. If she stops remanufacturing, the total carbon emissions of the remanufacturing system are higher than those of the non-TPR scenario. Note that $\hat{e}_r^{EI}$ is a linear function of e_n and $\hat{e}_r^{EI} < \delta\theta e_n/2$. It signifies that to reduce the negative environmental impacts, policymakers need to enforce stricter carbon emission standards for remanufactured products, i.e., ensuring at least a 50% reduction in emissions by remanufacturing a used product compared to producing a new product.

3.4.2 Coopetition scenario

As shown in Figure 3.3, in coopetition, the OEM and the TPR compete and cooperate simultaneously in both periods. In period 1, the OEM sells M and charges the TPR a total variable remanufacturing fee $f * q_{R1}^A$, in addition to F. The TPR remanufactures used products and sells remanufactured products as authorized by the OEM. In period 2, the OEM keeps selling M. The TPR competes with the OEM by selling AR and/or S. She needs to pay f to the OEM for every unit of AR that she sells.

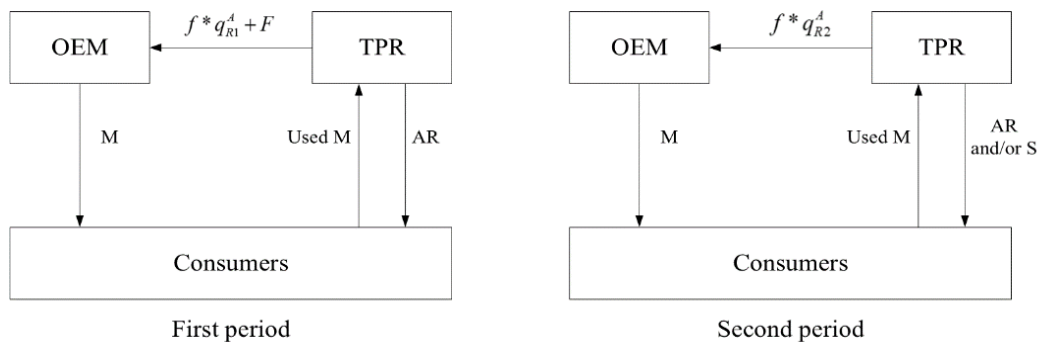


Figure 3.3. The remanufacturing system in coopetition

With the selling prices and costs in Section 3, the OEM's and the TPR's profit functions are formulated as follows:

$$\begin{aligned}
\max \pi_{OEM}^A &= (p_{M1}^A - c) * q_{M1}^A + (p_{M2}^A - c) * q_{M2}^A + F + f * (q_{R1}^A + q_{R2}^A) \\
\max \pi_{TPR}^A &= (p_S^A - \gamma * c) * q_S^A + (p_{R1}^A - \beta * c - f) * q_{R1}^A + (p_{R2}^A - \beta * c - f) * q_{R2}^A - F \quad (3-4) \\
s. t. & q_{M1}^A > 0, q_{M2}^A > 0, q_{R1}^A > 0, q_{R2}^A \geq 0, q_S^A \geq 0
\end{aligned}$$

To avoid the trivial case that no one buys M or AR in period 1, we assume $\bar{f}_L^A < f < \bar{f}_U^A$. As implied in [Figure 3.3](#), the TPR has three production strategy options in period 2: R, SR, and S. We derive the TPR's production strategies in different conditions, as presented in Proposition A-3. See the equilibria, the firm-level profits, and the expressions of related thresholds in [Appendix A-4](#).

Proposition A-3. Given $\bar{f}_L^A < f < \bar{f}_U^A$, there are four thresholds $\hat{\gamma}_1^A$, $\hat{\gamma}_2^A$, $\hat{\lambda}_1^A$, and $\hat{\lambda}_2^A$ ($\hat{\gamma}_1^A > \hat{\gamma}_2^A$, $\hat{\lambda}_2^A > \hat{\lambda}_1^A$) such that

- i) The TPR's production strategy is R, i.e., she engages in remanufacturing only in period 2, if $\lambda < \hat{\lambda}_1^A$ and $\gamma \geq \hat{\gamma}_1^A$;
- ii) The TPR's production strategy is SR, i.e., she engages in both remanufacturing and new product production in period 2, if
 - $\lambda < \hat{\lambda}_1^A$ and $\hat{\gamma}_2^A < \gamma < \hat{\gamma}_1^A$, or
 - $\hat{\lambda}_1^A < \lambda < \hat{\lambda}_2^A$ and $\gamma > \hat{\gamma}_2^A$; and
- iii) The TPR's production strategy is S, i.e., she engages in new product production only in period 2, if
 - $\lambda < \hat{\lambda}_2^A$ and $\gamma \leq \hat{\gamma}_2^A$, or
 - $\lambda > \hat{\lambda}_2^A$.

where $\hat{\lambda}_1^A$ increases in β , and $\hat{\lambda}_2^A$ decreases in β .

Precondition: $\bar{f}_L^A < f < \bar{f}_U^A$ guarantees that both firms make profits in coopetition. First, only when the unit authorization fee f is moderate does the coopetition scenario occur. Additionally, a high unit authorization fee increases the TPR's total costs, whilst a low counterpart cannot compensate for the OEM's profit loss resulting from the entry of the TPR.

Thus, both firms do not make profits when f is too high or low. Moreover, the OEM's profits gained from a moderate unit authorization fee compensate for the profit loss caused by market cannibalization.

As indicated in Proposition A-3, the TPR's production strategies depend on the innovation spillover level: λ and γ . Using parameters: $c = 1/2$, $\theta = 3/5$, $\delta = 1/2$, $\lambda = 1/2$, $\beta = 1/2$, and $f = 1/10$, we conduct a numerical analysis and summarize the result in Figure 3.4. As shown, when λ is low, i.e., $\lambda < \hat{\lambda}_1^A$, i) if $\gamma \geq \hat{\gamma}_1^A$, the TPR does not engage in new product production; ii) if $\hat{\gamma}_2^A < \gamma < \hat{\gamma}_1^A$, the TPR produces S while performing remanufacturing; and iii) if $\gamma < \hat{\gamma}_2^A$, the TPR produces S while stopping remanufacturing. When λ is moderate, i.e., $\hat{\lambda}_1^A < \lambda < \hat{\lambda}_2^A$, the TPR stops remanufacturing if $\gamma < \hat{\gamma}_2^A$ and continues remanufacturing otherwise. When λ is relatively high, i.e., $\lambda > \hat{\lambda}_2^A$, the TPR engages in new product production no matter how high γ is. As implied by this proposition, in practice, a TPR offering substitutable products should adopt the single-product strategy when one of her products has a significant price or cost advantage, i.e., λ is relatively high or γ is relatively low in this study. If neither product has this advantage, the TPR should adopt a diversified-product strategy.

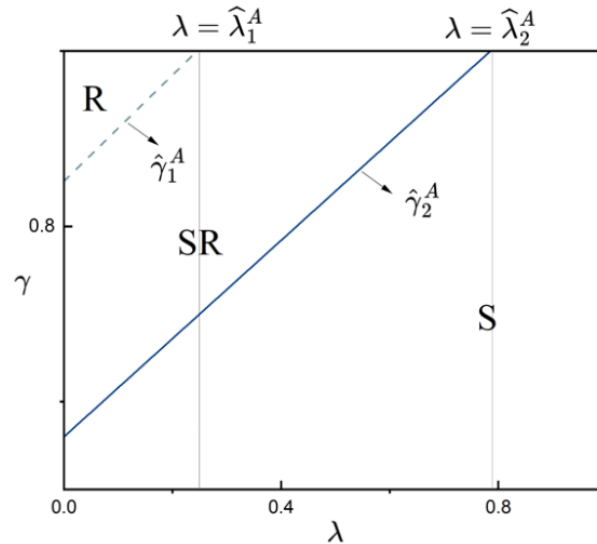


Figure 3.4. The TPR's production strategies in the competition scenario

3.4.3 Result comparison

This subsection examines when innovation spillovers in period 2 can increase the TPR's

willingness to engage in new product production. Specifically, we compare the TPR's new product production entry boundaries in Model A and Model U. We develop Proposition A-4 to show the comparison results. See the proof in [Appendix A-5](#).

Proposition A-4. Comparing $\hat{\gamma}_1^A$ and $\hat{\gamma}_1^U$, we obtain $\hat{\gamma}_1^A > \hat{\gamma}_1^U$ if and only if $\lambda \geq \lambda_T$.

$\hat{\gamma}_1^U$ and $\hat{\gamma}_1^A$ are the TPR's new product production entry boundaries in the competition and coopetition scenarios, respectively. Using the parameters: $c = 1/2$, $\theta = 3/5$, $\delta = 1/2$, $\beta = 2/5$, and $f = 1/10$, we illustrate this proposition using [Figure 3.5](#). As shown, if the degree of innovation spillovers is higher than λ_T , the TPR becomes more inclined to engage in new product production. Conversely, the TPR is discouraged from introducing new products when the degree is below this threshold. This result can be attributed to several factors. First, in the coopetition scenario, consumers' WTP for both S and AR increases compared to the competition scenario. This increase presents a potential opportunity for the TPR to capture additional market share, thus generating higher profits. Second, the increase in consumers' WTP for remanufactured products comes at a cost. That is, the TPR has to pay the authorization fees to the OEM. Lastly, introducing S may lead to a cannibalization effect. This is because some consumers may choose S instead of R, thus affecting the TPR's sales of remanufactured products and profits.

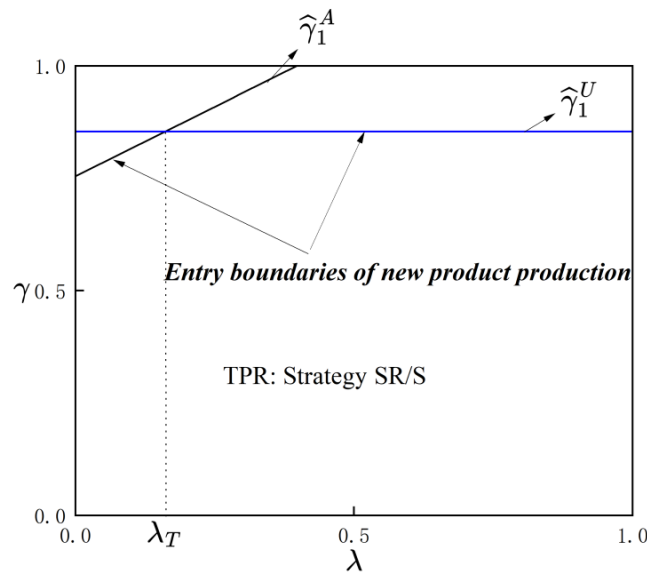


Figure 3.5. Comparison of entry boundaries for new product production

To conclude, the fact that coopetition encourages the TPR to produce new products

depends on the balance between the profits gained from the increased market share, the increased costs related to the authorization fees, and the potential profit loss from market cannibalization. In addition, we will examine if the OEM and the TPR can benefit from coopetition. To do so, we compare their profits in two scenarios. Proposition A-5 states the results. The proof is straightforward and omitted.

Proposition A-5. *The results of the profit comparisons in the two scenarios are as follows:*

- i) When the TPR chooses strategy R, there is a threshold F_{R1} such that $\pi_{OEM_R}^A > \pi_{OEM_R}^U$ if $F > F_R$. Meanwhile, when $F > F_R$, $\pi_{TPR_R}^A > \pi_{TPR_R}^U$ if $\bar{\beta}_{R1} < \beta < \bar{\beta}_{R2}$;
- ii) When the TPR chooses strategy SR, there is a threshold F_{SR} such that $\pi_{OEM_SR}^A > \pi_{OEM_SR}^U$ if $F > F_{SR}$. Meanwhile, when $F > F_{SR}$, $\pi_{TPR_SR}^A > \pi_{TPR_SR}^U$ if $\bar{\beta}_{SR1} < \beta < \bar{\beta}_{SR2}$; and
- iii) When the TPR chooses strategy S, there is a threshold F_S such that $\pi_{OEM_S}^A > \pi_{OEM_S}^U$ if $F > F_S$. Meanwhile, when $F > F_S$, $\pi_{TPR_S}^A > \pi_{TPR_S}^U$ if $\bar{\beta}_{S1} < \beta < \bar{\beta}_{S2}$.

As highlighted in Proposition A-5, in coopetition, regardless of the TPR's production strategies, both firms can achieve higher profits compared to the competition scenario. In other words, coopetition is a win-win situation. Obtained based on $c = 1/3$, $\theta = 3/5$, $\delta = 1/2$, $f = 1/20$, $\lambda = 1/5$, and $\gamma = 4/5$, Figure 3.6 visualizes the above conditions for the win-win situation. When the fixed authorization fee F is high enough and β is moderate, both firms benefit from coopetition. That is, in the coopetition scenario, both AR and S are improved compared to the competition scenario. Consequently, consumers' WTP for them increases. The increase in WTP generates additional profits for the TPR, which, in turn, the TPR has to share with the OEM as the authorization fees. This profit sharing allows both firms to benefit from coopetition, even though the increase in consumers' WTP for S and AR weakens the competitiveness of M, resulting in the OEM's profit loss from selling fewer M. To conclude, when the authorization fee offsets the OEM's profit loss and when the cost advantage of remanufacturing over the OEM's new product production remains moderate, the two firms can reach a win-win situation. Under these conditions, they gain higher profits than pure competition, and consumers can benefit from a broader range of affordable products.

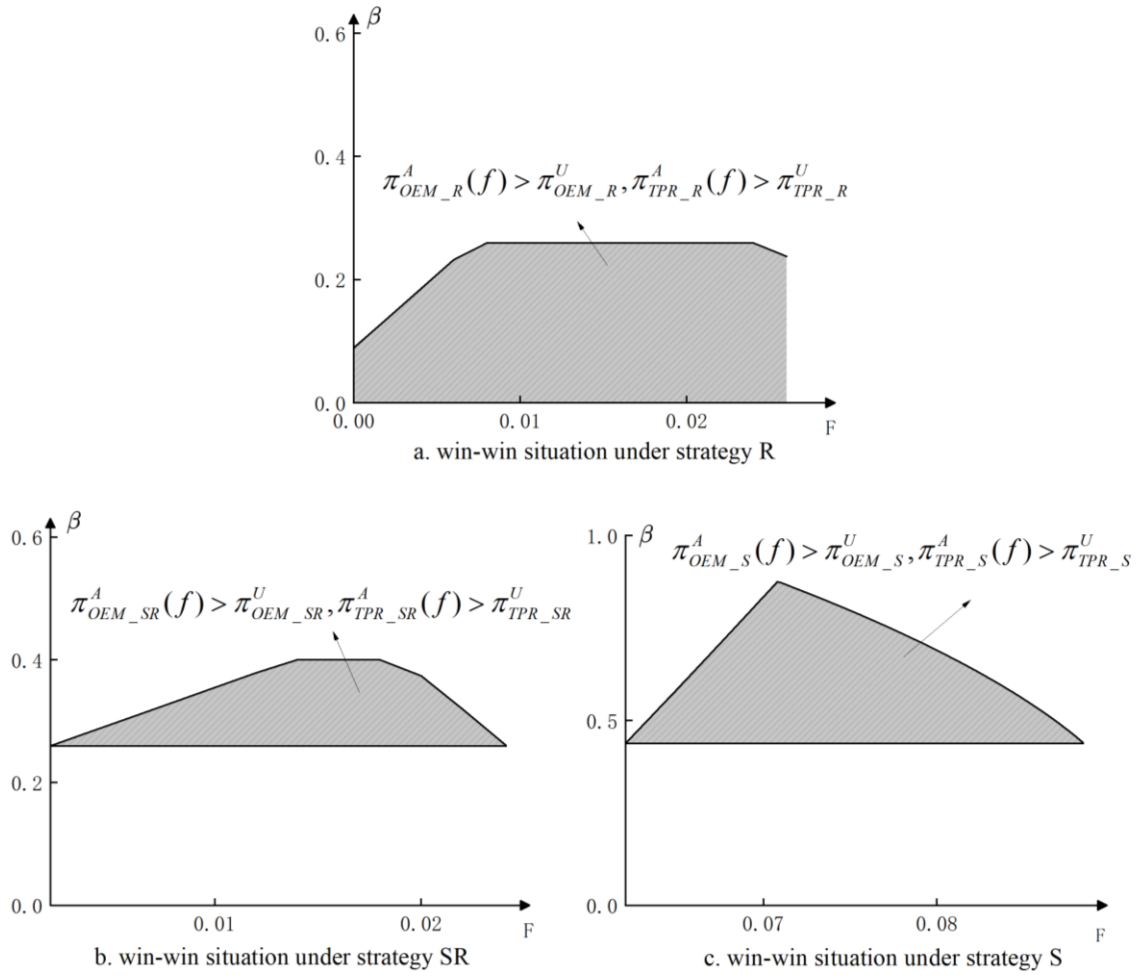


Figure 3.6. Conditions of the win-win situation for the OEM and the TPR

From a value creation perspective, as implied by Proposition A-5, remanufacturing authorization cooperation enables the effective utilization of the OEM's knowledge. This potentially enhances consumers' perceived value for the TPR's remanufactured and new products, i.e., creating additional value. The additional value is shared between the OEM and the TPR through an appropriate authorization fee when the cost advantage of remanufacturing over the OEM's new product production is moderate. Additionally, Proposition A-5 offers a practical insight: OEMs should set appropriate authorization fees that compensate for potential profit losses due to market cannibalization rather than simply deterring the entry of TPRs. Meanwhile, TPRs should foster cooperation with OEMs to benefit from innovation spillovers.

We further examine if coopetition positively affects consumer surplus and the environment. Corollary A-3 and Corollary A-4 summarize our results. The proof is in [Appendix A-6](#).

Corollary A-3. *Given precondition $\bar{f}_L^A < f < \bar{f}_U^A$, the results of the consumer surplus comparisons between the competition and coopetition scenarios are as follows:*

- i) *When the TPR's strategy is R, $CS_R^A > CS_R^U$ if and only if $f < \tilde{f}_1^{CS}$;*
- ii) *When the TPR's strategy is SR, $CS_{SR}^A > CS_{SR}^U$ if and only if $f < \tilde{f}_2^{CS}$; and*
- iii) *When the TPR's strategy is S, $CS_S^A > CS_S^U$ if and only if $\tilde{f}_3^{CS} < f < \tilde{f}_4^{CS}$.*

Based on Corollary A-3, regardless of the TPR's production strategies, coopetition generally leads to higher surplus compared to competition. Specifically, when the TPR focuses on remanufacturing (R) or a mix of new and remanufactured products (SR), consumers benefit more from coopetition if the unit authorization fee remains low. That is, consumer surplus is jointly decided by consumers' WTP, demand, and selling prices, as in [Eq \(3-1\)](#). Regarding consumers' WTP, thanks to remanufacturing authorization, coopetition increases consumers' WTP for both S and R when compared to the competition scenario. Concerning the selling prices, the optimal selling prices of S, R, and M are lower than those in competition when the unit authorization fee is relatively low (see the price formulas in [Appendix A-6](#)). Consequently, in the coopetition scenario, increases in consumers' WTP and decreases in selling prices grow consumer surplus. According to Part iii) of Corollary A-3, when the TPR's production strategy is S, a moderate unit authorization fee leads to an increase in consumer surplus (Note: When the unit authorization fee is too low or high, coopetition does not take place, as indicated in Proposition A-3). Finally, the corollary implies that the benefits of remanufacturing cooperation — including lower prices and higher perceived value — are ultimately passed on to consumers when authorization fees are set at appropriate levels.

Corollary A-4. *Given precondition $\bar{f}_L^A < f < \bar{f}_U^A$, the results of environmental impact comparisons between the competition and coopetition scenarios are as follows:*

- i) When the TPR's strategy is R, if $e_r \geq \tilde{e}_{r1}^{EI}$ and $f \geq \tilde{f}_1^{EI}$, or $e_r < \tilde{e}_{r1}^{EI}$ and $f < \tilde{f}_1^{EI}$, $EL_R^A \leq EL_R^U$;
- ii) When the TPR's strategy is SR, if $e_r \geq \tilde{e}_{r2}^{EI}$ and $f \geq \tilde{f}_2^{EI}$, or $e_r < \tilde{e}_{r2}^{EI}$ and $f < \tilde{f}_2^{EI}$, $EL_{SR}^A \leq EL_{SR}^U$; and
- iii) When the TPR's strategy is S, if $e_r \geq \tilde{e}_{r1}^{EI}$ and $f \geq \tilde{f}_3^{EI}$, or $e_r < \tilde{e}_{r1}^{EI}$ and $f < \tilde{f}_3^{EI}$, $EL_S^A \leq EL_S^U$.

As shown in Corollary A-4, irrelevant to the TPR's production strategies, coopetition can reduce total carbon emissions compared to competition, depending on carbon emissions from remanufacturing a used product (remanufacturing emissions, hereafter) and the unit authorization fee. Specifically, the environmental benefits of coopetition emerge when both factors are either relatively high or low. As shown, when the remanufacturing emissions are high, i.e., $e_r \geq \tilde{e}_{r1}^{EI}$ (or $e_r \geq \tilde{e}_{r2}^{EI}$), the total carbon emissions are lower in the coopetition scenario than in the competition scenario if and only if the unit authorization fee is relatively high. The reasons are as follows. The optimal selling prices of S, R, and M are higher in the coopetition scenario than in the competition scenario when the unit authorization fee is high (see the price formulas in [Appendix A-6](#)). The higher prices result in a decrease in consumers' utility in the coopetition scenario. Although remanufacturing authorization and innovation spillover in the coopetition scenario can increase consumers' WTP for S and R, the increase cannot offset the above decrease in consumers' utility. Consequently, consumers' demands for R and S decrease, leading to a reduction in total carbon emissions compared to competition.

Likewise, when the remanufacturing emissions are low, i.e., $e_r < \tilde{e}_{r1}^{EI}$ (or $e_r < \tilde{e}_{r2}^{EI}$), the total carbon emissions are lower in the coopetition scenario than in the competition scenario if and only if the unit authorization fee is relatively low. This is because a relatively low unit authorization fee allows the TPR to set a relatively low selling price of R, which, in turn, attracts more consumers to purchase R instead of S and M. Consequently, the demand for R increases, and the demand for S and M decreases. Given $e_r < \tilde{e}_{r1}^{EI}$ (or $e_r < \tilde{e}_{r2}^{EI}$), the increase in carbon emissions caused by increased demand for R is less than the reduction of carbon emissions related to the decreased demand for S and M, contributing to lower total carbon emissions in the coopetition scenario than in competition. Corollary A-4 suggests that

policymakers can reduce environmental impacts by fostering cooperation between OEMs and TPRs. In fostering cooperation, policymakers can offer subsidies for remanufacturing products with OEM labels when the emissions generated during the remanufacturing process are relatively low, and meanwhile remanufacturing authorization cooperation is hindered by high authorization fees.

3.4.4 Analysis of the unit authorization fee

In the earlier analysis, the unit authorization fee is an exogenous factor, i.e., as a parameter. In this subsection, we take it as an endogenous variable to be determined by the OEM and examine i) the OEM's decision on the unit authorization fee and ii) the TPR's corresponding production strategies. Proposition A-6 provides the results regarding the OEM's optimal decision and the TPR's production strategies. See the proof and expressions of the related thresholds in [Appendix A-7](#).

Proposition A-6. *The OEM's decision on the unit remanufacturing authorization fee and the TPR's production strategies are as follows:*

- i) When γ is low, i.e., $\gamma < \tilde{\gamma}_1$, $f_S^* = f_S$, and the TPR's production strategy is S;
- ii) When γ is moderate, i.e., $\tilde{\gamma}_1 \leq \gamma \leq \tilde{\gamma}_2$, $f_{SR}^* = f_{SR}$, and the TPR's production strategy is SR;
- iii) When γ is high, i.e., $\gamma > \tilde{\gamma}_2$,
 - if $\gamma < \tilde{\gamma}_3$, $f_R^* = f_{R1}$,
 - otherwise, $f_R^* = f_{R2} = f_S$,

and the TPR's production strategy is R.

Additionally, $f_S = f_{R2} \geq f_{SR}$ (or f_{R1}), where f_S and f_{R2} remain constant while f_{SR} decreases and f_{R1} increases as γ increases.

As indicated in the proposition, the OEM's optimal decision on f is influenced by γ , and his decision affects the TPR's production strategies. Additionally, the TPR's willingness to produce S or cease remanufacturing decreases in γ .

As shown in Part i), when γ is low: $\gamma \leq \tilde{\gamma}_1$, the OEM sets a high and fixed f , i.e., f_S (see

Figure 3.7(a) and the TPR engages in new product production only, i.e., selecting strategy S (see Figure 3.7(c)). (Note: Figure 3.7 is obtained using $c = 1/2$, $\theta = 3/5$, $\delta = 1/2$, and $\lambda = 1/5$.) The reasons are as follows. A low γ indicates a very low cost for the TPR to produce S. The low production cost encourages the TPR to engage in new product production. Moreover, a high f from the OEM increases the total variable remanufacturing fee (see Subsection 3.4.2), which, in turn, discourages the TPR from remanufacturing. Thus, the TPR ceases remanufacturing in period 2. Ceasing remanufacturing in period 2 does not cause TPR to lose consumers who bought R in period 1. Thanks to the low production cost, the TPR can reduce the selling price of S, thereby enticing consumers who initially bought R in period 1 into buying S in period 2. To conclude, driven by a low γ and a high f , the TPR selects strategy S.

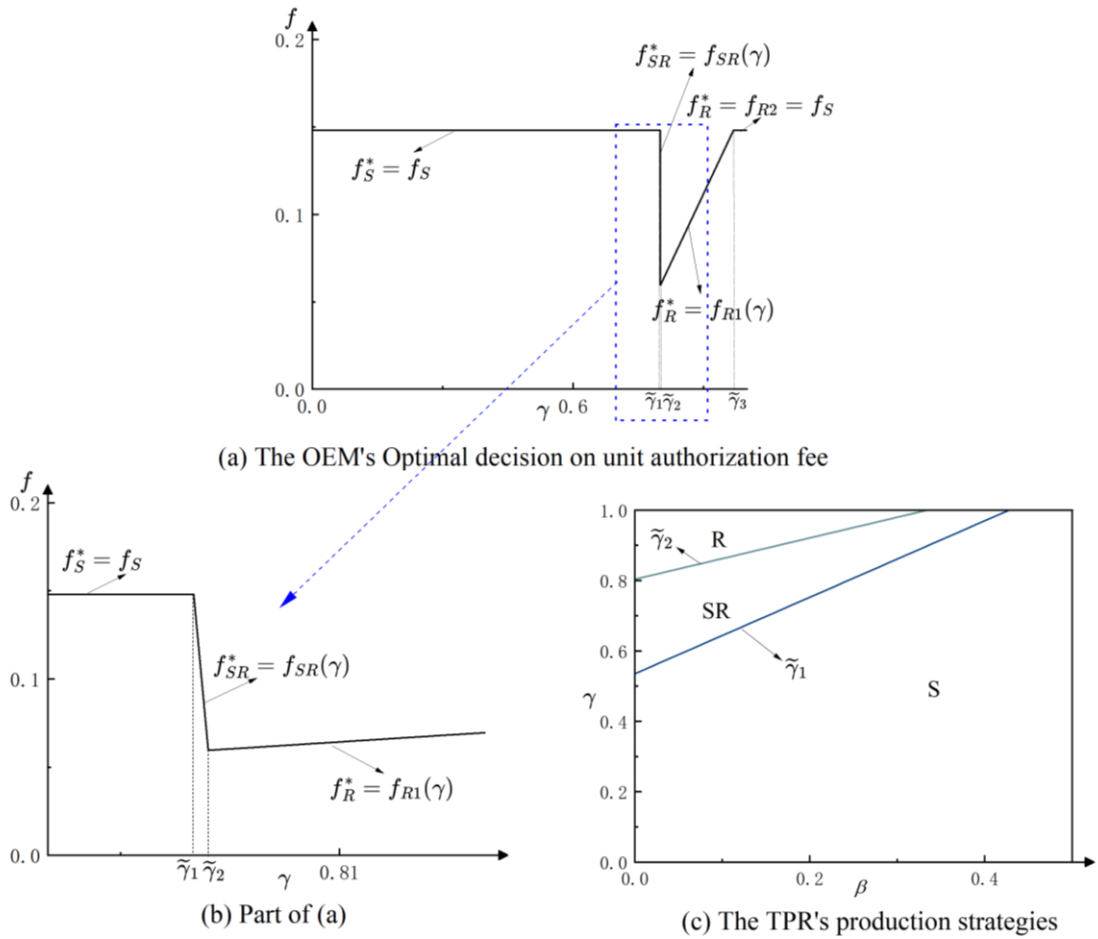


Figure 3.7. The OEM's decision on f and the TPR's production strategies

For the OEM, the TPR's low selling price of S negatively affects the demand for M and further his profit in period 2. However, a high f can help his increase profits in period 1, thus offsetting his profit loss caused by market cannibalization in period 2. As a result, the OEM

sets a high f when γ is low.

In Part ii), γ is moderate: $\tilde{\gamma}_1 \leq \gamma \leq \tilde{\gamma}_2$. In this condition, the OEM reduces f in γ (i.e., $f_{SR} \leq f_S$ and decreases in γ , Figure 3.7(b)), and the TPR's strategy is SR (Figure 3.7(c)). As mentioned in the above text, a high f discourages the TPR from remanufacturing R. Nevertheless, the OEM can share the TPR's profits from remanufacturing and selling R instead of S. Consequently, to encourage the TPR to perform remanufacturing, the OEM reduces f . Concerning the TPR's strategy SR, first, c_S (the unit production cost of S) increases in γ (see Subsection 3.3.3). This unit production cost increase forces the TPR to increase the selling price of S, which, in turn, causes the TPR to lose some demand. Consequently, the TPR keeps remanufacturing in period 2 to attract more consumers having a low WTP to buy R, and her inclination to carry out remanufacturing increases in γ (see Figure 3.7(c)). Second, because γ is moderate, it is still profitable for the TPR to produce S in period 2. Thus, the TPR's production strategy is SR.

As shown in Part iii), when γ is high: $\gamma > \tilde{\gamma}_2$, the TPR engages in remanufacturing only (i.e., selecting strategy R) in period 2, as shown in Figures 3.7(a) & (c). The TPR's production strategy decision depends on the profits generated from producing S and remanufacturing R. As mentioned earlier, when γ is moderate, the TPR loses some demand for S. Accordingly, when γ is high, the demand for S is minimal. As a result, the TPR is unwilling to produce S but selects strategy R in period 2 (see Figure 3.7(c)). Regarding f , the OEM has different decisions in different conditions. When $\gamma < \tilde{\gamma}_3$, the optimal f is f_{R1} and the OEM increases f in γ ; otherwise (i.e., $\gamma \geq \tilde{\gamma}_3$), the OEM sets a very high f (i.e., f_S), as shown in Figure 3.7(a). This is because when $\gamma < \tilde{\gamma}_3$, the TPR's decision about producing or not S depends on the tradeoff between the potential profits obtained from R and S, which are affected by f and γ . Consequently, the OEM applies different f values to influence the TPR's strategy such that he can make optimal profits. When $\gamma > \tilde{\gamma}_3$, it is not profitable for the TPR to produce S because the unit production cost of S is too high. Thus, the OEM sets a high f , hoping to get more remanufacturing authorization fees from the TPR. Nevertheless, the OEM should ensure the optimal value of f not exceed f_S , because it would not be profitable for the TPR to accept remanufacturing authorization cooperation when $f > f_S$.

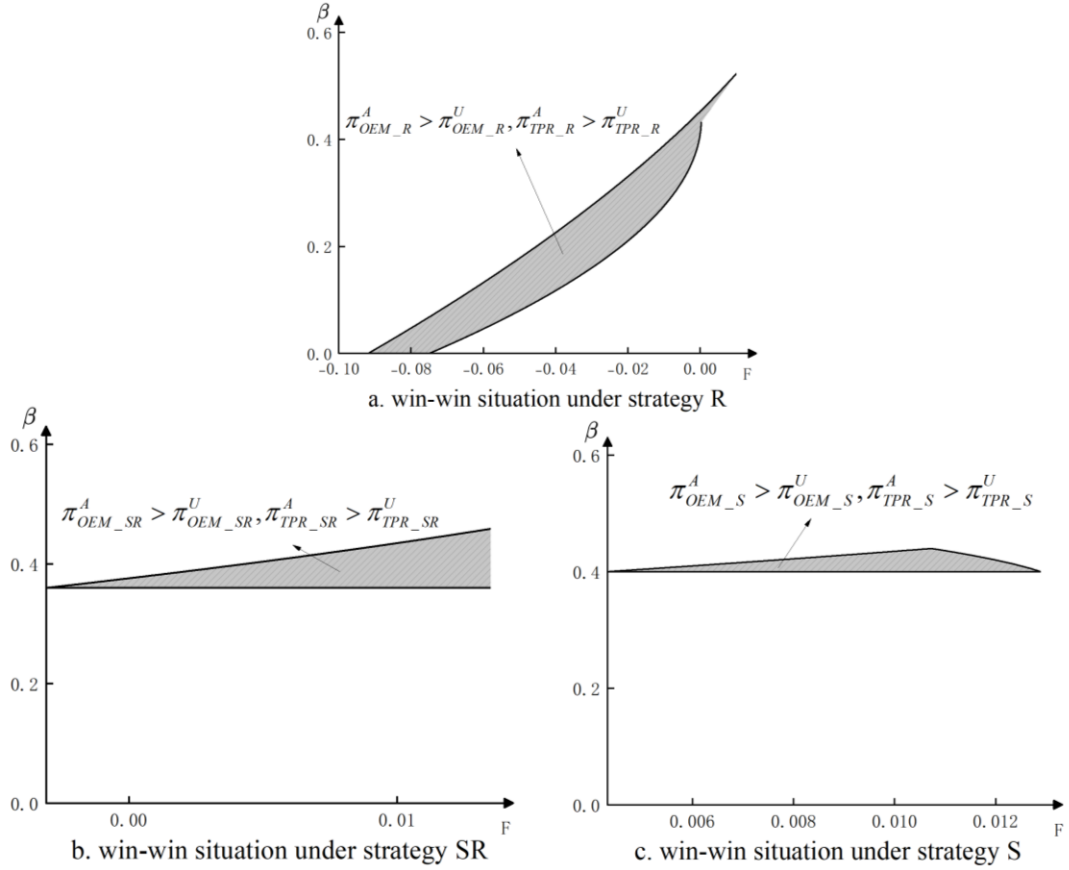


Figure 3.8. Conditions of win-win situations for the OEM and the TPR when f is endogenous

Based on Proposition A-6, we further obtain the OEM's and the TPR's profits in different conditions. See the details in [Appendix A-7](#). We also conduct numerical analysis involving $c = 1/2$, $\theta = 3/5$, $\delta = 1/2$, and $\lambda = 1/5$ to examine if two firms can reach a win-win situation when the unit authorization fee is endogenous. The results are summarized in [Figure 3.8](#). As implied by the results, even though the OEM possesses the exclusive authority to determine the unit authorization fee, if TPR's unit remanufacturing cost of R is moderate with respect to the OEM's unit production cost of M (i.e., β is moderate), the two firms are better off in the cooperation scenario.

3.5 Conclusions and contributions

Knowledge spillovers between an OEM and a TPR are common in remanufacturing. First, during remanufacturing, the TPR can observe and acquire valuable knowledge about the OEM's product and production processes, leading to spillovers of the OEM's general knowledge. This knowledge spillover enables the TPR to expand her business to include new

product production. Consequently, the OEM faces a potential threat of the TPR entering his new product market. In such remanufacturing environments, the TPR's new and remanufactured products potentially compete with OEM's new products in the same market. Likewise, TPR's new products could potentially compete with her remanufactured counterparts. These competitions unavoidably lead to market share cannibalization for both firms. Facing market share cannibalization, both firms need to optimize their production strategies and decisions to obtain higher profits. In this study, we considered the impact of knowledge spillovers and developed an analytical model to discover the conditions for both firms to make optimal strategies and decisions. Our results highlight the thresholds of γ (i.e., the ratio of TPR's unit production cost of S to OEM's unit production cost of M) for TPRs to engage in new product production and to cease remanufacturing. Also highlighted are the optimal production quantities for OEMs' new products and the specific conditions for TPRs' production strategies.

Remanufacturing cooperation with authorization (i.e., coopetition) between an OEM and a TPR is common. In coopetition, besides general knowledge spillovers, innovation spillovers occur when the OEM shares knowledge with the TPR to maintain his product standards and performance. They can potentially improve TPR's new products. Thus, it profoundly impacts the two firms' production strategies and decisions. In this study, we also developed an analytical model to reveal how to optimize two firms' strategies and decisions considering the impact of innovation spillovers in coopetition. Our results indicate that coopetition not only enhances TPR's capabilities in remanufacturing but also motivates him to engage in new product production. As a result, innovation spillovers may discourage the OEM from granting the TPR the remanufacturing authorization. Nevertheless, our study shows that the coopetition makes the two firms more profitable in certain situations than the competition does. Moreover, both consumer surplus and environmental performance improve under certain conditions in coopetition. At last, our study provides OEMs with guidance in determining the unit authorization fee, which is an important factor in remanufacturing systems.

Building on these results, we offer valuable managerial insights into remanufacturing systems involving spillovers, presents key strategies for OEMs and TPRs to optimize their

decisions, and guide policymakers in designing effective incentives.

(i) For TPRs: Building manufacturing capability through remanufacturing offers opportunities for TPRs to expand to new product production. TPRs' related decision-making process involves evaluating the ratio of their production costs to those of OEMs (denoted by γ in this study) and leveraging potential innovation spillovers. Specifically, TPRs should i) focus on remanufacturing when γ is low, ii) shift to new product production when γ is high, and iii) adopt a dual strategy of new and remanufactured products when γ is moderate. Additionally, collaboration with OEMs through remanufacturing authorization agreements can enhance the quality of TPRs' remanufactured products and provide access to innovation spillovers. In the authorization cooperation, they should adjust their production strategies based on the degree of innovation spillover. In particular, TPRs should engage in new product production when the degree is relatively high.

(ii) For OEMs: OEMs should not discourage the entry of TPRs. This is because they can share TPRs' profits through remanufacturing authorization cooperation. Moreover, their decision on the unit authorization fee (i.e., f in this study) accompanied by γ can influence TPRs' production strategies. Regarding this, when determining f , OEMs should balance the profits from their new products and remanufacturing authorization revenue considering changes in γ . Specifically, as γ increases, i) when γ is low, OEMs can set a high and constant f because a relatively low γ leads TPRs to cease remanufacturing in the second period, ii) as γ reaches a moderate level, OEMs should lower f to encourage TPRs to enhance remanufacturing efforts, iii) when γ increases further, OEMs can increase f to capture more from TPRs' remanufacturing as TPRs focus on remanufacturing, and iv) when γ is relatively high, OEMs should keep f constant because a high f drives TPRs out of the market.

(iii) For policymakers: Our analysis of consumer surplus and environmental impact offers a new perspective for policymakers to design remanufacturing incentives. They can develop performance measures aiming to foster collaboration between OEMs and TPRs. For instance, they could provide TPRs with subsidies for remanufacturing products with OEM labels or grant OEMs tax benefits for used products collected and remanufactured by TPRs.

In terms of academic contributions, our study makes several advances. We identify two

types of knowledge spillover in remanufacturing — general knowledge spillover and innovation spillover — and their impact on firms' business activities and performance. We complement the extant studies on decision-making in remanufacturing by modeling the impact of knowledge spillovers on consumer utility and incorporating it to optimize OEMs' and TPRs' decisions. We solve the game models analytically and provide TPRs' optimal production and remanufacturing strategies, OEMs' optimal quantity decisions in competition or coopetition scenario, and OEMs' optimal unit authorization fee charged to TPRs in the cooperative setting. Finally, we obtain the conditions under which coopetition fares better than competition for the two parties. For instance, when the fixed authorization fee exceeds a certain level and the remanufacturing cost is moderate, both firms achieve higher profits in coopetition. We also prove that coopetition benefits consumers and reduces negative environmental impacts under certain conditions. For example, when the unit authorization fee in coopetition is low, consumer surplus increases; when the emissions from remanufacturing a used product are low, the negative environmental impact decreases.

While our study makes significant contributions, it has several limitations that offer opportunities for future research. First, we focused on a two-period problem where the TPR competes with the OEM by remanufacturing used products in period 1 and may engage in new product production in period 2. As an initial study, we assumed that in the competition scenario, the quantity of new products in period 2 was not affected by the amount of general knowledge spilled at the end of period 1. Future studies could develop models considering the connection between the amount of knowledge spilled and the corresponding quantity of new products produced. Second, we assumed that consumers perceived a higher value for the TPR's new products than the remanufactured ones. In practice, in some cases consumers may perceive a higher value for a well-known OEM's remanufactured product than for a low-end new product. For example, the remanufactured iPhone 14 boasts 128GB storage and 5G connectivity and is priced at 559 euros. In contrast, a new Vivo model, equipped with 256GB storage and 5G capability, is sold at 529 euros by a well-known retailer in France¹⁵. Our models cannot provide strategy/decision-making support for such scenarios. This is due to the

¹⁵ <https://www.fnac.com/>

uncertain effect of innovation spillover, consumers' WTP for TPRs' new products could be either higher or lower than that of remanufactured products. Future research, thus, should explore approaches to enhance the model's applicability in diverse market conditions. Lastly, we considered only unilateral knowledge spillovers from the OEM to the TPR. In practice, it is possible that the TPR's remanufacturing knowledge and experience or remanufacturing market knowledge leak to the OEM. Regarding this, examining the impact of bidirectional knowledge spillovers on firms' optimal production strategies and decisions is interesting and relevant.

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3.7 A list of appendices

Appendix A-1. Proof of Proposition A-1

The Nash equilibrium solutions in the competition scenario can be obtained by maximizing the profits of the OEM and the TPR simultaneously. The profit expressions are:

$$\begin{aligned} \max_{q_{M1}^U, q_{M2}^U} \pi_{OEM}^U &= (1 - q_{M1}^U - \delta\theta q_{R1}^U - c)q_{M1}^U + (1 - q_{M2}^U - \theta(\delta q_{R2}^U + q_S^U) - c)q_{M2}^U \\ \max_{q_{R1}^U, q_{R2}^U, q_S^U} \pi_{TPR}^U &= (\delta\theta(1 - q_{M1}^U - q_{R1}^U) - \beta c)q_{R1}^U + (\theta(1 - q_{M2}^U - \delta q_{R2}^U - q_S^U) - \gamma c)q_S^U \quad (A-1) \\ &\quad + (\delta\theta(1 - q_{M2}^U - q_{R2}^U - q_S^U) - \beta c)q_{R2}^U \\ \text{s.t. } q_{M1}^U &> 0, q_{M2}^U > 0, q_{R1}^U \geq 0, q_{R2}^U \geq 0, q_S^U \geq 0 \end{aligned}$$

As the production quantity of R in period 2 is not constrained by the production quantity of M in period 1. The demands of R and M in two periods are independent. Thus, we first solve the optimal production quantity of M and the remanufacturing quantity in period 1 (i.e., q_{M1}^U and q_{R1}^U). Because the second derivatives of the OEM's profits with respect to her production quantity and the TPR's remanufacturing quantity with respect to his remanufacturing quantity are both less than zero (i.e., $\frac{\partial^2 \pi_{OEM}^U}{\partial q_{M1}^U \partial q_{M1}^U} = -2 < 0$, $\frac{\partial^2 \pi_{TPR}^U}{\partial q_{R1}^U \partial q_{R1}^U} = -2\delta\theta < 0$), π_{OEM}^U is concave in q_{M1}^U and π_{TPR}^U is concave in q_{R1}^U . Therefore, we get the optimal q_{M1}^U and q_{R1}^U by taking the first-order derivations of the OEM's and the TPR's profits with respect to q_{M1}^U and q_{R1}^U , respectively. i.e., $q_{M1}^{U*} = 1 - \frac{2+c(2-\beta)}{4-\delta\theta}$ and $q_{R1}^{U*} = \frac{(1+c)\delta\theta-2c\beta}{\delta\theta(4-\delta\theta)}$.

Further, we find that if $\beta \leq \beta^{U*}$, $q_{M1}^{U*} \leq 0$, where $\beta^{U*} = \frac{2c+\delta\theta-2}{c}$. Accordingly, to guarantee the inequality $q_{M1}^{U*} > 0$, we limit $\beta > \beta^{U*}$. We define $\tau = \frac{\delta}{\beta}$, we find that when $\beta > \beta^{U*}$, if $\tau \leq \tau^{R*}$, $q_{R1}^{U*} \leq 0$, where $\tau^{R*} = \frac{2c}{(1+c)\theta}$. Thus, given $\beta > \beta^*$: if $\tau \leq \tau^{R*}$ the TPR will not enter the market in period 1; otherwise, he will enter the market in period 1.

Appendix A-2. Proof of Proposition A-2

With the conditions $\tau > \tau^{R*}$ and $\beta > \beta^{U*}$, now we solve the equilibrium solutions in period 2. Because the second derivative of OEM's profit with respect to her production quantity in period 2 is less than zero (i.e., $\frac{\partial^2 \pi_{OEM}^U}{\partial q_{M2}^U \partial q_{M2}^U} = -2 < 0$), π_{OEM}^U is concave in q_{M2}^U . Meanwhile, the Hessian matrix of π_{TPR}^U with respect to q_S^U and q_{R2}^U is: $H_2 =$

$$\begin{pmatrix} \frac{\partial^2 \pi_{TPR}^U}{\partial q_S^U \partial q_S^U} & \frac{\partial^2 \pi_{TPR}^U}{\partial q_S^U \partial q_{R2}^U} \\ \frac{\partial^2 \pi_{TPR}^U}{\partial q_{R2}^U \partial q_S^U} & \frac{\partial^2 \pi_{TPR}^U}{\partial q_{R2}^U \partial q_{R2}^U} \end{pmatrix} = \begin{pmatrix} -2\theta & -2\theta\delta \\ -2\theta\delta & -2\theta\delta \end{pmatrix} = 4(1-\delta)\delta\theta^2. \text{ Because } \frac{\partial^2 \pi_{TPR}^U}{\partial q_S^U \partial q_S^U} = -2\theta < 0 \text{ and}$$

$H_2 = 4(1-\delta)\delta\theta^2 > 0$, the Hessian matrix is negative definite and the profit function π_{TPR}^U is jointly concave with respect to q_S^U and q_{R2}^U .

Additionally, the TPR's problem is characterized by Karush-Kuhn-Tucker (conditions). Let g_1 and g_2 denote the Lagrangian multipliers, then we have the Lagrangian function of the TPR's optimization problem as follows:

$$L(q_S^U, q_{R2}^U, g_1, g_2) = (\delta\theta(1 - q_{M1}^U - q_{R1}^U) - \beta c)q_{R1}^U + (\theta(1 - q_{M2}^U - \delta q_{R2}^U - q_S^U) - \gamma c)q_S^U + (\delta\theta(1 - q_{M2}^U - q_{R2}^U - q_S^U) - \beta c)q_{R2}^U + g_1 q_S^U + g_2 q_{R2}^U \quad (A-2)$$

With the first conditions

$$\frac{\partial L}{\partial q_S^U} = -c\gamma + \theta + g_1 - \theta(q_{M2}^U + 2(\delta q_{R2}^U + q_S^U)) = 0 \quad (A-3)$$

$$\frac{\partial L}{\partial q_{R2}^U} = -c\beta + \delta\theta + g_2 - \delta\theta(q_{M2}^U + 2(q_{R2}^U + q_S^U)) = 0 \quad (A-4)$$

and the constraints $g_1 * q_S^U = 0$ and $g_2 * q_{R2}^U = 0$. We have the following optimal solutions:

Case 1. When the TPR's production strategy is E: $g_1 > 0, g_2 > 0, q_S^U = 0$, and $q_{R2}^U = 0$. We have $q_{M2}^{U*} = \frac{1}{2}(1-c)$ and $g_2^* = c\beta - \frac{1}{2}(1+c)\delta$. The relative profits are $\pi_{OEM_E}^U = \frac{1}{2}(1-c)^2$ and $\pi_{TPR_E}^U = 0$. The conditions to ensure $g_2^* > 0$ is conflict with the precondition $\tau < \tau^{R*}$. Hence, we omit this case.

Case 2. When the TPR's production strategy is R: $g_1 > 0, g_2 = 0, q_S^U = 0$, and $q_{R2}^U > 0$. We have

$$g_1^* = \frac{-2\theta(\delta+\lambda)+2(\theta+\lambda)+c(\gamma(-4+\delta\theta)+\beta(4+\theta(-1+\lambda)-\lambda)+2\lambda-2\theta(-1+\delta+\lambda))}{-4+\delta\theta}, q_{M2_R}^{U*} = 1 + \frac{2-c(-2+\beta)}{-4+\delta\theta},$$

and $q_{R2_R}^{U*} = \frac{2c\beta-(1+c)\delta\theta}{\delta\theta(-4+\delta\theta)}$. The relative profits are $\pi_{OEM_R}^U = \frac{2(2+c(-2+\beta)-\delta\theta)^2}{(-4+\delta\theta)^2}$ and $\pi_{TPR_R}^U = \frac{2(-2c\beta+(1+c)\delta\theta)^2}{\delta\theta(-4+\delta\theta)^2}$. To ensure that $g_1^* > 0$ and $q_{M2_R}^{U*} > 0$, we obtain $\gamma > \hat{\gamma}_1^U$, where $\hat{\gamma}_1^U = \frac{-4c\beta-2\theta-2c\theta+c\beta\theta+2\delta\theta+2c\delta\theta-2\lambda-2c\lambda+c\beta\lambda+2\theta\lambda+2c\theta\lambda-c\beta\theta\lambda}{-4c+c\delta\theta}$.

Case 3. When the TPR's production strategy is SR: $g_1 = 0, g_2 = 0, q_S^U > 0$, and $q_{R2}^U >$

0. We have $q_{M2_SR}^{U*} = \frac{-2-c(-2+\gamma)+\theta}{-4+\theta}$, $q_{R2_SR}^{U*} = \frac{2c\beta-(1+c)\delta\theta}{\delta\theta(-4+\delta\theta)}$, and $q_{S_SR}^{U*} = \frac{1}{2} \left(\frac{-2+c(-2+\gamma)}{-4+\theta} + \frac{c(-\beta+\gamma)}{(-1+\delta)\theta} \right)$. The relative profits are $\pi_{TPR_SR}^U = \frac{(-2c\beta+(1+c)\delta\theta)^2}{\delta\theta(-4+\delta\theta)^2} + \frac{(2c\gamma-\theta-c\theta+(1+c)(-1+\theta)\lambda)(-2\theta(\delta+\lambda)+2(\theta+\lambda)+c(\gamma(-4+\delta\theta)+\beta(4+\theta(-1+\lambda)-\lambda)+2\lambda-2\theta(-1+\delta+\lambda)))}{2(-4+\theta+\lambda-\theta\lambda)^2(-\lambda+\theta(-1+\delta+\lambda))} + \frac{c(-2\delta\theta+c(-2+\gamma)\delta\theta+c\beta(4+\theta(-1+\lambda)-\lambda))(beta\theta+\gamma\delta\theta+\beta(-1+\theta)\lambda)}{4\delta\theta(4+\theta(-1+\lambda)-\lambda)(-\lambda+\theta(-1+\delta+\lambda))}$ and $\pi_{OEM_SR}^U = \frac{(2+c(-2+\beta)-\delta\theta)^2}{(-4+\delta\theta)^2} + \frac{(-2+2c-c\gamma+\theta+\lambda-\theta\lambda)^2}{(4+\theta(-1+\lambda)-\lambda)^2}$. To ensure that $q_{R2_SR}^{U*} > 0$ and $q_{S_SR}^{U*} > 0$, we obtain $\hat{\gamma}_2^U < \gamma < \hat{\gamma}_1^U$, where $\hat{\gamma}_2^U = \frac{\beta\theta+\beta\lambda-\beta\theta\lambda}{\delta\theta}$.

Case 4. When the TPR's production strategy is S: $g_1 = 0, g_2 > 0, q_S^{C*} > 0$, and $q_{R2}^C = 0$. We have $q_{M2_S}^{U*} = \frac{-2-c(-2+\gamma)+\theta}{-4+\theta}$, $q_{R2_S}^{U*} = 0$, and $q_{S_S}^{U*} = \frac{2c\beta-(1+c)\delta\theta}{\delta\theta(-4+\delta\theta)}$. The relative profits are $\pi_{OEM_S}^U = \frac{(2+c(-2+\gamma)-\theta)^2}{(-4+\theta)^2} + \frac{(2+c(-2+\beta)-\delta\theta)^2}{(-4+\delta\theta)^2}$ and $\pi_{TPR_S}^U = \frac{(-2c\beta+(1+c)\delta\theta)^2}{\theta\delta(-4+\delta\theta)^2} + \frac{(\theta+c(-2\gamma+\theta))^2}{\theta(-4+\theta)^2}$. To ensure that $g_2^* > 0$ and $q_{S_S}^{U*} > 0$, we obtain $\gamma^{U*} < \gamma < \hat{\gamma}_2^U$, where $\gamma^{U*} = \frac{-2+2c+\theta}{c}$.

In conclusion, the equilibria and the corresponding firm-level profits are summarized in Table A.1.

Table A. 1. The optimal decisions and the firm-level profits under different production strategies

Production quantities	The firm-level profits
$q_{M1_E}^{U*} = q_{M2_E}^{U*} = \frac{1-c}{2},$ $q_{R1_E}^{U*} = q_{R2_E}^{U*} = q_{S_E}^{U*} = 0.$	$\pi_{OEM_E}^U = \frac{1}{2}(1-c)^2, \pi_{S_E}^U = 0.$
$q_{M1_R}^{U*} = q_{M2_R}^{U*} = 1 + \frac{2-c(-2+\beta)}{-4+\delta\theta},$ $q_{R1_R}^{U*} = q_{R2_R}^{U*} = \frac{2c\beta-(1+c)\delta\theta}{\delta\theta(-4+\delta\theta)}, q_{S_R}^{U*} = 0$	$\pi_{OEM_R}^U = \frac{2(2+c(-2+\beta)-\delta\theta)^2}{(-4+\delta\theta)^2},$ $\pi_{TPR_R}^U = \frac{2(-2c\beta+(1+c)\delta\theta)^2}{\delta\theta(-4+\delta\theta)^2}.$
$q_{M1_SR}^{U*} = 1 + \frac{2-c(-2+\beta)}{-4+\delta\theta}, q_{M2_SR}^{U*} = \frac{-2-c(-2+\gamma)+\theta}{-4+\theta},$ $q_{R1_SR}^{U*} = \frac{2c\beta-(1+c)\delta\theta}{\delta\theta(-4+\delta\theta)}, q_{R2_SR}^{U*} = \frac{c(\beta-\gamma\delta)}{2(-1+\delta)\delta\theta},$ $q_{S_SR}^U = \frac{1}{2} \left(\frac{-2+c(-2+\gamma)}{-4+\theta} + \frac{c(-\beta+\gamma)}{(-1+\delta)\theta} \right).$	For clarity, the profits for SR are provided in Appendix A-2.
$q_{M1_S}^{U*} = 1 + \frac{2-c(-2+\beta)}{-4+\delta\theta}, q_{M2_S}^{U*} = \frac{-2-c(-2+\gamma)+\theta}{-4+\theta},$ $q_{R1_S}^{U*} = \frac{2c\beta-(1+c)\delta\theta}{\delta\theta(-4+\delta\theta)}, q_{R2_S}^{U*} = 0,$ $q_{S_S}^{U*} = -\frac{\theta+c(-2\gamma+\theta)}{(-4+\theta)\theta}.$	$\pi_{OEM_S}^U = \frac{(2+c(-2+\gamma)-\theta)^2}{(-4+\theta)^2} + \frac{(2+c(-2+\beta)-\delta\theta)^2}{(-4+\delta\theta)^2},$ $\pi_{TPR_S}^U = \frac{(-2c\beta+(1+c)\delta\theta)^2}{\theta\delta(-4+\delta\theta)^2} + \frac{(\theta+c(-2\gamma+\theta))^2}{\theta(-4+\theta)^2}.$

Appendix A-3. Corollary A.1

Corollary A.1. *The consumer surplus and total carbon emissions of the remanufacturing system under different production strategies are:*

i) *When the TPR is not included:*

$$CS_E^U = \frac{1}{4}(1-c)^2, EI_E^U = \frac{1}{4}(1-c)^2;$$

ii) *When the TPR implements strategy R:*

$$CS_R^U = \frac{4c^2\beta^2 + (4-8c(1+\beta) + c^2(4-3\beta^2))\delta\theta + (1+c(6+4\beta-c(3-2\beta)))\delta^2\theta^2 - (1+2c)\delta^3\theta^3}{\delta\theta(-4+\delta\theta)^2},$$

$$EI_R^U = \frac{2(\delta\theta(2-c(2-\beta))-\delta\theta)e_n + ((1+c)\delta\theta)e_r - 2c\beta}{\delta\theta(4-\delta\theta)};$$

iii) *When the TPR implements strategy SR:*

$$CS_{SR}^U = \frac{1}{8} \left(\frac{(14+c(6-\gamma))(2-c(2-\gamma))}{4-\theta} + \frac{c^2(\beta^2(-2+\delta)+2\beta\gamma\delta-\gamma^2\delta)}{(-1+\delta)\delta\theta} - \frac{8(-2+c(-2+\beta))^2}{(4-\delta\theta)^2} - \frac{8(2-c(2-\gamma))^2}{(4-\theta)^2} - 8 - 16c + \frac{(-14+c(-6+\beta))(-2+c(-2+\beta))}{4-\delta\theta} \right),$$

$$EI_{SR}^U = \left(\frac{\theta(4-\delta\theta)(1-\delta)(4(4-\theta)-2-c(2-\gamma))-(4-\theta)(c(\gamma-\beta)(4-\delta\theta)+(4+2c(2-\beta))\theta(1-\delta))}{2\theta(4-\delta\theta)(1-\delta)(4-\theta)} \right) e_n + \frac{c(\beta-\gamma\delta)(\delta\theta-4)-(4c\beta-2(1+c)\delta\theta)(1-\delta)}{2\delta\theta(4-\delta\theta)(1-\delta)} e_r;$$

iv) *When the TPR implements strategy S:*

$$CS_S^U = \frac{1}{8} \left(-8 - 16c - \frac{8(c(-2+\gamma))^2-2}{(-4+\theta)^2} + \frac{(14+c(6-\gamma))(-2+c(-2+\gamma))}{-4+\theta} + \frac{c^2(\beta^2+\gamma^2\delta)}{\delta\theta} - \frac{8(-2+c(-2+\beta))^2}{(-4+\delta\theta)^2} - \frac{(-14+c(-6+\beta))(-2+c(-2+\beta))}{-4+\delta\theta} \right), EI_S^U = \left(2 - \frac{2+c(2-\gamma)}{2(4-\theta)} - \frac{c\gamma}{2\theta} - \frac{2+c(2-\beta)}{4-\delta\theta} \right) e_n - \frac{(2c\beta-(1+c)\delta\theta)e_r}{\delta\theta(4-\delta\theta)}.$$

Appendix A-4. Proof of Proposition A-3

In coopetition scenario, the OEM's and the TPR's profits are as follows:

$$\begin{aligned} \max_{q_{M1}^A, q_{M2}^A} \pi_{OEM}^A &= (1 - q_{M2}^A - \delta q_{R2}^A - (\theta + (1-\theta)\lambda)q_S^A - c)q_{M2}^A \\ &\quad + (1 - q_{M1}^A - \delta q_{R1}^A - c)q_{M1}^A + F + f(q_{R1}^A + q_{R2}^A) \\ \max_{q_{R1}^A, q_{R2}^A, q_S^A} \pi_{TPR}^A &= (\delta(1 - q_{M1}^A - q_{R1}^A) - \beta c - f)q_{R1}^A + (\theta + (1-\theta)\lambda - \delta q_{R2}^A - F) \quad (A-5) \\ &\quad + (\delta(1 - q_{M2}^A - q_{R2}^A - q_S^A) - \beta c - f)q_{R2}^A - (\theta + (1-\theta)\lambda)(q_{M2}^A + q_S^A) - \gamma c)q_S^A \\ &\quad s. t. q_{M1}^A > 0, q_{M2}^A > 0, q_{R1}^A > 0, q_{R2}^A \geq 0, q_S^A \geq 0 \end{aligned}$$

When the unit authorization fee (i.e., f) is a parameter, the OEM and the TPR play the

Nash game in both periods. We first prove the existence of equilibrium solutions. In period 1, because $\frac{\partial^2 \pi_{OEM}^A}{\partial q_{M1}^A \partial q_{M1}^A} = -2 < 0$ and $\frac{\partial^2 \pi_{TPR}^A}{\partial q_{R1}^A \partial q_{R1}^A} = -2\delta\theta < 0$, π_{OEM}^A is concave in q_{M1}^A and π_{TPR}^A is concave in q_{R1}^A . Taking the first-order derivations of the OEM's and the TPR's profits with respect to q_{M1}^A and q_{R1}^A , respectively, we get $q_{M1}^{A*} = \frac{2+f+c(-2+\beta)-\delta}{4-\delta}$ and $q_{R1}^{A*} = \frac{2f+2c\beta-(1+c)\delta}{(-4+\delta)\delta}$.

In period 2, because the second derivative of the OEM's profit with respect to her production quantity is less than zero (i.e. $\frac{\partial^2 \pi_{OEM}^A}{\partial q_{M2}^A \partial q_{M2}^A} = -2 < 0$), π_{OEM}^A is concave in q_{M2}^A . Meanwhile, the Hessian matrix of π_{TPR}^A with respect to q_S^A and q_{R2}^A is: $H_2^A = \begin{pmatrix} \frac{\partial^2 \pi_{TPR}^A}{\partial q_S^A \partial q_S^A} & \frac{\partial^2 \pi_{TPR}^A}{\partial q_S^A \partial q_{R2}^A} \\ \frac{\partial^2 \pi_{TPR}^A}{\partial q_{R2}^A \partial q_S^A} & \frac{\partial^2 \pi_{TPR}^A}{\partial q_{R2}^A \partial q_{R2}^A} \end{pmatrix} = \begin{pmatrix} -2\theta(1-\lambda) - 2\lambda & -2\delta \\ -2\delta & -2\delta \end{pmatrix} = 4\delta(\theta - \delta + \lambda - \theta\lambda)$. Because $\frac{\partial^2 \pi_{TPR}^A}{\partial q_S^A \partial q_S^A} = -2\theta(1-\lambda) - 2\lambda < 0$ and $H_2^A = 4\delta(\theta - \delta + \lambda - \theta\lambda) > 0$, the Hessian matrix is negative definite and π_{TPR}^A is jointly concave with respect to q_S^A and q_{R2}^A .

To conclude, the Nash equilibrium solutions exist. The method and steps to get the Nash equilibrium solutions in this scenario is same as that in the competition scenario. Consequently, we do not present the calculation steps here. By solving equation (A-5) with KKT conditions, we get the equilibrium solutions, the OEM's and the TPR's profits, and the conditions for different production strategies below.

(i) When the TPR's production strategy is R: $q_{M1_R}^{A*} = q_{M2_R}^{A*} = \frac{2+f+c(-2+\beta)-\delta}{4-\delta}$, $q_{R1_R}^{A*} = q_{R2_R}^{A*} = \frac{2f+2c\beta-(1+c)\delta}{(-4+\delta)\delta}$, and $q_{S_R}^{A*} = 0$. The relative profits are $\pi_{TPR_R}^A = (8(f+c\beta)^2 - 8(2F + (1+c)(f+c\beta))\delta + 2((1+c)^2 + 4F)\delta^2 - F\delta^3) / ((-4+\delta)^2\delta)$ and $\pi_{OEM_R}^A = (-16f(f+c\beta) + 2(4+f(8+3f) + 8F + c^2(-2+\beta)^2 + 4c(-2+\beta+f\beta))\delta - 2(4+3f+4F+c(-4+f+2\beta))\delta^2 + (2+F)\delta^3) / ((-4+\delta)^2\delta)$. The conditions are $\lambda < \hat{\lambda}_1^A$ and $\gamma \geq \hat{\gamma}_1^A$.

(ii) When the TPR's production strategy is SR: $q_{M1_SR}^{A*} = \frac{2+f+c(-2+\beta)-\delta}{4-\delta}$, $q_{M2_SR}^{A*} = 1 + \frac{-2+c(-2+\gamma)}{4+\theta(-1+\lambda)-\lambda}$, $q_{R1_SR}^{A*} = \frac{2f+2c\beta-(1+c)\delta}{(-4+\delta)\delta}$, $q_{R2_SR}^{A*} = \frac{1}{2} \left(-\frac{f+c\beta}{\delta} + \right.$

$\frac{f+c(\beta-\gamma)}{\delta+\theta(-1+\lambda)-\lambda}$), and $q_{S_SR}^{A*} = \frac{1}{2} \left(\frac{2-c(-2+\gamma)}{4+\theta(-1+\lambda)-\lambda} - \frac{f+c(\beta-\gamma)}{\delta+\theta(-1+\lambda)-\lambda} \right)$. The relative profits are

$$\pi_{OEM_SR}^A = F + \frac{(2+f+c(-2+\beta)-\delta)^2}{(-4+\delta)^2} + \frac{1}{2} f \left(\frac{8(f+c\beta)-(2+f+c(2+\beta))\delta}{(-4+\delta)\delta} + \frac{f+c(\beta-\gamma)}{\delta+\theta(-1+\lambda)-\lambda} \right) +$$

$$\frac{(-2+2c-c\gamma+\theta+\lambda-\theta\lambda)^2}{(4+\theta(-1+\lambda)-\lambda)^2} \quad \text{and} \quad \pi_{TPR_SR}^A = \frac{1}{2} \left(-2F + (-8f(f+c\beta) + f(2+f+c(2+\beta))\delta)/((-4+\delta)\delta) + (2(-2f+\delta+c(-2\beta+\delta))(-f(-2+\delta)+\delta+c(-2\beta+\delta)))/((-4+\delta)^2\delta) - (f(f+c(\beta-\gamma)))/(\delta+\theta(-1+\lambda)-\lambda) + \right.$$

$$\left((2c\gamma-\theta-c\theta+(1+c)(-1+\theta)\lambda)(4f+4c\beta-4c\gamma-2\delta-2c\delta+c\gamma\delta+2\theta+2c\theta-f\theta-c\beta\theta+(-2+f+c(-2+\beta))(-1+\theta)\lambda) \right) / ((\delta+\theta(-1+\lambda)-\lambda)(-4+\theta+\lambda-\theta\lambda)^2) + ((c\gamma\delta-f\theta-c\beta\theta+(f+c\beta)(-1+\theta)\lambda)(-2\delta+c(-2+\gamma)\delta+c\beta(4+\theta(-1+\lambda)-\lambda)+f(-4+\theta+\lambda-\theta\lambda)))/(2\delta(4+\theta(-1+\lambda)-\lambda)(\delta+\theta(-1+\lambda)-\lambda)))$$
. The conditions are $\lambda < \hat{\lambda}_1^A$ and $\hat{\gamma}_2^A < \gamma < \hat{\gamma}_1^A$, or $\hat{\lambda}_1^A < \lambda < \hat{\lambda}_2^A$ and $\gamma > \hat{\gamma}_2^A$.

(iii) When the TPR's production strategy is S: $q_{M1_S}^{A*} = 1 + \frac{2-c(-2+\beta)}{-4+\delta\theta}$, $q_{M2_S}^{A*} = 1 + \frac{-2+c(-2+\gamma)}{4+\theta(-1+\lambda)-\lambda}$, $q_{R1_S}^{A*} = \frac{2f+2c\beta-(1+c)\delta}{(-4+\delta)\delta}$, $q_{R2_S}^{A*} = 0$, and $q_{S_S}^{A*} = \frac{1}{2} \left(\frac{2-c(-2+\gamma)}{4+\theta(-1+\lambda)-\lambda} - \frac{c\gamma}{\theta+\lambda-\theta\lambda} \right)$. The relative profits are $\pi_{OEM_S}^A = F + \frac{(2+f+c(-2+\beta)-\delta)^2}{(-4+\delta)^2} + \frac{f(2f+2c\beta-(1+c)\delta)}{(-4+\delta)\delta} + \frac{(-2+2c-c\gamma+\theta+\lambda-\theta\lambda)^2}{(4+\theta(-1+\lambda)-\lambda)^2}$ and $\pi_{TPR_S}^A = \frac{(-2f+\delta+c(-2\beta+\delta))^2}{(-4+\delta)^2\delta} + \frac{-4(1+c)^2+c^2\gamma^2}{4(4+\theta(-1+\lambda)-\lambda)} + \frac{(-2+c(-2+\gamma))^2}{(-4+\theta+\lambda-\theta\lambda)^2} + \frac{c^2\gamma^2}{4(\theta+\lambda-\theta\lambda)} - F$.

The conditions are $\lambda < \hat{\lambda}_2^A$ and $\gamma \leq \hat{\gamma}_2^A$, or $\lambda > \hat{\lambda}_2^A$,

where $\hat{\gamma}_1^A =$

$$\frac{2\delta+2c\delta-2\theta-2c\theta+f\theta+c\beta\theta-2\lambda-2c\lambda+f\lambda+c\beta\lambda+2\theta\lambda+2c\theta\lambda-f\theta\lambda-c\beta\theta\lambda-4f-4c\beta}{-4c+c\delta}, \hat{\gamma}_2^A = \frac{f\theta+c\beta\theta+f\lambda+c\beta\lambda-f\theta\lambda-c\beta\theta\lambda}{c\delta}, \hat{\lambda}_1^A = \frac{4c-4f-4c\beta+2\delta+c\delta-2\theta-2c\theta+f\theta+c\beta\theta}{2+2c-f-c\beta-2\theta-2c\theta+f\theta+c\beta\theta}, \text{ and } \hat{\lambda}_2^A = \frac{c\delta-f\theta-c\beta\theta}{f+c\beta-f\theta-c\beta\theta}.$$

Additionally, let $q_{M1}^{A*} > 0$ and $q_{R1}^{A*} > 0$, we get $\bar{f}_L^A < f < \bar{f}_U^A$, where $\bar{f}_L^A = \text{Max}\{-c *$

$$\beta, -2 + 2c - c\beta + \delta\}, \bar{f}_U^A = \text{Min}\{\frac{1}{2}(-2c\beta + \delta + c\delta), c(1 - \beta)\}.$$

Appendix A-5. Proof of Proposition A-4

We compare the TPR's entry boundaries of new product production in the competition and coopetition scenarios. In the competition scenario, the TPR introduces S when $\gamma < \hat{\gamma}_1^U$, i.e., his entry boundary of new product production is $\hat{\gamma}_1^C$. In the coopetition scenario, the TPR introduces S when $\gamma < \hat{\gamma}_1^A$, i.e., his entry boundary of new product production is $\hat{\gamma}_1^A$. Define $\Delta\gamma = \hat{\gamma}_1^A - \hat{\gamma}_1^U = \frac{a\lambda + b}{c(4-\delta)(4-\delta\theta)}$, where $a = -(-4(-2 + c(-2 + \beta))(-1 + \theta) + (-2 + c(-2 + \beta))\delta(-1 + \theta)\theta - f(-4 + \delta\theta) + f\theta(-4 + \delta\theta))$ and $b = 4(-2 + c(-2 + \beta))\delta(-1 + \theta) - 2 + c(-2 + \beta)\delta(-1 + \theta)\theta + 4f(-4 + \delta\theta) - f\theta(-4 + \delta\theta)$. We find that $a > 0$ is true when $\bar{f}_L^A < f < \bar{f}_U^A$. Let $\Delta\gamma = 0$, we get $\lambda = -\frac{a}{b} = \frac{(-4+\theta)((-2+c(-2+\beta))\delta(-1+\theta)+f(-4+\delta\theta))}{(-2+f+c(-2+\beta))(-1+\theta)(-4+\delta\theta)}$. Thus, if $\lambda > \lambda_T$, where $\lambda_T = \text{Max}\{0, ((-4 + \theta)((-2 + c(-2 + \beta))\delta(-1 + \theta) + f(-4 + \delta\theta)))/((-2 + f + c(-2 + \beta))(-1 + \theta)(-4 + \delta\theta))\}$, $\hat{\gamma}_1^A > \hat{\gamma}_1^U$ otherwise, $\hat{\gamma}_1^A \leq \hat{\gamma}_1^U$.

Appendix A-6. Proof of Corollary A-3 and Corollary A-4

We first calculate the total consumer surplus and environmental impacts in the coopetition scenario. Substituting the equilibrium solutions into Eqs. (2-1) and (2-2), we get the following:

(i) When the TPR's production strategy is R:

$$CS_R^A = \left(4(f + c\beta)^2 - 4 + f(8 + 3f) + c(8 + (8 + 6f)\beta + c(-4 + 3\beta^2))\right)\delta + (1 + 4f + c(6 - 3c + 2f + 2(2 + c)\beta))\delta^2 - (1 + 2c)\delta^3)/((-4 + \delta)^2\delta) \text{ and } EI_R^A = (2((2 + f + c(-2 + \beta) - \delta)\delta e_n + (-2f - 2c\beta + \delta + c\delta)e_r))/((4 - \delta)\delta);$$

(ii) When the TPR's production strategy is SR:

$$CS_{SR}^A = \left(f^2(-4 + 3\delta) - 2c\delta(12 + 4\beta - (9 - \delta)\delta) - c^2(\beta^2(-12 + \delta) - (12 - \delta)\delta + 2\beta(8 - \delta)\delta) + \delta(12 - (5 - \delta)\delta) + 2f(4c\beta + c(-4 + \beta)\delta - \delta^2) + \right.$$

$2(-4 + \delta)((2 + f + c(-2 + \beta) - \delta)\delta e_n - (2f + 2c\beta - \delta - c\delta)e_r)) / ((4 - \delta)^2\delta)$ and

$$EI_{SR}^A = \left(\frac{2(6+f+c(-2+\beta)-2\delta)}{2(4-\delta)} + \frac{-2+c(-2+\gamma)}{4+\theta(-1+\lambda)-\lambda} - \frac{f+c(\beta-\gamma)}{\delta+\theta(-1+\lambda)-\lambda} \right) e_n - \frac{(8(f+c\beta)-(2+f+c(2+\beta))\delta)(\delta-\theta(1-\lambda)-\lambda)-(f+c(\beta-\gamma))\delta(4-\delta)}{2\delta(4-\delta)(\delta-\theta(1-\lambda)-\lambda)};$$

(iii) When the TPR's production strategy is S:

$$CS_S^A = (-4\delta(\delta + \theta(-1 + \lambda) - \lambda)(-128 + 16\delta + 12\delta^2 + 16\theta + 16\delta\theta - 9\delta^2\theta + 12\theta^2 - 9\delta\theta^2 + 2\delta^2\theta^2 - (-1 + \theta)(8(2 + 3\theta) + \delta(16 - 18\theta + \delta(-9 + 4\theta))))\lambda + (12 + \delta(-9 + 2\delta))(-1 + \theta)^2\lambda^2) + f^2(4 + \theta(-1 + \lambda) - \lambda)^2(-\delta^2(12 + \theta) + 4\delta(4 + 5\theta) + (-20 + \delta)\delta(-1 + \theta)\lambda + 32\theta\lambda - 32(\theta + \lambda)) - 8c\delta(\delta + \theta(-1 + \lambda) - \lambda)(128 - 80\delta + 20\delta^2 - 80\theta + 48\delta\theta - 11\delta^2\theta + 20\theta^2 - 11\delta\theta^2 + 2\delta^2\theta^2 - (-1 + \theta)(40(-2 + \theta) + \delta(48 - 11\delta - 22\theta + 4\delta\theta))\lambda + (20 + \delta(-11 + 2\delta))(-1 + \theta)^2\lambda^2 + 2\gamma(-4 + \delta)^2(2 - \theta + (-1 + \theta)\lambda) - 2\beta(-2 + \delta)(-4 + \theta + \lambda - \theta\lambda)^2) + 2f(4 + \theta(-1 + \lambda) - \lambda)^2(8(-2 + \delta)\delta(\delta + \theta(-1 + \lambda) - \lambda) + c\beta(-\delta^2(12 + \theta) + 4\delta(4 + 5\theta) + (-20 + \delta)\delta(-1 + \theta)\lambda + 32\theta\lambda - 32(\theta + \lambda)) + c\delta(\gamma(-4 + \delta)^2 + 4\delta(\delta - \theta + (-1 + \theta)\lambda))) + c^2(\beta^2(-4 + \theta + \lambda - \theta\lambda)^2(-\delta^2(12 + \theta) + 4\delta(4 + 5\theta) + (-20 + \delta)\delta(-1 + \theta)\lambda + 32\theta\lambda - 32(\theta + \lambda)) + 2\beta\delta(-4 + \theta + \lambda - \theta\lambda)^2(\gamma(-4 + \delta)^2 + 4\delta(\delta - \theta + (-1 + \theta)\lambda)) + \delta(-8\gamma(-4 + \delta)^2(-\theta + (-1 + \theta)\lambda)(\delta - \theta + (-1 + \theta)\lambda) + \gamma^2(-4 + \delta)^2(-16 - 4\delta + 12\theta - \delta\theta + (-12 + \delta)(-1 + \theta)\lambda) + 4(\delta - \theta + (-1 + \theta)\lambda)(128 - 80\delta + 4\delta^2 - 80\theta + 48\delta\theta - 3\delta^2\theta + 4\theta^2 - 3\delta\theta^2 + (-1 + \theta)(80 - 8\theta + 3\delta(-16 + \delta + 2\theta))\lambda - (-4 + 3\delta)(-1 + \theta)^2\lambda^2)))) / (8(-4 + \delta)^2\delta(4 + \theta(-1 + \lambda) - \lambda)^2(\delta + \theta(-1 + \lambda) - \lambda)), and $EI_S^A = \frac{1}{2} \left(-\frac{2(6+f+c(-2+\beta)-2\delta)}{-4+\delta} + \frac{-2+c(-2+\gamma)}{4+\theta(-1+\lambda)-\lambda} - \frac{c\gamma}{\theta+\lambda-\theta\lambda} \right) e_n + \frac{(2f+2c\beta-(1+c)\delta)e_r}{(-4+\delta)\delta}.$$$

By comparing the total consumer surplus and environmental impacts in different production strategies, it is straightforward to obtain the results. Thus, we omit the calculation details here. The thresholds in this proposition are provided below.

$$\hat{e}_r^{EI} = \frac{\delta(2(1-\delta)\theta(4+(-2+\delta(-3+\theta))\theta)+c(\gamma(4+(\delta-2)\theta)(\delta\theta-4)-\beta(4-\theta)((3\delta-2)\theta-4)+2(1-\delta)\theta(4+(\delta(\theta-3)-2)\theta)))}{(-4+\theta)(-8c\beta+4c(\beta+\gamma)\delta+\delta(2-2\delta+c(2+\beta-(2+\gamma)\delta))\theta)} e_n,$$

$$\tilde{e}_{r1}^{EI} = \frac{\delta e_n}{2}, \tilde{e}_{r2}^{EI} = \frac{4\delta e_n - 3\delta^2 e_n + 2\delta\theta e_n + 2\delta\lambda e_n - 2\delta\theta\lambda e_n}{-4\delta + 8\theta - \delta\theta + 8\lambda - \delta\lambda - 8\theta\lambda + \delta\theta\lambda}.$$

$$\begin{aligned} \tilde{f}_1^{CS} = & \frac{1}{9} \left(-4 + 4c - 9c\beta + 3(2+c)\delta + \frac{16(-1+c)}{-4+3\delta} - 9\sqrt{\frac{1}{(4-3\delta)^2\theta(-4+\delta\theta)^2}} ((-4 + \right. \\ & \delta)^2 (4c^2\beta^2(4-3\delta) + \delta(-4c\beta(8+3c\beta) + (4+c(-8+24\beta+c(4+9\beta^2))))\delta)\theta + \\ & \delta^2(12+4c(2-c+2(2+c)\beta) + (-11+c(-2+c-6(2+c)\beta))\delta)\theta^2 + \delta^3(-5 - \\ & c(6+c) + 4\delta + c(4+c)\delta)\theta^3 \left. \right)^{1/2} \Big), \tilde{f}_2^{CS} = \frac{-A_{SR_b} - \sqrt{A_{SR_b}A_{SR_b} - 4A_{SR_a}A_{SR_c}}}{2A_{SR_a}}, \text{ where } A_{SR_a} = \\ & \frac{32+(-20+\delta)\delta}{(-4+\delta)^2\delta} + \frac{1}{-\delta+\theta+\lambda-\theta\lambda}, A_{SR_b} = \frac{8(-2+\delta)}{2(-4+\delta)^2} + \frac{c(4\delta^2+\beta(32+(-20+\delta)\delta))}{2(-4+\delta)^2\delta} + \\ & \frac{c(-\beta+\gamma)}{2\delta+2\theta(-1+\lambda)-\lambda}, \text{ and } A_{SR_c} = \frac{1}{8} \left(\frac{c^2(\beta^2(2-12\delta)-2\beta\gamma\delta+\gamma^2\delta)}{(-1+\delta)\delta\theta} - \frac{c^2(\beta-\gamma)^2}{\delta+\theta(-1+\lambda)-\lambda} + 8 + 16c + \right. \\ & \frac{32c^2\beta^2-4(12+8c(5+\beta)-c^2(4-5\beta^2))\delta+(36+c(88+16\beta+c(\beta(8+\beta)-12)))\delta^2-8(1+2c)\delta^3}{(-4+\delta)^2\delta} + \\ & \frac{(-2-c(2-\beta))(40+4c(2+\beta)+(-14+c(-6+\beta))\delta\theta)}{(-4+\delta\theta)^2} + \frac{(-2+c(-2+\gamma))(40-14\theta+c(8-6\theta+\gamma(4+\theta)))}{(-4+\theta)^2} + \\ & \left. (-2+c(-2+\gamma)) \left(\frac{-14+c(-6+\gamma)}{4+\theta(-1+\lambda)-\lambda} - \frac{8(-2+c(-2+\gamma))}{(-4+\theta+\lambda-\theta\lambda)^2} \right) \right). \end{aligned}$$

$$\begin{aligned} \tilde{f}_3^{CS} = & \frac{-A_{S_b} + \sqrt{A_{S_b}A_{S_b} - 4A_{S_a}A_{S_c}}}{2A_{S_a}} \text{ and } \tilde{f}_3^{CS} = \frac{-A_{S_b} - \sqrt{A_{S_b}A_{S_b} - 4A_{S_a}A_{S_c}}}{2A_{S_a}}, \text{ where } A_{S_a} = \\ & \frac{(3\delta-4)}{2(\delta-4)^2\delta}, A_{S_b} = \frac{1}{8} f \left(-\frac{8(2(-2+\delta)\delta+c(\beta(4-3\delta)+\delta^2))}{(-4+\delta)^2\delta} \right), \text{ and } A_{S_c} = \frac{1}{8} \left(\frac{c^2(\beta^2+\gamma^2\delta)}{\delta\theta} - \right. \\ & \frac{(-14+c(-6+\gamma))(-2+c(-2+\gamma))}{4+\theta(-1+\lambda)-\lambda} - \frac{c^2\gamma^2}{\theta+\lambda-\theta\lambda} + \\ & \frac{4((8c\beta-4(1+c)(5+c)+3c^2\beta^2-4c^2\beta^2)\delta+(7+c(10+3c-2(2+c)\beta))\delta^2)}{(-4+\delta)^2\delta} - \\ & \frac{(-2+c(-2+\gamma))(40-14\theta+c(8-6\theta+\gamma(4+\theta)))}{(-4+\theta)^2} - \frac{8(-2+c(-2+\gamma))^2}{(-4+\theta+\lambda-\theta\lambda)^2} + \\ & \left. \frac{(-2+c(-2+\beta))(40+4c(2+\beta)+(-14+c(-6+\beta))\delta\theta)}{(-4+\delta\theta)^2} \right). \end{aligned}$$

$$\tilde{f}_1^{EI} = \frac{(-1+\theta)((2-c(-2+\beta))\delta^2\theta e_n + (2c\beta(-4+\delta)-\delta(\delta+c(-2\beta+\delta))\theta)e_r)}{\theta(-4+\delta\theta)(\delta e_n - 2e_r)},$$

$$\begin{aligned} \tilde{f}_2^{EI} = & ((-4+\delta)\delta(\delta+\theta(-1+\lambda)-\lambda) \left(\frac{12e_n}{-4+\delta} + \frac{2c(-2+\beta)e_n}{-4+\delta} - \frac{4\delta e_n}{-4+\delta} + (4 + \frac{2-c(-2+\gamma)}{-4+\theta} + \right. \\ & \frac{c(-\beta+\gamma)}{(-1+\delta)\theta} + \frac{4-2c(-2+\beta)}{-4+\delta\theta} \Big) e_n + \frac{(2-c(-2+\gamma))e_n}{4+\theta(-1+\lambda)-\lambda} + \frac{c(\beta-\gamma)e_n}{\delta+\theta(-1+\lambda)-\lambda} + \frac{2e_r}{-4+\delta} + \frac{c(2+\beta)e_r}{-4+\delta} - \frac{8c\beta e_r}{(-4+\delta)\delta} + \\ & \left. \frac{(\frac{c(\beta-\gamma\delta)}{-1+\delta} + \frac{4c\beta-2(1+c)\delta\theta}{-4+\delta\theta})e_r}{\delta\theta} + \frac{c(-\beta+\gamma)e_r}{\delta+\theta(-1+\lambda)-\lambda} \right) / ((\delta(-3\delta+2(2+\theta+\lambda-\theta\lambda))e_n + (8\theta\lambda-8(\theta+ \end{aligned}$$

$$\lambda) + \delta(4 + \theta + \lambda - \theta\lambda))e_r) \quad , \quad \tilde{f}_3^{EI} = ((\delta - 4)\delta(\frac{6e_n}{-4+\delta} + \frac{c(\beta-2)e_n}{-4+\delta} - \frac{2\delta e_n}{-4+\delta} + (2 + \frac{2-c(\gamma-2)}{2(-4+\theta)} - \frac{c\gamma}{2\theta} + \frac{2-c(-2+\beta)}{-4+\delta\theta})e_n + \frac{(2-c(-2+\gamma))e_n}{8+2\theta(-1+\lambda)-2\lambda} + \frac{c\gamma e_n}{2(\theta+\lambda-\theta\lambda)} + \frac{(1+c)e_r}{-4+\delta} - \frac{2c\beta e_r}{(-4+\delta)\delta} - \frac{(-2c\beta+(1+c)\delta\theta)e_r}{\delta\theta(-4+\delta\theta)})) / (-\delta e_n + 2e_r).$$

Additionally, the selling prices when TPR's production strategy is R and SR are shown below.

$$\begin{cases} p_{M1_R}^A = 1 + c - \frac{-2 + f + c(-2 + \beta)}{-4 + \delta} \\ p_{M2_R}^A = 1 + c - \frac{-2 + f + c(-2 + \beta)}{-4 + \delta} \end{cases} \begin{cases} p_{M1_SR}^A = -\frac{2 + f + c(-2 + \beta) - \delta}{-4 + \delta} \\ p_{M2_SR}^A = 1 + \frac{-2 + c(-2 + \gamma)}{4 + \theta(-1 + \lambda) - \lambda} \end{cases} \quad (A-6)$$

$$\begin{cases} p_{M1_R}^U = 1 + c + \frac{2 - c(-2 + \beta)}{-4 + \delta\theta} \\ p_{M2_R}^U = 1 + c + \frac{2 - c(-2 + \beta)}{-4 + \delta\theta} \end{cases} \begin{cases} p_{M1_SR}^U = 1 + c + \frac{2 - c(-2 + \beta)}{-4 + \delta\theta} \\ p_{M2_SR}^U = 1 + c + \frac{2 - c(-2 + \gamma)}{-4 + \theta} \end{cases} \quad (A-7)$$

$$\begin{cases} p_{R1_R}^A = \frac{-2(f + c\beta) + (-1 + f + c(-1 + \beta))\delta}{-4 + \delta} \\ p_{R2_R}^A = \frac{-2(f + c\beta) + (-1 + f + c(-1 + \beta))\delta}{-4 + \delta} \\ p_{S_R}^A = \frac{\delta(1 + c) - 2(f + c\beta + \theta + c\theta) + f\theta + c\beta\theta + (f - c(2 - \beta))(1 - \theta)\lambda - 2}{-4 + \delta} \end{cases} \begin{cases} p_{R1_SR}^A = \frac{-2(f + c\beta) + (-1 + f + c(-1 + \beta))\delta}{-4 + \delta} \\ p_{R2_SR}^A = \frac{1}{2} \left(f + c\beta + \frac{(2 - c(-2 + \gamma))\delta}{4 + \theta(-1 + \lambda) - \lambda} \right) \\ p_{S_SR}^A = -1 - c + c\gamma + \frac{4 - 2c(-2 + \gamma)}{4 + \theta(-1 + \lambda) - \lambda} \end{cases} \quad (A-8)$$

$$\begin{cases} p_{R1_R}^U = \frac{-2c\beta + (-1 + c(-1 + \beta))\delta\theta}{-4 + \delta\theta} \\ p_{R2_R}^U = \frac{-2c\beta + (-1 + c(-1 + \beta))\delta\theta}{-4 + \delta\theta} \\ p_{S_R}^U = \frac{-2c\beta + (-2 + \delta + c(-2 + \beta + \delta))\theta}{-4 + \delta\theta} \end{cases} \begin{cases} p_{R1_SR}^U = \frac{-2c\beta + (-1 + c(-1 + \beta))\delta\theta}{-4 + \delta\theta} \\ p_{R2_SR}^U = \frac{c\beta(-4 + \theta) - 2\delta\theta + c(-2 + \gamma)\delta\theta}{2(-4 + \theta)} \\ p_{S_SR}^U = -\frac{\theta + c(-\gamma(-2 + \theta) + \theta)}{-4 + \theta} \end{cases} \quad (A-9)$$

Appendix A-7. Proof of Proposition A-6

In the coopetition scenario, when f is endogenous and decided by the OEM, the TPR's problem is same as that in (A-5), and the OEM's problem is as follows:

$$\max_{f, q_{R1}^A, q_{R2}^A, q_S^A} \pi_{OEM}^A = (1 - q_{M2}^A - \delta q_{R2}^A - (\theta + (1 - \theta)\lambda)q_S^A - c)q_{M2}^A + f(q_{R1}^A + q_{R2}^A) + F \quad (A-10)$$

The decision sequence is as follows: firstly, the OEM decides f . Secondly, the OEM and

the TPR decide the production quantity for M and the remanufacturing quantity in period 1, respectively. Lastly, the OEM decides production quantity for M in period 2. At the same time, the TPR decides the production quantity for S and remanufacturing quantity in period 2. We use backward induction and begin by characterizing the best-response functions of the OEM's production quantities and the TPR's production strategies in response to f . Additionally, in Appendix A-3 we have proved the convexity of π_{OEM}^A with respect to q_{M1}^A and q_{M2}^A respectively, the convexity of π_{TPR}^A with respect to q_{R1}^A , and the jointly convexity of π_{TPR}^A with respect to q_{R2}^A and q_S^A . Thus, we do not repeat them here.

Let g_1^A and g_2^A denote the Lagrangian multipliers, then we have the Lagrangian function of the TPR's optimization problem as follows:

$$L^A(q_S^A, q_{R2}^A, g_1^A, g_2^A) = (\delta(1 - q_{M1}^A - q_{R1}^A) - \beta c)q_{R1}^A + (\delta(1 - q_{M2}^A - q_{R2}^A - q_S^A) - \beta c)q_{R2}^A * \\ (\theta + (1 - \theta)\lambda - \delta q_{R2}^A - (\theta + (1 - \theta)\lambda)(q_{M2}^A + q_S^A) - \gamma c)q_S^A + g_1^A q_S^A + g_2^A q_{R2}^A \quad (A - 11)$$

with the first conditions

$$\frac{\partial L^A}{\partial q_S^A} = \theta + \lambda - \theta\lambda + g_1^A - 2\delta q_{R2}^A + (\theta(-1 + \lambda) - \lambda)(q_{M2}^A + 2q_S^A) - c\gamma = 0 \quad (A - 12)$$

$$\frac{\partial L^A}{\partial q_{R2}^A} = -f - c\beta + \delta + g_2^A - \delta(q_{M2}^A + 2(q_{R2}^A + q_S^A)) = 0 \quad (A - 13)$$

and the constraints $g_1^A q_S^A = 0$ and $g_2^A q_{R2}^A = 0$. We have the following cases:

Case AE. When the TPR's production strategy is E: $g_1^A > 0, q_S^A = 0, g_2^A > 0$, and $q_{R2}^A = 0$. We have $q_{M2}^{A*} = \frac{1}{2}(1 - c)$, $g_1^A = \frac{1}{2}(2c\gamma - \theta - c\theta + (1 + c)(-1 + \theta)\lambda)$, and $g_2^A = \frac{1}{2}(2(f + c\beta) - (1 + c)\delta)$. Let $g_1^A > 0$ and $g_2^A > 0$, we get $\lambda < \frac{-2c\gamma + \theta + c\theta}{-1 - c + \theta + c\theta}$ and $f > \frac{1}{2}(-2c\beta + \delta + c\delta)$. Since $q_{R1}^{A*} < 0$ if $f > \frac{1}{2}(-2c\beta + \delta + c\delta)$, we omit this case.

Case AR. When the TPR's production strategy is R: $g_1^A > 0, g_2^A = 0, q_S^A = 0$, and $q_{R2}^A > 0$. We have $q_{M2_R}^{A*} = \frac{-2+2c-f-c\beta+\delta}{-4+\delta}$, $q_{R2_R}^{A*} = \frac{2f+2c\beta-(1+c)\delta}{(-4+\delta)\delta}$ and $g_1^{A*} = \frac{f(4-s)+s(2-c(-2+\beta))+4c(\beta-\gamma)+(c(-2+\gamma)-2)\delta}{-4+\delta}$. Submitting the optimal decisions into (A-5) and (A-10), taking the first-order derivations of the OEM's the TPR's profits with respect to q_{M1}^A

and q_{R1}^A respectively, we get $q_{M1}^{A*} = -\frac{2+f+c(-2+\beta)-\delta}{-4+\delta}$ and $q_{R1}^{A*} = \frac{2f+2c\beta-(1+c)\delta}{(-4+\delta)\delta}$.

Let $g_1^A > 0$ and $q_{R2_R}^{A*} > 0$, we get

- if $\gamma \leq \frac{\theta+c\theta+\lambda+c\lambda-\theta\lambda-c\theta\lambda}{2c}$, $f < \frac{4c(\gamma-\beta)+2\delta+2c\delta-c\gamma\delta-2\theta-2c\theta+c\beta\theta-2\lambda-2c\lambda+c\beta\lambda+2\theta\lambda+c\theta\lambda(2-\beta)}{4-\theta-\lambda+\theta\lambda}$,
- if $\gamma > \frac{\theta+c\theta+\lambda+c\lambda-\theta\lambda-c\theta\lambda}{2c}$, $f < \frac{1}{2}(-2c\beta + \delta + c\delta)$.

Now, we solve the OEM's optimal decision on f . The OEM's problem is characterized by Karush-Kuhn-Tucker (conditions). Let b_1 and b_2 denote the Lagrangian multipliers. Because the second derivative of the OEM's profit with respect to f is less than zero (i.e., $\frac{\partial^2 \pi_{OEM}^A}{\partial f \partial f} = -\frac{4(8-3\delta)}{(4-\delta)^2\delta} < 0$), π_{OEM}^A is concave in f .

(i) When $\gamma \leq \frac{\theta+c\theta+\lambda+c\lambda-\theta\lambda-c\theta\lambda}{2c}$, the Lagrangian function for the OEM's optimization problem is $L_{OEM}^{R1} = \pi_{OEM}^A + b_1 \left(\frac{-4c\beta+4c\gamma+2\delta+2c\delta-c\gamma\delta-2\theta-2c\theta+c\beta\theta-2\lambda-2c\lambda+c\beta\lambda+2\theta\lambda+2c\theta\lambda-c\beta\theta\lambda}{4-\theta-\lambda+\theta\lambda} - f \right)$. With the first-order condition $\frac{\partial L_{OEM}^{R1}}{\partial f} = \frac{-16c\beta+8(2+c\beta)\delta-2(3+c)\delta^2+4f(-8+3\delta)-(-4+\delta)^2\delta b_1}{(-4+\delta)^2\delta} = 0$ and the constraint $b_1 \left(\frac{-4c\beta+4c\gamma+2\delta+2c\delta-c\gamma\delta-2\theta-2c\theta+c\beta\theta-2\lambda-2c\lambda+c\beta\lambda+2\theta\lambda+2c\theta\lambda-c\beta\theta\lambda}{4-\theta-\lambda+\theta\lambda} - f \right) = 0$, we have the following two subcases:

Case AR1: when $b_1 = 0$ and $f < \frac{-4c\beta+4c\gamma+2\delta+2c\delta-c\gamma\delta-2\theta-2c\theta+c\beta\theta-2\lambda-2c\lambda+c\beta\lambda+2\theta\lambda+2c\theta\lambda-c\beta\theta\lambda}{4-\theta-\lambda+\theta\lambda}$, we have $f_R^* = f_{R1} = \frac{8c\beta-4(2+c\beta)\delta+(3+c)\delta^2}{-16+6\delta}$. Let $f_R^* < \frac{4c(\gamma-\beta)+2\delta(1+c)-2\theta(1-c)+c\beta\theta-2\lambda(1+c)+c\beta\lambda+2\theta\lambda(1+c)-c\beta\theta\lambda-c\gamma\delta}{4-\theta-\lambda+\theta\lambda}$, we get the condition $\gamma_2 < \gamma \leq \gamma_1$, where $\gamma_1 = \frac{(\theta+c\theta+\lambda+c\lambda-\theta\lambda-c\theta\lambda)}{(2c)}$ and $\gamma_2 = \frac{1}{2} \left(\frac{-8\beta+8\delta-8\theta+2\beta\theta+\delta\theta-(-8+2\beta+\delta)(-1+\theta)\lambda}{-8+3\delta} + \frac{\theta+\lambda-\theta\lambda}{c} \right)$. The relative profits are $\pi_{OEM_R1}^A = \frac{2c(8-3\delta)\delta+(1+2F)\delta(-8+3\delta)-c^2(4\beta^2-8\beta\delta+\delta(8+\delta))}{2\delta(-8+3\delta)}$ and $\pi_{TPR_R1}^A = \frac{8c^2(\beta-\delta)^2-F(8-3\delta)^2\delta}{(8-3\delta)^2\delta}$.

Case AR2: when $b_1 > 0$, $f > \frac{-4c\beta+4c\gamma+2\delta+2c\delta-c\gamma\delta-2\theta-2c\theta+c\beta\theta-2\lambda-2c\lambda+c\beta\lambda+2\theta\lambda+2c\theta\lambda-c\beta\theta\lambda}{4-\theta-\lambda+\theta\lambda}$ does not hold. Thus, this case does not hold.

(ii) When $\gamma > \frac{\theta+c\theta+\lambda+c\lambda-\theta\lambda-c\theta\lambda}{2c}$, the Lagrangian function for the OEM's optimization problem is $L_{OEM}^{R2} = \pi_{OEM}^A + b_2 \left(\frac{1}{2}(-2c\beta + \delta + c\delta) - f \right)$. With the first-order condition $\frac{\partial L_{OEM}^{R2}}{\partial f} = \frac{-16c\beta+8(2+c\beta)\delta-2(3+c)\delta^2+4f(-8+3\delta)-(-4+\delta)^2\delta b_2}{(-4+\delta)^2\delta} = 0$ and the constraint $b_2 \left(\frac{1}{2}(-2c\beta + \delta + c\delta) - f \right) = 0$, we have the following two subcases:

Case AR3: when $b_2 = 0$ and $f < \frac{1}{2}(-2c\beta + \delta + c\delta)$, we have $f_R^* = f_{R2} = \frac{8c\beta-4(2+c\beta)\delta+(3+c)\delta^2}{-16+6\delta}$. Let $f_R^* < \frac{1}{2}(-2c\beta + \delta + c\delta)$, we get the condition $\gamma > \gamma_1$. The relative profits are $\pi_{OEM_R3}^A = \frac{2c(8-3\delta)\delta+(1+2F)\delta(-8+3\delta)-c^2(4\beta^2-8\beta\delta+\delta(8+\delta))}{2\delta(-8+3\delta)}$ and $\pi_{TPR_R3}^A = \frac{8c^2(\beta-\delta)^2-F(8-3\delta)^2\delta}{(8-3\delta)^2\delta}$.

Case AR4: when $b_2 > 0$, $f > \frac{1}{2}(-2c\beta + \delta + c\delta)$ does not hold. Thus, this case does not hold.

Case ASR. When the TPR's production strategy is SR: $g_1^A = 0, g_2^A = 0, q_S^A > 0$, and $q_{R2}^A > 0$. We have $q_{M2_SR}^{A*} = \frac{2-c(2-\gamma)-\theta-\lambda+\theta\lambda}{4-\theta(1-\lambda)-\lambda}$, $q_{R2_SR}^{A*} = \frac{1}{2} \left(-\frac{f+c\beta}{\delta} + \frac{f+c(\beta-\gamma)}{\delta+\theta(-1+\lambda)-\lambda} \right)$, and $q_{S_SR}^{A*} = \frac{1}{2} \left(\frac{2-c(-2+\gamma)}{4+\theta(-1+\lambda)-\lambda} - \frac{f+c(\beta-\gamma)}{\delta+\theta(-1+\lambda)-\lambda} \right)$. q_{M1}^A and q_{R1}^A remain consistent with those in Case AR. Let $q_{R2_SR}^{A*} > 0$ and $q_{S_SR}^{A*} > 0$, we get that $\gamma < \frac{s+cs}{2c}$ and $\frac{2s+2cs+4c\beta-cs\beta-4c\gamma-2\delta-2c\delta+c\gamma\delta}{-4+s} < f < \frac{-cs\beta+c\gamma\delta}{s}$, where $s = (1-\theta)\lambda + \theta$.

Now, we solve the OEM's optimal decisions on f . The OEM's problem is characterized by Karush-Kuhn-Tucker (conditions). Let c_1 and c_2 denote the Lagrangian multipliers. The Lagrangian function for the OEM's optimization problem is $L_{OEM}^{SR} = \pi_{OEM}^A + c_1 \left(f - \frac{2s+2cs+4c\beta-cs\beta-4c\gamma-2\delta-2c\delta+c\gamma\delta}{-4+s} \right) + c_2 \left(\frac{-cs\beta+c\gamma\delta}{s} - f \right)$. With the first-order condition $\frac{\partial L_{OEM}^{SR}}{\partial f} = \frac{2f+c(\beta-\gamma)}{\delta+\theta(-1+\lambda)-\lambda} + c_1 - c_2 + \frac{4(4+7f+4c\beta)\delta-(2(3+c+f)+c\beta)\delta^2-32(2f+c\beta)}{2(-4+\delta)^2\delta} = 0$ and the constraints $c_2 \left(\frac{c\gamma\delta-cs\beta}{s} - f \right) = 0$ and $c_1 \left(f - \frac{2s+2cs+4c\beta-cs\beta-4c\gamma-2\delta-2c\delta+c\gamma\delta}{-4+s} \right) = 0$, we have the following subcases:

Case ASR1. when $c_1 = c_2 = 0$, $\frac{2s(1+c)+c\beta(4-s)-(4-\delta)c\gamma-2\delta(1+c)}{-4+s} < f < \frac{c\gamma\delta-cs\beta}{s}$, we get $f_{SR} = \frac{16(s+cs\beta+c(\beta+\gamma))\delta-(16+6s+cs(2+\beta)+8c(\beta+\gamma))\delta^2+(6+c(2+\gamma))\delta^3-32cs\beta}{64s-4(8+7s)\delta+2(6+s)\delta^2}$. Let $\frac{2s(1+c)+c\beta(4-s)-(4-\delta)c\gamma-2\delta(1+c)}{-4+s} < f_{SR} < \frac{c\gamma\delta-cs\beta}{s}$, we have $\gamma_4 < \gamma < \gamma_3$, where $\gamma_3 = (2(-16+5\delta)(\theta(-1+\lambda)-\lambda)(\delta+\theta(-1+\lambda)-\lambda)-c\beta(4+\theta(-1+\lambda)-\lambda)(-4\delta+8\theta-\delta\theta+(-8+\delta)(-1+\theta)\lambda)+2c(\delta+\theta(-1+\lambda)-\lambda)(-8\delta+16\theta-3\delta\theta+(-16+3\delta)(-1+\theta)\lambda))/\left(c(24\delta(2+\theta)-\delta^2(16+\theta)+(-24+\delta)\delta(-1+\theta)\lambda+64\theta\lambda-64(\theta+\lambda))\right)$ and $\gamma_4 = \left((\theta(-1+\lambda)-\lambda)\left(2\delta(-8+3\delta)(\delta-\theta+(-1+\theta)\lambda)+c(2\delta^2(\delta-\theta+(-1+\theta)\lambda)-\beta(-4+\delta)(-4\delta+8\theta-\delta\theta+(-8+\delta)(-1+\theta)\lambda))\right)\right)/\left(c\delta(-\delta^2(12+\theta)+4\delta(8+5\theta)+(-20+\delta)\delta(-1+\theta)\lambda+48\theta\lambda-48(\theta+\lambda))\right)$.

The relative profits are $\pi_{OEM_SR1}^A = F + (-2 + 2c - c\gamma + \theta + \lambda - \theta\lambda)^2 / (4 - \theta(1 - \lambda) - \lambda)^2 - (8(4 - c(4 - \beta))(\theta(1 - \lambda) + \lambda) + \delta^2(c(2 + \gamma) + 2\theta(-1 + \lambda) - 2(3 + \lambda)) + (\delta(16 - 18\theta(-1 + \lambda) + 18\lambda - 2c(8 + 2\gamma - 3\theta(-1 + \lambda) + 3\lambda) + c\beta(4 + \theta + \lambda - \theta\lambda)))^2) / (4(-2\delta(-8 + 7\theta(-1 + \lambda) - 7\lambda) + \delta^2(-6 + \theta(-1 + \lambda) - \lambda) + 32(\theta(-1 + \lambda) - \lambda))^2) + ((c\beta(\delta^2(-8 + \theta(-1 + \lambda) - \lambda) - 16\delta(-1 + \theta(-1 + \lambda) - \lambda) + 32(\theta(-1 + \lambda) - \lambda)) + c\delta(\gamma(4 - \delta)^2 + 2\delta(\delta + \theta(-1 + \lambda) - \lambda)) + 2\delta(-8 + 3\delta)(\delta + \theta(-1 + \lambda) - \lambda))(2\delta^2(\theta(1 - \lambda) + \lambda)(\delta + \theta(-1 + \lambda) - \lambda) + c(\beta(8\theta(-1 + \lambda) - 8\lambda + \delta(4 + \theta + \lambda - \theta\lambda))^2 + \delta(2\delta^2(-8 + \theta(-1 + \lambda) - \lambda) - \gamma\delta^2(8 + \theta(1 - \lambda) + \lambda) - 16\gamma\delta(-1 + \theta(-1 + \lambda) - \lambda) + 32\gamma(\theta(-1 + \lambda) - \lambda) - 32(\theta + \lambda - \theta\lambda)^2 + 2\delta(\theta^2(1 - \lambda)^2 + \lambda(24 + \lambda) - 2\theta(-12 + 11\lambda + \lambda^2)))))) / (8\delta(2\delta(8 - 7\theta(1 - \lambda) + 7\lambda) - \delta^2(6 + \theta(1 - \lambda) - \lambda) + 32(\theta(1 - \lambda) + \lambda))^2(\delta - \theta(1 - \lambda) - \lambda))$ and $\pi_{TPR_SR1}^A = -((16F\delta(4 + \theta(-1 + \lambda) - \lambda)^2(\delta + \theta(-1 + \lambda) - \lambda)(2\delta(-8 + 7\theta(-1 + \lambda) - 7\lambda) + 32(\theta + \lambda - \theta\lambda) + \delta^2(6 + \theta + \lambda - \theta\lambda))^2 - 8(4 + \theta(-1 + \lambda) - \lambda)^2(\delta + \theta(-1 + \lambda) - \lambda)(6\delta^3 + c\beta(-6\delta(-4 + 3\theta(-1 + \lambda) - 3\lambda) + \delta^2(-8 + \theta(-1 + \lambda) - \lambda) + 48(\theta(-1 + \lambda) - \lambda)) + 8\delta^2(-2 + \theta(-1 + \lambda) - \lambda) + 24\delta(\theta + \lambda - \theta\lambda) + c(-4 + \delta)\delta(\gamma(-2 + \delta) + 2(\delta - 2\theta - 2\lambda + 2\theta\lambda)))((-4 + \delta)\delta(\theta(-1 + \lambda) - \lambda) +$

$$\begin{aligned}
& c(\delta(\gamma(-4 + \delta) + \delta(-4 + \theta(-1 + \lambda) - \lambda) + 8(\theta + \lambda - \theta\lambda)) + \beta(8\theta(-1 + \lambda) - \\
& 8\lambda + \delta(4 + \theta + \lambda - \theta\lambda)))) + 4(4 - \delta)\delta(c(2\gamma + \theta(-1 + \lambda) - \lambda) + \theta(-1 + \lambda) - \\
& \lambda)(2\delta(-8 + 7\theta(-1 + \lambda) - 7\lambda) + 32(\theta + \lambda - \theta\lambda) + \delta^2(6 + \theta + \lambda - \theta\lambda))(2(-16 + \\
& 5\delta)(\theta(-1 + \lambda) - \lambda)(\delta + \theta(-1 + \lambda) - \lambda) - c(\gamma(\delta^2(-16 + \theta(-1 + \lambda) - \lambda) - \\
& 24\delta(-2 + \theta(-1 + \lambda) - \lambda) + 64(\theta(-1 + \lambda) - \lambda)) + 2\delta^2(8 - 3\theta(-1 + \lambda) + 3\lambda) + \\
& 32(\theta + \lambda - \theta\lambda)^2 + \beta(4 + \theta(-1 + \lambda) - \lambda)(\delta(-4 + \theta(-1 + \lambda) - \lambda) + 8(\theta + \lambda - \\
& \theta\lambda)) - 6\delta(\theta^2(-1 + \lambda)^2 + \lambda(8 + \lambda) - 2\theta(-4 + 3\lambda + \lambda^2)))) - 2(c\beta(\delta^2(-8 + \\
& \theta(-1 + \lambda) - \lambda) - 16\delta(-1 + \theta(-1 + \lambda) - \lambda) + 32(\theta(-1 + \lambda) - \lambda)) + \\
& 2(c\beta(\delta^2(-8 + \theta(-1 + \lambda) - \lambda) - 16\delta(-1 + \theta(-1 + \lambda) - \lambda) + 32(\theta(-1 + \lambda) - \\
& \lambda)) + c\delta(\gamma(-4 + \delta)^2 + 2\delta(\delta + \theta(-1 + \lambda) - \lambda)) + 2\delta(-8 + 3\delta)(\delta + \theta(-1 + \lambda) - \\
& \lambda))(4 + \theta(-1 + \lambda) - \lambda)^2(2\delta^2(\theta(-1 + \lambda) - \lambda)(\delta + \theta(-1 + \lambda) - \lambda) - c(\beta(8\theta(-1 + \\
& \lambda) - 8\lambda + \delta(4 + \theta + \lambda - \theta\lambda))^2 + \delta(2\delta^2(-8 + \theta(-1 + \lambda) - \lambda) + \gamma\delta^2(-8 + \theta(-1 + \\
& \lambda) - \lambda) - 16\gamma\delta(-1 + \theta(-1 + \lambda) - \lambda) + 32\gamma(\theta(-1 + \lambda) - \lambda) - 32(\theta + \lambda - \theta\lambda)^2 + \\
& 2\delta(\theta^2(-1 + \lambda)^2 + \lambda(24 + \lambda) - 2\theta(-12 + 11\lambda + \lambda^2)))))) + (4 + \theta(-1 + \lambda) - \\
& \lambda)(2\delta(-8 + 3\delta)(\theta(-1 + \lambda) - \lambda)(\delta + \theta(-1 + \lambda) - \lambda) - c(\gamma\delta(-4\delta(-8 + 5\theta(-1 + \\
& \lambda) - 5\lambda) + \delta^2(-12 + \theta(-1 + \lambda) - \lambda) + 48(\theta(-1 + \lambda) - \lambda)) + (\theta(-1 + \lambda) - \\
& \lambda)(2\delta^2(-\delta + \theta + \lambda - \theta\lambda) + \beta(-4 + \delta)(\delta(-4 + \theta(-1 + \lambda) - \lambda) + 8(\theta + \lambda - \\
& \theta\lambda)))))(2\delta(\delta^2(24 + \theta(-1 + \lambda) - \lambda) + \delta(-64 + 3\theta^2(-1 + \lambda)^2 - 32\lambda + 3\lambda^2 + \\
& \theta(-32 + 38\lambda - 6\lambda^2)) - 8(\theta^2(-1 + \lambda)^2 + (-12 + \lambda)\lambda - 2\theta(6 - 7\lambda + \lambda^2))) + \\
& c(\beta(4 + \theta(-1 + \lambda) - \lambda)(\delta^2(-20 + 3\theta(-1 + \lambda) - 3\lambda) + 96(\theta(-1 + \lambda) - \lambda) + \\
& \delta(48 - 44\theta(-1 + \lambda) + 44\lambda)) + \delta(\gamma(16(4 + 5\theta(-1 + \lambda) - 5\lambda) + \delta^2(-8 + 3\theta(-1 + \\
& \lambda) - 3\lambda) - 36\delta(\theta(-1 + \lambda) - \lambda)) + 2(64(\theta + \lambda - \theta\lambda) + \delta^2(16 + \theta + \lambda - \theta\lambda) + \\
& \delta(-32 + \theta^2(-1 + \lambda)^2 - 32\lambda + \lambda^2 - 2\theta(16 - 17\lambda + \lambda^2)))))))/(16\delta(4 + \theta(-1 + \\
& \lambda) - \lambda)^2(\delta + \theta(-1 + \lambda) - \lambda)(2\delta(-8 + 7\theta(-1 + \lambda) - 7\lambda) + 32(\theta + \lambda - \theta\lambda) + \\
& \delta^2(6 + \theta + \lambda - \theta\lambda))^2)).
\end{aligned}$$

Case ASR2. when $c_1 > 0$ and $c_2 = 0$, we get $f^* = 2 + 2c - c\beta - ((-2 + c(-2 + \gamma))(-4 + \delta))/(4 + \theta(-1 + \lambda) - \lambda)$. When substituting it into $q_{S_SR}^{A*}$, we get $q_{S_SR}^{A*} = 0$. This conflicts with the condition of Case ASR, hence, this case does not hold.

Case ASR3. when $c_1 = 0$ and $c_2 > 0$, we get $f^* = c(\gamma\delta/(\theta + \lambda - \theta\lambda) - \beta)$. When substituting it into $q_{R2_SR}^{A*}$, we get $q_{R2_SR}^{A*} = 0$, This is conflict with the condition of Case ASR, thus, this case does not hold.

Case AS. When the TPR's production strategy is S: $g_1^A = 0, q_S^A > 0, g_2^A > 0$, and $q_{R2}^A = 0$. We get $q_{M2_S}^{A*} = \frac{2-c(2-\gamma)-\theta-\lambda+\theta\lambda}{4-\theta(1-\lambda)-\lambda}$, $q_{R2_S}^{A*} = \frac{1}{2}\left(-\frac{f+c\beta}{\delta} + \frac{f+c(\beta-\gamma)}{\delta+\theta(-1+\lambda)-\lambda}\right)$, $q_{S_S}^{A*} = \frac{1}{2}\left(\frac{2-c(-2+\gamma)}{4+\theta(-1+\lambda)-\lambda} - \frac{f+c(\beta-\gamma)}{\delta+\theta(-1+\lambda)-\lambda}\right)$, and $g_2^{A*} = \frac{c\gamma\delta-f\theta-c\beta\theta+(f+c\beta)(-1+\theta)\lambda}{\theta(-1+\lambda)-\lambda}$. q_{M1}^A and q_{R1}^A remain consistent with those in Case AR. Let $q_{S_S}^{A*} > 0$ and $g_2^{A*} > 0$, we get $\gamma < \frac{\theta+c\theta+\lambda+c\lambda-\theta\lambda-c\theta\lambda}{2c}$ and $f > \frac{-c\gamma\delta+c\beta\theta+c\beta\lambda-c\beta\theta\lambda}{-\theta-\lambda+\theta\lambda}$. Now, we solve the OEM's optimal decisions on f . The OEM's problem is characterized by Karush-Kuhn-Tucker (conditions). Let d_1 denote the Lagrangian multiplier. The Lagrangian function for the OEM's optimization problem is $L_{OEM}^S = \pi_{OEM}^A + d_1\left(f - \frac{-c\gamma\delta+c\beta\theta+c\beta\lambda-c\beta\theta\lambda}{-\theta-\lambda+\theta\lambda}\right)$. With the first-order condition $\frac{\partial L_{OEM}^S}{\partial f} = \frac{4c\beta(-2+\delta)+(8+d(-4+\delta)^2-3\delta)\delta-c\delta^2+2f(-8+3\delta)}{(-4+\delta)^2\delta} = 0$, and the constraint $d_1\left(f - \frac{-c\gamma\delta+c\beta\theta+c\beta\lambda-c\beta\theta\lambda}{-\theta-\lambda+\theta\lambda}\right) = 0$, we have the following subcases:

Case AS1. when $d_1 = 0$, we get $f_S^* = f_{R1} = \frac{8c\beta-4(2+c\beta)\delta+(3+c)\delta^2}{-16+6\delta}$. Let $f_S^* > \frac{-c\gamma\delta+c\beta\theta+c\beta\lambda-c\beta\theta\lambda}{-\theta-\lambda+\theta\lambda}$, we get $\gamma < \gamma_5$, where $\gamma_5 = \frac{(\delta(-8+3\delta)+c(2\beta(-4+\delta)+\delta^2))(\theta(-1+\lambda)-\lambda)}{2c\delta(8-3\delta)}$.

The relative profits are $\pi_{OEM_S}^A = \frac{(-2+2c-c\gamma+\theta+\lambda-\theta\lambda)^2}{(4+\theta(-1+\lambda)-\lambda)^2} - \frac{c(-\beta+\delta)(\delta(-8+3\delta)+c(-4\beta(-2+\delta)+\delta^2))}{(8-3\delta)^2\delta} + F + \frac{(8-3\delta+c(-8+2\beta+\delta))^2}{4(8-3\delta)^2}$ and $\pi_{TPR_S}^A = \frac{c(\beta-\delta)(-4c\beta(-3+\delta)+c(-4+\delta)\delta+\delta(-8+3\delta))}{(8-3\delta)^2\delta} - F + \frac{c(-\beta+\delta)(\delta(-8+3\delta)+c(-4\beta(-2+\delta)+\delta^2))}{(8-3\delta)^2\delta} - \frac{(\theta+\lambda-\theta\lambda+c(-2\gamma+\theta+\lambda-\theta\lambda))^2}{(\theta(-1+\lambda)-\lambda)(4+\theta(-1+\lambda)-\lambda)^2}$.

Case AS2. when $d_1 > 0$, $f > (-c\gamma\delta + c\beta\theta + c\beta\lambda - c\beta\theta\lambda)/(-\theta - \lambda + \theta\lambda)$ does not hold. Thus, this case does not hold.

In conclusion, the OEM has four potential decisions on f , i.e., Case AR1, Case AR3, Case ASR1, and Case AS1. He makes decisions by maximizing his profit. By comparing the thresholds and the corresponding profit for OEM in these four cases, we can obtain the

OEM's optimal decision on f in different conditions, which are shown in Proposition 6. The formulas of thresholds in Proposition 6 are shown as follows:

$$\begin{aligned} \tilde{\gamma}_1 = & \sqrt{2}\sqrt{-\left(\frac{1}{(c^2(-4+\delta)^4\delta^2(-8+3\delta))}\right)(8c\beta - 4(2+c\beta)\delta + (3+c)\delta^2)^2(\delta + \theta(-1 + \\ & \lambda) - \lambda)(-\delta^2(6+\theta) + 2\delta(8+7\theta) + (-14+\delta)\delta(-1+\theta)\lambda + 32\theta\lambda - 32(\theta+\lambda)) + \\ & (-2\delta(-8+3\delta)(\delta + \theta(-1+\lambda) - \lambda) + 2c\delta^2(-\delta + \theta + \lambda - \theta\lambda) + c\beta(16\delta(-1 + \theta(-1 + \\ & \lambda) - \lambda) + 32(\theta + \lambda - \theta\lambda) + \delta^2(8 + \theta + \lambda - \theta\lambda))) / (c(-4 + \delta)^2\delta)} \quad , \quad \tilde{\gamma}_3 = \gamma_2 \quad , \quad \tilde{\gamma}_2 = \\ & \max\{\gamma_3, \min\{\gamma_3, \gamma_5\}\}. \end{aligned}$$

The proof is completed.

4. Study 2: Used products remanufacturing, recovery, or reuse?

Interactions between OEMs and TPRs under environmental policies

This study examines used product management and production decisions in a CLSC under two environmental policies: emission taxes and waste management regulations. The supply chain comprises an original equipment manufacturer (OEM, he) and a third-party remanufacturer (TPR, she). When managing the used products that he has sold, the OEM must either pay waste management taxes or outsource their management to the TPR. The TPR recovers value from these used products by remanufacturing them or recovering materials; she may also produce new products using the recovered materials. Because both firms sell products in the same market, their offerings cannibalize each other's market share. Such a closed-loop supply chain (CLSC) is not uncommon in practice. We develop analytical models to examine how key factors (e.g., cost structures, environmental policies) influence the OEM's used product management outsourcing decision and the TPR's used product recovery and new product production decisions. To cover practical cases as comprehensively as possible, we describe the two firms' decision-making problems in three scenarios: (i) no outsourcing, (ii) outsourcing without the TPR's new product production, and (iii) outsourcing with the TPR's new product production. Our analytical results reveal the conditions under which the TPR engages in remanufacturing or new product production and the OEM outsources used product management to the TPR. For example, an extremely high collection cost discourages the TPR from remanufacturing, whilst a high waste management tax incentivizes the TPR to produce new products; despite market competition, the introduction of the TPR's new products can prompt the OEM to outsource used product management when the emission tax is high and the waste management tax is moderate.

4.1 Introduction

In recent decades, rapid industrialization has escalated the volume of waste. This increase, coupled with a growing emphasis on resource circularity, has intensified the need for effective management of used products (King et al., 2005). As a result, in practice, regulations in many countries require original equipment remanufacturers (OEMs) to either bear financial responsibility for used products or ensure their proper management (Yenipazarli, 2016). For instance, China's Administrative Measures for the Recovery of Scrapped Motor Vehicles (State Council of China, 2001, revised 2019) and the EU's End-of-Life Vehicles Directive (Directive 2000/53/EC; European Parliament and Council, 2000) mandate that OEMs ensure the proper management of end-of-life vehicles. However, many OEMs lack the resources, expertise, or infrastructure necessary for effective used product management (Zhao et al., 2022). Faced with these constraints, they must choose between directly paying waste management fees and outsourcing used product management to third-party remanufacturers (TPRs). According to Liao and Ho (2014) and Vedantam and Iyer (2021), outsourcing the management of used products is a common practice. For example, HP and Dell collaborate with certified recyclers, e.g., Sims Lifecycle Services, to manage electronic waste (Atasu and Van Wassenhove, 2012; Vedantam and Iyer, 2021); a renowned OEM of batteries in China: BYD outsources the handling of his end-of-life batteries to a TPR called GEM (Liu, 2021).

In the used product management outsourcing business, TPRs collect used products originally produced by OEMs and create value from them through two potential used product recovery (hereafter product recovery) strategies: remanufacturing used products and recovering materials from used products. Additionally, to maximize resource utilization and strengthen their market presence, they may produce new products under their own brands using recovered materials, competing directly with OEMs and their remanufactured offerings (Xue et al., 2021; Chen et al., 2023). For instance, GEM manufactures new batteries from materials recovered from BYD's used batteries and competes with BYD by offering both remanufactured and new batteries in the same market (Liu, 2021). To summarize, such outsourcing practices create a dual dynamic in the relationship between OEMs and TPRs. In

other words, their interactions involve both cooperation and competition. Cooperation emerges when OEMs outsource used product management to TPRs to avoid paying waste management taxes; competition arises when TPRs decide to remanufacture used products and to produce their own-branded new products. Furthermore, the entry of TPRs' new products into the same markets not only intensifies OEMs' competitive pressure but also challenges the market shares of OEMs' new products and TPRs' remanufactured ones.

Caused by the entry of TPRs' new products into the same markets, the coexistence of cooperation and competition (termed as "coopetition" in literature) complicates decision-making for OEMs and TPRs in used product management outsourcing, production quantities, and so on. Regarding OEMs, the challenge lies in weighing cost savings from outsourcing used product management against potential revenue losses from market cannibalization. It is difficult for OEMs to quantify these losses because they are jointly influenced by both their own production decisions and those of TPRs, which are difficult for OEMs to predict. For TPRs, they have to determine i) the unit outsourcing fee and ii) product recovery (mentioned above) and new product production strategies. Similarly, TPRs' decision-making is not straightforward. This is because when making decisions, they must weigh revenues from outsourcing fees, remanufactured product sales, new product sales, and salvage value of recovered materials. First, estimating corresponding revenue from outsourcing fees to be paid by OEMs is barely possible (because it is OEMs, not TPRs, who determine OEMs' production quantities). Additionally, because costs and market situations are dynamic and change according to OEMs' and TPRs' decisions, prioritizing revenue sources is complex. To recap, coopetition makes OEMs' and TPRs' decision-making highly mutually dependent and complicated. The complexity is compounded by market conditions¹⁶ and environmental policy interventions.

In the relevant literature, authors studied decision-making interactions between OEMs and TPRs. Per their results, both OEMs and TPRs can be better off when cooperating through outsourcing rather than engaging in pure competition (e.g., [Zou et al., 2016](#); [Li et al., 2023](#), to

¹⁶ Market conditions refer to consumers' willingness to pay (WTP) for OEMs' and TPRs' products.

name but two). However, the context of these studies lies in remanufacturing outsourcing where used product management and its outsourcing (our study context) are not included. Moreover, limited research has addressed the additional complexities introduced by the entry of TPRs' new products into OEMs' markets. In fact, as suggested by our literature review, no investigation has been made to examine the decision-making interactions between OEMs and TPRs in the context involving used product management outsourcing and TPRs' involvement in new product production. (This might be partially caused by the decision-making difficulty and complexity mentioned above.) Due to the lack of research, the interaction mechanism between OEMs and TPRs is unclear. Consequently, the solutions supporting OEMs' and TPRs' decision-making are not available. Recognizing that the above decision-making problem is realistic, in this study, we investigate the interactions between OEMs and TPRs to provide decision-making support. More specifically, we seek to answer the following research questions: (i) When should OEMs outsource used product management to TPRs? (ii) What product recovery strategies should TPRs adopt? (iii) When should TPRs produce new products? (iv) How does introducing the TPRs' new products influence the OEMs' outsourcing strategy?

To answer these questions, this study examines a CLSC consisting of an OEM and a TPR operating under emission taxes and waste management regulations. Both firms aim to maximize their profits by making diverse decisions. The OEM determines his production quantities and decides whether or not to outsource used product management; the TPR sets the unit outsourcing fee, selects product recovery strategies, and determines production quantities for her remanufactured and/or new products. To cover practical cases as comprehensively as possible, we analyze three scenarios: (i) no outsourcing, (ii) outsourcing without the TPR's new product production, and (iii) outsourcing with the TPR's new product production. We first derive the two firms' optimal decisions in all three scenarios and assess the impact of environmental policies. Subsequently, we examine the TPR's product recovery strategies and explore the conditions that discourage her from remanufacturing, as well as the conditions under which she chooses to produce new products. Finally, we analyze the OEM's outsourcing strategy and evaluate how introducing the TPR's new products influences this

decision.

The remainder of this paper is organized as follows. Section 4.2 reviews the related literature. We present the problem context and modeling framework in Section 4.3. In the following section, we analyze optimal decisions under the three scenarios and highlight the TPR's strategies for product recovery and new product production, as well as the OEM's outsourcing strategies. We end the paper in Section 4.5 by pointing out the limitations and suggesting avenues for future research.

4.2 Literature review

Our study is related to two streams in the operations management literature. The first stream focuses on used product management and provides context information. The second one examines the coopetition dynamics between OEMs and other partners in CLSCs. Below, we review articles in each stream.

4.2.1 Firms' decisions related to used product management

Environmental policies require firms to manage their end-of-life products effectively ([Atasu and Van Wassenhove, 2012](#)), significantly affecting their operational decision-making. This regulatory pressure has driven extensive research into firms' decisions related to used product management, which includes both the collection and recovery of used products. Among the countless articles published, some examine firms' collection strategies¹⁷ and the corresponding performance under mandatory environmental policies.

Playing an important role in promoting the circular economy, product recovery has been receiving much attention. In an early study, [Thierry et al. \(1995\)](#) define five product recovery strategies, including remanufacturing and recycling. Their work provides a theoretical basis for product recovery. Based on [Thierry et al. \(1995\)](#), [Krikke et al. \(1998\)](#) propose a stochastic dynamic programming model to optimize OEMs' recovery and disposal strategies for durable assembly products under extended producer responsibility (EPR). [King et al. \(2005\)](#) prove

¹⁷ Our study mainly focuses on product recovery and accordingly, we limit our discussion on collection strategies. For a comprehensive review of the literature on firms' collection strategies under mandatory environmental policies, please refer to the literature review (e.g., [Hong et al., 2022](#); [Gunasekara et al., 2023](#)).

that remanufacturing is the most effective option among four product recovery strategies — repairing, reconditioning, remanufacturing, and recycling. [Ullah and Sarkar \(2020\)](#) examine firms' recovery-channel selection in a hybrid manufacturing-remanufacturing system. [Wang et al. \(2025\)](#) study how remanufacturing authorization from an OEM and knowledge spillovers influence a TPR's decisions on remanufacturing.

Researchers also explore how environmental policies influence product recovery decisions and the corresponding performance of firms. [Özdemir et al. \(2012\)](#) examine the role of EPR legislation and redesign opportunities in firms' product recovery decisions. The findings show that EPR legislation can promote product recovery through charging disposal fees and setting recovery quotas. [Pazoki and Zaccour \(2019\)](#) analyze the mechanism of subsidies and penalties in encouraging product recovery. Regarding how mandatory policies affect firms' remanufacturing decisions, authors, such as [Mao et al. \(2023\)](#) and [Zhang et al. \(2024\)](#), examine the impact of policies (e.g., carbon emission quota, cap-and-trade policies) on firms' engagement in remanufacturing; [Wang et al. \(2017\)](#) and [Wang et al. \(2021\)](#) analyze OEMs' remanufacturing decisions in response to carbon cap-and-trade policy; [Esenduran et al. \(2017\)](#) study the influence of take-back regulation on the remanufacturing levels for the OEM and the TPR; [Li et al. \(2023\)](#) investigate how taxes and tariffs shape an OEM's decision on remanufacturing outsourcing in a global supply chain context. Under take-back legislation, authors also examine how product recovery decisions interact with other strategic choices of firms. [Webster and Mitra \(2007\)](#) and [Esenduran and Kemahlioğlu-Ziya \(2015\)](#) investigate the impact of collective and individual collections on firms' remanufacturing decisions. [Webster and Mitra \(2007\)](#) suggest that collective collection can encourage OEMs to engage in remanufacturing; [Esenduran and Kemahlioğlu-Ziya \(2015\)](#) confirm this view but note that individual collection may encourage OEMs to improve product recyclability. In another study, [Pazoki and Samarghandi \(2020\)](#) explore an OEM's strategic choice between remanufacturing and eco-design. Their results indicate that the OEM prefers remanufacturing when the cost of eco-design is high.

To summarize, the above available literature examines how firms make product recovery

strategies and decisions considering various factors (e.g., environmental policies). Building on top of the published studies, we examine how two prevalent environmental policies: emission taxes and waste management regulations jointly shape the practical decisions of OEMs and TPRs on used product management outsourcing, product recovery strategies, and new product production.

4.2.2 Firms' coopetition strategies in CLSCs

The second stream of research focuses on firms' coopetition strategies in CLSCs. [Zhou et al. \(2021a\)](#) investigate whether or not an OEM should cooperate with his contract manufacturer to remanufacture used products. [Jalali et al. \(2021\)](#) analyze the OEM's inclination to choose between competition and coopetition with a third-party collector. [Jin et al. \(2022\)](#) examine the OEM's decisions regarding the remanufacturing mode, comparing dealer authorization with remanufacturing authorization. Other authors, e.g., [Jung and Hwang \(2011\)](#), [Zhou et al. \(2021b\)](#), [Li et al. \(2023\)](#), examine similar problems where OEMs can choose to purely compete and/or cooperate with other parties. Although these studies approach similar problems considering different factors and/or conditions, a feature common to them is that OEMs consistently prefer coopetition over pure competition. Extending the above studies, [Qin et al. \(2023\)](#) investigate the OEM's preferences among several coopetition modes, including outsourcing, authorization, and integrated remanufacturing.

In contrast to studies that focus exclusively on the impact of coopetition on OEMs' performance, several authors indicate that coopetition can also benefit TPRs and enhance the overall supply chain performance. For instance, [Zhou et al. \(2021a\)](#) compare two scenarios in which a TPR sells remanufactured products with and without the OEM's authorization. [Zhou et al. \(2022\)](#) explore a TPR's strategic choices between collaborating with an OEM using his technology or developing technology independently. Both studies indicate that under certain conditions, cooperation among competitors in CLSCs yields mutual benefits.

Moreover, several studies focus on how environmental policies influence firms' coopetition strategies. For example, [Shi and Bai \(2023\)](#) examine how recycling subsidies affect an OEM's decision to cooperate with a competing TPR for used product collection.

The results show that a low recycling subsidy encourages cooperation. [Niu et al. \(2022\)](#) study how environmental taxes and remanufacturing subsidies affect an OEM's component purchasing strategies. Their results suggest that combined with a high subsidy, a relatively high (or low) environmental tax rate encourages the OEM to purchase remanufactured components from a competitive supplier, instead of a non-competitive one.

To conclude, our study differs from prior research in three aspects. First, most existing studies focus on a single activity of TPRs: remanufacturing. Although [Xue et al. \(2021\)](#) and [Wang et al. \(2025\)](#) examine the TPR's decisions regarding both remanufacturing and new product production, they do not consider material recovery and reuse of recovered materials. Our study incorporates three of TPRs' activities — remanufacturing, material recovery, and new product production. Second, we consider the environmental impact across the entire product lifecycle and analyze how different activities affect both OEMs' used product management outsourcing strategies and TPRs' product recovery strategies. Third, we identify the conditions under which TPRs engage in new product production and examine how this production influences OEMs' outsourcing strategies.

Table 4.1. Summary of reviewed articles in coopetition

Studies	The TPR's activities			Policies	Interactions between firms	
	Material recovery	Remanufacturing	New product production		Competition	Cooperation
Zhou et al. (2021a)		√			√	√
Jalali et al. (2021)					√	√
Jin et al. (2022)		√			√	√
Jung and Hwang (2011)				√	√	√
Zhou et al. (2021b)		√			√	√
Li et al. (2023)		√		√	√	√
Qin et al. (2023)		√			√	√
Zhou et al. (2022)		√			√	√
Xue et al. (2021)		√	√			
Wang et al. (2025)		√	√		√	√
Shi and Bai (2023)				√	√	√
Niu et al. (2022)				√	√	√
Our work	√	√	√	√	√	√

4.3 Model development

4.3.1 Problem description

In the CLSC considered, the OEM produces and sells a new product (N). He pays emission taxes for production and is responsible for all used products originating from him. The OEM has the option to either manage them through remanufacturing or material recovery or pay a waste management tax (t_w) for a used product that cannot be recovered. The TPR is a government-certified specialist in used product management. Because the OEM lacks the capability for used product management, outsourcing used product management to the TPR is an alternative for the OEM to pay waste management taxes, as shown in Figure 4.1.

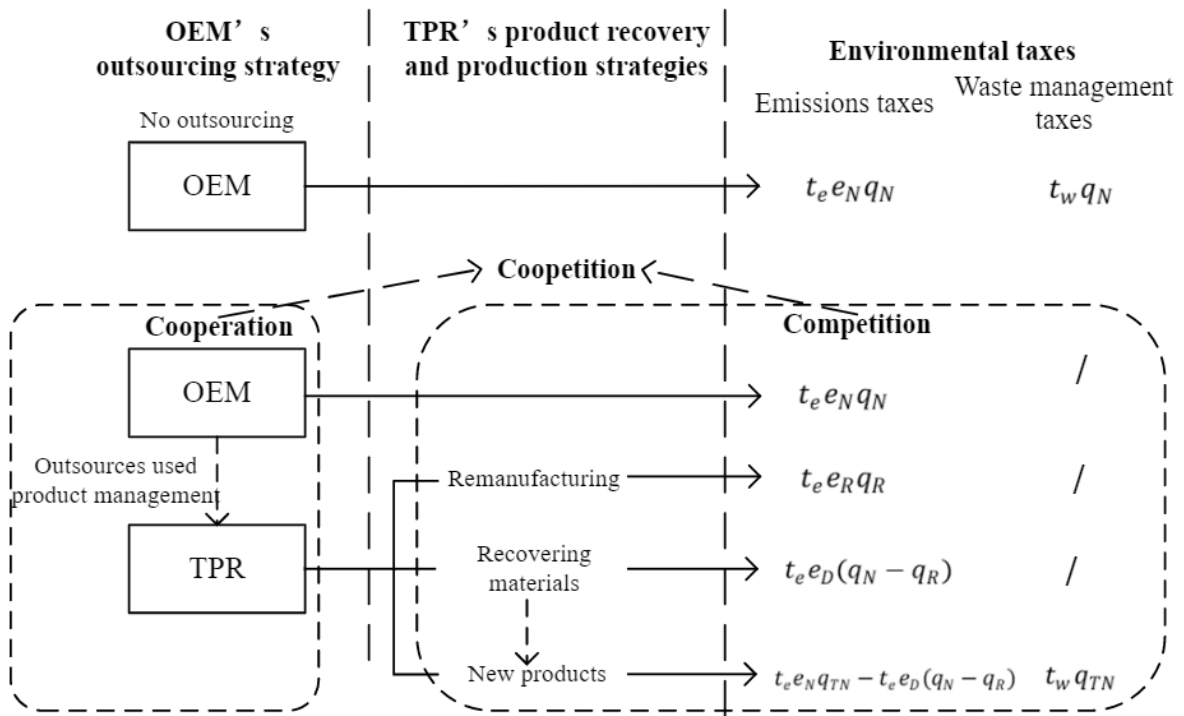


Figure 4.1. Problem description

Being consistent with the literature (Qian et al., 2019), we assume that all decisions are made in a steady-state period. As the OEM lacks capabilities for used product management, we assume that the TPR holds the power to decide the unit outsourcing fee (d_N). The sequence of decisions is outlined below. First, the TPR announces d_N . Given d_N , the OEM decides his production quantity of N (q_N) and whether to pay waste management taxes or

outsource used product management. If the OEM considers outsourcing used product management, the TPR collects used products from the market in an amount equal to q_N ¹⁸. Regarding this, this study does not address the collection rate of used products which has been a research topic on its own (Kushwaha et al., 2022; Hong et al., 2023). Meanwhile, to manage the collected used products, the TPR selects product recovery strategies and determines the optimal remanufacturing quantity (q_R). Her product recovery strategies include (i) strategy NR: recovering materials from all used products; (ii) strategy PR: remanufacturing part of the used products and recovering materials for the rest; and (iii) strategy AR: remanufacturing all used products. The TPR also determines whether or not to produce her own-branded new products (TNs) using recovered materials, as shown in Figure 4.1. If the selected strategy includes material recovery, the TPR simultaneously decides whether or not to produce TNs using the recovered materials and determines the corresponding production quantity (q_{TN}). Both remanufactured products and TNs are sold in the same market as the OEM's new products. Following Ferguson and Toktay (2006), we assume that all used products can either be remanufactured or recovered for materials¹⁹, and that each used product can be remanufactured only once. Consequently, q_R is constrained by q_N , i.e., $q_R \leq q_N$.

Based on the OEM's outsourcing strategy and the TPR's product recovery and new product production strategies, there are three possible scenarios: (i) Scenario NO: the OEM does not outsource used product management, i.e., no outsourcing; (ii) Scenario O: the OEM outsources used product management and the TPR does not produce new products, i.e., outsourcing without the TPR's new product production; and (iii) Scenario OS: the OEM outsources used product management and the TPR produces new products, i.e., outsourcing with the TPR's new product production. Below, we first derive the price functions in the three scenarios. All parameters and decision variables are summarized in Table 4.2.

¹⁸ This assumption is reasonable. As mentioned in (Atasu and VanWassenhove, 2012), laws are implemented to reinforce the collection of all used products.

¹⁹ Corresponding to this assumption, our study does not examine the situations where not all collected products can be remanufactured or recovered.

Table 4.2. Parameters and decision variables

Parameters	
t_w	waste management tax for a used product not properly recovered, i.e., unit waste management tax
t_e	unit emission tax
V	consumers' WTP for OEM's new product (N)
δ	consumers' value discount for remanufactured product (R) compared to N, $0 < \delta < 1$
θ	consumers' value discount for TPR's new product (TN) compared to N, $0 < \theta < 1$
p_N, p_R, p_{TN}	selling price for N, R, and TN, respectively
e_N, e_R, e_D	emissions released from producing a new product, remanufacturing a used product, and recovering materials from a used product, respectively
c_N	unit production cost for OEM's N
c_R	unit remanufacturing cost
c_A	unit used product collection cost
c_D	cost for the TPR to recover materials from one unit of used products
s	salvage value of recovered materials from one unit of used products
γ	emission reduction thanks to the use of recovered materials in producing one unit of the TPR's new products
Decision variables	
d_N^i	unit used product management outsourcing fee in Scenario i
q_N^i	production quantity of N in Scenario i
q_R^i	remanufacturing quantity in Scenario i
q_{TN}^{OS}	production quantity of TN

$i \in [NO, O, OS]$

4.3.2 Price functions

According to [Moorthy \(1988\)](#), consumers' WTP, V , for N is heterogeneous and uniformly distributed in the interval $[0,1]$. Additionally, per the available literature ([e.g., Chen and Chen, 2019; Xue et al., 2021](#)), consumers typically have a lower WTP for the TPR's remanufactured products than her new products due to quality perceptions, and a lower WTP for the TPR's new products than the OEM's new products due to brand differences. (Note: We exclude scenarios where consumers' WTP for the TPR's remanufactured products

exceeds that for the TPR's new products. This is because our study focuses on the comparative dynamics between the OEM's and the TPR's new offerings.) Thus, we assume a consumer's WTP is δV for R and θV for TN, respectively, where $0 < \delta < \theta < 1$. Denote p_N , p_R , and p_{TN} as the selling prices of N, R, and TN, respectively. Consumer utilities for N, R, and TN are formulated as $U_N = V - p_N$, $U_R = \delta V - p_R$, and $U_{TN} = \theta V - p_{TN}$, respectively. Based on our utility functions and the approach used by [Ferrer and Swaminathan \(2010\)](#), we derive the price functions in the three scenarios, as shown in [Table 4.3](#).

Table 4.3. Price functions in three cases

Case	NO	O	OS
Inverse demand functions	$p_N^{NO} = 1 - q_N^{NO}$	$p_N^O = 1 - q_N^O - \delta q_R^O,$ $p_R^O = \delta(1 - q_N^O - q_R^O).$	$p_N^{OS} = 1 - q_N^{OS} - \theta q_{TN}^{OS} - \delta q_R^{OS},$ $p_{TN}^{OS} = \theta - \theta(q_{TN}^{OS} + q_N^{OS}) - \delta q_R^{OS},$ $p_R^{OS} = \delta(1 - q_N^{OS} - q_{TN}^{OS} - q_R^{OS}).$

4.3.3 Costs and emissions

Denote c_N as the OEM's unit production cost of new products, c_R as the TPR's unit remanufacturing cost of used products, and c_D as the TPR's cost of recovering materials from each used product. In accordance with the literature and industrial practice ([Savaskan et al., 2004](#)), c_R is lower than c_N . Further denote c_A , s , and c_{TN} as the unit used product collection cost, the salvage value of recovered materials from one unit of used products, and the TPR's unit production cost of new products, respectively. Let e_N , e_R , and e_D represent the emissions released from the OEM's producing a new product, the TPR's remanufacturing a used product, and the TPR's recovering materials from a used product, respectively. For analytical simplicity, we normalize e_N to 1. Being in line with literature (e.g., [King et al., 2005](#)), we assume $0 < e_R < e_D < 1$.

4.3.4 Profit function

[Figure 4.2](#) visualizes the supply chain structures corresponding to the three scenarios introduced earlier, including Scenario NO, Scenario O, and Scenario OS.

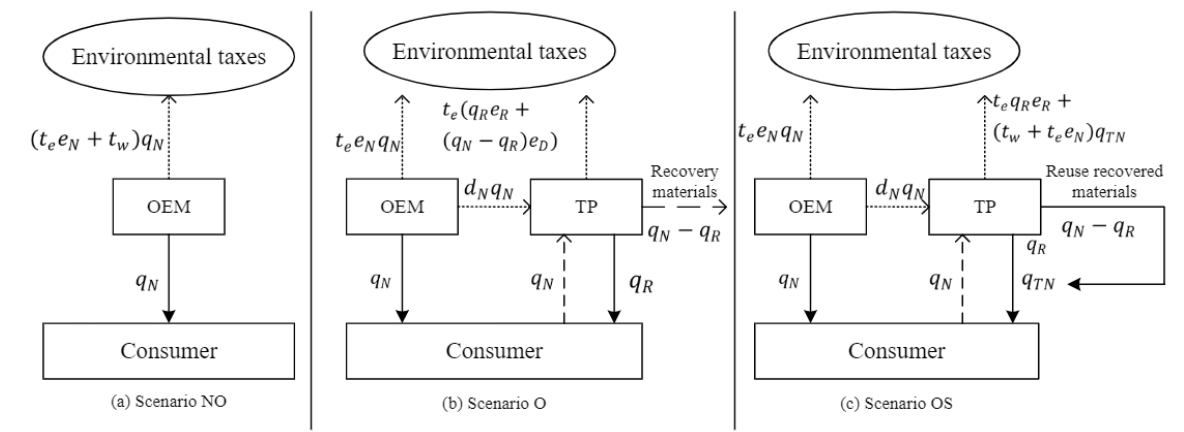


Figure 4.2. Three supply chain structures

As shown in Figure 4.2(a), in Scenario NO, the OEM does not outsource used product management. He pays both emission and waste management taxes for each product produced and sold, respectively. The OEM decides the production quantity of N (q_N^{NO}) to maximize his profit (π_O^{NO}) in Eq. (4-1).

$$\text{Max } \pi_O^{NO}(q_N) = (p_N^{NO} - c_N)q_N^{NO} - t_e q_N^{NO} e_N - t_w q_N^{NO} \quad (4-1)$$

As shown in Figure 4.2(b), in Scenario O, the OEM and the TPR not only cooperate, but also compete. In the cooperation, the OEM pays the TPR d_N for each new product that he sells. The TPR collects all the used products at the same quantity sold by the OEM. In managing the collected products, she carries out remanufacturing and/or recovers materials from them. When the TPR does remanufacturing, she sells remanufactured products in the same market as the OEM, and thus, competes with him. Accordingly, the coopetition takes place between the two firms. In this scenario, the OEM pays emission taxes for his production activities, whilst the TPR pays emission taxes for her activities of used product management. Both firms independently maximize their profits in Eqs. (4-2) and (4-3).

$$\text{Max } \pi_O^O(q_N^O) = (p_N^O - c_N)q_N^O - t_e q_N^O e_N - q_N^O d_N^O \quad (4-2)$$

and

$$\begin{aligned} \text{Max } \pi_R(d_N^O, q_R^O) = & (p_R^O - c_R)q_R^O + q_N^O d_N^O - c_A q_N^O - (q_N^O - q_R^O)(c_D - s) \\ & - (q_R^O e_R + (q_N^O - q_R^O) e_D) t_e \end{aligned} \quad (4-3)$$

$$q_N^O \geq q_R^O \geq 0 \text{ for both.}$$

As shown in [Figure 4.2\(c\)](#), in Scenario OS, in addition to remanufacturing and recovering materials, the TPR reuses the recovered materials to produce new products. In this scenario, the TPR needs to pay emission taxes for both recovering used products and producing new products. Moreover, the TPR has to pay waste management taxes for the new products produced. We formulate the OEM's and the TPR's profit maximization problems in [Eqs. \(4-4\) and \(4-5\)](#), respectively.

$$\text{Max } \pi_O^{OS}(q_N^{OS}) = (p_N^{OS} - c_N)q_N^{OS} - t_e q_N^{OS} e_N - q_N^{OS} d_N^{OS} \quad (4-4)$$

and

$$\begin{aligned} \text{Max } \pi_R^{OS}(d_N^{OS}, q_R^{OS}, q_{TN}^{OS}) = & (p_{TN}^{OS} - c_{TN})q_{TN}^{OS} + (p_R^{OS} - c_R)q_R^{OS} + q_N^{OS} d_N^{OS} - c_A q_N^{OS} - \\ & (q_N^{OS} - q_R^{OS})(c_D - s) - t_e(q_R^{OS} e_R + q_{TN}^{OS} e_N + (q_N^{OS} - q_R^{OS})e_D(1 - \gamma)) - t_w q_{TN}^{OS} \end{aligned} \quad (4-5)$$

$q_N^{OS} > q_R^{OS} > 0$ and $q_{TN}^{OS} > 0$ for both. In [Eq. \(4-5\)](#), γ is the emission reduction achieved by the TPR using recovered materials to produce one unit of her new product. For analytical simplicity, we normalize it to 1.

4.4. Results, analysis, and managerial implications

In this section, the optimal decisions in three cases are presented. Subsequently, the monotonicity of optimal decisions with respect to t_e and/or t_w is analyzed. In addition, the TPR's used product recovery and new product production strategies as well as the OEM's used product management outsourcing strategy are examined.

4.4.1 Optimal decisions

Using backward induction, we obtain the two firms' optimal decisions in three cases, as presented in Proposition B-1 (See the proof in [Appendix B-1](#)). Because we focus on whether or not the TPR uses recovered materials to produce new products when her recovery strategy is PR, in Scenario OS, we omit the cases where the TPR does not engage in remanufacturing and new product production.

Proposition B-1. *The optimal decisions of the OEM and the TPR, their corresponding profits, and the conditions ensuring that all optimal decisions remain non-negative across three scenarios are presented below.*

i) In Scenario NO, the OEM's optimal production quantity is $q_N^{NO*} = 1/2(1 - c_N - t_e - t_w)$, and his profit is $\pi_O^{NO*} = 1/4(1 - c_N - t_e - t_w)^2$, subject to $t_w < 1 - c_N - t_e$.

ii) In Scenario O, the optimal decisions for the TPR and the OEM, as well as their corresponding profits and non-negativity conditions are presented in [Table B.1](#) and [B.2](#) in [Appendix B-1](#);

iii) In Scenario OS, the optimal decisions²⁰ for the OEM and the TPR are: $d_N^{OS*} = \frac{(4-\theta)(2(c_A+c_D-s)-\theta)+\theta(4c_N-c_{TN}+3t_e-t_w)-8(c_N+t_e-1)}{2(8-3\theta)}$, $q_N^{OS*} = \frac{2(\theta+s+t_w+1-c_A-c_D-c_N+c_{TN})}{8-3\theta}$, $q_{TN}^{OS*} = \frac{(s-c_D)(8+2\delta-5\theta)+(\theta-\delta)(6-\theta+2c_A+2c_N)+(2\delta+\theta-8)(t_w+c_{TN})-(8-3\theta)(t_e(1-e_R)-c_R)}{2(\theta-\delta)(8-3\theta)}$, and $q_R^{OS*} = \frac{\theta(c_D-c_R-e_R t_e-s)+\delta(c_{TN}+t_e+t_w)}{2\delta(\theta-\delta)}$, with the profits in [Appendix B-1](#), subject to $s > \hat{s}^{OS}$ and $\hat{t}_w^{OS2} < t_w \leq \hat{t}_w^{OS121}$.

Based on Proposition B-1, we examine the monotonicity of two firms' optimal decisions with respect to emission and waste management taxes to understand how the taxes affect the optimal decisions. See the results in Propositions B-2 and B-3. Because the proofs are straightforward, they are omitted in the text.

Proposition B-2. In Case O, the monotonicity of optimal decisions with respect to the unit emission tax is shown in [Table 4.4](#) and [Figure 4.3](#).

Table 4.4. The monotonicity of optimal decisions with respect to t_e in Case O ($\delta > \hat{\delta}$)

	d_N^{O*}	q_N^{O*}	q_R^{O*}
$c_A < \hat{c}_A^{ON2}$	↓	↓	/
$\hat{c}_A^{ON2} \leq c_A < \hat{c}_A^{O1}$	↓	↑	/
$\hat{c}_A^{O1} \leq c_A < \hat{c}_A^{O2}$	If $e_D > e_D^{M1}, \uparrow$; otherwise, ↓	↓	↑
$\hat{c}_A^{O2} \leq c_A < \hat{c}_A^{O3}$		↓	↓
$c_A \geq \hat{c}_A^{O3}$	↓	/	/

²⁰ These optimal decisions are based on one earlier assumption: $\delta < \theta$. In reality, because of brand loyalty, some consumers may perceive a higher value in remanufactured products from well-known OEMs than in new products from other firms, i.e., $\delta > \theta$. The equilibrium solution of this scenario is presented in [Appendix B-1](#).

²¹ Note that in reality, consumers may perceive the value of remanufactured products from well-known OEMs as higher than new products from other brands, i.e., $\delta > \theta$; the equilibrium solution of this scenario is also presented in [Appendix B-1](#).

* (i) “ $\uparrow$ ” and “ $\downarrow$ ” represent monotonically increasing and decreasing, respectively; “/” represents being irrelevant. (ii) $e_D^{M1} = (8 - 4\delta + \delta e_R)/(8 - \delta)$; $\hat{\delta} = s - c_D - t_e e_D + c_R + e_R t_e$. (iii) When $c_A \geq \hat{c}_A^{O3}$, i.e., $t_e \geq t_e(c_A = \hat{c}_A^{O3})$ in Figure 4.3(a), $q_N^{O*} = q_R^{O*} = 0$

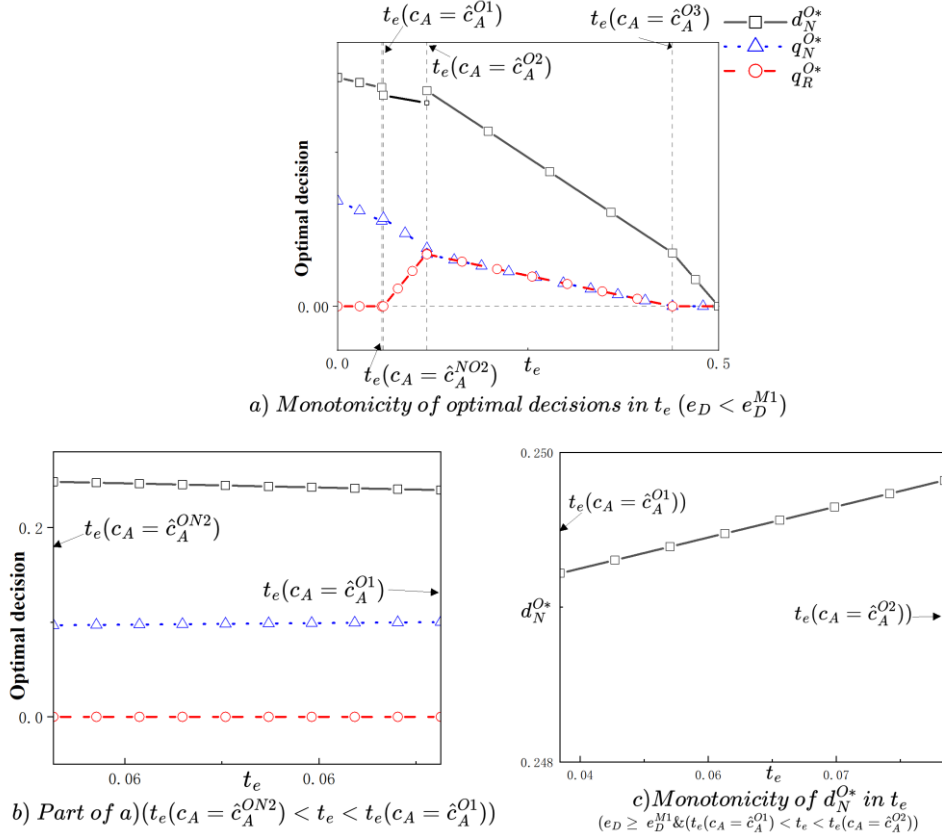


Figure 4.3. Monotonicity of optimal decisions with respect to t_e

Proposition B-2 describes how optimal decisions for the OEM and the TPR in Scenario O ($\delta > \hat{\delta}$) change in t_e , as shown in Table 4.4. For a better understanding, we visualize the monotonicity in Figure 4.3. In the calculation, the parameters used include $\theta = 7/10$, $\delta = 1/3$, $c_D = 1/20$, $c_N = 1/2$, $c_R = 3/10$, $e_R = 1/10$, $s = 2/25$, and $e_D = 6/10$ in Figures 4.3 (a) and (b) (or $e_D = 9/10$ in Figure 4.3(c)). As shown in Figure 4.3(a), when the unit used product collection cost (c_A) is low (i.e., $c_A \leq \hat{c}_A^{ON2}$), the TPR decreases the optimal unit outsourcing fee (d_N^{O*}) as t_e increases. For the OEM, when t_e increases, his optimal production quantity (q_N^{O*}) decreases if c_A is very low (i.e., $c_A \leq \hat{c}_A^{ON2}$), but increases if c_A is relatively low (i.e., $\hat{c}_A^{ON2} \leq c_A < \hat{c}_A^{O1}$), as shown in Figure 4.3(a). Moreover, when c_A is moderate (i.e., $\hat{c}_A^{O1} \leq c_A < \hat{c}_A^{O2}$), the TPR adjusts d_N^{O*} based on the emissions released from recovering materials (e_D). If $e_D > e_D^{M1}$, she increases d_N^{O*} as t_e increases, as shown in Figure 4.3(c); otherwise, she decreases d_N^{O*} , as shown in Figure 4.3(a). Meanwhile, q_N^{O*} decreases in

t_e and the TPR's optimal remanufacturing quantity (q_R^{O*}) increases in t_e . Moreover, when c_A is high (i.e., $\hat{c}_A^{O2} \leq c_A < \hat{c}_A^{O3}$), q_N^{O*} , q_R^{O*} , and d_N^{O*} decrease in t_e . At last, when c_A is relatively high (i.e., $c_A \geq \hat{c}_A^{O3}$), d_N^{O*} decreases in t_e , both q_N^{O*} and q_R^{O*} are independent of t_e .

The above monotonicity is caused by the reasons below. First, when $c_A < \hat{c}_A^{O1}$, as t_e increases, the OEM's costs of producing and selling new products increase. This, in turn, leads to a reduced market demand for the OEM's new products. This reduction can decrease the TPR's total outsourcing revenue. Thus, to maintain high revenue, the TPR lowers d_N^{O*} to encourage the OEM to sustain a high production quantity. However, when $c_A \leq \hat{c}_A^{ON2}$, reducing d_N^{O*} cannot offset the increase in the OEM's costs due to the increase in t_e . Conversely, when $\hat{c}_A^{ON2} < c_A \leq \hat{c}_A^{O1}$, lowering d_N^{O*} can offset the OEM's increase in cost. Therefore, when $c_A \leq \hat{c}_A^{ON2}$, q_N^{O*} decreases in t_e ; when $\hat{c}_A^{ON2} < c_A \leq \hat{c}_A^{O1}$, q_N^{O*} increases in t_e . Second, when $\hat{c}_A^{O1} < c_A \leq \hat{c}_A^{O2}$, as t_e increases, (i) if $e_D > e_D^{M1}$, a high e_D increases the TPR's total costs. This, in turn, makes the TPR increase d_N^{O*} to pass some costs to the OEM; (ii) if $e_D < e_D^{M1}$, the TPR lowers d_N^{O*} to ensure that the OEM maintains a high production quantity. Meanwhile, the increase in both t_e and c_A increases the TPR's total costs. To maximize profit, the TPR engages in remanufacturing and increases q_R^{O*} as t_e increases. For the OEM, the increase in his production costs due to an increasing t_e and competition from remanufactured products result in a reduced market demand for his new products. Consequently, q_N^{O*} decreases in t_e . Third, when $\hat{c}_A^{O2} \leq c_A < \hat{c}_A^{O3}$, as t_e increases, (i) the TPR decreases d_N^{O*} for the same reasons mentioned above; (ii) the OEM reduces q_N^{O*} because lowering d_N^{O*} cannot offset the increase in his production costs; (iii) the TPR reduces q_R^{O*} because it is constrained by q_N^{O*} (see details in [Table B.2](#)). At last, when c_A is very high (i.e., $c_A \geq \hat{c}_A^{O3}$), the high costs of producing new products and collecting used products force both firms to exit the market. Thus, both q_N^{O*} and q_R^{O*} become irrelevant to t_e .

Based on the analysis of the monotonicity, we offer guidance for OEMs and TPRs in practice to adjust their decisions in response to an increase in the unit emission tax, in the hope of maintaining cooperation and/or gaining higher profits. For OEMs, they should evaluate the unit used product collection cost and adjust their production quantity accordingly. When the unit emission tax increases, they should increase production quantity if the unit

used product collection cost is low ($\hat{c}_A^{ON2} \leq c_A < \hat{c}_A^{O1}$ in this study), otherwise they should reduce it. Regarding TPRs, they should adjust the unit outsourcing fee based on the unit used product collection cost and emissions from material recovery. When the unit emission tax increases, if the unit collection cost is moderate and the emissions from material recovery are high, they should increase the unit outsourcing fee; otherwise, they should decrease the unit outsourcing fee to maintain cooperation. Moreover, when the unit collection cost is very high ($c_A \geq \hat{c}_A^{O3}$ in this study), both parties should stop cooperation or explore strategies to generate profits.

Proposition B-3. *In Scenario OS, given the preconditions $s > \hat{s}^{OS}$ and $\hat{t}_w^{OS2} < t_w \leq \hat{t}_w^{OS1}$, the effects of the unit emission tax (t_e) and waste management tax (t_w) on optimal decisions are summarized below:*

- i) d_N^{OS*} and q_{TN}^{OS*} decrease in t_w and t_e ;
- ii) q_R^{OS*} increases in t_w . If $e_R < \delta/\theta$, q_R^{OS*} increases in t_e , otherwise, it decreases in t_e ;
- iii) q_N^{OS*} increases in t_w and is independent of t_e .

Proposition B-3 explores how t_e and t_w shape the decisions for the OEM and the TPR when the TPR engages in both remanufacturing and new product production. For the TPR, as t_w (or t_e) increases, she decreases both the unit outsourcing fee (d_N^{OS*}) and the production quantity of her new products (q_{TN}^{OS*}). Regarding her remanufacturing quantity (q_R^{OS*}), the TPR increases it along with the increase in t_w . Meanwhile, as t_e increases, if the unit remanufacturing emission (e_R) is low (i.e., $e_R < \delta/\theta$), the TPR increases q_R^{OS*} ; otherwise, she decreases q_R^{OS*} . This reflects a strategic shift toward remanufacturing to offset the higher costs imposed by taxes. For the OEM, his production quantity (q_N^{OS*}) increases in t_w and is independent of t_e .

The reasons for these multiple impacts are as follows. Contributing to her profit, the TPR's revenues related to outsourcing fees, sales of remanufactured products and TNs, and the salvage value of recovered materials are directly affected by q_N^{OS*} , d_N^{OS*} , q_R^{OS*} , and q_{TN}^{OS*} . Intuitively, a high value of t_w or t_e indicates high costs for the TPR to produce and sell TNs. Thus, the TPR reduces q_{TN}^{OS*} when either t_w or t_e increases. This reduction in production

quantity inevitably leads to a decrease in sales revenue from TNs. To compensate for this and maintain the revenue from outsourcing fees and sales of remanufactured products, the TPR i) lowers d_N^{OS*} when t_w or t_e increases, thus motivating the OEM to produce more and ii) increases q_R^{OS*} when t_w increases. Regarding the impact of t_e on q_R^{OS*} , when e_R is low, compared to producing TNs, remanufacturing alleviates tax burdens. Thus, the TPR increases remanufacturing quantity as t_e increases. Conversely, when e_R is high, an increase in t_e causes the TPR to increase the selling price of remanufactured products. The price increase drives some consumers away, thereby resulting in reduced demand. Therefore, the TPR reduces her remanufacturing quantity.

As implied by Proposition B-3, in practice, when TPRs produce new products using recovered materials, to maintain profit despite increasing environmental taxes, (i) they should lower the unit outsourcing fee and increase the remanufacturing quantity, especially when the unit remanufacturing emission is below a certain threshold ($e_R < \delta/\theta$ in this study); and (ii) OEMs should increase production quantity in response to the increasing waste management tax.

As we focus on the TPR's decision on new product production when her recovery strategy is PR, we further investigate the effect of introducing the TPR's new products (TNs) on firms' optimal decisions regarding the unit outsourcing fee and production (remanufacturing) quantity. The results are summarized in Proposition B-4. See the proof in [Appendix B-2](#).

Proposition B-4. *Given the TPR's product recovery strategy PR, by comparing the optimal decisions in Scenario OS and Scenario O, we obtain three thresholds $\bar{t}_{w1}$, $\bar{t}_{w2}$, and $\bar{t}_{w3}$ (see [Appendix B-2](#) for the expressions) such that:*

- i) *When $t_w > \bar{t}_{w1}$, the optimal outsourcing fee in Scenario OS is lower than that in Scenario O, i.e., $d_N^{OS*} < d_N^{O*}$;*
- ii) *When $t_w > \bar{t}_{w2}$ ($t_w > \bar{t}_{w3}$), the OEM's (TPR's) optimal production (remanufacturing) quantity in Scenario OS is higher than that in Scenario O, i.e., $q_N^{OS*} > q_N^{O*}$ ($q_R^{OS*} > q_R^{O*}$).*

According to Proposition B-4, introducing TN affects both the OEM's production and

the TPR's remanufacturing quantities in the same direction, whilst it influences the unit outsourcing fee in the opposite direction. More specifically, when t_w exceeds the threshold: $\bar{t}_{w1}$, the unit outsourcing fee in Scenario OS becomes lower than that in Scenario O. When t_w is higher than the threshold: $\bar{t}_{w2}$ (or $\bar{t}_{w3}$), the TPR's production (or remanufacturing) quantity in Scenario OS is higher than in Scenario O. The reasons are as follows. The TPR's revenue sources — outsourcing fees, sales of TNs, and sales of remanufactured products — are interdependent. When the waste management tax is high, the profit margin from producing TN decreases, prompting the TPR to focus more on revenue from outsourcing fees and remanufactured products. By lowering the unit outsourcing fee, the TPR can encourage the OEM to increase production. This, in turn, enables the TPR to obtain higher total outsourcing fees.

This proposition implies that in practice, when TPRs introduce their own-branded new products, they should adjust their production and revenue strategies according to waste management taxes. Under low waste management taxes, TPRs should increase the production quantity of their new products, thus benefiting from low taxes. However, under high waste management taxes, TPRs should lower the unit outsourcing fee to incentivize OEMs to increase production quantity and meanwhile increasing remanufacturing quantities to offset high total costs.

3.4.2 TPR's product recovery and new product production strategies

With the two firms' optimal decisions in three scenarios, we examine the TPR's product recovery and new product production strategies. We first explore the conditions under which the TPR opts not to remanufacture used products. The results are summarized in Proposition B-5.

Proposition B-5. *In Scenario O, the conditions under which the TPR does not engage in remanufacturing and the reasons are as follows:*

- i) *When $\delta \leq \hat{\delta}$ and $c_A > \hat{c}_A^{ON1}$, or when $\delta > \hat{\delta}$ and $c_A \geq \hat{c}_A^{O3}$, the TPR does not engage in remanufacturing. This is due to the high cost of used product management;*
- ii) *When $\delta \leq \hat{\delta}$ and $c_A < \hat{c}_A^{ON1}$, or $\delta > \hat{\delta}$ and $c_A < \hat{c}_A^{ON2}$, the TPR does not engage in*

remanufacturing. This is because the profit from recovering materials is higher than that from remanufacturing;

iii) When $\delta > \hat{\delta}$ and $\hat{c}_A^{ON2} \leq c_A < \hat{c}_A^{O1}$, the TPR does not engage in remanufacturing. This is because nobody buys remanufactured products.

As shown in Proposition B-5, when consumers' value discount for the remanufactured product (δ) is low, the TPR does not engage in remanufacturing. Even when δ is high, the TPR still does not engage in remanufacturing if the unit collection cost of used products (c_A) is either very high (i.e., $c_A \geq \hat{c}_A^{O3}$) or very low (i.e., $c_A < \hat{c}_A^{ON2}$). The reasons for the TPR not engaging in remanufacturing vary under different conditions. Regardless of the value of δ , when c_A is high²², the revenue from selling remanufactured goods cannot make up for the high collection cost. Consequently, there is no profit from remanufacturing. In other words, if collecting used products is too expensive, the TPR should avoid remanufacturing due to excessive total costs. On the contrary, regardless of the value of δ , when c_A is low²³, the TPR finds that the profit from only recovering materials is higher than that from remanufacturing. Furthermore, when $\delta > \hat{\delta}$ and $\hat{c}_A^{ON2} \leq c_A < \hat{c}_A^{O1}$ (see Part iii)), the TPR does not engage in remanufacturing because the price of the OEM's new products is relatively low. Such a low price of new products discourages consumers from buying remanufactured products. Regarding this, we put forward very important guidance below for OEMs to take strategic actions in practice. OEMs can deter the entry of remanufactured products by adopting a low-price strategy for their new products when consumers' WTP for remanufactured products and the collection costs of used products are both high. Our guidance aligns with the theoretical findings from [Zhao and Jagpal \(2006\)](#) who highlight that firms can strategically use pricing decisions to mitigate competitive threats posed by secondhand markets.

When $\delta \leq \hat{\delta}$ and $c_A \geq \hat{c}_A^{ON1}$ (or $c_A < \hat{c}_A^{ON1}$), the optimal decisions and profits for the two firms are identical to those when $\delta > \hat{\delta}$ and $c_A \geq \hat{c}_A^{O3}$ (or $c_A < \hat{c}_A^{ON2}$). Therefore, our analysis in the following sections focuses on the situations where $\delta > \hat{\delta}$. Based on part ii) of Proposition B-1, we outline the TPR's product recovery strategies in Scenario O, which are

²² Either $c_A > \hat{c}_A^{ON1}$ (when $\delta \leq \hat{\delta}$) or $c_A > \hat{c}_A^{O3}$ (when $\delta > \hat{\delta}$) (refer to Part i)).

²³ Either $c_A < \hat{c}_A^{ON1}$ (when $\delta \leq \hat{\delta}$) or $c_A < \hat{c}_A^{ON2}$ (when $\delta > \hat{\delta}$) (refer to Part ii)).

presented in Proposition B-6.

Proposition B-6. *Given $\delta > \hat{\delta}$, the TPR's optimal product recovery strategy in Scenario O is as follows:*

- i) *If $\hat{c}_A^{O1} \leq c_A < \hat{c}_A^{O2}$, the TPR's product recovery strategy is PR;*
- ii) *If $\hat{c}_A^{O2} \leq c_A < \hat{c}_A^{O3}$, the TPR's product recovery strategy is AR;*
- iii) *If $c_A < \hat{c}_A^{O1}$ or $c_A \geq \hat{c}_A^{O3}$, the TPR's product recovery strategy is NR.*

As shown in Proposition B-6, the TPR adopts remanufacturing when the collection cost (c_A) is moderate and refrains from doing so when c_A is high or low. More specifically, when c_A is very low (i.e., $c_A \leq \hat{c}_A^{O1}$), the TPR does not engage in remanufacturing (NR); when it increases to a relatively low level (i.e., $\hat{c}_A^{O1} \leq c_A < \hat{c}_A^{O2}$), she remanufactures some of the used products (PR); for a moderate c_A (i.e., $\hat{c}_A^{O2} \leq c_A < \hat{c}_A^{O3}$), the TPR switches to remanufacturing all used products (AR); and if c_A becomes very high (i.e., $c_A \geq \hat{c}_A^{O3}$), she does not engage in remanufacturing (NR). To summarize, when c_A increases from very low to very high, the TPR's optimal strategy changes from NR to PR, then to AR, and eventually back to NR.

The reasons for the above strategy changes are as follows. When c_A is very low, the profit from recovering materials is higher than that from remanufacturing (as mentioned in Proposition B-5 ii)), and the TPR, thus, selects NR. When c_A increases to the relatively low level, the TPR's total costs increase. To counterbalance the increased costs, she increases her unit outsourcing fee. The increasing unit outsourcing fee causes the OEM to reduce production quantity. This, in turn, provides the TPR with an opportunity to remanufacture more used products for the same market. Additionally, with reduced revenue from the OEM's outsourcing fees, the TPR turns to remanufacturing to diversify her revenue sources. Therefore, when $\hat{c}_A^{O1} \leq c_A < \hat{c}_A^{O2}$, the TPR changes her product recovery strategy from NR to PR. As c_A continues to increase, the unit outsourcing fee keeps increasing and the OEM's production quantity continues to decrease. As a result, remanufacturing becomes increasingly attractive. Thus, the TPR finds it optimal to remanufacture all collected used products when $\hat{c}_A^{O2} \leq c_A < \hat{c}_A^{O3}$. However, once c_A exceeds a certain threshold: $\hat{c}_A^{O3}$, the outsourcing

cooperation does not occur (see earlier text). In other words, the TPR does not engage in remanufacturing (i.e., NR).

As implied by Proposition B-6, in practice, when the unit collection cost is high, the TPR should prioritize remanufacturing instead of material recovery. However, when the unit collection cost is very high, the TPR should either stop managing the OEM's used products or seek other effective solutions to reduce used product management costs and further increase revenue. For example, being one of the largest remanufacturers, Caterpillar cooperates with a Chinese OEM: Yuchai to develop advanced remanufacturing technologies (Chen et al., 2023). This collaboration lowers Caterpillar's collection and remanufacturing costs. Additionally, as mentioned in Introduction, GEM uses materials recovered from BYD's used batteries to produce her own-branded new batteries, thereby creating an additional revenue stream. These two real-world examples demonstrate how TPRs can respond to the high costs of used product management: investing in technological innovation or expanding businesses into new product production.

Based on the TPR's profits in Scenario O and Scenario OS, Proposition B-7 highlights conditions under which the TPR reuses recovered materials to produce new products given that her product recovery strategy is PR. See the proof in Appendix B-3.

Proposition B-7. *The TPR produces new products when $t_w < t_{w1}^T$ or $t_w > t_{w2}^T$, where $t_{w1}^T < t_{w2}^T$.*

According to this proposition, the TPR produces new products (TNs) when the unit waste management tax (t_w) is low. This is reasonable. When t_w is low, the TPR can set a more interesting price of her TNs than remanufactured products thanks to consumers' higher WTP for TNs. The TPR also has a cost advantage. This is because the TPR's producing TNs based on recovered materials leads to lower emission taxes than those from the OEM's producing new products. With both price and cost advantages, the TPR's producing TNs can increase her profit when t_w is low (i.e., $t_w < t_{w1}^T$). Interestingly, a high t_w also incentivizes the TPR to produce TNs. This can be explained as follows. According to Proposition B-4, when t_w is high, the TPR's introducing TNs does not necessarily reduce her revenues from

outsourcing fees and sales of remanufactured products. Thus, when t_w is high, the TPR engages in new product production.

Based on our assumption (see in subsection 4.3.2), our analysis focuses on the case where $\theta > \delta$. Nevertheless, we also examine the TPR's new product production strategy under the scenario where $\theta < \delta$. In this scenario, the conclusion of Proposition B-7 remains unchanged, though the threshold values are different. For details, see [Appendix B-3](#).

4.4.3 OEM's outsourcing strategy

In this subsection, we compare the OEM's optimal production quantities in two scenarios: Scenario NO and Scenario O and further examine his outsourcing strategies. We first analyze the effect of outsourcing cooperation on the OEM's optimal production quantity and provide the results in Proposition B-8. See the proof in [Appendix B-4](#).

Proposition B-8. *As long as the OEM does not exit the market in Scenario O, there is a threshold $t_w^{Q,i}$ (where $i = [NR1, NR2, PR, AR]$) such that the optimal production quantity of N is higher in Case O when $t_w > t_w^{Q,i}$ than in Case NO.*

As stressed in Proposition B-8, used product management outsourcing encourages the OEM to produce more in Scenario O than in Scenario NO as long as t_w is high, regardless of the TPR's product recovery strategy. This is because by outsourcing, the OEM does not pay the high waste management taxes, which are unavoidable in Scenario NO. This significantly reduces the OEM's total costs. Consequently, the OEM can reduce the selling price of his products. The price reduction attracts more consumers, especially those having a lower WTP for his new products.

When the TPR's product recovery strategy is PR, her remanufactured products may cannibalize the market share of the OEM's products, which potentially prevents the OEM from outsourcing. To better understand the above interaction, we examine the OEM's outsourcing strategy when the TPR's product recovery strategy is PR and summarize the results in B-9. See the proof in [Appendix B-4](#).

Proposition B-9. *Given that the TPR does not produce new products and her product*

recovery strategy is PR in Scenario O (i.e., $\delta > \hat{\delta}$ and $\hat{c}_A^{01} < c_A \leq \hat{c}_A^{02}$), there are two thresholds t_w^{RN} and $\bar{t}_w^{RN}$ such that the OEM outsources used product management to the TPR when $t_w^{RN} < t_w \leq \bar{t}_w^{RN}$. Additionally, when $t_w > t_w^{NO}$, the OEM exits the market if he cannot outsource used product management.

For a better understanding, we develop Figure 4.4 to illustrate the proposition. The parameters used include $\theta = 7/10$, $\delta = 1/3$, $c_D = 1/20$, $c_A = 1/20$, $c_N = 1/2$, $c_R = 3/10$, $e_R = 1/10$, $s = 1/25$, $t_e = 1/20$, and $e_D = 6/10$. As shown, the OEM outsources used product management to the TPR if and only if t_w is moderate (i.e., $t_w^{RN} < t_w \leq \bar{t}_w^{RN}$). This is understandable. Whether or not the OEM outsources used product management to the TPR depends on the trade-off between his cost savings from waste management taxes and the increased outsourcing costs and potential sales revenue reduction. When $t_w^{RN} < t_w \leq \bar{t}_w^{RN}$, the sum of savings in waste management taxes and additional revenue from increased production of N is high. As a result, the OEM gains a higher profit in Scenario O than in Scenario NO, as shown in the figure. Figure 4.4 also suggests that outsourcing used product management becomes a more sustainable strategy for the OEM if high waste management taxes threaten his profits (i.e., $t_w^{NO} < t_w < \bar{t}_w^{RN}$). The reasons are as follows. When $t_w \geq t_w^{NO}$, the OEM cannot make profits in Scenario NO. However, he can generate profits as long as $t_w < \bar{t}_w^{RN}$ by outsourcing used product management, as shown in Figure 4.4.

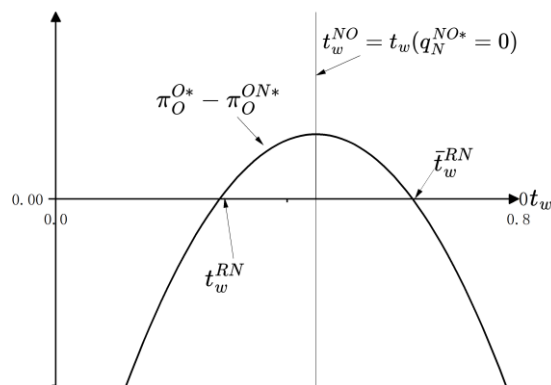


Figure 4.4. The OEM's outsourcing strategy in Case O

Interestingly, the OEM does not outsource used product management when t_w exceeds $\bar{t}_w^{RN}$. Although this result seems counterintuitive, it is explainable. When $t_w > \bar{t}_w^{RN}$, $t_e > \bar{t}_e^{RN}$.

A high t_e stimulates an increase in the quantity of remanufactured products (as shown in Proposition B-2). This increase intensifies market competition and reduces the OEM's sales revenue from new products. The resulting revenue losses outweigh the savings from reduced waste management taxes, thereby discouraging the OEM from outsourcing. Moreover, if $e_D > e_D^{M1}$, the unit outsourcing fee increases as t_e increases (as shown in Proposition B-2), further reducing the attractiveness of outsourcing. Thus, when emission taxes are high, directly paying waste management taxes is economically more beneficial for the OEM than outsourcing. As implied by Proposition B-9, in practice, when making outsourcing decisions, OEMs should consider the interplay among environmental taxes, outsourcing costs, and potential market cannibalization.

We further investigate how the introduction of the TPR's new products impacts the OEM's outsourcing strategy and summarize the results in Proposition B-10 (See [Appendix B-5](#) for proof). For simplicity, we focus on the scenario where the following three conditions exist simultaneously: (i) the OEM can always make profits in Scenario NO (i.e., $t_w < t_w^{NO}$), (ii) the TPR's product recovery strategy is PR in Scenario O (i.e., $\delta > \hat{\delta}$ and $\hat{c}_A^{01} < c_A \leq \hat{c}_A^{02}$); and (iii) the TPR engages in both remanufacturing and new product production in Scenario OS (i.e., $s > \hat{s}^{OS}$ and $\hat{t}_w^{OS2} < t_w \leq \hat{t}_w^{OS1}$).

Proposition B-10. *Given that the TPR's product recovery strategy is PR in Scenario O and Scenario OS, we divide the space of (t_e, t_w) into five regions as follows:*

- i) *Region ND ($t_w < \min [t_w^{RN}, t_w^{SN}]$): the OEM does not outsource used product management, i.e., $\pi_0^{NO} > \max [\pi_0^O, \pi_0^{OS}]$;*
- ii) *Region D ($t_e \leq t_e^p$ and $t_w^{RN} < t_w < t_w^{SN}$): introducing TNs prevents the OEM from outsourcing used product management, i.e., $\pi_0^O > \pi_0^{NO} > \pi_0^{OS}$;*
- iii) *Region E ($t_e > t_e^p$ and $t_w^{SN} < t_w < t_w^{RN}$): introducing TNs encourages the OEM to outsource used product management, i.e., $\pi_0^{OS} > \pi_0^{NO} > \pi_0^O$;*
- iv) *Region N1 ($t_e \leq t_e^p$ and $t_w^{SN} < t_w < t_w^{SR}$): the OEM outsources used product management and does not wish the TPR to produce new products, i.e., $\pi_0^O > \pi_0^{OS} > \pi_0^{NO}$;*
- v) *Region N2 ($t_w > \max [t_w^{SR}, t_w^{RN}]$): the OEM outsources used product management and*

hopes the TPR to produce new products, i.e., $\pi_O^{OS} > \pi_O^O > \pi_O^{NO}$;

where if $t_e > t_e^p$, $t_w^{RN} > t_w^{SN} > t_w^{SR}$, otherwise, $t_w^{RN} \leq t_w^{SN} \leq t_w^{SR}$.

With parameters $\theta = 7/10$, $\delta = 1/3$, $c_D = 1/20$, $c_A = 1/20$, $c_N = 1/2$, $c_R = 3/10$, $e_R = 1/10$, $s = 1/25$, $c_{TN} = 8/25$, and $e_D = 6/10$, we conduct a numerical study to explain Proposition B-10 and summarize the results in Figure 4.5. As shown in Region ND, when t_w is low (i.e., $t_w < \min[t_w^{RN}, t_w^{SN}]$), regardless of the TPR's strategy, the OEM does not outsource used product management (see Proposition B-10 i)). In other words, introducing TNs does not influence the OEM's outsourcing strategy when t_w is low. This is because under this condition, the OEM gains higher profit in Scenario NO compared to either Scenario O or OS.

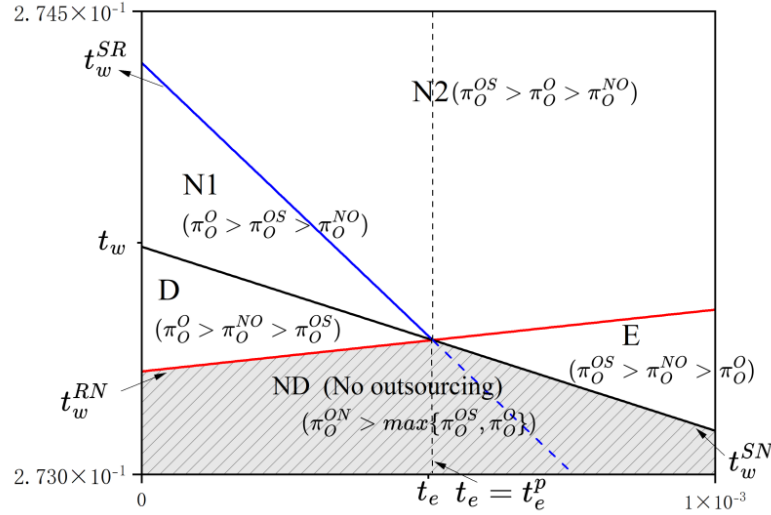


Figure 4.5. The impact of introducing TN on OEM's outsourcing strategy

When t_e is low (or high), if t_w is moderate (i.e., $\min[t_w^{RN}, t_w^{SN}] < t_w < \max[t_w^{RN}, t_w^{SN}]$), introducing TNs discourages (or encourages) the OEM from outsourcing (or to outsource) used product management, as highlighted by Region D (or E). More specifically, in Scenario OS, (i) if $t_e < t_e^p$, the threshold of t_w necessary to incentivize the OEM to outsource used product management becomes higher than in Scenario O (i.e., $t_w^{SN} < t_w^{RN}$). This indicates that introducing TNs discourages the OEM from outsourcing used product management when $t_e < t_e^p$ and $t_w^{SN} < t_w < t_w^{RN}$; (ii) if $t_e > t_e^p$, the threshold of t_w becomes lower than in Scenario O (i.e., $t_w^{SN} > t_w^{RN}$). In other words, introducing TNs encourages the OEM to outsource used product management when $t_e > t_e^p$ and $t_w^{RN} < t_w < t_w^{SN}$. The reasons are as

follows. The production quantities of TN and remanufactured products decrease as the emission tax increases, as highlighted in Proposition B-3. Consequently, under a low emission tax, the TPR produces high quantities of both TNs and remanufactured products. As TNs compete directly with the OEM's new products, this intensifies the competition with the OEM. The increased competition raises the threshold of the waste management tax to the level at which the OEM finds outsourcing used product management justified. Consequently, under the same level of waste management tax set by the government, the OEM finds outsourcing used product management in Scenario OS is less attractive than in Scenario O. Conversely, when the emission tax is high, the production quantities of TNs and remanufactured products decrease due to the increased emission taxes. This reduces the competitive pressure on the OEM. As a result, the threshold of t_w needed to encourage the OEM's outsourcing decreases, thus making the OEM inclined to outsource used product management.

When t_w is high (i.e., $t_w > \max[t_w^{SN}, t_w^{RN}]$), introducing TNs does not influence the OEM's outsourcing strategy, as shown in Regions N1 and N2. This finding aligns with Proposition B-9. Nevertheless, introducing TN can either raise or lower the OEM's profit. Specifically, when $\max[t_w^{SN}, t_w^{RN}] < t_w < t_w^{SR}$, the market cannibalization reduces the OEM's profit (see Proposition B-10 iv)). In view of the profit reduction, the OEM does not expect the TPR to produce TNs. When $t_w > \max[t_w^{SR}, t_w^{RN}]$, despite cannibalization, introducing TNs contributes to a higher profit for the OEM (see Proposition B-10 v)). Accordingly, the OEM expects the TPR to produce TNs.

To summarize, [Figure 4.5](#) highlights the conditions under which the OEM's profit in Scenario OS is higher or lower than that in Scenario NO or Scenario O. It also stresses that when $t_e < t_e^p$, the gap between the thresholds t_w^{RN} and t_w^{SN} narrows as t_e increases, whilst when $t_e \geq t_e^p$ the gap widens with a further increase in t_e . This indicates that when $t_e < t_e^p$, as t_e increases, the likelihood that introducing TNs discourages the OEM from outsourcing decreases. Once t_e reaches t_e^p , introducing TNs no longer discourages outsourcing as long as $t_w > t_w^{SN}$. Moreover, when $t_e \geq t_e^p$, along with the t_e increase, the OEM is more and more inclined to outsource used product management.

With Proposition B-10, we arrive at practical guidance for firms to make optimal strategies considering two common environmental regulations: emission taxes and waste management taxes, as shown in Table 4.5. For OEMs, when the unit waste management tax is low (or high), they should not (or should) outsource used product management. When the unit waste management tax is moderate, and along with the increase of the unit emission tax, OEMs should change their strategy i) from NO to O if TPRs reuse recovered materials to produce their own-branded new products, or ii) from O to NO if TPRs do not produce new products. Regarding TPRs, they should adjust their strategies for new product production based on the unit emission tax and unit waste management tax so that the outsourcing cooperation with OEMs can be maintained. As shown in Table 4.5, when the unit emission tax is low and the unit waste management tax is moderate, TPRs should avoid introducing new products. However, when the unit emission tax is high and the unit waste management tax is moderate, they should introduce their new products to encourage OEMs to outsource used product management

Table 4.5. Guidance on firms' strategies

Parameters (t_e, t_w)		OEM's outsourcing strategies (O: outsourcing; NO: no outsourcing) / TPR's new product production strategies (Y: producing TNs; N: no TNs)
Unit waste management tax (t_w)	High	O/Y
	Moderate	NO (with TN) / N O (without TN)
	Low	NO
		Unit emission tax (t_e)
		Low High
		O/Y
		O (with TN) / Y NO (without TN)
		NO

As a final note: Proposition B-10 is derived under the assumption that $\theta > \delta$. To assess the robustness of our results, we analyze the case where $\theta < \delta$. As shown by the analysis, the impact of introducing TN on the OEM's outsourcing decision changes from being neutral to being positive along with the t_w increase (see Remark 2 in Appendix B-5). This consistent directional influence confirms the robustness of our results across different configurations of θ and δ .

4.5 Conclusions and contributions

In CLSCs in practice, OEMs and TPRs carry out multiple activities ranging from production to used product management, such as producing new products, remanufacturing used products, recovering materials from used products, and producing new products using recovered materials. Practical examples of such supply chains are i) the electrical equipment supply chains where OEMs and TPRs remanufacture e-waste and produce new devices from recycled materials and ii) personal computer supply chains where OEMs make devices and TPRs remanufacture old units and produce new products from recovered parts (Özdemir et al., 2012; Govindan and Popiuc, 2014; Vedantam and Iyer, 2021; Niu et al., 2024). To maximize their profits, firms have to make strategies and decisions to guide their activities mentioned above. However, making optimal strategies and decisions is very difficult for them due to i) the complex decision-making interactions and ii) the compulsory environmental policies that they have to comply with such as emission taxes and waste management regulations. Due potentially to the decision-making difficulties, no investigations have been conducted to examine how firms should make optimal strategies and decisions. As a pioneering study, we examined the decision interactions between an OEM and a TPR in a CLSC involving both production and used product management activities under emission taxes and waste management regulations, and addressed the corresponding decision making. For the OEM, he decided whether or not to outsource used product management and the production quantity of his new products. Regarding the TPR, she needed to determine product recovery and new product production strategies and the production quantities of her remanufactured and/or new products. To comprehensively cover practical cases, we analyzed the decision-making in three scenarios, including no outsourcing, outsourcing without the TPR's new product production, and outsourcing with the TPR's new product production.

In shedding light on the decision interactions, we followed the widely accepted literature to describe the price function for the OEM's new products and the TPR's new and remanufactured products, and put forward a unique analytical model to capture the two firms' profit-maximization decision-making under the two environmental policies. Our results highlight the optimal decisions for the OEM and the TPR as well as the corresponding

conditions, e.g., the specific values of emissions taxes. Additionally, per the results, we point out that the strategies of the two firms are influenced by cost structures, environmental taxes, and consumers' value discount for remanufactured products (δ) as follows. (1) When δ is low, the TPR does not engage in remanufacturing, whilst when δ is high, either high or low collection costs of used products prevent the TPR from remanufacturing; (2) When the unit waste management tax is either low or high, the OEM does not outsource used product management if the TPR does not produce new products; (3) When the unit waste management tax is moderate, as the unit emission tax increases, the OEM's strategy changes from no outsourcing to outsourcing if the TPR produces new products.

Based on the results and analysis, we arrived at valuable managerial implications and guidelines for firms in similar CLSCs in practice to optimize their decisions. For OEMs, when making used product management outsourcing decisions, they need to balance the gains from reduced waste management taxes and the increased outsourcing costs and the potential market cannibalization caused by TPRs' products. More specifically, as shown in [Table 4.5](#), when the unit waste management tax is moderate, (i) if TPRs do not introduce their new products, OEMs should outsource used product management; and (ii) otherwise, OEMs should avoid outsourcing when the unit emission tax is low. Regarding TPRs, they can increase their profits by adopting various product recovery strategies and seeking additional revenue from materials recovered from used products. When the unit collection cost is high, TPRs should prioritize remanufacturing over material recovery to manage used products. Nevertheless, when the unit collection cost becomes extremely high, TPRs should cease cooperation with OEMs. When the unit waste management tax is very low or high, they can increase profits by reusing recovered materials to produce their own-branded new products. Additionally, to maintain the outsourcing cooperation, when the unit emission tax is high/low and the unit waste management tax is moderate, TPRs should/should not produce new products.

Our study makes several contributions. First, we extend the available remanufacturing literature by examining firms' strategic choices among remanufacturing, material recovery, and reuse of recovered materials in used product management. In other words, building on

top of the available articles, our study investigates the decision-making problem involving comprehensive used product management activities. Second, we investigate the role of emission and waste management taxes in shaping strategic decisions within a CLSC involving coopetition where TPRs engage in new product production. Third, we provide the conditions under which (i) the OEM benefits from outsourcing used product management, (ii) the TPR engages in remanufacturing and new product production, and (iii) the OEM benefits from the TPR's introducing new products. At last, our findings offer managerial implications for OEMs and TPRs to optimize their decisions (e.g., outsourcing and product recovery strategies, unit outsourcing fee) in compliance with environmental policies.

Despite the contributions, our study has some limitations that are related to the assumptions. As a pioneering study, we assumed that each used product can be remanufactured or be used to recover materials. However, in practice, not all used products have sufficient quality for such processes ([Ferrer and Swaminathan, 2010](#)). Regarding this, new models considering the uncertain quality of used products can be developed to help OEMs and TPRs to make relevant decisions and strategies. Additionally, in our study, all used products were collected. In the real world, not all the used products are collected, and the collection rate is either certain or uncertain. Future efforts could explore new models incorporating variable collection rates and investigate their influence on firms' decisions and performance. Moreover, our assumption that the TPR unilaterally sets the unit outsourcing fee may not always hold in practice. In some cases, OEMs and TPRs co-determine it through negotiation ([Zhou et al., 2021b](#)). Regarding this, future studies can delve into the dynamics of these negotiations and analyze their impact on firms' decision-making. In our study, we took the environmental policies for granted and focused on their impact. Because tax rates play an important role in firms' decision-making, it is both interesting and relevant to examine how regulators can determine the policies, which benefit all the parties including: OEMs, TPRs, and regulators ([Zhang et al., 2020](#); [Chai et al., 2024](#)).

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4.7 A list of appendices

Appendix B-1. Derivation of optimal solutions

Optimal solution for Case N. In Case NO, the optimal decision regarding the OEM's production quantity can be obtained by maximizing the OEM's profit, i.e., $Max\pi_O^{NO}(q_N) = (1 - q_N^{NO} - c_N)q_N^{NO} - t_e q_N^{NO} e_N - t_w q_N^{NO}$. As the second derivate of OEM's profit with respect to his production quantity is less than zero, i.e., $\frac{\partial^2 \pi_O^{NO}}{\partial q_N^{NO} \partial q_N^{NO}} = -2 < 0$, π_O^{NO} is concave in q_N^{NO} . Therefore, we get the optimal q_N^{NO} by solving the first-order condition of the OEM's profit with respect to q_N^{NO} , i.e., $q_N^{NO*} = 1/2(1 - c_N - t_e - t_w)$. The corresponding profit is $\pi_O^{NO*} = 1/4(1 - c_N - t_e - t_w)^2$.

Optimal solution for Case O. In Case O, by substituting the inverse demand functions into Eqs. (3-2) and (3-3), we get the OEM's and the TPR's problems as follows:

$$Max\pi_O^O(q_N^O) = (1 - q_N^O - \delta q_R^O - c_N)q_N^O - t_e q_N^O e_N - q_N^O d_N^O, \text{ and}$$

$$Max\pi_R^O(d_N^O, q_R^O) = (\delta(1 - q_N^O - q_R^O) - c_R)q_R^O + q_N^O d_N^O - c_A q_N^O - (q_N^O - q_R^O)(c_D - s) - (q_R^O e_R + (q_N^O - q_R^O)e_D)t_e, \text{ respectively. With the constraint that } q_N^O \geq q_R^O \geq 0.$$

We use backward induction and begin by characterizing the best-response functions of the OEM's production quantity (i.e., q_N^O) and the TPR's remanufacturing quantity (i.e., q_R^O) to the unit disposal outsourcing fee, d_N^O . Because the second order derivatives of both the OEM's profit with respect to q_N^O and the TPR's profit with respect to q_R^O are less than zero (i.e., $\frac{\partial^2 \pi_O^O}{\partial q_N^O \partial q_N^O} = -2 < 0$, $\frac{\partial^2 \pi_R^O}{\partial q_R^O \partial q_R^O} = -2\delta < 0$), π_O^O and π_R^O are concave in q_N^O and q_R^O , respectively.

The necessary condition for the OME's optimal decision, q_N^O , is:

$$\frac{\partial \pi_O^O}{\partial q_N^O} = 1 - c_N - d_N^O - 2q_N^O - \delta q_R^O - t_e = 0 \quad (B - 1)$$

The TPR's problem is characterized by Karush-Kuhn-Tucker (KKT) conditions. Let g_1 and g_2 denote the Lagrangian multipliers, then we have the Lagrangian function of the TPR's optimization problem as follows:

$$L(q_R^O, g_1, g_2) = (\delta(1 - q_N^O - q_R^O) - c_R)q_R^O - (q_N^O - q_R^O)(c_D - s) + q_N^O d_N^O - c_A q_N^O - (q_R^O e_R + (q_N^O - q_R^O)e_D)t_e + g_1 q_R^O + g_2 (q_N^O - q_R^O) \quad (B-2)$$

With the first condition

$$\frac{\partial L}{\partial q_R^O} = \delta - s + c_D - c_R + g_1 - g_2 - \delta(q_N^O + 2q_R^O) + (e_D - e_R)t_e = 0 \quad (B-3)$$

and the constraints $g_1 q_R^O = 0$ and $g_2 (q_N^O - q_R^O) = 0$, we have the following cases:

Case 1. When $g_1 > 0$ and $g_2 = 0$, solving Eqs. (B-1), (B-2), and (B-3) simultaneously yields: $q_N^O = \frac{1}{2}(1 - c_N - d_N^O - t_e)$, $q_R^O = 0$, and $g_1 = s - \delta/2 - c_D + c_R - 1/2\delta(c_N + d_N^O) - 1/2(\delta + 2e_D - 2e_R)t_e$. Let $q_N^O > 0$ and $g_1 > 0$, we get i) if $c_D \leq s - \delta + c_R - e_D t_e + e_R t_e$, $d_N^O < 1 - c_N - t_e$; ii) if $c_D > s - \delta + c_R - e_D t_e + e_R t_e$, $d_N^O < (2s - \delta - 2c_D - \delta c_N + 2c_R - \delta t_e - 2e_D t_e + 2e_R t_e)/\delta$. Now, we solve the TPR's optimal decision on d_N^O , which is also characterized by KKT conditions. Let a_1 and a_2 denote the Lagrangian multipliers.

(1) When $c_D \leq s - \delta + c_R - e_D t_e + e_R t_e$, the Lagrangian function for the TPR's optimization problem is $L_O^{a1} = \pi_O^O + a_1(1 - c_N - t_e - d_N^O)$. With the first-order condition $\frac{\partial L_O^{a1}}{\partial d_N^O} = 1/2(1 - s + c_A + c_D - c_N - 2d_N^O + (-1 + e_D)t_e) = 0$ and the constraint $a_1(1 - c_N - t_e - d_N^O) = 0$, we have the following two subcases:

Case 1-1. When $a_1 > 0$, solving the first-order condition and the constraint simultaneously, we have $a_1 = 1/2(-1 - s + c_A + c_D + c_N + (1 + e_D)t_e)$ and $d_N^{O*} = 1 - c_N - t_e$. Let $a_1 > 0$ and $c_D \leq s - \delta + c_R - e_D t_e + e_R t_e$, we get the conditions $c_D \leq s - \delta + c_R - e_D t_e + e_R t_e$ and $c_A > \hat{c}_A^{ON1}$, where $\hat{c}_A^{ON1} = 1 + s - c_D - c_N - t_e - e_D t_e$. The relative profits are $\pi_O^O = 0$ and $\pi_R^O = 0$.

Case 1-2. When $a_1 = 0$, solving the first-order condition and the constraint simultaneously, we have $d_N^{O*} = 1/2(1 - s + c_A + c_D - c_N + (-1 + e_D)t_e)$. Let $d_N^{O*} < 1 - c_N - t_e$ and $c_D \leq s - \delta + c_R - e_D t_e + e_R t_e$, we get the conditions $c_D \leq s - \delta +$

$c_R - e_D t_e + e_R t_e$ and $c_A < \hat{c}_A^{ON1}$. The relative profits are $\pi_O^0 = 1/16(-1 - s + c_A + c_D + c_N + (1 + e_D)t_e)^2$ and $\pi_R^0 = 1/8(-1 - s + c_A + c_D + c_N + (1 + e_D)t_e)^2$.

(2) When $c_D > s - \delta + c_R - e_D t_e + e_R t_e$, the Lagrangian function for the TPR's optimization problem is $L_O^{a2} = \pi_R^0 + a_2((2s - \delta - 2c_D - \delta c_N + 2c_R - \delta t_e - 2e_D t_e + 2e_R t_e)/\delta - d_N^0)$. With the first-order condition $\frac{\partial L_O^{a2}}{\partial d_N^0} = 1/2(1 - s + c_A + c_D - c_N - 2d_N^0 + (-1 + e_D)t_e) = 0$ and the constraint $a_2((2s - \delta - 2c_D - \delta c_N + 2c_R - \delta t_e - 2e_D t_e + 2e_R t_e)/\delta - d_N^0) = 0$, we have the following two subcases:

Case 1-3. When $a_2 > 0$, solving the first-order condition and the constraint simultaneously, we have $a_2 = (3\delta - s(4 + \delta) + \delta c_A + (4 + \delta)c_D + \delta c_N - 4c_R + (\delta + (4 + \delta)e_D - 4e_R)t_e)/(2\delta)$ and $d_N^{0*} = (\delta - 2s + 2c_D + \delta c_N - 2c_R + (\delta + 2e_D - 2e_R)t_e)/\delta$. Let $a_2 > 0$ and $c_D > s - \delta + c_R - e_D t_e + e_R t_e$, we get the conditions $c_D > s - \delta + c_R - e_D t_e + e_R t_e$ and $c_A > \hat{c}_A^{ON2}$, where $\hat{c}_A^{ON2} = (4s - 3\delta + s\delta - 4c_D - \delta c_D - \delta c_N + 4c_R - \delta t_e - 4e_D t_e - \delta e_D t_e + 4e_R t_e)/\delta$. The relative profits are $\pi_O^0 = (-s + \delta + c_D - c_R + (e_D - e_R)t_e)^2/\delta^2$ and $\pi_R^0 = (2s + (-1 + s)\delta - 2c_D - \delta(c_A + c_D + c_N) + 2c_R - (\delta + (2 + \delta)e_D - 2e_R)t_e)(-s + \delta + c_D - c_R + (e_D - e_R)t_e)/\delta^2$.

Case 1-4. When $a_2 = 0$, solving the first-order condition and the constraint simultaneously, we have $d_N^{0*} = \frac{1}{2}(1 - s + c_A + c_D - c_N + (-1 + e_D)t_e)$. Let $c_D > s - \delta + c_R - e_D t_e + e_R t_e$ and $d_N^{0*} < (2s - \delta - 2c_D - \delta c_N + 2c_R - \delta t_e - 2e_D t_e + 2e_R t_e)/\delta$, we get the conditions $c_D > s - \delta + c_R - e_D t_e + e_R t_e$ and $c_A < \hat{c}_A^{ON2}$. The relative profits are $\pi_O^0 = 1/16(-1 - s + c_A + c_D + c_N + (1 + e_D)t_e)^2$ and $\pi_R^0 = 1/8(-1 - s + c_A + c_D + c_N + (1 + e_D)t_e)^2$.

Case 2. When $g_1 = 0$ and $g_2 = 0$, solving Eqs. (B-1), (B-2), and (B-3) simultaneously yields: $q_N^0 = (\delta + c_D + 2c_N - 2 - s - c_R + 2d_N^0 + (2 + e_D - e_R)t_e)/(-4 + \delta)$ and $q_R^0 = (\delta + 2c_D - 2s - 2c_R + \delta(c_N + d_N^0) + (\delta + 2e_D - 2e_R)t_e)/((4 - \delta)\delta)$. Let $q_N^0 > q_R^0 > 0$, we get $c_D > s - \delta + c_R - e_D t_e + e_R t_e$, $(2c_D + \delta c_N - 2c_R + \delta + t_e(\delta + 2e_D - 2e_R) - 2s)/(-\delta) < d_N^0 < (\delta - \delta^2 + s(2 + \delta) - (2 + \delta)c_D + 2c_R - \delta(3c_N - c_R) + ((2 + \delta)e_D - 3\delta + (2 + \delta)e_R)t_e)/(3\delta)$. Now, we solve the TPR's optimal decision on d_N^0 , which is also characterized by KKT conditions. Let b_1 and b_2 denote the Lagrangian multipliers, the Lagrangian function for the TPR's optimization problem is $L_O^b = \pi_R^0 + b_2((\delta - \delta^2 +$

$s(2 + \delta) - (2 + \delta)c_D + 2c_R - \delta(3c_N - c_R) + ((2 + \delta)e_D - 3\delta + (2 + \delta)e_R)t_e)/(3\delta) - d_N^0) + b_1(d_N^0 - (2c_D + \delta c_N - 2c_R + \delta + t_e(\delta + 2e_D - 2e_R) - 2s)/(-\delta))$. With the first-order condition $\frac{\partial L_O^b}{\partial d_N^0} = (8 + s(-8 + \delta) + (-4 + \delta)\delta + (-4 + \delta)^2 b_1 - (-4 + \delta)^2 b_2 + 8c_A + 8c_D - 8c_N - \delta(2c_A + c_D - 4c_N + c_R - 6d_N^0) - 16d_N^0 - 8t_e - ((-8 + \delta)e_D + \delta(-4 + e_R))t_e)/(-4 + \delta)^2 = 0$ and the constraints $b_1(d_N^0 - (2c_D + \delta c_N - 2c_R + \delta + t_e(\delta + 2e_D - 2e_R) - 2s)/(-\delta)) = 0$ and $b_2((\delta - \delta^2 + s(2 + \delta) - (2 + \delta)c_D + 2c_R - \delta(3c_N - c_R) + ((2 + \delta)e_D - 3\delta + (2 + \delta)e_R)t_e)/(3\delta) - d_N^0) = 0$, we have the following three subcases:

Case 2-1. When $b_1 > 0$ and $b_2 = 0$, solving the first-order condition and the constraints, we have $d_N^{0*} = (2c_D + \delta c_N - 2c_R + \delta + t_e(\delta + 2e_D - 2e_R) - 2s)/(-\delta)$ and $b_1 = (\delta(a_2(\delta - 4) + 2c_A + c_D + 2c_N + c_R) + 8c_D - 8c_R - ((\delta - 6)\delta) + t_e(2\delta + (\delta + 8)e_D + (\delta - 8)e_R) - (\delta + 8)s)/((\delta - 4)\delta)$. Let $d_N^{0*} < (\delta - \delta^2 + s(2 + \delta) - (2 + \delta)c_D + 2c_R - \delta(3c_N - c_R) + ((2 + \delta)e_D - 3\delta + (2 + \delta)e_R)t_e)/(3\delta)$, $b_1 > 0$, and $\delta > s - c_D + c_R - e_D t_e + e_R t_e$, we get the conditions $\delta > s - c_D + c_R - e_D t_e + e_R t_e$ and $c_A < \hat{c}_A^{01}$, where $\hat{c}_A^{01} = (-\delta(2c_N + c_R) - (\delta + 8)c_D + 8c_R + (\delta - 6)\delta - t_e(2\delta + (\delta + 8)e_D + (\delta - 8)e_R) + (\delta + 8)s)/(2\delta)$. The relative profits are $\pi_O^0 = (-s + \delta + c_D - c_R + (e_D - e_R)t_e)^2/\delta^2$ and $\pi_R^0 = ((2s - (1 - s)\delta - 2c_D - \delta(c_A + c_D + c_N) + 2c_R - (\delta + (2 + \delta)e_D - 2e_R)t_e)(\delta - s + c_D - c_R + (e_D - e_R)t_e))/\delta^2$.

Case 2-2. When $b_1 = 0$ and $b_2 = 0$, solving the first-order condition and the constraints yields $d_N^{0*} = ((\delta - 4)(2c_A - \delta) + (\delta - 8)c_D + 8(c_N + 1) + \delta(c_R - 4c_N) - (\delta - 4) - t_e((4 - e_R - e_D)\delta + 8(e_D - 1)) + (8 - \delta)s)/(6\delta - 16)$. Let $\delta > s - c_D + c_R - e_D t_e + e_R t_e$ and $(2c_D + \delta c_N - 2c_R + \delta + t_e(\delta + 2e_D - 2e_R) - 2s)/(-\delta) < d_N^{0*} < (\delta - \delta^2 + s(2 + \delta) - (2 + \delta)c_D + 2c_R - \delta(3c_N - c_R) + ((2 + \delta)e_D - 3\delta + (2 + \delta)e_R)t_e)/(3\delta)$, we get the conditions $\delta > s - c_D + c_R - e_D t_e + e_R t_e$ and $\hat{c}_A^{01} < c_A < c_A^1$, where $c_A^1 = (3\delta(c_R - 2c_N) - (9\delta + 8)c_D + 8c_R - \delta(3\delta + 2) + t_e((3\delta + 8)e_R - 6\delta - (9\delta + 8)e_D) + (9\delta + 8)s)/(6\delta)$. The relative profits are $\pi_O^0 = 4(-1 - 2s + \delta + c_A + 2c_D + c_N - c_R + (1 + 2e_D - e_R)t_e)^2/(8 - 3\delta)^2$ and $\pi_R^0 = (4\delta - 10s\delta^2 + \delta^3 + s^2(8 + 13\delta) + 4\delta c_A^2 + (8 + 13\delta)c_D^2 - 8\delta c_N - 16s\delta c_N +$

$$\begin{aligned}
& 8\delta^2 c_N + 4\delta c_N^2 + 16s c_R - 8\delta c_R + 10s\delta c_R - 2\delta^2 c_R - 8\delta c_N c_R + 8c_R^2 + \delta c_R^2 + \\
& 2(4\delta(-1 - 2s + \delta) + (5\delta^2 - s(8 + 13\delta))e_D + 4\delta c_N(1 + 2e_D - e_R) + (-\delta(4 + \delta) + \\
& s(8 + 5\delta))e_R + c_R(-4\delta - (8 + 5\delta)e_D + (8 + \delta)e_R))t_e + (4\delta + e_D(16\delta + (8 + \\
& 13\delta)e_D) - 2(4\delta + (8 + 5\delta)e_D)e_R + (8 + \delta)e_R^2)t_e^2 + 8\delta c_A(-1 - 2s + \delta + 2c_D + c_N - \\
& c_R + (1 + 2e_D - e_R)t_e) + 2c_D(5\delta^2 - s(8 + 13\delta) + 8\delta c_N - (8 + 5\delta)c_R + (8\delta + (8 + \\
& 13\delta)e_D - (8 + 5\delta)e_R)t_e))/4\delta(8 - 3\delta).
\end{aligned}$$

Case 2-3. When $b_1 = 0$ and $b_2 > 0$, solving the first-order condition and the constraints yields $d_N^{0*} = (\delta(c_R - 3c_N) - (\delta + 2)c_D + 2c_R - \delta^2 + \delta + t_e(-3\delta - (\delta + 2)e_D + (\delta + 2)e_R) + (\delta + 2)s)/(3\delta)$ and $b_2 = (3\delta(-2c_A - 3c_D - 2c_N + c_R) - 8c_D + 8c_R - \delta(3\delta + 2) + t_e(-6\delta - (9\delta + 8)e_D + (3\delta + 8)e_R) + (9\delta + 8)s)/(3(\delta - 4)\delta)$. Let $\delta > s - c_D + c_R - e_D t_e + e_R t_e$ and $-(2c_D + \delta c_N - 2c_R + \delta + t_e(\delta + 2e_D - 2e_R) - 2s)/\delta < d_N^{0*} < (\delta - \delta^2 + s(2 + \delta) - (2 + \delta)c_D + 2c_R - \delta(3c_N - c_R) + ((2 + \delta)e_D - 3\delta + (2 + \delta)e_R)t_e)/(3\delta)$, we get the conditions $\delta > s - c_D + c_R - e_D t_e + e_R t_e$ and $c_A > c_A^1$. The relative profits are $\pi_R^0 = ((2s + \delta + 3s\delta - 2c_D - 3\delta(c_A + c_D + c_N) + 2c_R - (3\delta + (2 + 3\delta)e_D - 2e_R)t_e)(-s + \delta + c_D - c_R + (e_D - e_R)t_e))/(9\delta^2)$ and $\pi_O^0 = (s - \delta - c_D + c_R + (-e_D + e_R)t_e)^2/(9\delta^2)$.

Case 3. When $g_1 = 0$ and $g_2 > 0$, solving Eqs. (B-1), (B-2), and (B-3) simultaneously yields: $g_2 = ((2 + \delta)c_D - (1 - \delta)\delta - s(2 + \delta) - 2c_R + \delta(3c_N - c_R + 3d_N) + (3\delta + (2 + \delta)e_D - (2 + \delta)e_R)t_e)/(2 + \delta)$, $q_N^0 = (1 - c_N - d_N - t_e)/(2 + \delta)$, and $q_R^0 = (1 - c_N - d_N - t_e)/(2 + \delta)$. Let $g_2 > 0$ and $q_N^0 = q_R^0 > 0$, we get $(\delta - \delta^2 + s(2 + \delta) - (2 + \delta)c_D + 2c_R - \delta(3c_N - c_R) + ((2 + \delta)e_D - 3\delta + (2 + \delta)e_R)t_e)/(3\delta) < d_N^0 < 1 - c_N - t_e$ and $c_D > s - \delta + c_R - e_D t_e + e_R t_e$. Now, we solve the TPR's optimal decision on d_N^0 which is also characterized by KKT conditions. Let b_1 and b_2 denote the Lagrangian multipliers, the Lagrangian function for the TPR's optimization problem is $L_O^c = \pi_R^0 + c_2(d_N^0 - (\delta - \delta^2 + s(2 + \delta) - (2 + \delta)c_D + 2c_R - \delta(3c_N - c_R) + ((2 + \delta)e_D - 3\delta + (2 + \delta)e_R)t_e)/(3\delta)) + c_2(1 - c_N - t_e - d_N^0)$. With the first-order condition $\frac{\partial L_O^b}{\partial d_N^0} = (2 + \delta(3 - \delta) + (2 + \delta)^2 c_1 - (2 + \delta)^2 c_2 + (2 + \delta)(c_A + c_R) - c_N(2 + 5\delta) - 4d_N^0 - 6\delta d_N^0 + ((2 + \delta)e_R - 2 - 5\delta)t_e)/(2 + \delta)^2 = 0$ and the constraints $c_2(1 - c_N - t_e - d_N^0) = 0$ and $c_2(d_N^0 - (2s + \delta + s\delta - \delta^2 - 2c_D - \delta c_D - 3\delta c_N + 2c_R + \delta c_R - 3\delta t_e - 2e_D t_e - \delta e_D t_e + 2e_R t_e +$

$\delta e_R t_e)/(3\delta)) = 0$, we have the following three subcases:

Case 3-1. When $c_1 > 0$ and $c_2 = 0$, solving the first-order condition and the constraints yields $d_N^{0*} = (2s + \delta + s\delta - \delta^2 - 2c_D - \delta c_D - 3\delta c_N + 2c_R + \delta c_R - 3\delta t_e - 2e_D t_e - \delta e_D t_e + 2e_R t_e + \delta e_R t_e)/(3\delta)$ and $c_1 = (s(4 + 6\delta) - \delta(1 + 3\delta) - 4c_D - 3\delta(c_A + 2c_D + c_N - c_R) + 4c_R + (-3\delta - 2(2 + 3\delta)e_D + (4 + 3\delta)e_R)t_e)/(3\delta(2 + \delta))$. Let $c_1 > 0$, $c_D > s - \delta + c_R - e_D t_e + e_R t_e$, and $d_N^{0*} < 1 - c_N - t_e$, we get the conditions $c_D > s - \delta + c_R - e_D t_e + e_R t_e$ and $c_A < c_A^2$, where $c_A^2 = (3\delta(c_R - c_N) - 2(3\delta + 2)c_D + 4c_R - \delta(3\delta + 1) + t_e(-3\delta - 2(3\delta + 2)e_D + (3\delta + 4)e_R) + (6\delta + 4)s)/(3\delta)$. The relative profits are $\pi_O^0 = (s - \delta - c_D + c_R + (-e_D + e_R)t_e)^2/(9\delta^2)$ and $\pi_R^0 = (2(s - c_D) + \delta(1 + 3s) - 3\delta(c_A + c_D + c_N) + 2c_R - (3\delta + (2 + 3\delta)e_D - 2e_R)t_e)(-s + \delta + c_D - c_R + (e_D - e_R)t_e)/(9\delta^2)$.

Case 3-2. When $c_1 = 0$ and $c_2 = 0$, solving the first-order condition and the constraints yields $d_N^{0*} = (2 + 3\delta - \delta^2 + (2 + \delta)c_A - (2 + 5\delta)c_N + 2c_R + \delta c_R + (-2 - 5\delta + (2 + \delta)e_R)t_e)/(4 + 6\delta)$. Let $(2s + \delta + s\delta - \delta^2 - 2c_D - \delta c_D - 3\delta c_N + 2c_R + \delta c_R - 3\delta t_e - 2e_D t_e - \delta e_D t_e + 2e_R t_e + \delta e_R t_e)/(3\delta) < d_N^{0*} < 1 - c_N - t_e$ and $c_D > s - \delta + c_R - e_D t_e + e_R t_e$, and $(2s + \delta + s\delta - \delta^2 - 2c_D - \delta c_D - 3\delta c_N + 2c_R + \delta c_R - 3\delta t_e - 2e_D t_e - \delta e_D t_e + 2e_R t_e + \delta e_R t_e)/(3\delta) < d_N^{0*} < 1 - c_N - t_e$, we get the conditions $c_D > s - \delta + c_R - e_D t_e + e_R t_e$ and $c_A^2 < c_A < \hat{c}_A^{03}$, where $\hat{c}_A^{03} = 1 + \delta - c_N - c_R - t_e - e_R t_e$. The relative profits are $\pi_O^0 = (-1 - \delta + c_A + c_N + c_R + (1 + e_R)t_e)^2/(4(2 + 3\delta)^2)$ and $\pi_R^0 = (-1 - \delta + c_A + c_N + c_R + (1 + e_R)t_e)^2/(8 + 12\delta)$.

Case 3-3. When $c_1 = 0$ and $c_2 > 0$, solving the first-order condition and the constraints yields $c_2 = (-1 - \delta + c_A + c_N + c_R + (1 + e_R)t_e)/(2 + \delta)$ and $d_N^{0*} = 1 - c_N - t_e$ and . Let $d_N^{0*} > (2s + \delta + s\delta - \delta^2 - 2c_D - \delta c_D - 3\delta c_N + 2c_R + \delta c_R - 3\delta t_e - 2e_D t_e - \delta e_D t_e + 2e_R t_e + \delta e_R t_e)/(3\delta)$ and $c_D > s - \delta + c_R - e_D t_e + e_R t_e$, we get the conditions $c_D > s - \delta + c_R - e_D t_e + e_R t_e$, and $c_A > \hat{c}_A^{03}$. The relative profits are $\pi_R^0 = 0$ and $\pi_O^0 = 0$.

$$c_A^1 = (3\delta(c_R - 2c_N) - (9\delta + 8)c_D + 8c_R - \delta(3\delta + 2) + t_e(-6\delta - (9\delta + 8)e_D + (3\delta + 8)e_R) + (9\delta + 8)s)/(6\delta), \quad c_A^2 = (3\delta(c_R - c_N) - 2(3\delta + 2)c_D + 4c_R - \delta(3\delta + 1) +$$

$$t_e(-3\delta - 2(3\delta + 2)e_D + (3\delta + 4)e_R) + (6\delta + 4)s)/(3\delta), \hat{c}_A^{ON1} = 1 + s - c_D - c_N - t_e - e_D t_e, \hat{c}_A^{ON2} = (4s - 3\delta + s\delta - 4c_D - \delta c_D - \delta c_N + 4c_R - \delta t_e - 4e_D t_e - \delta e_D t_e + 4e_R t_e)/\delta, \hat{c}_A^{O1} = (8s - 6\delta + s\delta + \delta^2 - 8c_D - \delta c_D - 2\delta c_N + 8c_R - \delta c_R - 2\delta t_e - 8e_D t_e - \delta e_D t_e + 8e_R t_e - \delta e_R t_e)/(2\delta), \hat{c}_A^{O3} = 1 + \delta - c_N - c_R - t_e - e_R t_e.$$

In conclusion, the TPR has 10 potential decisions on d_N^O as c_A and c_D change. She makes decisions by maximizing her profit. By comparing the thresholds and the corresponding profit for the TPR in each case, we can obtain the TPR's optimal decision on d_N^O as well as the OEM's and the TPR's production/remanufacturing quantity and profits under different conditions, which are shown in Tables B.1 and B.2. Note that these conditions can ensure the non-negative of optimal production and remanufacturing quantities.

Table B. 1. Optimal decisions and profits in Case O when $\delta \leq \hat{\delta}$

Optimal decisions			
Unit disposal outsourcing fee (i.e., d_N^{O*})	Production quantity of N (i.e., q_N^{O*})	Remanufacturing quantity (i.e., q_R^{O*})	Condition
$1 - c_N - t_e,$	0	0	$c_A \geq \hat{c}_A^{ON1}$
$\frac{1}{2}(1 - s + c_A + c_D - c_N + (-1 + e_D)t_e),$	$\frac{1}{4}(1 + s - c_A - c_D - c_N - (1 + e_D)t_e),$	0	$c_A < \hat{c}_A^{ON1}$
Profits			
The OEM's profits (i.e., π_O^{O*})	The TPR's profit (i.e., π_R^{O*})		Condition
0	0		$c_A \geq \hat{c}_A^{ON1}$
$\frac{1}{16}(c_A + c_D + c_N + (e_D + 1)t_e - s - 1)^2$	$\frac{1}{8}(-1 - s + c_A + c_D + c_N + (1 + e_D)t_e)^2$		$c_A < \hat{c}_A^{ON1}$

Table B. 2. Optimal decisions and profits in Case O when $\delta > \hat{\delta}$

Optimal decisions			
Unit disposal outsourcing fee (i.e., d_N^{O*})	Production quantity of N (i.e., q_N^{O*})	Remanufacturing quantity (i.e., q_R^{O*})	Condition
$\frac{1}{2}(1-s+c_A+c_D-c_N+(-1+e_D)t_e),$ $(2c_R-2c_D-\delta c_N-\delta-t_e(\delta+2e_D-2e_R)+2s/\delta),$	$\frac{1}{4}(1+s-c_A-c_D-c_N-(1+e_D)t_e),$ $(\delta-s+c_D-c_R+(e_D-e_R)t_e)/\delta,$	0, 0,	if $c_A < \hat{c}_A^{ON2},$ if $\hat{c}_A^{ON2} \leq c_A < \hat{c}_A^{O1},$
$\frac{1}{16-6\delta}(8-8s-4\delta+s\delta+\delta^2+2(4-\delta)c_A+(8-\delta)c_D-8c_N+4\delta c_N-\delta c_R-(8-4\delta-(8-\delta)e_D+\delta e_R)t_e),$	$(2(c_A+2c_D+c_N-c_R+\delta+t_e(2e_D-e_R+1)-2s-1))/(3\delta-8),$	$\frac{1}{2\delta(3\delta-8)}(8c_R+(\delta-6)\delta-\delta(2c_A+c_D+2c_N+c_R)-8c_D-t_e(2\delta+(\delta+8)e_D+(\delta-8)e_R)+(\delta+8)s),$	if $\hat{c}_A^{O1} \leq c_A < \hat{c}_A^{O2},$
$(2+3\delta-\delta^2+(2+\delta)c_A-(2+5\delta)c_N+2c_R+\delta c_R+(-2-5\delta+(2+\delta)e_R)t_e)/(4+6\delta),$ $1-c_N-t_e.$	$\frac{1-c_A-c_N-c_R+\delta-(e_R+1)t_e}{6\delta+4},$ 0.	$\frac{1-c_A-c_N-c_R+\delta-(e_R+1)t_e}{6\delta+4},$ 0.	if $\hat{c}_A^{O2} \leq c_A < \hat{c}_A^{O3},$ otherwise.
Profits			
The OEM's profits (i.e., π_O^{O*})	The TPR's profit (i.e., π_R^{O*})		Condition
$\frac{1}{16}(c_A+c_D+c_N+(e_D+1)t_e-s-1)^2,$ $\frac{(c_D-c_R+\delta+t_e(e_D-e_R)-s)^2}{\delta^2},$ $\frac{4(c_A+2c_D+c_N-c_R+\delta+t_e(2e_D-e_R+1)-2s-1)^2}{(8-2\delta)^2},$ $\frac{(c_A+c_N+c_R-\delta+(e_R+1)t_e-1)^2}{4(2\delta+2)^2},$ 0	$\frac{1}{8}(c_A+c_D+c_N+(e_D+1)t_e-s-1)^2,$ $\frac{1}{\delta^2}((c_D-c_R+\delta+t_e(e_D-e_R)-s)(-\delta(c_A+c_D+c_N)-2c_D+2c_R-t_e(\delta+(\delta+2)e_D-2e_R)+\delta(s-1)+2s)),$ $\pi_R^{O*}, (see the formula in Appendix A)$ $\frac{(c_A+c_N+c_R-\delta+(e_R+1)t_e-1)^2}{12\delta+8},$ 0		if $c_A < \hat{c}_A^{ON2},$ if $\hat{c}_A^{ON2} < c_A < \hat{c}_A^{O1},$ if $\hat{c}_A^{O1} < c_A \leq \hat{c}_A^{O2},$ if $\hat{c}_A^{O2} < c_A < \hat{c}_A^{O3},$ otherwise.

Where $\hat{c}_A^{OS} = (\delta(-1 + 24s - 15c_N + 9c_R - 3(5 + 8e_D - 3e_R)t_e) - 9\delta^2 - 8(2 + 3\delta)c_D - \delta\sqrt{(8 - 3\delta)(2 + 3\delta)(-s + \delta + c_D - c_R + (e_D - e_R)t_e)^2/\delta^2 + 16(s + c_R + (-e_D + e_R)t_e)})/(15\delta)$ and $\hat{\delta} = s - c_D - t_e e_D - c_R - e_R t_e$.

Optimal solution for Case OS when $\theta > \delta$. In Case OS, by substituting the inverse demand functions into Eqs. (3-4) and (3-5), we get the OEM's and the TPR's problems as follows:

$$\text{Max}\pi_O^{OS}(q_N^{OS}) = (1 - q_N^{OS} - \theta q_{TN}^{OS} - \delta q_R^{OS} - c_N)q_N^{OS} - t_e q_N^{OS} e_N - q_N^{OS} d_N^{OS} \quad (B-4)$$

and

$$\begin{aligned} \text{Max}\pi_R^{OS}(d_N^{OS}, q_R^{OS}, q_{TN}^{OS}) = & (\theta - \theta(q_{TN}^{OS} + q_N^{OS}) - \delta q_R^{OS} - c_{TN})q_{TN}^{OS} \\ & + (\delta(1 - q_N^{OS} - q_{TN}^{OS} - q_R^{OS}) - c_R)q_R^{OS} + q_N^{OS} d_N^{OS} - c_A q_N^{OS} \\ & - (q_N^{OS} - q_R^{OS})(c_D - s) - t_e(q_R^{OS} e_R + q_{TN}^{OS} e_N + (q_N^{OS} - q_R^{OS})e_D(1 - \gamma)) - t_w q_{TN}^{OS}, \end{aligned} \quad (B-5)$$

respectively.

In this case, we only consider the situation where $q_N^{OS} > q_R^{OS} > 0$ and $q_{TN}^{OS} > 0$. We use backward induction and begin by characterizing the best-response functions of the OEM's production quantity (i.e., q_N^{OS}) and the TPR's remanufacturing quantity (i.e., q_R^{OS}) and production quantity (i.e., q_{TN}^{OS}) to the unit disposal outsourcing fee, d_N^{OS} . Because the second order derivatives of OEM's profit with respect to his production quantity is less than zero (i.e., $\frac{\partial^2 \pi_O^{OS}}{\partial q_N^{OS} \partial q_N^{OS}} = -2 < 0$), π_O^{OS} is concave in q_N^{OS} . Meanwhile, the Hessian matrix of π_R is:

$$H_2 = \begin{pmatrix} \frac{\partial^2 \pi_R^{OS}}{\partial q_R^{OS} \partial q_R^{OS}} & \frac{\partial^2 \pi_R^{OS}}{\partial q_R^{OS} \partial q_{TN}^{OS}} \\ \frac{\partial^2 \pi_R^{OS}}{\partial q_{TN}^{OS} \partial q_R^{OS}} & \frac{\partial^2 \pi_R^{OS}}{\partial q_{TN}^{OS} \partial q_{TN}^{OS}} \end{pmatrix} = \begin{pmatrix} -2\delta & -2\delta \\ -2\delta & -2\theta \end{pmatrix} = 4\delta(\theta - \delta) > 0. \quad \text{Because } \frac{\partial^2 \pi_R^{OS}}{\partial q_R^{OS} \partial q_R^{OS}} =$$

$-2\delta < 0$ and $H_2 > 0$, the Hessian matrix is negative definite. Thus, the profit function π_O^{OS} is jointly concave in q_R^{OS} and q_{TN}^{OS} . The necessary conditions for optimal decisions are:

$$\frac{\partial \pi_O^{OS}}{\partial q_N^{OS}} = 1 - c_N - d_N^{OS} - 2q_N^{OS} - \delta q_R^{OS} - \theta q_{TN}^{OS} - t_e = 0 \quad (B-6)$$

$$\frac{\partial \pi_R^{OS}}{\partial q_R^{OS}} = c_D - c_R - s - \delta q_R^{OS} - \delta q_{TN}^{OS} - \delta(-1 + q_N^{OS} + q_R^{OS} + q_{TN}^{OS}) - \gamma e_D t_e - (-e_D + e_R) t_e = 0 \quad (B-7)$$

$$\frac{\partial \pi_R^{OS}}{\partial q_{TN}^{OS}} = \theta - c_{TN} - 2\delta q_R^{OS} - \theta q_{TN}^{OS} - \theta(q_N^{OS} + q_{TN}^{OS}) - t_e - t_w = 0 \quad (B-8)$$

Solving Eqs. (B-6), (B-7), and (B-8) simultaneously yields $q_N^{OS}(d_N^{OS}) = (-2 + \theta + 2c_N - c_{TN} + 2d_N^{OS} + t_e - t_w)/(-4 + \theta)$, $q_R^{OS}(d_N^{OS}) = (s\theta + \theta(-c_D + c_R + ((-1 + \gamma)e_D + e_R)t_e) - \delta(c_{TN} + t_e + t_w))/(2\delta(\delta - \theta))$, and $q_{TN}^{OS}(d_N^{OS}) = (4s - 2\delta + 2\theta - s\theta - (4 - \theta)c_D - 2\delta c_N + 4c_R - (4 - \delta)c_{TN} - 2\delta d_N^{OS} + \theta(2c_N - c_R + 2d_N^{OS}) - 4t_e - \delta t_e + (2\theta - (1 - \gamma)(4 - \theta)e_D - (-4 + \theta)e_R)t_e - (4 - \delta)t_w)/(2(\theta - \delta)(\theta - 4))$. Substituting $q_N^{OS}(d_N^{OS})$, $q_R^{OS}(d_N^{OS})$, and $q_{TN}^{OS}(d_N^{OS})$ into Eq. (B-5), the second order derivatives of Eq. (B-5) with respect to d_N^{OS} is less than zero (i.e., $\frac{\partial^2 \pi_R^{OS}(d_N^{OS})}{\partial d_N^{OS} \partial d_N^{OS}} = -\frac{2(8-3\theta)}{(4-\theta)^2} < 0$). Hence, $\pi_R^{OS}(d_N^{OS})$ is concave in d_N^{OS} . We get the optimal d_N^{OS} by solving the first-order condition of $\pi_R^{OS}(d_N^{OS})$ with respect to d_N^{OS} , i.e., $d_N^{OS*} = ((4 - \theta)(2c_A + 2c_D - \theta - 2s) + \theta(4c_N - c_{TN} + 3t_e - t_w) - 8(c_N + t_e - 1))/(2(8 - 3\theta))$. Substituting d_N^{OS*} into $q_N^{OS}(d_N^{OS})$, $q_R^{OS}(d_N^{OS})$, and $q_{TN}^{OS}(d_N^{OS})$, we obtain $q_N^{OS*} = (2(\theta + s + t_w + 1 - c_A - c_D - c_N + c_{TN}))/ (8 - 3\theta)$, $q_R^{OS*} = (\theta(c_D - c_R - e_R t_e - s) + \delta(c_{TN} + t_e + t_w))/(2\delta(\theta - \delta))$, and $q_{TN}^{OS*} = ((s - c_D)(8 + 2\delta - 5\theta) + (\theta - \delta)(6 - \theta + 2c_A + 2c_N) + (2\delta + \theta - 8)(t_w + c_{TN}) - (8 - 3\theta)(t_e(1 - e_R) - c_R))/ (2(\theta - \delta)(8 - 3\theta))$. The profits for the OEM and the TPR are $\pi_O^{OS} = 4(-1 - s + \theta + c_A + c_D + c_N - c_{TN} - t_w)^2 / (8 - 3\theta)^2$ and $\pi_R^{OS} = (s^2(8 - 3\theta)\theta - \delta^2(4(1 + s)^2 - 8s\theta + \theta^2) + \delta\theta(4(1 + s)^2 - 8s\theta + \theta^2) + 4\delta(-\delta + \theta)c_A^2 + (-4\delta^2 + 4\delta\theta + (8 - 3\theta)\theta)c_D^2 + 8\delta^2c_N + 8s\delta^2c_N - 8\delta\theta c_N - 8s\delta\theta c_N - 8\delta^2\theta c_N + 8\delta\theta^2 c_N - 4\delta^2c_N^2 + 4\delta\theta c_N^2 + 16s\theta c_R - 6s\theta^2 c_R + 8\theta c_R^2 - 3\theta^2 c_R^2 - 16s\delta c_{TN} + 8\delta^2 c_{TN} - 8s\delta^2 c_{TN} - 8\delta\theta c_{TN} + 14s\delta\theta c_{TN} + 2\delta^2\theta c_{TN} - 2\delta\theta^2 c_{TN} + 8\delta^2 c_N c_{TN} - 8\delta\theta c_N c_{TN} - 16\delta c_R c_{TN} + 6\delta\theta c_R c_{TN} + 8\delta c_{TN}^2 - 4\delta^2 c_{TN}^2 + \delta\theta c_{TN}^2 - 16s\delta t_e + 16\delta^2 t_e - 16\delta\theta t_e + 6s\delta\theta t_e - 6\delta^2\theta t_e + 6\delta\theta^2 t_e - 16\delta c_R t_e + 6\delta\theta c_R t_e + 16\delta c_{TN} t_e - 6\delta\theta c_{TN} t_e + 16s\theta e_R t_e - 6s\theta^2 e_R t_e + 16\theta c_R e_R t_e - 6\theta^2 c_R e_R t_e - 16\delta c_{TN} e_R t_e + 6\delta\theta c_{TN} e_R t_e + 8\delta t_e^2 - 3\delta\theta t_e^2 - 16\delta e_R t_e^2 + 6\delta\theta e_R t_e^2 + 8\theta e_R^2 t_e^2 - 3\theta^2 e_R^2 t_e^2 + 2\delta((\delta - \theta)(4 + \theta) + s(-8 - 4\delta + 7\theta) +$

$4(\delta - \theta)c_N + (-8 + 3\theta)c_R - 4(-2 + \delta)c_{TN} + \theta c_{TN} + 8t_e + (-3\theta + (-8 + 3\theta)e_R)t_e + \delta(8 - 4\delta + \theta)t_w^2 + 8\delta(\delta - \theta)c_A(1 + s - \theta - c_D - c_N + c_{TN} + t_w) + 2c_D(4(1 + s)\delta^2 - 4(\delta + \delta^2 + s(2 + \delta))\theta + (3s + 4\delta)\theta^2 + 4\delta(-\delta + \theta)c_N + \theta(-8 + 3\theta)c_R + 4\delta(2 + \delta)c_{TN} - 7\delta\theta c_{TN} + 8\delta t_e - 3\delta\theta t_e - 8\theta e_R t_e + 3\theta^2 e_R t_e + \delta(8 + 4\delta - 7\theta)t_w)/(4\delta(\delta - \theta)(-8 + 3\theta))$, respectively.

Additionally, let $q_N^{OS*} > q_R^{OS*} > 0$ and $q_{TN}^{OS*} > 0$, we get $s > \hat{s}^{OS}$ and $\hat{t}_w^{OS2} < t_w \leq \hat{t}_w^{OS1}$, where $\hat{s}_1^{OS} = (-\delta + \delta\theta + \delta c_A + \delta c_D + \theta c_D + \delta c_N - \theta c_R + \delta t_e - \theta e_R t_e)/(\delta + \theta)$, $\hat{t}_{w1}^{OS} = \min [(-4\delta^2 - 4s\delta^2 + 8s\theta + 4\delta\theta + 4s\delta\theta + 4\delta^2\theta - 3s\theta^2 - 4\delta\theta^2 + 4\delta^2 c_A - 4\delta\theta c_A + 4\delta^2 c_D - 8\theta c_D - 4\delta\theta c_D + 3\theta^2 c_D + 4\delta^2 c_N - 4\delta\theta c_N + 8\theta c_R - 3\theta^2 c_R - 8\delta c_{TN} - 4\delta^2 c_{TN} + 7\delta\theta c_{TN} - 8\delta t_e + 3\delta\theta t_e + 8\theta e_R t_e - 3\theta^2 e_R t_e)/(8\delta + 4\delta^2 - 7\delta\theta), (-8s + 6\delta - 2s\delta - 6\theta + 5s\theta - \delta\theta + \theta^2 + 2\delta c_A - 2\theta c_A + 8c_D + 2\delta c_D - 5\theta c_D + 2\delta c_N - 2\theta c_N - 8c_R + 3\theta c_R + 8c_{TN} - 2\delta c_{TN} - \theta c_{TN} + 8t_e - 3\theta t_e - 8e_R t_e + 3\theta e_R t_e)/(-8 + 2\delta + \theta)]$, $\hat{t}_{w2}^{OS} = (s\theta - \theta c_D + \theta c_R - \delta c_{TN} - \delta t_e + \theta e_R t_e)/\delta$.

Optimal solution for Case OS when $\theta < \delta$. When $\delta > \theta$, the inverse demand functions for Case OS are $p_N = 1 - q_N^{OS,E} - \delta q_R^{OS,E} - \theta q_{TN}^{OS,E}$, $p_R = \delta - \delta(q_N^{OS,E} + q_R^{OS,E}) - \theta q_{TN}^{OS,E}$, and $p_{TN} = \theta(1 - q_N^{OS,E} - q_R^{OS,E} - q_{TN}^{OS,E})$. By substituting the inverse demand functions into Eqs. (3-4) and (3-5), we get the OEM's and the TPR's problems as follows:

$$Max \pi_O^{OS,E}(q_N^{OS,E}) = (1 - q_N^{OS,E} - \theta q_{TN}^{OS,E} - \delta q_R^{OS,E} - c_N)q_N^{OS,E} - t_e q_N^{OS,E} e_N - q_N^{OS,E} d_N^{OS,E} (B - 9)$$

and

$$\begin{aligned} Max \pi_R^{OS,E}(d_N^{OS,E}, q_R^{OS,E}, q_{TN}^{OS,E}) &= (\theta(1 - q_{TN}^{OS,E} - q_N^{OS,E} - q_R^{OS,E}) - c_{TN})q_{TN}^{OS,E} \\ &+ (\delta - \delta(q_R^{OS,E} + q_N^{OS,E}) - \theta q_{TN}^{OS,E} - c_R)q_R^{OS,E} + q_N^{OS,E} d_N^{OS,E} - c_A q_N^{OS,E} \\ &- (q_N^{OS,E} - q_R^{OS,E})(c_D - s) - t_e (q_R^{OS,E} e_R + q_{TN}^{OS,E} e_N + (q_N^{OS,E} - q_R^{OS,E})e_D(1 - \gamma)) - t_w q_{TN}^{OS,E}, \end{aligned} \quad (B - 10)$$

respectively. Because the second order derivatives of OEM's profit with respect to his production quantity is less than zero (i.e., $\frac{\partial^2 \pi_O^{OS,E}}{\partial q_N^{OS,E} \partial q_N^{OS,E}} = -2 < 0$), $\pi_O^{OS,E}$ is concave in $q_N^{OS,E}$.

Meanwhile, the Hessian matrix of π_R is: $H_2 = \begin{pmatrix} \frac{\partial^2 \pi_R^{OS,E}}{\partial q_R^{OS,E} \partial q_R^{OS,E}} & \frac{\partial^2 \pi_R^{OS,E}}{\partial q_R^{OS,E} \partial q_{TN}^{OS,E}} \\ \frac{\partial^2 \pi_R^{OS,E}}{\partial q_{TN}^{OS,E} \partial q_R^{OS,E}} & \frac{\partial^2 \pi_R^{OS,E}}{\partial q_{TN}^{OS,E} \partial q_{TN}^{OS,E}} \end{pmatrix} = \begin{pmatrix} -2\delta & -2\theta \\ -2\theta & -2\theta \end{pmatrix} =$

$4\theta(\delta - \theta) > 0$. Because $\frac{\partial^2 \pi_R^{OS,E}}{\partial q_R^{OS,E} \partial q_R^{OS,E}} = -2\delta < 0$ and $H_2 > 0$, the Hessian matrix is negative definite.

Thus, the profit function $\pi_O^{OS,E}$ is jointly concave in $q_R^{OS,E}$ and $q_{TN}^{OS,E}$. The necessary conditions for optimal decisions are:

$$\frac{\partial \pi_O^{OS,E}}{\partial q_N^{OS,E}} = 1 - c_N - d_N^{OS,E} - 2q_N^{OS,E} - \delta q_R^{OS,E} - \theta q_{TN}^{OS,E} - t_e = 0 \quad (B-11)$$

$$\frac{\partial \pi_R^{OS,E}}{\partial q_R^{OS,E}} = -s + \delta + c_D - c_R - \delta(q_N^{OS,E} + 2q_R^{OS,E}) - 2\theta q_{TN}^{OS,E} - e_R t_e = 0 \quad (B-12)$$

$$\frac{\partial \pi_R^{OS,E}}{\partial q_{TN}^{OS,E}} = \theta - c_{TN} - \theta(q_N^{OS,E} + 2(q_R^{OS,E} + q_{TN}^{OS,E})) - t_e - t_w = 0 \quad (B-13)$$

Solving Eqs. (B-11), (B-12), and (B-13) simultaneously yields $q_N^{OS,E}(d_N) = (-2 - s + \delta + c_D + 2c_N - c_R + 2d_N - (-2 + e_R)t_e)/(-4 + \delta)$, $q_R^{OS,E}(d_N) = (4s - 2\delta + 2\theta - s\theta + (-4 + \theta)c_D - 2\delta c_N + 4c_R + (-4 + \delta)c_{TN} - 2\delta d_N + \theta(2c_N - c_R + 2d_N) - 4t_e - \delta t_e + (2\theta - (-4 + \theta)e_R)t_e + (-4 + \delta)t_w)/(2(-4 + \delta)(\delta - \theta))$, and $q_{TN}^{OS,E}(d_N) = (s\theta + \theta(-c_D + c_R + e_R t_e) - \delta(c_{TN} + t_e + t_w))/(2(\delta - \theta)\theta)$. Substituting $q_N^{OS,E}(d_N)$, $q_R^{OS,E}(d_N)$, and $q_{TN}^{OS,E}(d_N)$ into Eq. (B-10), the second order derivatives of Eq. (B-10) with respect to $d_N^{OS,E}$ is less than zero (i.e., $\frac{\partial^2 \pi_R^{OS,E}(d_N^{OS,E})}{\partial d_N^{OS,E} \partial d_N^{OS,E}} = -\frac{2(8-3\delta)}{(4-\delta)^2} < 0$). Hence, $\pi_R^{OS,E}(d_N^{OS,E})$ is concave in $d_N^{OS,E}$. We get the optimal $d_N^{OS,E}$ by solving the first-order condition of $\pi_R^{OS,E}(d_N^{OS,E})$ with respect to $d_N^{OS,E}$, i.e., $d_N^{OS,E*} = (-8 - s(-8 + \delta) - (-4 + \delta)\delta + 2(-4 + \delta)c_A + (-8 + \delta)c_D + 8c_N + 8t_e + \delta(-4c_N + c_R + (-4 + e_R)t_e))/(-16 + 6\delta)$. Accordingly, the optimal production and remanufacturing quantities are: $q_N^{OS,E*} = 2(-1 - 2s + \delta + c_A + 2c_D + c_N - c_R + t_e - e_R t_e)/(-8 + 3\delta)$, $q_{TN}^{OS,E*} = (s\theta + \theta(-c_D + c_R + e_R t_e) - \delta(c_{TN} + t_e + t_w))/(2(\delta - \theta)\theta)$, and $q_R^{OS,E*} = (s(8 + \delta - 4\theta) + (-6 + \delta)(\delta - \theta) + 2(-\delta + \theta)c_A - (8 + \delta - 4\theta)c_D - 2\delta c_N + 2\theta c_N + 8c_R - \delta c_R - 2\theta c_R - 8c_{TN} + 3\delta c_{TN} - 8t_e + \delta t_e + 2\theta t_e + 8e_R t_e - \delta e_R t_e - 2\theta e_R t_e - 8t_w + 3\delta t_w)/(2(-8 + 3\delta)(\delta - \theta))$. The profits for the OEM and the TPR are $\pi_O^{OS,E} = 4(-1 - 2s + \delta + c_A + 2c_D + c_N - c_R + t_e - e_R t_e)^2/(8 - 3\delta)^2$ and $\pi_R^{OS,E} = (\theta(10s\delta(\delta - \theta) + (4 + \delta^2)(-\delta + \theta) + s^2(-8 - 13\delta + 16\theta)) + 4\theta(-\delta + \theta)c_A^2 + \theta(-8 - 13\delta + 16\theta)c_D^2 + 8\delta\theta c_N + 16s\delta\theta c_N - 8\delta^2\theta c_N - 8\theta^2 c_N - 16s\theta^2 c_N + 8\delta\theta^2 c_N - 4\delta\theta c_N^2 + 4\theta^2 c_N^2 - 16s\theta c_R + 8\delta\theta c_R - 10s\delta\theta c_R + 2\delta^2\theta c_R - 8\theta^2 c_R + 16s\theta^2 c_R - 2\delta\theta^2 c_R + 8\delta\theta c_N c_R -$

$$\begin{aligned}
& 8\theta^2 c_N c_R - 8\theta c_R^2 - \delta\theta c_R^2 + 4\theta^2 c_R^2 + 16s\theta c_{TN} - 6s\delta\theta c_{TN} + 16\theta c_R c_{TN} - 6\delta\theta c_R c_{TN} - 8\delta c_{TN}^2 + \\
& 3\delta^2 c_{TN}^2 + 16s\theta t_e + 8\delta\theta t_e + 10s\delta\theta t_e - 8\delta^2\theta t_e - 8\theta^2 t_e - 16s\theta^2 t_e + 8\delta\theta^2 t_e - 8\delta\theta c_N t_e + \\
& 8\theta^2 c_N t_e + 16\theta c_R t_e + 2\delta\theta c_R t_e - 8\theta^2 c_R t_e - 16\delta c_{TN} t_e + 6\delta^2 c_{TN} t_e - 16s\theta e_R t_e + 8\delta\theta e_R t_e - \\
& 10s\delta\theta e_R t_e + 2\delta^2\theta e_R t_e - 8\theta^2 e_R t_e + 16s\theta^2 e_R t_e - 2\delta\theta^2 e_R t_e + 8\delta\theta c_N e_R t_e - 8\theta^2 c_N e_R t_e - \\
& 16\theta c_R e_R t_e - 2\delta\theta c_R e_R t_e + 8\theta^2 c_R e_R t_e + 16\theta c_{TN} e_R t_e - 6\delta\theta c_{TN} e_R t_e - 8\delta t_e^2 + 3\delta^2 t_e^2 - 4\delta\theta t_e^2 + \\
& 4\theta^2 t_e^2 + 16\theta e_R t_e^2 + 2\delta\theta e_R t_e^2 - 8\theta^2 e_R t_e^2 - 8\theta e_R^2 t_e^2 - \delta\theta e_R^2 t_e^2 + 4\theta^2 e_R^2 t_e^2 - 8(\delta - \theta)\theta c_A(-1 - \\
& 2s + \delta + 2c_D + c_N - c_R + t_e - e_R t_e) - 2(-8 + 3\delta)(s\theta - \delta(c_{TN} + t_e) + \theta(c_R + e_R t_e))t_w + \\
& \delta(-8 + 3\delta)t_w^2 - 2\theta c_D(5\delta(\delta - \theta) + s(-8 - 13\delta + 16\theta) + 8(\delta - \theta)c_N + (-8 - 5\delta + 8\theta)c_R + \\
& 8c_{TN} - 3\delta c_{TN} + 8t_e + 5\delta t_e - 8\theta t_e - 8e_R t_e - 5\delta e_R t_e + 8\theta e_R t_e + 8t_w - 3\delta t_w))/(-8 + \\
& 3\delta)(\delta - \theta)\theta), \text{ respectively.}
\end{aligned}$$

Additionally, let $q_N^{OS-E*} > q_R^{OS-E*} > 0$ and $q_{TN}^{OS-E*} > 0$, we get $s > \hat{s}^{OS-E}$ and $\hat{t}_w^{OS2-E} < t_w \leq \hat{t}_w^{OS1-E}$, where $\hat{s}_1^{OS-E} = (-1 + \delta + c_A + 2c_D + c_N - c_R + t_e - e_R t_e)/2$, $\hat{t}_{w1}^{OS-E} = \min [(-8s + 2\delta - 9s\delta + 3\delta^2 - 2\theta + 12s\theta - 3\delta\theta + 6\delta c_A - 6\theta c_A + 8c_D + 9\delta c_D - 12\theta c_D + 6\delta c_N - 6\theta c_N - 8c_R - 3\delta c_R + 6\theta c_R + 8c_{TN} - 3\delta c_{TN} + 8t_e + 3\delta t_e - 6\theta t_e - 8e_R t_e - 3\delta e_R t_e + 6\theta e_R t_e)/(-8 + 3\delta), (s\theta - \theta c_D + \theta c_R - \delta c_{TN} - \delta t_e + \theta e_R t_e)/\delta]$, $\hat{t}_{w2}^{OS-E} = (-8s + 6\delta - s\delta - \delta^2 - 6\theta + 4s\theta + \delta\theta + 2\delta c_A - 2\theta c_A + 8c_D + \delta c_D - 4\theta c_D + 2\delta c_N - 2\theta c_N - 8c_R + \delta c_R + 2\theta c_R + 8c_{TN} - 3\delta c_{TN} + 8t_e - \delta t_e - 2\theta t_e - 8e_R t_e + \delta e_R t_e + 2\theta e_R t_e)/(-8 + 3\delta)$.

The proof is completed.

Appendix B-2. Proof of Proposition B-4

In Proposition B-1, when the TPR's disposal strategy is PR, the optimal decision regarding unit disposal outsourcing fee in Case O and Case OS are $d_N^{O*} = (8 - 8s - 4\delta + s\delta + \delta^2 + 2(4 - \delta)c_A + (8 - \delta)c_D - 8c_N + 4\delta c_N - \delta c_R - (8 - 4\delta - (8 - \delta)e_D + \delta e_R)t_e)/(16 - 6\delta)$ and $d_N^{OS*} = (2(\theta - 4)c_A + 2(\theta - 4)c_D + \theta(-4c_N + c_{TN} - 3t_e + t_w) + 8c_N + 8t_e - \theta(\theta - 4) - 2(\theta - 4)s - 8)/(6\theta - 16)$, respectively. We define $\Delta d_N = d_N^{OS*} - d_N^{O*}$. Let $\Delta d_N = 0$, we get $t_w = \bar{t}_{w1}$, where $\bar{t}_{w1} = (-(a_1(\delta - 4)^2(3\theta - 8)) + a_2(\delta - 4)^2(3\theta - 8) + 8\delta c_A - 8\theta c_A - 3\delta\theta c_D + 16\delta c_D - 8\theta c_D + 8\delta c_N - 8\theta c_N + 3\delta\theta c_R - 8\delta c_R - 3\delta\theta c_{TN} + 8\theta c_{TN} + (3\delta - 8)\theta^2 + (3\theta - 8)t_e((\delta - 8)e_D + \delta(e_R - 1)) + \theta(-3\delta^2 + (3\delta + 8)s + 8) + 8\delta(\delta - 2s - 1))/((3\delta - 8)\theta)$. Because the first order derivate of Δd_N for t_w is

less than zero (i.e., $\frac{\partial \Delta d_N}{\partial t_w} = -\frac{\theta}{16-6\theta} < 0$), Δd_N decreases in t_w . Therefore, when $t_w > \bar{t}_{w1}$, $\Delta d_N < 0$, i.e., $d_N^{OS*} < d_N^{O*}$. The proof of part ii) is simple to follow and so omitted. Regarding the thresholds, $\bar{t}_{w2} = (3(c_D - s)(\delta - 2\theta) + (5 + 3c_N + 3c_A)(\delta - \theta) + (3\theta - 8)(c_R - t_e(2e_D - e_R + 1)) + (8 - 3\delta)c_{TN} - 8(s - c_D))/(\delta(3\delta - 8))$ and $\bar{t}_{w3} = (\delta(2c_A(\delta - \theta) + c_D(\delta - 4\theta + 8) + 2\delta c_N - 2\theta c_N + \delta c_R + 2\theta c_R - 8c_R - 3\delta c_{TN} + 8c_{TN} - ((\delta - 6)(\delta - \theta)) - s(\delta - 4\theta + 8)) + t_e((\delta + 8)(\delta - \theta)e_D + \delta(\delta + 2\theta - 8)(e_R - 1)))/(\delta(3\delta - 8))$.

The proof is completed.

Appendix B-3. Proof of Proposition B-7 and extended analysis for the $\theta < \delta$ case

Proof of Proposition 7. According to Proposition B-1, when the TPR's production strategy is PR, the TPR's profits in Case O and Case OS are: $\pi_R^{O*} = (4\delta - 10s\delta^2 + \delta^3 + s^2(8 + 13\delta) + 4\delta c_A^2 + (8 + 13\delta)c_D^2 - 8\delta c_N - 16s\delta c_N + 8\delta^2 c_N + 4\delta c_N^2 + 16sc_R - 8\delta c_R + 10s\delta c_R - 2\delta^2 c_R - 8\delta c_N c_R + (\delta + 8)c_R^2 + 2(4\delta(\delta - 1 - 2s) + (5\delta^2 - s(8 + 13\delta))e_D + 4\delta c_N(1 + 2e_D - e_R) + (-\delta(4 + \delta) + s(8 + 5\delta))e_R + c_R(-4\delta - (8 + 5\delta)e_D + (8 + \delta)e_R))t_e + (4\delta + e_D(16\delta + (8 + 13\delta)e_D) - 2(4\delta + (8 + 5\delta)e_D)e_R + (8 + \delta)e_R^2)t_e^2 + 8\delta c_A(\delta - 1 - 2s + 2c_D + c_N - c_R + (1 + 2e_D - e_R)t_e) + 2c_D(5\delta^2 - s(8 + 13\delta) + 8\delta c_N - (8 + 5\delta)c_R + (8\delta + (8 + 13\delta)e_D - (8 + 5\delta)e_R)t_e))/(\delta(8 - 3\delta))$ and $\pi_R^{OS*} = (s^2(8 - 3\theta)\theta - \delta^2(4(1 + s)^2 - 8s\theta + \theta^2) + \delta\theta(4(1 + s)^2 - 8s\theta + \theta^2) + 4\delta(-\delta + \theta)c_A^2 + (-4\delta^2 + 4\delta\theta + (8 - 3\theta)\theta)c_D^2 + 8\delta^2 c_N + 8s\delta^2 c_N - 8\delta\theta c_N - 8s\delta\theta c_N - 8\delta^2\theta c_N + 8\delta\theta^2 c_N - 4\delta^2 c_N^2 + 4\delta\theta c_N^2 + 16s\theta c_R - 6s\theta^2 c_R + 8\theta c_R^2 - 3\theta^2 c_R^2 - 16s\delta c_{TN} + 8\delta^2 c_{TN} - 8s\delta^2 c_{TN} - 8\delta\theta c_{TN} + 14s\delta\theta c_{TN} + 2\delta^2\theta c_{TN} - 2\delta\theta^2 c_{TN} + 8\delta^2 c_N c_{TN} - 8\delta\theta c_N c_{TN} - 16\delta c_R c_{TN} + 6\delta\theta c_R c_{TN} + 8\delta c_{TN}^2 - 4\delta^2 c_{TN}^2 + \delta\theta c_{TN}^2 - 16s\delta t_e + 16\delta^2 t_e - 16\delta\theta t_e + 6s\delta\theta t_e - 6\delta^2\theta t_e + 6\delta\theta^2 t_e - 16\delta c_R t_e + 6\delta\theta c_R t_e + 16\delta c_{TN} t_e - 6\delta\theta c_{TN} t_e + 16s\theta e_R t_e - 6s\theta^2 e_R t_e + 16\theta c_R e_R t_e - 6\theta^2 c_R e_R t_e - 16\delta c_{TN} e_R t_e + 6\delta\theta c_{TN} e_R t_e + 8\delta t_e^2 - 3\delta\theta t_e^2 - 16\delta e_R t_e^2 + 6\delta\theta e_R t_e^2 + 8\theta e_R^2 t_e^2 - 3\theta^2 e_R^2 t_e^2 + 2\delta((\delta - \theta)(4 + \theta) + s(-8 - 4\delta + 7\theta) + 4(\delta - \theta)c_N + (-8 + 3\theta)c_R - 4(-2 + \delta)c_{TN} + \theta c_{TN} + 8t_e + (-3\theta + (-8 + 3\theta)e_R)t_e)t_w + \delta(8 - 4\delta + \theta)t_w^2 + 8\delta(\delta - \theta)c_A(1 + s - \theta - c_D - c_N + c_{TN} + t_w) + 2c_D(4(1 + s)\delta^2 - 4(\delta + \delta^2 + s(2 + \delta))\theta + (3s + 4\delta)\theta^2 + 4\delta(-\delta + \theta)c_N + \theta(-8 + 3\theta)c_R + 4\delta(2 + \delta)c_{TN} - 7\delta\theta c_{TN} + 8\delta t_e - 3\delta\theta t_e - 8\theta e_R t_e + 3\theta^2 e_R t_e + \delta(8 + 4\delta -$

$7\theta)t_w)))/(4\delta(\delta - \theta)(-8 + 3\theta))$, respectively.

We define $\Delta\pi_R = \pi_R^{OS} - \pi_R^O$. Because $\frac{\partial^2 \Delta\pi_R}{\partial t_w \partial t_w} = \frac{8-4\delta+\theta}{2(\delta-\theta)(-8+3\theta)} > 0$, $\Delta\pi_R$ is convex in t_w .

By solving the first condition of $\Delta\pi_R$ for t_w , we get $t_{w1}^T = \frac{1}{(8-4\delta+\theta)(-\delta+\theta)}(\delta - \theta)(-8s + 4\delta - 4s\delta - 4\theta + 7s\theta + \delta\theta - \theta^2 + 4\delta c_A - 4\theta c_A + 8c_D + 4\delta c_D - 7\theta c_D + 4\delta c_N - 4\theta c_N - 8c_R + 3\theta c_R + 8c_{TN} - 4\delta c_{TN} + \theta c_{TN} + 8t_e - 3\theta t_e - 8e_R t_e + 3\theta e_R t_e + (\delta - \theta)(-8 + 3\theta)\sqrt{(\frac{1}{\delta(-8+3\delta)(\delta-\theta)(-8+3\theta)}(4\delta(-1 - 2s + \delta)^2(\delta - \theta) + 4\delta(\delta - \theta)c_A^2 + 16\delta(\delta - \theta)c_D^2 + 4\delta(\delta - \theta)(c_N - c_R)(-2 - 4s + 2\delta + c_N - c_R) + 2(4\delta(-1 - 2s + \delta)(\delta - \theta) + (5\delta^2 - s(8 + 13\delta))(-8 + 4\delta - \theta)e_D + 4\delta c_N(2(-8 + 4\delta - \theta)e_D - (\delta - \theta)(-1 + e_R)) + c_R(-((8 + 5\delta)(-8 + 4\delta - \theta)e_D) + 4\delta(\delta - \theta)(-1 + e_R)) - 4\delta(-1 - 2s + \delta)(\delta - \theta)e_R)t_e + ((8 + 13\delta)(-8 + 4\delta - \theta)e_D^2 + 4\delta(\delta - \theta)(-1 + e_R)^2 - 2(-8 + 4\delta - \theta)e_D(-8\delta + (8 + 5\delta)e_R))t_e^2 + 8\delta c_A((\delta - \theta)(-1 - 2s + \delta + 2c_D + c_N - c_R) + (2(-8 + 4\delta - \theta)e_D - (\delta - \theta)(-1 + e_R))t_e) + 2c_D(8\delta(\delta - \theta)(-1 - 2s + \delta + c_N - c_R) + ((8 + 13\delta)(-8 + 4\delta - \theta)e_D - 8\delta(\delta - \theta)(-1 + e_R))t_e)))))$ and $t_{w2}^T = \frac{1}{(8-4\delta+\theta)(-\delta+\theta)}(\delta - \theta)(-8s + 4\delta - 4s\delta - 4\theta + 7s\theta + \delta\theta - \theta^2 + 4\delta c_A - 4\theta c_A + 8c_D + 4\delta c_D - 7\theta c_D + 4\delta c_N - 4\theta c_N - 8c_R + 3\theta c_R + 8c_{TN} - 4\delta c_{TN} + \theta c_{TN} + 8t_e - 3\theta t_e - 8e_R t_e + 3\theta e_R t_e + (-\delta + \theta)(-8 + 3\theta)\sqrt{(\frac{1}{\delta(-8+3\delta)(\delta-\theta)(-8+3\theta)}(4\delta(-1 - 2s + \delta)^2(\delta - \theta) + 4\delta(\delta - \theta)c_A^2 + 16\delta(\delta - \theta)c_D^2 + 4\delta(\delta - \theta)(c_N - c_R)(-2 - 4s + 2\delta + c_N - c_R) + 2(4\delta(-1 - 2s + \delta)(\delta - \theta) + (5\delta^2 - s(8 + 13\delta))(-8 + 4\delta - \theta)e_D + 4\delta c_N(2(-8 + 4\delta - \theta)e_D - (\delta - \theta)(-1 + e_R)) + c_R(-((8 + 5\delta)(-8 + 4\delta - \theta)e_D) + 4\delta(\delta - \theta)(-1 + e_R)) - 4\delta(-1 - 2s + \delta)(\delta - \theta)e_R)t_e + ((8 + 13\delta)(-8 + 4\delta - \theta)e_D^2 + 4\delta(\delta - \theta)(-1 + e_R)^2 - 2(-8 + 4\delta - \theta)e_D(-8\delta + (8 + 5\delta)e_R))t_e^2 + 8\delta c_A((\delta - \theta)(-1 - 2s + \delta + 2c_D + c_N - c_R) + (2(-8 + 4\delta - \theta)e_D - (\delta - \theta)(-1 + e_R))t_e) + 2c_D(8\delta(\delta - \theta)(-1 - 2s + \delta + c_N - c_R) + ((8 + 13\delta)(-8 + 4\delta - \theta)e_D - 8\delta(\delta - \theta)(-1 + e_R))t_e)))))$. When $t_w < t_{w1}^T$ or $t_w > t_{w2}^T$, $\Delta\pi_R > 0$.

The proof is completed.

Extended analysis for the $\theta < \delta$ case. We define $\Delta\pi_R^E = \pi_R^{OS-E} - \pi_R^O$. Because $\frac{\partial^2 \Delta\pi_R^E}{\partial t_w \partial t_w} =$

$\frac{\delta}{2(\delta-\theta)\theta} > 0$, $\Delta\pi_R^E$ is convex in t_w . By solving the first condition of $\Delta\pi_R$ for t_w , we get $t_{w1}^{T-E} = \frac{1}{\delta(-8+3\delta)}(s(-8+3\delta)\theta + \delta\theta\sqrt{(\frac{1}{(\delta-\theta)\theta}(-8+3\delta)e_D t_e(2(8s+13s\delta-5\delta^2-8\delta c_A-(8+13\delta)c_D-8\delta c_N+(8+5\delta)c_R)+(-16\delta-(8+13\delta)e_D+2(8+5\delta)e_R)t_e)) - \theta^2\sqrt{(\frac{1}{(\delta-\theta)\theta}(-8+3\delta)e_D t_e(2(8s+13s\delta-5\delta^2-8\delta c_A-(8+13\delta)c_D-8\delta c_N+(8+5\delta)c_R)+(-16\delta-(8+13\delta)e_D+2(8+5\delta)e_R)t_e)) - (-8+3\delta)(\theta c_D + \delta(c_{TN} + t_e) - \theta(c_R + e_R t_e))})}$ and $t_{w2}^{T-E} = \frac{1}{\delta(-8+3\delta)}(s(-8+3\delta)\theta - \delta\theta\sqrt{(\frac{1}{(\delta-\theta)\theta}(-8+3\delta)e_D t_e(2(8s+13s\delta-5\delta^2-8\delta c_A-(8+13\delta)c_D-8\delta c_N+(8+5\delta)c_R)+(-16\delta-(8+13\delta)e_D+2(8+5\delta)e_R)t_e)) + \theta^2\sqrt{(\frac{1}{(\delta-\theta)\theta}(-8+3\delta)e_D t_e(2(8s+13s\delta-5\delta^2-8\delta c_A-(8+13\delta)c_D-8\delta c_N+(8+5\delta)c_R)+(-16\delta-(8+13\delta)e_D+2(8+5\delta)e_R)t_e)) - (-8+3\delta)(\theta c_D + \delta(c_{TN} + t_e) - \theta(c_R + e_R t_e))})}$. Therefore, when $t_w < t_{w1}^{T-E}$ or $t_w > t_{w2}^{T-E}$, $\Delta\pi_R^E > 0$. Accordingly, we get the following remark:

Remark 1. When $\theta < \delta$, the qualitative conclusion of Proposition 7 remains unchanged — only the threshold values differ.

Appendix B-4. Proof of Proposition B-8 and B-9

Proof of Proposition B-8. According to Proposition B-1, we know that in Case NO, the OEM's optimal decision regarding production quantity is $q_N^{NO*} = \frac{1}{2}(1 - c_N - t_e - t_w)$. In Case O, when the TPR's disposal strategy is NR, $q_N^{O-N1*} = \frac{1}{4}(1 + s - c_A - c_D - c_N - (1 + e_D)t_e)$, $q_N^{O-N2*} = (\delta - s + c_D - c_R + (e_D - e_R)t_e)/\delta$; when the TPR's strategy is PR, $q_N^{O-PR*} = (2(c_A + 2c_D + c_N - c_R + \delta + t_e(2e_D - e_R + 1) - 2s - 1))/(4(3\delta - 8))$; when the TPR's disposal strategy is AR, $q_N^{O-AR*} = (1 - c_A - c_N - c_R + \delta - (e_R + 1)t_e)/(6\delta + 4)$. We define $\Delta q_N^{N1*} = q_N^{O-N1*} - q_N^{NO*}$, $\Delta q_N^{N2*} = q_N^{O-N2*} - q_N^{NO*}$, $\Delta q_N^{PR*} = q_N^{O-PR*} - q_N^{NO*}$, and $\Delta q_N^{AR*} = q_N^{O-AR*} - q_N^{NO*}$. Solving $\Delta q_N^{N1*} = 0$, $\Delta q_N^{N2*} = 0$, $\Delta q_N^{PR*} = 0$, and $\Delta q_N^{AR*} = 0$ respectively, we get $t_w = t_w^{Q-NR1}$, $t_w = t_w^{Q-NR2}$, $t_w = t_w^{Q-NR1}$, and $t_w = t_w^{Q-NR1}$, respectively,

where $t_w^{Q-NR1} = 1/2(1 - s + c_A + c_D - c_N - t_e + e_D t_e)$, $t_w^{Q-NR2} = (2s - \delta - 2c_D - \delta c_N + 2c_R - \delta t_e - 2e_D t_e + 2e_R t_e)/\delta$, $t_w^{Q-PR} = (-4 + 8s - \delta - 4c_A - 8c_D + 4c_N - 3\delta c_N + 4c_R + 4t_e - 3\delta t_e - 8e_D t_e + 4e_R t_e)/(-8 + 3\delta)$, and $t_w^{Q-AR} = (1 + 2\delta + c_A - c_N - 3\delta c_N + c_R - t_e - 3\delta t_e + e_R t_e)/(2 + 3\delta)$. Because $\frac{\partial \Delta q_N^{N1*}}{\partial t_w} = \frac{\partial \Delta q_N^{N2*}}{\partial t_w} = \frac{\partial \Delta q_N^{PR*}}{\partial t_w} = \frac{\partial \Delta q_N^{AR*}}{\partial t_w} = \frac{1}{2} > 0$, Δq_N^{N1*} , Δq_N^{N2*} , Δq_N^{PR*} , and Δq_N^{AR*} are increases in t_w . Therefore, when $t_w > t_w^{Q-i}$, $q_N^{O-i*} > q_N^{NO*}$, where $i = [NR1, NR2, PR, AR]$.

Proof of Proposition B-9. The proof is simple to follow and so omitted. The thresholds appearing in this proposition are as follows: $t_w^{NO} = 1 - 1 - c_N - t_e$, $t_w^{RN} = ((4 - 3\delta)c_N + 4(c_R - c_A - 2c_D + 2s - 1) - \delta + t_e(4(e_R + 1 - 2e_D) - 3\delta))/(3\delta - 8)$, $\bar{t}_w^{RN} = (4(c_A + 2(c_D - s) - c_R - 3) - 3(\delta - 4)c_N + 7\delta + t_e(4(e_D - e_R + 3) - 3\delta))/(3\delta - 8)$, and $\bar{t}_e^{RN} = (7\delta + 4c_A + 8c_D + 12c_N - 3\delta c_N - 4c_R + (8 - 3\delta)t_w - 12 - 8s)/(3\delta - 8e_D + 4e_R - 12)$.

The proof is completed.

Appendix B-5. Proof of Proposition B-10 and extended analysis for the $\theta < \delta$ case

Proof of Proposition B-10. By Proposition B-1, we know that i) in Case NO, the OEM's optimal profit is $\pi_O^{NO} = 1/4(1 - c_N - t_e - t_w)^2$; and ii) when the TPR's disposal strategy is PR in both Case O and Case OS, the OEM's optimal profits are $\pi_O^O = 4(c_A + 2c_D + c_N - c_R + \delta + t_e(2e_D - e_R + 1) - 2s - 1)^2/(8 - 3\delta)^2$ and $\pi_O^{OS} = 4(-1 - s + \theta + c_A + c_D + c_N - c_{TN} - t_w)^2/(8 - 3\theta)^2$, respectively. By comparing π_O^{NO} and π_O^{OS} , as well as π_O^{OS} and π_O^O respectively (the process is simple to follow and so omitted), we get that i) when $t_w > t_w^{SN}$, $\pi_O^{OS} > \pi_O^{NO}$, and ii) when $t_w > t_w^{SR}$, $\pi_O^{OS} > \pi_O^O$, where $t_w^{SN} = (4c_A + 4c_D + (3\theta - 4)c_N - 4c_{TN} + (3\theta - 8)t_e + \theta - 4s + 4)/(3(4 - \theta))$ and $t_w^{SR} = (3c_A(\delta - \theta) + c_D(3\delta - 6\theta + 8) + 3\delta c_N - 3\theta c_N + 3\theta c_R - 8c_R - 3\delta c_{TN} + 8c_{TN} + 5\delta - (3\theta - 8)t_e(2e_D - e_R + 1) - 5\theta - 3\delta s + 6\theta s - 8s)/(3\delta - 8)$. Additionally, according to Proposition B-9, we know that given the precondition that $t_w < t_w^{NO}$, when $t_w > t_w^{RN}$, $\pi_O^O > \pi_O^{NO}$. Comparing t_w^{RN} , t_w^{SN} , and t_w^{SR} , we obtain that if $t_e > t_e^p$, $t_w^{RN} > t_w^{SN} > t_w^{SR}$; otherwise, $t_w^{RN} \leq t_w^{SN} \leq t_w^{SR}$. Accordingly, we get Proposition B-10.

The proof is completed.

Extended analysis for the $\theta < \delta$ case. When $\theta < \delta$, given that the TPR's disposal strategy is PR in Case O and Case OS, by comparing π_0^{NO} and π_0^O , π_0^{NO} and π_0^{OS-E} , as well as π_0^{OS-E} and π_0^O respectively (the process is simple to follow and so omitted), we get that i) when $t_w > t_w^{RN}$, $\pi_0^O > \pi_0^{NO}$, ii) when $t_w > t_w^{SN-E}$, $\pi_0^{OS-E} > \pi_0^{NO}$, and iii) $\pi_0^{OS-E} > \pi_0^O$, where $t_w^{RN} > t_w^{SN-E}$ and $t_w^{SN-E} = (-4 + 8s - \delta - 4c_A - 8c_D + (4 - 3\delta)c_N + 4c_R + (4 - 3\delta + 4e_R)t_e)/(-8 + 3\delta)$. Accordingly, we get the following remark:

Remark 2. When $\theta < \delta$, given that the TPR's disposal strategy is PR in Case O and Case OS, we get the following.

- i) When $t_w < t_w^{SN-E}$, the OEM does not outsource disposal to the TPR, i.e., $\pi_0^{NO} > \max [\pi_0^O, \pi_0^{OS-E}]$;
- ii) When $t_w^{SN-E} < t_w < t_w^{RN}$, the introduction of TN encourages the OEM to outsource disposal to the TPR, i.e., $\pi_0^{OS-E} > \pi_0^{NO} > \pi_0^O$;
- iii) When $t_w > t_w^{RN}$, the OEM still outsources disposal to the TPR and he hopes the TPR to produce new products, i.e., $\pi_0^{OS-E} > \pi_0^O > \pi_0^{NO}$.

5. Study 3: Remanufacturing strategies for a local OEM and an MNR under policy interventions and FDI-induced technology spillovers

This study examines the strategic interactions between a local original equipment manufacturer (OEM, he) and an independent multinational remanufacturer (MNR, she) operating within such global supply chains under varied government policies, including environmental taxes, tariffs, and remanufacturing incentives. We first investigate how these policies shape the OEM's decision to adopt remanufacturing and influence the MNR's choice between exporting remanufactured products and establishing local remanufacturing centers. The results reveal that the local OEM engages in remanufacturing if environmental taxes on new products are high and the MNR establishes a local remanufacturing center when either the taxes on her locally produced remanufactured products or technology spillover effects are low. Additionally, we study the impact of relevant factors (e.g., environmental impact of new product production, technology spillovers) on the policymaker's policy design and provide implications for policy design. For instance, our policy analysis suggests that when the environmental impact of new product production is high, the policymaker should tax the MNR's products regardless of her location strategies; when the degree of technology spillovers is low and the environmental impact is moderate, the policymaker should subsidize the MNR when she establishes a local remanufacturing center.

5.1 Introduction

As an important strategy for achieving sustainability, remanufacturing offers significant advantages over new product production in reducing resource waste, enhancing environmental protection, and lowering production costs (Örsdemir et al., 2014; Xiong et al., 2016). These economic and environmental benefits have driven governments worldwide to promote domestic remanufacturing industries (Hong et al., 2021). To this end, many nations have implemented policies that encourage the engagement of both local original equipment manufacturers (OEMs) and independent multinational remanufacturer (MNRs). These MNRs are established foreign remanufacturing firms that operate independently of local OEMs and possess both stronger brand equity and more advanced technologies in remanufacturing. To incentivize OEMs to engage in remanufacturing, governments provide remanufacturing tax incentives to them. For example, the Chinese government applies lower value-added tax rates to remanufactured automotive components than to new ones (Hsu and Zhu, 2011; Hong et al., 2019). To encourage MNRs' market entry, nations like Brazil have shifted from prohibiting imports of remanufactured products to permitting them with import tariffs (hereafter tariffs)²⁴. Meanwhile, some nations (e.g., China, Vietnam) offer tax incentives for MNRs' locally produced remanufactured products to attract foreign direct investment (FDI) in remanufacturing²⁵. In effect, these policies encourage MNRs to establish local remanufacturing centers in domestic markets.

When MNRs enter domestic markets (i.e., the sales markets traditionally served by local OEMs), their remanufactured products provide consumers with cost-effective, high-quality alternatives to local OEMs' new products, thereby leading to market competition (Atasu et al., 2008). Meanwhile, when MNRs establish local remanufacturing centers and maintain long-term operations, their advanced remanufacturing technologies (e.g., efficient processes, quality control systems) can spill over to local OEMs through channels such as shared

²⁴ <https://www.trade.gov/country-commercial-guides/brazil-prohibited-restricted-imports>

²⁵ <https://english.shanghai.gov.cn/en-PolicyInsights/20250124/9c44653aec864687a2d7b361e6a353d3.html> and <https://www.vietnam-briefing.com/doing-business-guide/vietnam/taxation-and-accounting/tax-incentives-for-businesses>

supplier networks, knowledge diffusion, labor mobility, and imitation ([Kohpaiboon, 2006](#); [Crespo and Fontoura, 2007](#); [Han et al., 2014](#)). In this study, we refer to this phenomenon as FDI-induced technology spillovers (hereafter technology spillovers). For local OEMs, these technology spillovers provide access to improved infrastructure, skilled labor, and shared expertise. By leveraging these resources, local OEMs can improve their remanufacturing efficiency, thereby reducing their remanufacturing costs ([Kohpaiboon, 2006](#)). To summarize, the involvement of MNRs not only poses competitive pressure on local OEMs but also offers them substantial benefits by fostering technology spillovers.

This dual impact and the policy interventions (e.g., tax incentives, tariffs) complicate decision-making for local OEMs in determining whether or not to engage in remanufacturing. On the one hand, the competitive pressure from MNRs' lower-priced remanufactured offerings drives them to adopt remanufacturing as a competitive response, while tax incentives offer direct financial motivation to do so ([Hong et al., 2021](#)). In addition, technology spillovers from MNRs further enhance this motivation by reducing their remanufacturing costs. On the other hand, the concern that their own remanufactured products may cannibalize their new product sales discourages OEMs from engaging in remanufacturing, while competition from MNRs' remanufactured products may deter consumers from buying their remanufactured products. Consequently, OEMs must weigh the benefits of cost reductions and policy support against the potential loss of new product revenue caused by internal and external competition. However, quantifying these cost reductions and revenue losses is challenging because they depend on MNRs' decisions regarding remanufacturing locations and remanufacturing quantities, which are very difficult for OEMs to predict.

Similarly, market competition, policy interventions, and technology spillovers increase the complexity of MNRs' decisions on whether or not to enter domestic markets and to establish local remanufacturing centers. The complexity arises from the need to weigh conflicting incentives and risks. Although eased trade restrictions in domestic markets provide opportunities for MNRs to make profits through exporting remanufactured products, import tariffs may drive them out of domestic markets. Establishing local remanufacturing

centers is a possible solution to avoid tariffs. In addition, it helps MNRs lower overall costs by enabling them to benefit from tax incentives and reducing remanufacturing-related costs (e.g., labor costs, transportation expenses) (Wu and Zhang, 2014). However, local remanufacturing also entails the risk of technology spillovers to OEMs, which could reduce MNRs' competitive advantage. This, in turn, may prevent MNRs from localizing remanufacturing (Fan et al., 2020). Weighing these incentives and risks — such as export profits versus tariffs, and the benefits of exporting versus localizing production — is difficult. This is because they are jointly affected by MNRs' and OEMs' production decisions. OEMs' decisions are unpredictable to MNRs for two main reasons: i) they are decided by OEMs and ii) OEMs also face decision-making dilemmas, as mentioned earlier.

To recap, competition and technology spillovers make OEMs' and MNRs' decision-making highly mutually dependent and complex. The complexity is further compounded by policy interventions. This, in turn, makes it difficult for the policymaker to predict how OEMs and MNRs respond to policy interventions. Such uncertainty hinders the ability of policymakers to accurately assess the overall contribution of MNRs' presence in enhancing remanufacturing development and social welfare. These assessments are essential for designing effective policies that leverage competition and spillovers to promote remanufacturing development. As a result, the policymaker also faces the critical challenge of designing effective policies that promote domestic remanufacturing growth while retaining both OEMs and MNRs in domestic markets.

In the relevant literature, a rich body of work has examined the impact of policy interventions on firms' remanufacturing decision-making (e.g., whether or not to engage in remanufacturing, how to implement it). Their results highlight that policy interventions can encourage firms to engage in remanufacturing. However, most remanufacturing studies focus narrowly on domestic supply chains (Li et al., 2023; Li et al., 2024), neglecting the impact of tariffs and competition from MNRs' remanufactured products. This focus leads to overlooking the additional complexity introduced by technology spillovers generated by MNRs' FDI. In other words, as suggested by our literature review, no study has examined how tariffs, MNR market entry, and technology spillovers collectively shape the decision-

making dynamics between OEMs and MNRs. This gap might be exacerbated by decision-making complications mentioned above. The lack of research leaves the impact of these elements on OEM-MNR decision-making unaddressed. This, in turn, makes the decision-making mechanism between OEMs and MNRs unclear. Consequently, the solutions supporting OEMs' and MNRs' decision-making and implications for policymakers in designing effective regulations are not available. Recognizing the practical need to bridge theory and real-world application and to provide decision-making support for both firms and policymakers, this study examines optimal remanufacturing strategies for OEMs and MNRs and addresses related policymaking problems. Specifically, we aim to answer the following research questions: i) When should OEMs engage in remanufacturing? ii) Under what conditions should MNRs establish local remanufacturing centers instead of exporting remanufactured products? iii) How should governments design policies to promote remanufacturing while retaining both OEMs and MNRs in domestic markets?

To answer these questions, this study examines a cross-border supply chain involving an OEM and an MNR operating under tariffs and remanufacturing incentives. Both firms aim to maximize their profits by making diverse decisions. The OEM determines his production quantities and decides whether or not to engage in remanufacturing; the MNR determines whether or not to enter the OEM's market by either exporting remanufactured products or establishing a local remanufacturing center to produce remanufactured products. To cover practical cases as comprehensively as possible, we analyze three scenarios: (i) where only the OEM is present, (ii) where the MNR exports her remanufactured products, and (iii) where the MNR establishes a local remanufacturing center. We first derive the two firms' optimal decisions in all three scenarios and present their remanufacturing strategies. Subsequently, we assess the impact of the MNR's presence on the OEM's remanufacturing strategic choice, the overall remanufacturing output, and consumer surplus. Finally, we examine policymaking decisions when the MNR either exports remanufactured products or establishes a local remanufacturing center.

The remainder of the paper is organized as follows. Section 5.2 reviews relevant literature. We present the problem context and model setup in Section 5.3. In Section 5.4, we

develop decision-making models for the OEM and MNR under three scenarios, followed by analyzing each firm's remanufacturing strategies and the impact of introducing the MNR. The policymaker's optimal decisions on taxes and tariffs are examined in Section 5.5. Lastly, we end the paper by discussing limitations and proposing directions for future research.

5.2 Literature review

Our work is primarily related to two streams: firms' decision-making related to cross-border operations and spillover effects in global operations management. Below, we review the relevant literature in each stream and explain how our study differs from available studies.

5.2.1 Firms' decision-making related to cross-border operations

Cross-border operations allow firms to reduce costs, diversify risks, and access new markets through activities such as overseas sourcing, onshoring production, and production outsourcing ([Meixell and Gargeya, 2005](#); [Mallidis et al., 2014](#); [Guchhait and Sarkar, 2024](#)). Despite these benefits, firms' decision-making on if and how to engage in cross-border activities is complicated by factors including policy interventions, spillover effects, and market competition. This decision-making complexity has driven extensive research into how these factors influence firms' decisions in cross-border operations. Among the numerous published studies, some investigate the impact of trade policies, spillover effects, and market competition on firms' sourcing decisions. For instance, [Niu et al. \(2018\)](#) consider a duopoly market consisting of a multinational firm (MNF) and a domestic manufacturer. They examine the impact of quality spillover and tariffs on the MNF's sourcing decision and find that sourcing from the domestic manufacturer increases the MNF's profit by avoiding tariffs when the quality spillover is low. [Wu and Zhang \(2014\)](#) analyze how two rival firms choose between efficient offshore sourcing and more responsive domestic sourcing. Their results indicate that firms prefer offshore sourcing even when it offers no cost advantage over domestic sourcing due to other strategic factors. In a service-driven digital global supply chain, [Guchhait and Sarkar \(2024\)](#) examine how multiple manufacturers and multiple retailers make product outsourcing decisions under the influence of international taxes, tariffs, and exchange rate conditions. Unlike the above studies which consider a single sales market,

[Chen et al. \(2022\)](#) study how tariffs influence the MNF's sourcing decision when the MNF sells products to both domestic and foreign markets. Their results show that high tariffs in the MNF's home country discourage it from sourcing from home country.

After sourcing, firms must decide where and how to produce products. Accordingly, firms' decision-making in production is among the most critical dimensions of cross-border operations examined in prior research. For instance, [Yang et al. \(2021\)](#) explore how tariffs charged by an MNF's home country influences the MNF's choice between producing at home and in a lower-cost foreign country. They find that when tariffs are very low, the MNF moves production to the foreign country. [Niu et al. \(2024\)](#) analyze how a supplier chooses its production location when competing with a remanufacturer that sources components from it to produce high-quality remanufactured products. Their results show that when the income tax disparity between the production and sales countries and the supplier's production costs are low, the supplier chooses overseas production over domestic production. [Xie et al. \(2023\)](#) investigate a local OEM's strategic choice between in-house and outsourced production. Their findings show that when local labor costs are low, subsidies for locally produced products can incentivize the local OEM to shift production back to the home country.

Within broader production literature, remanufacturing has recently attracted research attention in global operations management. Authors study OEMs' cross-border remanufacturing decisions under different policy regimes. [Huang et al. \(2024\)](#) examine the remanufacturing decisions of a multinational OEM who sells both new and remanufactured products abroad through a local retailer. Their results indicate that when cross-border recycling costs are low, the OEM prefers in-house remanufacturing over licensing it to a local firm. [Li et al. \(2023\)](#) and [Li et al. \(2024\)](#) focus on the impact of taxes and tariffs imposed by the importing country on an OEM's remanufacturing location decisions. More specifically, [Li et al. \(2023\)](#) analyze the OEM's strategic choice between in-house and outsource remanufacturing. The results show that a small sales-tax gap between new and remanufactured goods makes in-house remanufacturing optimal. [Li et al. \(2024\)](#) study how carbon taxes and carbon tariffs affect the OEM's remanufacturing mode selections. The findings reveal that when the carbon emissions from remanufactured products closely mirror

those of new ones, the OEM prefers to authorize remanufacturing to a local retailer rather than conduct it in-house.

In summary, the above studies examine how firms optimize their cross-border operations in different policy contexts. Despite the fact that some focus on decision-making in remanufacturing systems, studies on how policy interventions influence independent remanufacturers' decisions related to remanufacturing within global supply chains remain limited ([Li et al., 2023](#); [Huang et al., 2024](#)). Our study enriches this stream by analyzing how policy interventions (e.g., tariffs, remanufacturing incentives) shape an MNR's choice of remanufacturing location.

5.2.2 Spillover effects in global operations management

The second stream focuses on spillover effects in global operations management and their impact on social welfare and firms' decision-making. The broad empirical literature confirms that FDI-induced spillovers benefit host-country firms and society. For example, [Crespo and Fontoura \(2007\)](#) emphasize that advanced technological knowledge from MNEs can spill over to domestic firms through FDI and enhance the productivity level of domestic firms. Similarly, [Mun and Nadiri \(2002\)](#) stress that FDI-induced technology spillovers help local firms reduce production costs, while [Kohpaiboon \(2006\)](#) highlights that such spillovers can reach both affiliated and unaffiliated local firms. [Buckley et al. \(2007\)](#) use Chinese industrial data to examine how foreign and local ownership and industry characteristics, influence spillover effects. Their results indicate that spillovers vary by investor origin and industry type, with Western firms benefiting technology sectors and investors from Hong Kong, Macau, and Taiwan benefit labor-intensive industries. [Han et al. \(2014\)](#) analyze how information technology investments in supplier industries spill over to downstream industries through interindustry economic transactions. Their study shows that the magnitude of IT spillovers depends on the IT intensity and competitiveness of downstream industries, with more pronounced effects over the long term due to learning dynamics.

Within global operations management, some authors explore how spillover effects interact with policy and firms' strategy influence social welfare. For instance, [Glass and](#)

[Saggi \(2002\)](#) study the impact of technology spillovers from an MNF to a host firm on the social welfare of the host country. Their results show that such spillovers can incentivize host governments to attract FDI to promote local technological advancement; however, when the MNF's cost reduction through FDI is significantly high, banning FDI can raise host welfare. [Niu et al. \(2018\)](#) examine a scenario in which an MNF's adoption of domestic sourcing triggers quality spillovers that enhance its competitors' product quality. They find that when tariffs are either very low or very high, the MNF's domestic-sourcing strategy yields greater social welfare than overseas sourcing. [Fan et al. \(2020\)](#) investigate how subsidies on the domestic manufacturer and technology spillover brought by a foreign manufacturer influence the social welfare of the host country. The findings reveal that implementing subsidy and tariff policies benefits consumers when the degree of technology spillovers is relatively high. In examining the role of spillovers in firm decision-making, [Xie et al. \(2023\)](#) analyze the impact of brand spillovers on a local OEM's production outsourcing strategies. Their results suggest that a very high or very low brand spillover motivates the OEM to choose in-house production instead of outsourcing.

Our study advances the literature in three main aspects. First, although the impact of spillover effects on firms' decision-making has been widely studied ([Fan et al., 2020](#)), the impact of technology spillovers on firms' remanufacturing decisions is often overlooked. By analyzing how FDI-induced spillovers influence remanufacturing strategies of both the local OEM and the MNR, our study addresses this gap. Second, unlike most existing studies that consider either production or sourcing decisions, we focus on remanufacturing strategies under multiple policy instruments in a global supply chain setting. Third, our model identifies the conditions under which policy interventions such as subsidies or taxes on the MNR can achieve regulatory goals while enhancing social welfare, thus offering new insights into policy design beyond the contexts considered in prior literature.

5.3 Model setup

5.3.1 Problem description

We consider a cross-border supply chain consisting of a local OEM (hereafter OEM) and

an independent MNR (hereafter MNR), operating under government policies. In the cross-border supply chain considered, the local OEM (hereafter OEM), located in the domestic market, primarily focuses on new product (denoted as N) production and may produce remanufactured products (denoted as ORs). The independent MNR (hereafter MNR), originally based in a foreign country, competes with the OEM by either exporting her remanufactured products (denoted as MRs) to the domestic market or establishing a local remanufacturing center to leverage potential cost benefits. The remanufacturing industry in the OEM's region is relatively underdeveloped and faces challenges such as limited technological advancements. The MNR's advanced remanufacturing technologies spill over to the OEM when the MNR establishes a local remanufacturing center. To regulate this market, the domestic government imposes environmental taxes on new products produced by the OEM, levies import tariffs on remanufactured products exported by the MNR, and provides remanufacturing incentives for locally produced remanufactured products.

To examine how these policies and technology spillovers influence the two firms' remanufacturing strategies and to provide policymaking insights, we consider three scenarios representing different market conditions (i.e., whether or not the MNR enters the domestic market and whether or not she establishes a local remanufacturing center). [Figure 5.1](#) illustrates the three scenarios.

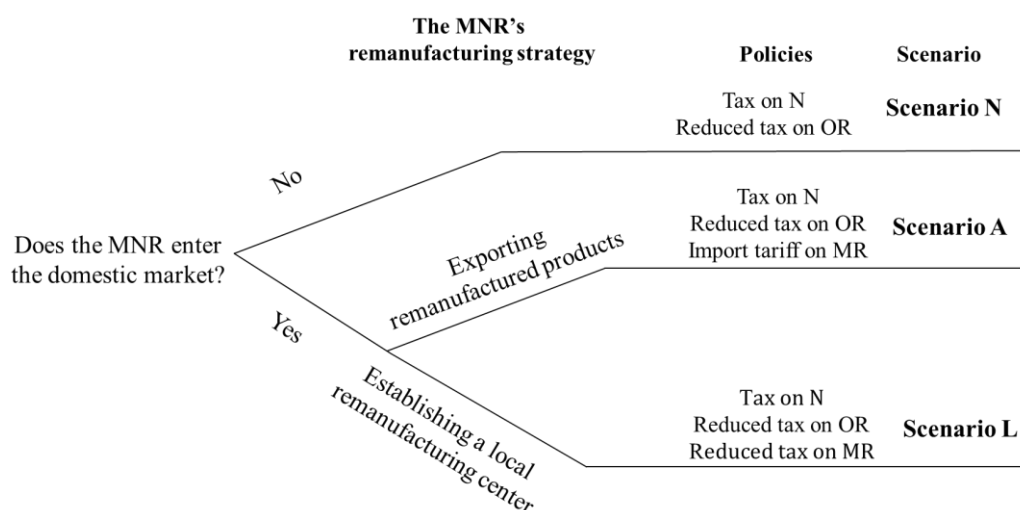


Figure 5.1. Overview of three scenarios

As shown in [Figure 5.1](#): i) In Scenario N, only the OEM is present, focusing on

producing N and potentially engaging in remanufacturing; ii) In Scenario A, the MNR exports MR to the domestic market, competing with the OEM's N and/or OR; iii) In Scenario L, the MNR establishes a local remanufacturing center to produce MR. Further details on each scenario, including supply chain structure, strategic decisions, and policy interventions, will be detailed in Section 5.4.1.

5.3.2 Notation and assumptions

In this section, to support assumptions, we first present the notation involved in the models in Table 5.1. Then we list our key assumptions and explain their rationale.

Table 5.1. Parameters and decision variables

Notation Parameter	Description
V	Consumers' willingness to pay (WTP) for OEM's new products, N
θ	Discount rate of consumers' WTP for MNR's remanufactured products, MR, compared to N
δ	Discount rate of consumers' WTP for OEM's remanufactured products, OR, compared to N
c_N	The unit production cost of N
c_{OR}, c_{MR}	The unit remanufacturing cost of OR and MR in scenario A, respectively
Δ	The per-unit cost savings for the MNR when establishing a local remanufacturing center
β	The degree of technology spillovers in scenario L
ϵ	The environmental impact of per unit of new product
a	The indirect benefit brought by the MNR's domestic remanufacturing
t_e	The environmental tax on per-unit new product
t_r	The tariffs on per-unit imported MR
t_{rL}	The reduced environmental tax on per-unit locally produced MR
$p_N^i, p_{OR}^i, p_{MR}^i$	Unit selling price of N, OR, and MR in Scenario i, where $i \in \{N, A, L\}$
π_O^i, π_{MR}^i	The OEM's and/or the MNR's profits in Scenario i, where $i \in \{N, A, L\}$
CS_O^i	Consumer surplus in Scenario i, where $i \in \{A, L\}$
SW_O^i	Social welfare of the domestic country in Scenario i, where $i \in \{A, L\}$
Decision variables	
q_N^i	The OEM's new product production quantity in Scenario i, where $i \in \{N, A, L\}$
q_{OR}^i, q_{MR}^i	The OEM's and/or the MNR's remanufacturing quantities in Scenario i, where $i \in \{N, A, L\}$

Consistent with the literature (Niu et al., 2017; Hong et al., 2018; Fan et al., 2020), we assume that both firms and consumers are completely rational, with firms aiming to maximize their respective profits and consumers aiming to maximize their individual utilities, ensuring non-negative outcomes. Following (Ferrer and Swaminathan, 2010), who indicate that in a remanufacturing system, all players make the same decisions in every period after the initial ramp-up, and in line with the existing literature (Xiong et al., 2013; Qian et al., 2019), we assume that all decisions are made within a steady-state period. In each of the aforementioned scenarios, based on government policies, the two firms simultaneously determine their production quantities for new and/or remanufactured products. All products are sold out at market-clearing prices, where production quantities are aligned with effective market demand to prevent excess supply.

On the consumer side, each consumer purchases a single product and bases their purchasing decisions on the utility derived from consuming the product, which is widely defined as the difference between the consumer's WTP and the product's selling price. Following the approach used in (Atasu et al., 2008; Örsdemir et al., 2014), we normalize the market size to 1 and assume that consumers' WTP for the OEM's new products, denoted as V , is uniformly distributed in the interval $[0,1]$. A well-established perspective suggests that consumers perceive new products to have higher value compared to remanufactured ones, despite the fact that the majority of remanufactured products have the same quality as the new ones (Atasu et al., 2008; Örsdemir et al., 2014; Xiong et al., 2016). Furthermore, research on remanufacturing strategies (Fang et al., 2023) indicates that independent remanufacturers often achieve higher efficiency than OEMs newly entering remanufacturing. This advantage arises from their specialized expertise, well-developed remanufacturing systems, and economies of scale, which enable cost-effective operations and consistent quality. Accordingly, we assume that consumers' WTP for remanufactured products from the MNR and the OEM are represented as fractions of V , denoted by θV and δV , respectively, where $0 < \delta < \theta < 1$ (Atasu et al., 2008; Chen and Chen, 2019; Zhou et al., 2021). Following the existing studies (Esenduran et al., 2015; Zhang et al., 2020), consumer surplus

is defined as $CS^i = \int_{\frac{p_N^i - p_{MR}^i}{1-\theta}}^1 (V - p_N^i) dV + \int_{\frac{p_{MR}^i - p_{OR}^i}{\theta-\delta}}^{\frac{p_N^i - p_{MR}^i}{1-\theta}} (\theta V - p_{MR}^i) dV + \int_{\frac{p_{OR}^i}{\delta}}^{\frac{p_{MR}^i - p_{OR}^i}{\theta-\delta}} (\delta V - p_{OR}^i) dV$, where $i \in \{N, A, L\}$.

Based on the approach used in (Ferrer and Swaminathan, 2010) and the above assumptions, we can derive the inverse demand functions from consumers' utility functions (See Appendix C-1) in each scenario. Specifically, in scenario N, i.e., the MNR is not included in the market, we have $p_N^N = 1 - q_N^N - \delta q_{OR}^N$ and $p_{OR}^N = \delta(1 - q_N^N - q_{OR}^N)$. In Scenario A (and L), we have $p_N^i = 1 - \theta q_{MR}^i - q_N^i - \delta q_{OR}^i$, $p_{MR}^i = \theta - \theta(q_{MR}^i + q_N^i) - \delta q_{OR}^i$, and $p_{OR}^i = \delta(1 - q_{MR}^i - q_N^i - q_{OR}^i)$, where $i \in \{A, L\}$.

To simplify the model without loss of generality and to concentrate on the strategic decisions of the OEM and the MNR, the following cost-related assumptions are made. First, consistent with prior studies (Xiong et al., 2013; Li et al., 2023), costs of all remanufacturing-related activities — such as used product collection and making ready for sale — are fully incorporated into the remanufacturing cost. Second, as widely acknowledged in the literature (Xiong et al., 2013; Reimann et al., 2019; Li et al., 2023), the cost of remanufacturing a used product is not higher than that of manufacturing a new product²⁶. Furthermore, both practical observations and existing studies suggest that establishing operational centers close to the target market — particularly in developing countries — results in cost advantages. These advantages arise from factors such as reduced logistics expenses, improved supply chain coordination, and access to lower-cost labor compared to operating in a developed country (Wu and Zhang, 2014; Xu et al., 2018; Fan et al., 2020; Yang et al., 2021). Accordingly, in this study, the per-unit cost savings for the MNR when establishing a local remanufacturing

²⁶ This assumption also aligns with industry practices, where remanufacturing benefits from the reuse of valuable components, reduced material consumption, and lower energy requirements, thereby leading to cost savings compared to new product manufacturing (USITC, 2012). Although there are practical cases where remanufacturing costs may exceed those of new product manufacturing due to factors such as variability in product conditions, additional processing requirements, and compliance with regulatory standards, we do not consider such exceptions in this study. Instead, we focus on the general case where remanufacturing is more cost-effective, which aligns with prevailing literature and typical industry conditions.

center (Scenario L) instead of remanufacturing in her home country (Scenario A) are denoted as Δ . At the same time, the local presence of the MNR facilitates technology spillovers to the OEM, as discussed earlier. Following Fan et al. (2020), the OEM's remanufacturing costs in scenario L are expressed as $c_{OR}(1 - \beta)$, where β represents the degree of technology spillovers. Lastly, to simplify the model without compromising the analysis of policy impacts, both the fixed costs associated with establishing a local remanufacturing center and the reduced tax on the OEM's remanufactured products are normalized to 0.

5.4 Modeling and analyzing firms' remanufacturing decisions and strategies

5.4.1 Firms' decision-making model

In this section, we formulate the decision-making problems of the OEM and the MNR across the three scenarios under specific policy conditions. Figure 5.2 visualizes the supply chain structures of the three scenarios.

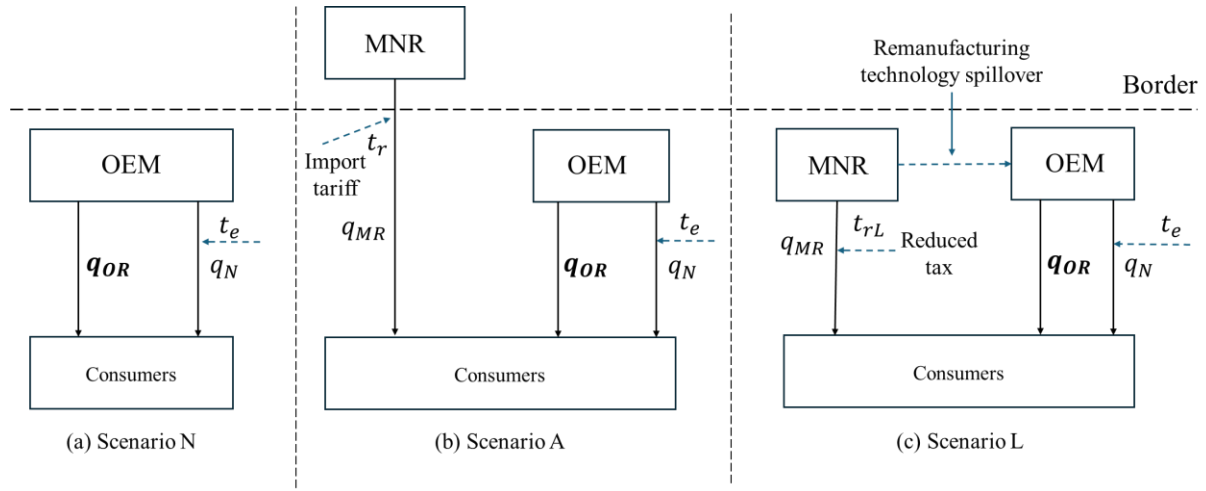


Figure 5.2. Supply chain structures under different scenarios

(1) Scenario N

As shown in Figure 5.2(a), in this scenario, only the OEM is present, focusing on producing N and potentially engaging in remanufacturing. The government imposes environmental taxes (t_e) on N, while OR is tax-exempt to encourage remanufacturing. There is no competition from the MNR in this scenario. The OEM determines his optimal production and remanufacturing quantities to maximize his profit, formulated as follows:

$$\begin{aligned} \text{Max } \pi_O^N(q_N^N, q_{OR}^N) &= q_N^N(p_N^N - c_N - t_e) + q_{OR}^N(p_{OR}^N - c_{OR}) \\ \text{s. t.}, q_N^N &> 0, q_{OR}^N \geq 0 \end{aligned} \quad (5-1)$$

(2) Scenario A

In this scenario, as demonstrated in [Figure 5.2\(b\)](#), the MNR exports MR to the domestic market, competing with the OEM's N and/or OR. The government imposes t_e on each N, provides tax exemptions on OR (simplified as zero for modeling purposes), and levies tariffs (t_r) on the MNR's exported remanufactured products (MR). Given t_e and t_r , the OEM optimizes his production and remanufacturing decisions, while the MNR determines her export quantity. Their decision-making problems are formulated as follows:

$$\begin{aligned} \text{Max } \pi_O^A(q_N^A, q_{OR}^A) &= q_N^A(p_N^A - c_N - t_e) + q_{OR}^A(p_{OR}^A - c_{OR}) \\ \text{Max } \pi_M^A(q_{MR}^A) &= q_{MR}^A(p_{MR}^A - c_{MR} - t_r) \\ \text{s. t.}, q_N^A &> 0, q_{OR}^A \geq 0, q_{MR}^A > 0 \end{aligned} \quad (5-2)$$

(3) Scenario L

As demonstrated in [Figure 5.2\(c\)](#), in this scenario, the OEM faces t_e on each N, enjoying tax-free benefits on OR. Meanwhile, the MNR establishes a local remanufacturing center to produce MR, benefiting from government FDI incentives: a reduced tax amount (t_{rL}) compared to N. The remanufacturing technology spillover occurs in this scenario. Given t_e and t_{rL} , the OEM determines his new product production and remanufacturing quantities and the MNR decides her remanufacturing quantity simultaneously. The two firms' decision-making problems are as follows:

$$\begin{aligned} \text{Max } \pi_O^L(q_N^L, q_{OR}^L) &= q_N^L(p_N^L - c_N - t_e) + q_{OR}^L(p_{OR}^L - c_{OR}(1 - \beta)) \\ \text{Max } \pi_M^L(q_{MR}^L) &= q_{MR}^L(p_{MR}^L - (c_{MR} - \Delta) - t_{rL}) \\ \text{s. t.}, q_N^L &> 0, q_{OR}^L \geq 0, q_{MR}^L > 0 \end{aligned} \quad (5-3)$$

To avoid the trivial cases in which the MNR is always unprofitable and/or the MNR always prefers Scenario A to Scenario L, we limit $c_{MR} + t_r > c_{MR} - \Delta + t_{rL}$.

5.4.2 Analyzing firms' remanufacturing strategies

In this section, we start by solving the two firms' optimal decisions. Then, we derive the

two firms' remanufacturing strategies by analyzing their optimal decisions. Given t_e , t_r , and t_{rL} , using backward induction, we derive the two firms' optimal decisions in each scenario, which are summarized in [Table 5.2](#). The detailed derivation processes, the relative profits for the OEM and the MNR, and the thresholds expressions are provided in [Appendix C-2](#).

Table 5.2. The optimal decisions in three scenarios

		$t_e > \tilde{t}_e^{i1}$	$t_e \leq \tilde{t}_e^{i1}$
Scenario N	q_N	$\frac{1-c_N-t_e+\delta-c_{OR}}{2(1-\delta)},$	$\frac{1}{2}(1-c_N-t_e),$
	q_{OR}	$\frac{\delta(c_N+t_e)-c_{OR}}{2\delta(1-\delta)},$	0
	q_{MR}	$/$	$/$
Scenario A	q_N	$\frac{(4\theta-\delta)(1-c_N-t_e)+2(\theta-\delta)(\theta+c_{MR}+t_r)+\theta(\delta-4\theta+3c_{OR})}{2((4\theta-\delta)-2\delta\theta-\theta^2)},$	$\frac{2-\theta+c_{MR}-2c_N-2t_e+t_r}{4-\theta},$
	q_{OR}	$\frac{\delta(1-\theta)(2c_{MR}-\theta+2t_r)+3\delta\theta(c_N+t_e)-\theta c_{OR}(4-\theta)}{2\delta((4\theta-\delta)-2\delta\theta-\theta^2)},$	0
	q_{MR}	$\frac{(\theta-\delta)(c_N+t_e)-2(1-\delta)(t_r+c_{MR})+\theta(1-\delta)+(1-\theta)c_{OR}}{(4\theta-\delta)-2\delta\theta-\theta^2},$	$\frac{\theta(1+c_N+t_e)-2(c_{MR}+t_r)}{(4-\theta)\theta},$
Scenario L	q_N	$\frac{(4\theta-\delta)(1-c_N-t_e)+2(\theta-\delta)(\theta+c_{MR}-\Delta+t_{rL})-3\theta(\theta-c_{OR}(1-\beta))}{2((4\theta-\delta)-2\delta\theta-\theta^2)},$	$\frac{2(1-c_N-t_e)-\Delta-\theta+c_{MR}+t_{rL}}{4-\theta},$
	q_{OR}	$\frac{2\delta(1-\theta)(\theta+c_{MR}-\Delta+t_{rL})-3\delta\theta(1-c_N-t_e)-\theta c_{OR}(1-\beta)(4-\theta)+3\delta\theta^2}{2\delta((4\theta-\delta)-2\delta\theta-\theta^2)},$	0
	q_{MR}	$\frac{(\theta-\delta)(1+c_N+t_e)-2(1-\delta)(\theta+c_{MR}-\Delta+t_{rL})+(1-\theta)(\delta+(1-\beta)c_{OR})+2\theta(1-\beta)}{(4\theta-\delta)-2\delta\theta-\theta^2},$	$\frac{2(\Delta-c_{MR}-t_{rL})+\theta(1+c_N+t_e)}{4\theta-\theta^2}$

* $i \in \{N, A, L\}$

With these optimal decisions, we first examine the OEM's remanufacturing strategy in each scenario and identify the regulatory conditions under which optimal decisions are non-negative, as shown in Proposition C-1. We use Wolfram Mathematica to obtain these conditions and therefore omit the proof in this paper. The expressions for the relevant thresholds are provided in [Appendix C-3](#).

Proposition C-1. In Scenario i ($i \in \{N, A, L\}$), there exists a threshold $\tilde{t}_e^{i1}$, such that

(i) if $t_e \geq \tilde{t}_e^{i1}$, the OEM engages in remanufacturing. To ensure non-negative optimal decisions, the tariffs (or reduced environmental taxes) on MR and the environmental taxes on N must meet the following conditions:

- In Scenario N, $\tilde{t}_e^{N1} < t_e < \tilde{t}_e^{N2}$;
- In Scenario A, $\tilde{t}_r^{A1} < t_r < \tilde{t}_r^{A2}$ and $\max\{\tilde{t}_e^{A0}, \tilde{t}_e^{A1}\} \leq t_e < \tilde{t}_e^{A2}$;
- In Scenario L, $\tilde{t}_{rL}^{L1} < t_{rL} < \tilde{t}_{rL}^{L2}$ and $\max\{\tilde{t}_e^{L0}, \tilde{t}_e^{L1}\} \leq t_e < \tilde{t}_e^{L2}$.

(ii) Otherwise, the OEM does not engage in remanufacturing. To ensure non-negative optimal decisions, the tariffs (or reduced environmental taxes) on MR and the environmental taxes on N must meet the following conditions:

- In Scenario N, $t_e < \tilde{t}_e^{N1}$;
- In Scenario A, $t_r < \tilde{t}_r^{AN}$ and $\tilde{t}_e^{AN} < t_e < \min\{\tilde{t}_e^{A1}, \tilde{t}_e^{A3}\}$;
- In Scenario L, $t_{rL} < \tilde{t}_{rL}^{LN}$ and $\tilde{t}_e^{LN} < t_e < \min\{\tilde{t}_e^{L1}, \tilde{t}_e^{L3}\}$.²⁷

For a better understanding, we visualize this proposition in [Figure 5.3](#). (Note: [Figure 5.3](#) is developed using $\delta = 1/2$, $c_{OR} = 2/5$, $c_N = 3/5$, $\theta = 3/5$, $c_{MR} = 1/2$, $\Delta = 1/50$, and $\beta = 1/50$.) As shown in this figure, there exists a threshold of environmental tax on N ($\tilde{t}_e^{i1}$, where $i \in \{N, A, L\}$) above which the OEM engages in remanufacturing in Scenario i . Moreover, [Figure 5.3 \(b\) and \(c\)](#) show that $\tilde{t}_e^{A1}$ (or $\tilde{t}_e^{L1}$) decreases in t_r (or t_{rL}). This suggests that in Scenario A (or L), the OEM's willingness to engage in remanufacturing increases in t_r (or t_{rL}). The reasons are as follows. The OEM's decision in whether or not to engage in remanufacturing is driven by a trade-off between the profit of engaging in remanufacturing and the revenue losses due to the competition between remanufactured products (OR and/or MR) and N. When t_e is low (i.e., $t_e \leq \tilde{t}_e^{i1}$), the OEM does not engage in remanufacturing because the profit of producing only N is higher. However, with the increase of t_e , the cost of producing N increases. This increase, in turn, enhances the cost advantage of remanufacturing and makes the profits from producing both OR and N exceed those from producing only N when $t_e > \tilde{t}_e^{i1}$. Furthermore, an increasing t_r (or t_{rL}) increases the costs of MR, thereby weakening its competitive advantage over OR. Since OR and MR are substitutes, higher costs of MR make OR more attractive to consumers. Consequently, the OEM's willingness to engage in remanufacturing increases in t_r (or t_{rL}).

²⁷ (i) $\tilde{t}_r^{i1} < \tilde{t}_r^{iN} < \tilde{t}_r^{i2}$; (ii) when $\tilde{t}_r^{i1} < t_r < \tilde{t}_r^{iN}$, $\min\{\tilde{t}_e^{i1}, \tilde{t}_e^{i0}\} = \max\{\tilde{t}_e^{i1}, \tilde{t}_e^{i3}\} = \tilde{t}_e^{i1}$; when $t_r \leq \tilde{t}_r^{i1}$, $\min\{\tilde{t}_e^{i1}, \tilde{t}_e^{i3}\} = \tilde{t}_e^{i3}$, $i = A, L$.

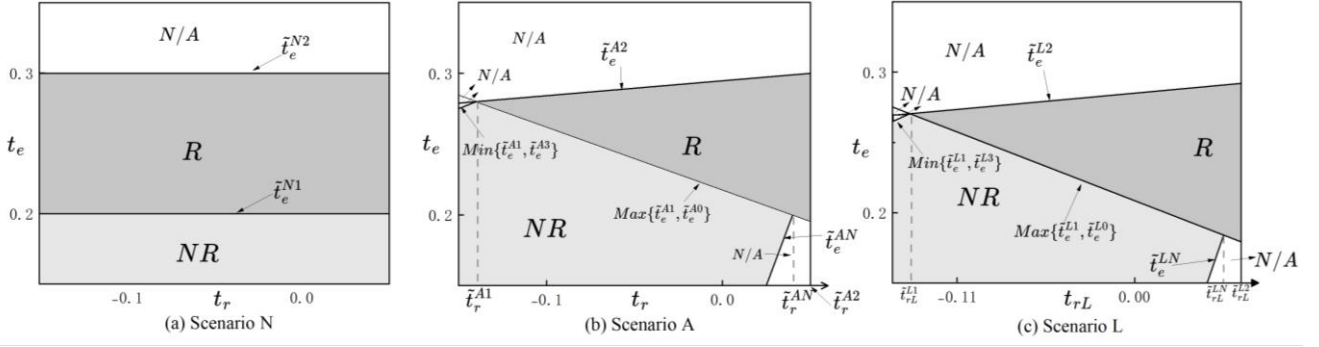


Figure 5.3. The OEM's remanufacturing strategies and product coexistence conditions

Figure 5.3 also outlines the regulatory conditions in scenarios A and L under which the MNR's remanufactured products, the OEM's new products, and, if applicable, the OEM's remanufactured products coexist in the market. The coexistence of N, OR, and MR is feasible when $t_e < \tilde{t}_e^{i2}$ and t_r (or t_{rL}) is neither too high nor too low. The reasons are as follows. A very high t_e (i.e., $t_e > \tilde{t}_e^{i2}$) increases the OEM's production cost for N, making N uncompetitive in the market²⁸. Similarly, an excessively high t_r (or t_{rL}) increases the MNR's cost burden for MR, deterring the MNR's market entry. Conversely, when t_r (or t_{rL}) is excessively low, MR gains a significant competitive advantage over OR and/or N, leading to no consumers buying N and/or OR.

Proposition C-1 suggests that when environmental taxes on new products are high, OEMs should adopt remanufacturing. It also provides implications for policymakers. To encourage OEMs to engage in remanufacturing, policymakers can impose environmental taxes on new products, facilitate the entry of imported remanufactured products, and grant tax exemptions for remanufactured products — particularly in environmentally-intensive sectors such as automotive and electronics. Meanwhile, to ensure the coexistence of new and remanufactured products, policymakers should avoid implementing extremely high or low taxes.

We now analyze the MNR's remanufacturing location strategies, i.e., whether or not to establish a local remanufacturing center in the domestic market. The corresponding results are presented in Proposition C-2, with the threshold expressions provided in Appendix C-3.

²⁸ Policy interventions aim to incentivize remanufacturing instead of eliminating new production. Thus, the case where new products become uncompetitive falls beyond the scope of our analysis.

The proofs are omitted as they are straightforward.

Proposition C-2. (The MNR's remanufacturing location strategy) When the OEM engages in remanufacturing, the MNR's strategic choices are as follows:

(i) MR prefers Scenario A if $t_{rL} > t_{rL}^L$ and $\beta > \beta^L$.

(ii) MR prefers Scenario L if

- $t_{rL} \leq t_{rL}^L$, or
- $t_{rL} > t_{rL}^L$ and $\beta \leq \beta^L$.

Proposition C-2 characterizes the MNR's preference between Scenario L (establishing a local remanufacturing center) and Scenario A (exporting MRs to the same market as the OEM). Note that we exclusively consider the situation in which the OEM engages in remanufacturing²⁹. Using parameters $\delta = 1/2$, $c_{OR} = 2/5$, $c_N = 3/5$, $\theta = 3/5$, $c_{MR} = 1/2$, $\Delta = 1/50$, $t_e = 21/100$, and $t_r = 1/25$, we visualize this proposition using Figure 5.4.

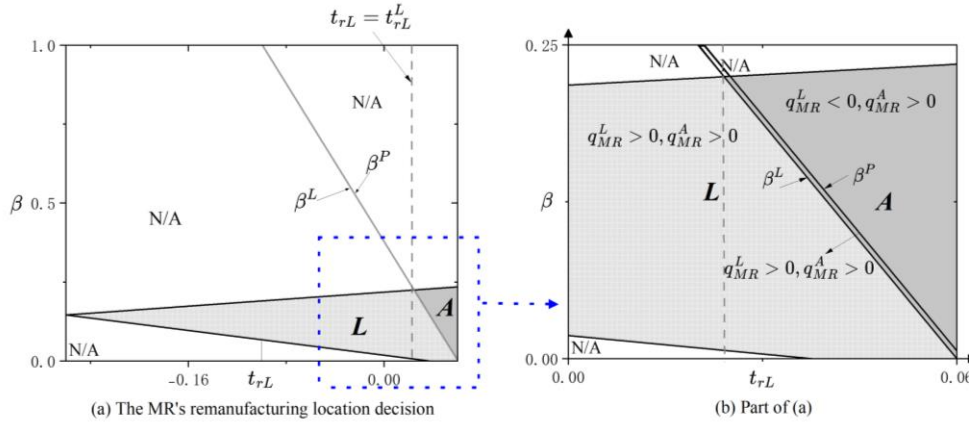


Figure 5.4. The MNR's remanufacturing location strategies

As shown in Figure 5.4 (a), the MNR prefers Scenario A if both reduced taxes on MR and the technology spillover are high (i.e., $t_{rL} > t_{rL}^L$ and $\beta > \beta^L$). Otherwise (i.e., when $t_{rL} \leq t_{rL}^L$, or $t_{rL} > t_{rL}^L$ and $\beta \leq \beta^L$), the MNR opts for Scenario L. This is explainable. On

²⁹ This is because a key objective of this study is to examine the impact of government policies and technology spillovers on promoting local remanufacturing. If the OEM does not participate in remanufacturing, technology spillover does not make sense and the role of policy incentives in facilitating local remanufacturing becomes irrelevant to our research scope.

the one hand, the MNR's remanufacturing costs in Scenario L are lower than those in Scenario A. On the other hand, the technology spillover in Scenario L reduces the MR's cost advantage over OR. When β is high (i.e., $\beta > \beta^P$), there is no profit for the MNR to produce MR in Scenario L, as shown in [Figure 5.4 \(b\)](#). Thus, the MNR always prefers Scenario A when $\beta > \beta^P$. When $\beta \leq \beta^P$, the MNR's decision on whether or not to establish a local remanufacturing center depends on the trade-off between her cost savings from localized remanufacturing and the potential revenue losses resulting from her reduced cost advantage over OR. Specifically, when both t_{rL} and β are high (i.e., $t_{rL} > t_{rL}^L$ and $\beta > \beta^L$), the cost savings are insufficient to offset the revenue losses, leading the MNR to prefer Scenario A. Conversely, when either t_{rL} or β is low, the MNR's cost savings outweigh her revenue losses, making Scenario L the preferred choice.

Proposition C-2 indicates that in practice, MNRs must balance the cost savings of establishing local remanufacturing centers against the risk of competitors benefiting from technology spillovers. In industries such as aerospace, medical equipment, and semiconductors, remanufacturing requires specialized expertise, strict regulatory compliance, and proprietary technology that restricts knowledge diffusion. Consequently, MNRs in these sectors should establish local remanufacturing centers to capitalize on lower labor costs, favorable tax policies, and proximity to key markets while maintaining their competitive advantage. Conversely, in industries such as consumer electronics, automotive components, and industrial equipment, local firms can rapidly absorb remanufacturing expertise, potentially eroding the MNR's market position. Therefore, MNRs in these industries should only pursue local remanufacturing if remanufacturing incentives can offset their potential revenue losses caused by technology spillovers.

5.4.3 Impact of introducing MNR strategy

The entry of the MNR into the domestic market, whether through exporting remanufactured products or establishing a local remanufacturing center, introduces competition and potential technology spillovers. These factors influence the OEM's strategic choices, the overall remanufacturing output, and consumer surplus. In this section, we first

examine if the MNR's entry can encourage the OEM to engage in remanufacturing. The results are shown in Proposition C-3. Since the derivation is straightforward, we omit the proof. The relevant threshold expressions can be found in [Appendix C-3](#).

Proposition C-3. *When $t_e < \tilde{t}_e^{N1}$, i.e., the OEM does not engage in remanufacturing in Scenario N, the MNR's establishment of a local remanufacturing center (Scenario L) can effectively encourage the OEM to engage in remanufacturing if and only if $\beta > \beta^{M1}$ and $t_{rL}^{M1} < t_{rL} < t_{rL}^{M2}$, whereas the MNR's exportation of remanufactured products (Scenario A) cannot.*

Proposition C-3 states that when $t_e < \tilde{t}_e^{N1}$, whether or not the MNR's entry into the domestic market can encourage the OEM to participate in remanufacturing depends on the MNR's entry mode, the technology spillover (β), and the reduced taxes on locally produced MR (t_{rL}). Specifically, the MNR's exportation of remanufactured products (Scenario A) fails to encourage the OEM to remanufacture. The key reasons are that under Scenario A, the OEM's products do not gain cost reductions compared to Scenario N. Meanwhile, the imported remanufactured products compete directly with the OEM's new and remanufactured products, thereby cannibalizing the OEM's market share. As a result, Scenario A does not make remanufacturing more attractive to the OEM than Scenario N. In contrast, the MNR's establishment of a local remanufacturing center encourages the OEM to engage in remanufacturing under specific conditions, as shown in [Figure 5.5](#). (Note that the parameters used include $\delta = 1/2$, $c_{OR} = 2/5$, $c_N = 3/5$, $\theta = 3/5$, $c_{MR} = 1/2$, $\Delta = 1/50$, and $t_e = 1/20$). The conditions are $\beta > \beta^{M1}$ and $t_{rL}^{M1} < t_{rL} < t_{rL}^{M2}$ (i.e., Region I of [Figure 5.5](#)). This is because when $\beta > \beta^{M1}$ and $t_{rL}^{M1} < t_{rL} < t_{rL}^{M2}$, a high degree of technology spillovers significantly reduces the OEM's remanufacturing costs. This cost reduction makes remanufacturing under Scenario L more attractive to the OEM than under Scenario N. Additionally, [Figure 5.5](#) also illustrates that Scenario L cannot encourage the OEM in other conditions. The reasons are different in different parameter ranges. Specifically, when either β or t_{rL} is high (i.e., Regions N/A, II, and III), the reason is that the MNR cannot make a profit in Scenario L. When both t_{rL} and β are low (i.e., Region IV), the limited cost reduction

for OR and a low t_{rL} make OR uncompetitive, the OEM does not engage in remanufacturing.

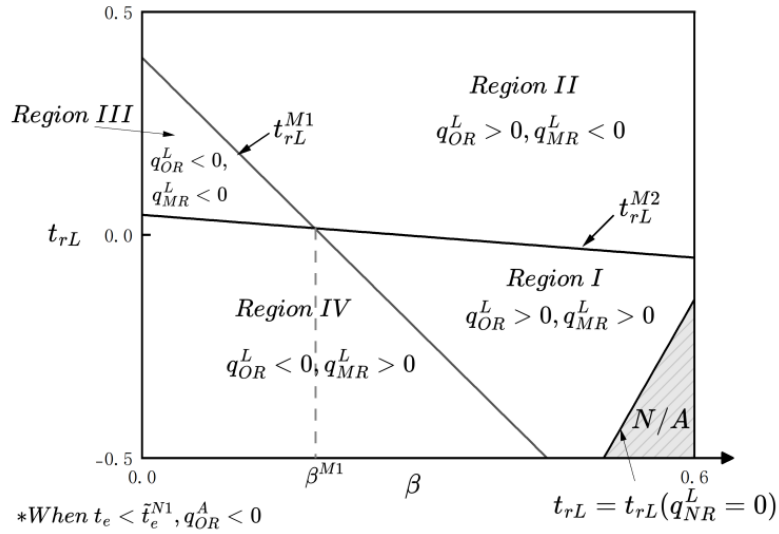


Figure 5.5. Firms' remanufacturing feasibility across parameter conditions

Proposition C-3 suggests that to promote remanufacturing, policymakers should recognize that simply allowing the importation of remanufactured products cannot encourage OEMs to engage in remanufacturing. Instead, attracting MNRs to establish local remanufacturing centers is a more effective strategy if technology spillovers are high and taxes on locally remanufactured products by MNRs are moderate. For MNRs, entering a market through establishing local remanufacturing centers can be a strategic opportunity. However, there is no profit for them to adopt it if tax incentives are low or technology spillovers are high.

We then analyze how the MNR's presence and her remanufacturing location affect the domestic market's remanufacturing output. The results are presented in Proposition C-4, with the proof omitted for brevity. The corresponding threshold expressions can be found in [Appendix C-3](#).

Proposition C-4. *Given that the OEM engages in remanufacturing,*

(i) *By comparing the OEM's remanufacturing quantities in Scenario N and Scenario A/L, we get*

- $q_{OR}^A < q_{OR}^N$;

- If $t_{rL} > t_{rL}^{Q1}$, $q_{OR}^L > q_{OR}^N$; otherwise, $q_{OR}^L \leq q_{OR}^N$.

(ii) By comparing the OEM's and the MNR's remanufacturing quantities in Scenario A and Scenario L, we get

- if $\beta^{Q1} < \beta < \beta^{Q2}$, $q_{OR}^L > q_{OR}^A$ and $q_{MR}^L > q_{MR}^A$;
- if $\beta < \beta^{Q1}$, $q_{OR}^L < q_{OR}^A$ and $q_{MR}^L > q_{MR}^A$;
- otherwise, $q_{OR}^L \geq q_{OR}^A$ and $q_{MR}^L \leq q_{MR}^A$.

(iii) By comparing the total local remanufacturing output across three scenarios, we get $q_R^L > q_R^A > q_R^N$, where $q_R^L = q_{OR}^L + q_{MR}^L$, $q_R^A = q_{OR}^A$, and $q_R^N = q_{OR}^N$.

This proposition shows how remanufacturing output changes across the three scenarios. Part (i) indicates that in Scenario A, the OEM's remanufacturing quantity is lower than that in Scenario N, whereas in Scenario L, the OEM's remanufacturing quantity exceeds that of Scenario N when the reduced tax on MR (t_{rL}) is high (i.e., $t_{rL} > t_{rL}^{Q1}$). This is explainable. In Scenario A, the introduction of the MNR's remanufactured products simply creates competition for the OEM. However, in Scenario L, the cost reduction for OR resulting from technology spillovers can reduce the OEM's competitive pressure from the MNR when $t_{rL} > t_{rL}^{Q1}$, leading the OEM to increase remanufacturing quantity. Part (ii) shows that when the degree of technology spillovers is moderate (i.e., $\beta^{Q1} < \beta < \beta^{Q2}$), compared to Scenario A, both firms' remanufacturing quantities increase in Scenario L. When $\beta < \beta^{Q1}$, the OEM's remanufacturing quantity decreases but the MNR's increases. Conversely, when $\beta \geq \beta^{Q2}$, the OEM's remanufacturing quantity increases while the MNR's decreases. This indicates that only a moderate degree of technology spillovers can encourage the OEM and the MNR to remanufacture more. Moreover, Part (iii) demonstrates that among these three scenarios, Scenario N has the lowest total remanufacturing output, as only the OEM engages in remanufacturing. The total remanufacturing output in Scenario A is higher than that in Scenario N. Additionally, Scenario L has the highest total remanufacturing output among the three scenarios, although it may lead to a decreased remanufacturing quantity for the OEM or the MNR.

This proposition provides implications for OEMs and MNRs to determine remanufacturing quantities. For OEMs, compared to the scenario without MNRs, when the MNR exports remanufactured products to the domestic market, they should reduce remanufacturing quantities. In contrast, if MNRs establish local remanufacturing centers, they should increase their remanufacturing quantities when taxes on MNR products are high. For MNRs, compared to exporting remanufactured products, establishing a local remanufacturing center enables them to increase optimal remanufacturing quantities when technology spillovers are low.

Next, we analyze the impact of the MNR's presence and her remanufacturing location on consumer surplus. The findings are detailed in Proposition C-5, with the proof omitted for brevity. The expressions of consumer surplus in three scenarios and relevant thresholds are provided in [Appendix C-3](#).

Proposition C-5. *Given that the OEM engages in remanufacturing, the comparisons of consumer surplus in different scenarios are as follows:*

- (i) $CS_R^A > CS_R^N$.
- (ii) If $t_e^{CS1} < t_e < t_e^{CS2}$, $CS_R^L > CS_R^N$; otherwise, $CS_R^L \leq CS_R^N$.
- (iii) If $\beta > \beta^{CS1}$ and $t_e > t_e^{CS3}$, or $\beta < \beta^{CS1}$ and $t_e < t_e^{CS3}$, $CS_R^L > CS_R^A$; otherwise, $CS_R^L \leq CS_R^A$.

As stated in Part (i), consumer surplus in Scenario A is higher than that in Scenario N. This is because the competition between the OEM's and the MNR's products leads to lower prices, thereby benefiting consumers. Part (ii) shows that compared with Scenario N, the MNR's local remanufacturing (Scenario L) can enhance consumer surplus when the environmental tax on the OEM's new products (t_e) is moderate (i.e., $t_e^{CS1} < t_e < t_e^{CS2}$). However, when t_e is high or low, consumer surplus declines. This implies that when policymakers allow the importation of remanufactured products, to increase consumer surplus, they should set appropriate environmental taxes to prevent either the OEM or the MNR from dominating the market. Part (iii) indicates that compared with Scenario A, Scenario L can further enhance consumer surplus when both the degree of technology

spillovers (β) and t_e are either high or low. In other words, the benefits of technology spillovers are shared with consumers when certain conditions are met. However, when β is high but t_e is low, or when β is low but t_e is high, consumer surplus in Scenario L is lower than that in Scenario A. This happens because in such cases, one firm gains an excessive competitive advantage. This imbalance of market power allows the dominant firm to raise prices, ultimately harming consumers.

5.5 Modeling and analyzing policy design

In this section, we focus on the policymaker's decision-making problem in scenarios A and L. We start by formulating the policymaker's objective functions and explaining their rationale. Then, we derive the policymaker's optimal decisions on taxes and tariffs under each scenario. Finally, we analyze these optimal decisions and outline conditions under which the policymaker should tax or subsidize the MNR.

5.5.1 Policymaking model

In this study, the policymaker's primary objective is to maximize social welfare on the basis of encouraging the OEM to engage in remanufacturing. The firms' responses to taxes and tariffs are reflected in the equilibrium outcomes; their profits are implicitly accounted for. Thus, following (Han et al., 2022), we do not include the firms' profits in the policymaker's objective function. Accordingly, incorporating consumer surplus, government tax and tariff revenues, environmental impact, and external benefits from the MNR's FDI, and being consistent with (Chen et al., 2019; Han et al., 2022; Xie et al., 2023), the policymaker's objectives in scenarios A and L can be expressed as follows:

$$\begin{aligned} \text{Max } SW^A(t_e, t_r) &= CS^A + t_e q_N^A + t_r q_{MR}^A - \epsilon q_N^A \\ \text{s. t.}, t_e &> \tilde{t}_e^{A1} \end{aligned} \quad (5-4)$$

$$\begin{aligned} \text{Max } SW^L(t_e, t_{rL}) &= CS^L + t_e q_N^L + t_{rL} q_{MR}^L - \epsilon q_N^L + a q_{MR}^L \\ \text{s. t.}, t_e &> \tilde{t}_e^{L1} \end{aligned} \quad (5-5)$$

where $i \in \{A, L\}$. $t_e q_N^i$ denotes the total taxes paid by the OEM, while $t_r q_{MR}^A$ and $t_{rL} q_{MR}^L$ represent the total tariffs and taxes paid by the MNR in Scenario A and Scenario L, respectively. Additionally, ϵq_N^i captures the total environmental impact caused by producing

new products in Scenario i^{30} . Beyond the financial and environmental aspects, the MNR's FDI generates external benefits such as job creation, skill development, and infrastructure improvements (Crespo and Fontoura, 2007; Xie et al., 2023). To quantify these benefits, following (Chen et al., 2019; Xie et al., 2023), we use aq_{MR} to denote the indirect gains brought by the MNR's FDI. Moreover, the constraint $t_e > \tilde{t}_e^{i1}$ ensures that the OEM engages in remanufacturing.

5.5.2 Calculating optimal taxes and tariffs

By substituting firms' responses to policies in Scenarios A and L (i.e., the optimal decisions shown in Table 5.2) into Eqs. (5-4) and (5-5), respectively, we derive the policymaker's optimal decisions on tariff and taxes for each scenario. The results are shown in Propositions C-6 and C-7. The detailed proofs, expressions of thresholds, relevant formulas, and the two firms' optimal production and remanufacturing quantities are provided in Appendix C-4.

Proposition C-6. *In scenario A,*

(i) *when $\epsilon \leq \bar{\epsilon}_1^A$, the policymaker cannot simultaneously achieve both objectives of ensuring the OEM engages in remanufacturing and maximizing social welfare. To ensure the OEM engages in remanufacturing, the tax on N must satisfy $t_e^{A*} > \underline{t}_e^A$. Moreover, the optimal tariff t_r^{A*} is an increasing function of t_e , given by: $t_r^{A*} = t_r^A(t_e)$.*

(ii) *When $\epsilon > \bar{\epsilon}_1^A$, the policymaker can simultaneously ensure the OEM's engagement in remanufacturing while maximizing social welfare. The optimal taxes and tariffs are given by:*

$$t_e^{A*} = \frac{(1-\delta)(4(-3+\theta)\theta + \delta(3+5\theta) + 4(\delta-\theta)c_{MR} - 3(\delta-4\theta)c_N - 9\theta c_{OR}) + 2\epsilon(\delta^2 + 2(6-\theta)\theta - \delta(3+8\theta))}{4(3-\theta)\theta - \delta(3+4\theta) - \delta^2},$$

$$t_r^{A*} = \frac{(\theta-\delta)((4\theta-\delta)(c_N+\epsilon) - 3\theta c_{OR}) - \delta(\delta+2\delta\theta - (4-\theta)\theta) - (1-\delta)(4\theta-\delta)c_{MR}}{4(3-\theta)\theta - \delta(3+4\theta) - \delta^2}.$$

Additionally, to avoid trivial cases in which either q_N^{A*} or q_{MR}^{A*} is non-positive, our

³⁰ For simplicity in the model, while ensuring analytical accuracy, the environmental impact of remanufactured products is set to zero. When it is not zero, ϵ can be explained as the additional environmental impact of producing a new product compared with remanufacturing one. Accordingly, ϵq_N^i represents the total additional environmental impact caused by producing new products compared with remanufacturing.

analysis is conducted under the conditions: $c_{OR} > \frac{1}{3}(3\delta - 4\theta + 4c_{MR})$ and $\bar{\epsilon}_2^A < \epsilon < \bar{\epsilon}_3^A$.

Proposition C-7. In Scenario L,

(i) when $\epsilon \leq \bar{\epsilon}_1^L$, the policymaker cannot simultaneously achieve both objectives of ensuring the OEM's engagement in remanufacturing and maximizing social welfare. To ensure the OEM engages in remanufacturing, the tax on N must satisfy $t_e^{L*} > \underline{t}_e^L$. Additionally, the optimal tax on MR t_{rL}^{L*} is a function of t_e^L , given by: $t_{rL}^{L*} = t_r^L(t_e^L)$.

(ii) When $\epsilon > \bar{\epsilon}_1^L$, the government can simultaneously ensure the OEM's engagement in remanufacturing while maximizing social welfare. The optimal taxes are given by:

$$t_e^{L*} = \frac{((3\delta - 12\theta)(1 - c_N) + 4(a + \theta - c_{MR} + \Delta)(\theta - \delta) + 9\theta(\delta - c_{OR}(1 - \beta)) - 2\epsilon(\delta - 8\theta))(1 - \delta) + 4\epsilon(\theta - \delta) + 4\epsilon\theta(1 - \theta)}{4\theta(3 - \delta) - \delta(3 + \delta) - 4\theta^2},$$

$$t_{rL}^{L*} = \frac{(\delta + (1 - \delta)(\Delta - c_{MR}) - 2a)(4\theta - \delta) - 3\theta c_{OR}(1 - \beta)(\theta - \delta) + 4\theta^2(a + c_N + \epsilon) - 5\delta\theta(c_N + \epsilon) + \delta^2(2a - 2\theta + c_N + \epsilon) - \delta\theta^2}{4\theta(3 - \delta) - \delta(3 + \delta) - 4\theta^2}.$$

Additionally, to avoid trivial cases in which q_N^{A*} or q_{MR}^{A*} is non-positive, our analysis is conducted under the conditions: $\Delta > \frac{1}{4}(-4a + 3\delta - 4\theta + 4c_{MR} - 3c_{OR} + 3\beta c_{OR})$ and $\bar{\epsilon}_L^2 < \epsilon < \bar{\epsilon}_L^3$.

Propositions C-6 and C-7 highlight that when the environmental impact of the OEM's new products is low (i.e., $\epsilon \leq \bar{\epsilon}_1^i$), the policymaker cannot simultaneously maximize social welfare and ensure the OEM's engagement in remanufacturing. To encourage the OEM to engage in remanufacturing, the taxes on new products must exceed the minimum threshold, namely $t_e^{A*} > \underline{t}_e^A$ in Scenario A and $t_e^{L*} > \underline{t}_e^L$ in Scenario L. Moreover, if the policymaker wants the OEM to increase remanufacturing quantity, t_e should be increased accordingly. Meanwhile, as t_e increases, the tariffs or taxes on the MNR's remanufactured products should also be increased to prevent the OEM from exiting the market. Conversely, when $\epsilon > \bar{\epsilon}_1^i$, the policymaker can optimize social welfare on the basis of ensuring the OEM's participation in remanufacturing and by implementing the tax and tariff levels derived in Propositions C-6 and C-7. In summary, when ϵ is low and there are no specific targets for the OEM's remanufacturing quantity, the optimal combination of taxes and tariffs is not available. In this situation, the policymaker can adjust taxes on the OEM's new products and tariffs (or taxes)

on the MNR's remanufactured products based on policymakers' expectations of the OEM's remanufacturing quantity. In contrast, when ϵ is high, it becomes possible to satisfy both goals, and a set of optimal tax and tariff levels derived from Propositions C-6 and C-7 should be followed. Building on these closed-form solutions, the following analysis focuses on the case where $\epsilon > \bar{\epsilon}_1^i$.

5.5.3 Analyzing conditions for different policy designs

In this section, we first examine the monotonicity of the policymaker's optimal decisions with respect to the negative environmental impact of new products (ϵ) and the degree of technology spillovers (β). This helps us understand how changes in ϵ and β shape the direction of policy design. The results are presented in Proposition C-8, with proof omitted for simplicity.

Proposition C-8. *Given $\epsilon > \bar{\epsilon}_1^i$, t_e^{i*} , t_r^{A*} and t_{rL}^{L*} increase in ϵ , where $i \in \{A, L\}$. t_e^{L*} and t_{rL}^{L*} increase in β .*

Proposition C-8 shows that as ϵ increases, the policymaker increases the taxes on new products (t_e) and the tariffs or taxes on the MNR's remanufactured products (t_r^{A*} or t_{rL}^{L*}). Additionally, in Scenario L, the policymaker increases t_e^{L*} and t_{rL}^{L*} along with the increase in β . The reasons are as follows. As ϵ increases, the policymaker increases t_e to hold the OEM accountable for the greater environmental damage. However, the increase in t_e leads to an increase in production costs for new products, thereby reducing their market competitiveness compared to the MNR's products. To balance the market competition, the policymaker also increases the tariffs or taxes on the MNR's remanufactured products (t_r^{A*} or t_{rL}^{L*}). In Scenario L, as β increases, the policymaker increases t_e to encourage the OEM to remanufacture more. Meanwhile, to safeguard consumer welfare by ensuring balanced market competition between the OEM's new products and the MNR's remanufactured products, the policymaker also increases t_{rL} .

So far, our discussion has centered on taxes and tariffs imposed on the MNR's remanufactured products. However, in practice, many policymakers — particularly those aiming to promote circular economy practices or boost FDI — may choose to offer subsidies

for remanufacturing activities. For example, the German government offers a range of incentives to encourage foreign investors to engage in the remanufacturing or repurposing of used lithium batteries³¹; the Indian government provides subsidies for the remanufacturing of electronic products to stimulate the sector and attract investment³². With this perspective, Proposition C-9 clarifies the conditions under which the policymaker opts to impose taxes/tariffs versus providing subsidies on the MNR's remanufactured products in each scenario. Due to its straightforward nature, the proof of Proposition C-9 is omitted. The expressions for the relevant thresholds can be found in [Appendix C-3](#).

Proposition C-9. *Given $t_e^{A*} > \underline{t}_e^A$ and $t_e^{L*} > \underline{t}_e^L$, the policymaker's decisions regarding the imposition of taxes/tariffs versus the provision of subsidies on the MNR's remanufactured products are as follows:*

- (i) *When $\epsilon < \min\{\epsilon_1^P, \epsilon_2^P\}$, subsidies are provided in both Scenario A and Scenario L;*
- (ii) *When $\beta < \beta^P$ (i.e., $\epsilon_2^P > \epsilon_1^P$) and $\epsilon_1^P < \epsilon < \epsilon_2^P$, tariffs are imposed in Scenario A, while subsidies are provided in Scenario L;*
- (iii) *When $\beta \geq \beta^P$ (i.e., $\epsilon_2^P < \epsilon_1^P$) and $\epsilon_2^P < \epsilon < \epsilon_1^P$, subsidies are provided in Scenario A, while taxes are imposed in Scenario L;*
- (iv) *When $\epsilon > \max\{\epsilon_1^P, \epsilon_2^P\}$, tariffs are imposed in Scenario A and taxes are imposed in Scenario L.*

Proposition C-9 outlines the policymaker's decision framework for choosing between subsidies and taxation (i.e., tariffs and taxes) on the MNR's remanufactured products in Scenario A and Scenario L, based on the environmental impact of producing a new product (i.e., ϵ) and the degree of technology spillovers (i.e., β). Obtained based on $\delta = 1/2$, $\theta = 3/5$, $c_{MR} = 1/2$, $c_{OR} = 19/50$, $c_N = 3/5$, $\Delta = 1/100$, and $a = 217/4000$, [Figure 5.6](#) provides a numerical example illustrating this proposition.

³¹ <https://www.gtai.de/en/invest/industries/environmental-technologies/battery-recycling-market-opportunities-in-germany-995330#toc-anchor--3>

³² <https://www.livemint.com/Politics/JnYd4X6aCHF18h7jEVMJ3L/Govt-extends-capital-subsidy-to-electronic-products-to-boost.html>

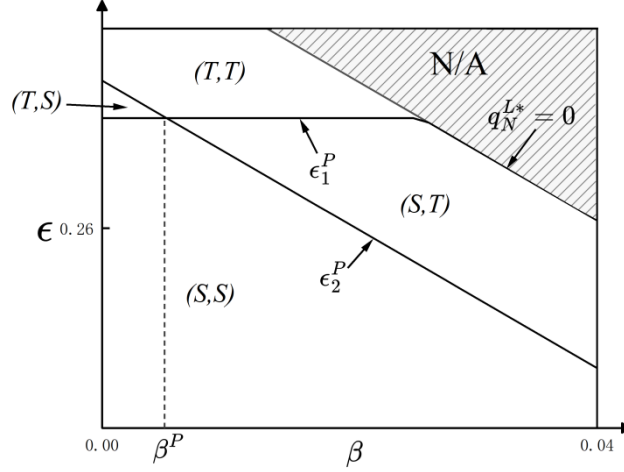


Figure 5.6. Policy selections between subsidies and taxation on MR

As shown in Regions (S, S) and (T, T) of Figure 5.6, when ϵ is either low or high (i.e., $\epsilon < \min\{\epsilon_1^P, \epsilon_2^P\}$ or $\epsilon > \max\{\epsilon_1^P, \epsilon_2^P\}$), the policymaker adopts the same policy approach in both scenarios. Specifically, when $\epsilon < \min\{\epsilon_1^P, \epsilon_2^P\}$, the policymaker provides subsidies in both scenarios. Conversely, when $\epsilon > \max\{\epsilon_1^P, \epsilon_2^P\}$, the policymaker imposes taxation in both scenarios. However, when β is low and ϵ is moderate, the policymaker imposes tariffs in Scenario A, while subsidizing the MNR in Scenario L, as indicated by Region (T, S) of Figure 5.6. In contrast, when β is high and ϵ is moderate, the policymaker subsidizes the MNR in Scenario A, while imposing taxes in Scenario L, as indicated by Region (S,T) of Figure 5.6.

The reasons are as follows. Given the monotonicity of t_e^{i*} , t_r^{A*} , and t_{rL}^{L*} with respect to ϵ (as shown in Proposition C-8), we can derive that regardless of the level of β , when ϵ is very low (high), both t_r^{A*} and t_{rL}^{L*} are negative (positive). This indicates that the policymaker chooses to subsidize (tax) the MNR's remanufactured products (MR) in both scenarios. Additionally, when β is low — meaning that the MNR's local production does not significantly enhance the OEM's remanufacturing capabilities — and ϵ is moderate, the OEM's remanufacturing costs remain high in Scenario L. Since high remanufacturing costs limit the OEM's contribution to social welfare, the policymaker prioritizes attracting the MNR's local remanufacturing to increase social welfare. Thus, the policymaker continues subsidizing MR in Scenario L. On the contrary, when β is high and ϵ is moderate, the MNR's local presence significantly reduces the OEM's remanufacturing costs, thereby increasing the

OEM's willingness to engage in remanufacturing. In this situation, the policymaker taxes MR in Scenario L to ensure that the OEM remanufactures more. Moreover, if $\epsilon > \epsilon_1^P$, the policymaker always subsidizes MR in Scenario A; otherwise, the policymaker taxes MR in Scenario A.

Proposition C-9 provides important insights into policymaking. Specifically, when the environmental impact of new product production (i.e., ϵ in this study) is low, policymakers should focus on promoting the growth of the remanufacturing sector to enhance market competition and increase consumer acceptance of remanufactured products. To achieve this, they should provide subsidies for MNRs' remanufactured products, either imported or locally produced. As ϵ increases, policymakers need to balance environmental goals with market competition. If the degree of technology spillovers (i.e., β in this study) is low, policymakers should impose tariffs on imported remanufactured products while offering subsidies to encourage MNRs to establish local remanufacturing centers. However, when β is high, policymakers should subsidize imported remanufactured products and tax locally produced ones. When ϵ reaches a high level, policymakers should impose taxes on MNRs' remanufactured products, either imported or locally produced.

5.6. Conclusions and contributions

Remanufacturing delivers both economic and environmental benefits while addressing growing concerns about resource sustainability. Recognizing its potential, many governments have implemented policies to incentivize local OEMs to engage in remanufacturing and to attract MNRs into domestic markets (Hong et al., 2021; Li et al., 2023). In a remanufacturing system consisting of a local OEM and an MNR, the local OEM needs to decide whether or not to engage in remanufacturing; the MNR should determine whether or not to enter the domestic market and, if so, whether to export remanufactured products or establish a local remanufacturing facility. Both firms' decision-making is complicated by policy interventions and FDI-induced technology spillovers. Meanwhile, the policymaker also faces critical decision-making challenges in determining tax and tariff levels. To assist firms and policymakers in making optimal remanufacturing and policy decisions, respectively, this

study develops analytical models to examine three scenarios: (i) only the OEM is present (Scenario N), (ii) the MNR exports remanufactured products to the domestic market (Scenario A), and (iii) the MNR establishes a local remanufacturing center in the domestic market (Scenario L).

Based on the analysis of solutions, our findings highlight key factors influencing remanufacturing decisions and policy effectiveness, demonstrating how firms respond to varying government policies and taxation levels. Specifically, we find: (1) the OEM engages in remanufacturing if environmental taxes on new products (t_e) are high, while the MNR establishes a local remanufacturing center when either the tax on her locally-produced remanufactured products (t_{rL}) or the degree of technology spillover effects (β) is low; (2) Products from the OEM and the MNR can coexist in the market when tax levels are moderate; (3) Compared to Scenario N, only Scenario L can encourage the OEM to engage in remanufacturing, but only if t_{rL} is moderate and β is high; (4) Compared to Scenario N, Scenario A always improves consumer surplus, while Scenario L improves consumer surplus only when t_e is moderate; (5) In scenarios A and L, if the environmental impact of producing a new product (ϵ) is low (i.e., $\epsilon < \bar{\epsilon}_1^i$ in this study), the policymaker cannot simultaneously ensure the OEM's participation in remanufacturing and optimize social welfare. Otherwise, an optimal tax structure can achieve both objectives simultaneously; and (6) When ϵ is very low, the policymaker subsidizes the MNR in both scenarios A and L, whereas when ϵ is high, he taxes the MNR.

Our work offers practical guidance for both firms and policymakers in optimizing remanufacturing strategies and policy decisions, respectively:

(i) For firms (OEMs and MNRs): OEMs should adopt remanufacturing when environmental taxes on new products are high. If an MNR exports remanufactured products, OEMs need to reduce remanufacturing quantities. However, if an MNR establishes a local remanufacturing center, OEMs should increase their remanufacturing quantities, especially when environmental taxes on MNR products are high. MNRs must evaluate the trade-offs between exporting remanufactured products and localizing remanufacturing, considering

tariffs, tax incentives, and spillover risks. Specifically, they should establish local remanufacturing centers to benefit from lower costs and tax advantages if the degree of technology spillovers is low, otherwise, they should choose to export their products.

(ii) For policymakers: To encourage OEMs to engage in remanufacturing, policymakers should impose environmental taxes on new products. However, to avoid disrupting market stability, taxes should not be overly aggressive. Additionally, import facilitation and tax exemptions for remanufactured products can encourage OEMs to engage in remanufacturing, particularly in environmentally intensive sectors. Additionally, when designing policies, if the environmental impact of producing a new product is very low, policymakers must recognize the trade-off between encouraging OEMs to engage in remanufacturing and optimizing social welfare. In this context, they should adjust their tax levels based on their expectations of OEMs' remanufacturing quantities. Otherwise, there are optimal tax levels that can simultaneously achieve the dual objectives of ensuring OEMs' engagement in remanufacturing and maximizing social welfare. Moreover, policymakers should determine whether to tax or subsidize MNRs based on the specific values of the environmental impact of producing a new product and the degree of technology spillovers.

Our study makes several contributions. First, we extend the available remanufacturing literature by examining how the OEM and MNR adjust their decision-making in response to different government policy instruments and remanufacturing technology spillovers. Second, we outline the regulatory conditions under which the MNR's remanufactured products, the OEM's new products, and, if applicable, the OEM's remanufactured products coexist in the market. Third, we examine the impact of the MNR's presence on encouraging the OEM to engage in remanufacturing, promoting the overall remanufacturing output, and enhancing consumer surplus. Next, we investigate how policymakers optimize taxes and tariffs in different scenarios. Meanwhile, we explore how changes in the negative environmental impact of new products and technology spillovers shape the direction of policy design. At last, we offer managerial insights for OEMs and MNRs to optimize their remanufacturing strategies and provide recommendations for policymakers to design effective policies that encourage OEM engagement in remanufacturing while maximizing social welfare.

Despite the contributions, our study has several limitations that open avenues for future research. First, we assumed that all remanufactured products from MNRs meet the importing country's quality standards. In reality, local governments may impose stringent quality requirements, potentially restricting the export of remanufactured products and creating a risk of rejection (Zhang et al., 2023). Incorporating such quality-based import restrictions into our model would yield a more realistic assessment of the challenges faced by MNRs in exporting remanufactured products. Second, our study considered a scenario in which the MNR operates within a single market, whereas many MNRs (e.g., Caterpillar³³) operate across multiple regions. Extending our models to include multi-market operations of MNRs would enable a more comprehensive understanding of how policy interventions affect remanufacturing strategies. Finally, our study examined interactions between a single OEM and a single MNR, but real-world markets typically involve multiple competing firms. Future research could explore multi-agent competition and apply dynamic game-theoretic models to better capture evolving market behaviors.

5.7 References

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³³ <https://www.caterpillar.com/>

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5.8 A list of appendices

Appendix C-1. Derivations of inverse demand functions

Each consumer makes his/her purchasing decision by maximizing utility. The utility functions for the OEM's new and remanufactured products and the MNR's remanufactured products are $U_N^i = V - p_N^i$, $U_{OR}^i = \delta V - p_{OR}^i$, and $U_{MR}^i = \theta V - p_{MR}^i$, respectively, where $i \in \{N, A, L\}$ and $V \in [0,1]$.

In Scenario N, a consumer buys i) N if $U_N^N > U_{OR}^N$ and $U_N^N > 0$, i.e., $V \in (\frac{p_N^N - p_{OR}^N}{1-\delta}, 1]$, ii) OR if $U_{OR}^N \geq U_N^N$ and $U_{OR}^N > 0$, i.e., $V \in (\frac{p_{OR}^N}{\delta}, \frac{p_N^N - p_{OR}^N}{1-\delta}]$, and iii) nothing otherwise. To avoid

the trivial case in which no customer buys OR, we restrict $\frac{p_{OR}^N}{\delta} \geq \frac{p_N^N - p_{OR}^N}{1-\delta}$, which simplifies to $p_{OR}^N \leq \delta p_N^N$. Accordingly, the demand functions are derived as follows: $q_N^N = \int_{\frac{p_N^N - p_{OR}^N}{1-\delta}}^1 1 dV = 1 - \frac{p_N^N - p_{OR}^N}{1-\delta}$, $q_{OR}^N = \int_{\frac{p_{OR}^N}{\delta}}^{\frac{p_N^N - p_{OR}^N}{1-\delta}} 1 dV = \frac{p_N^N - p_{OR}^N}{1-\delta} - \frac{p_{OR}^N}{\delta}$. From these, we obtain the inverse demand functions: $p_N^N = 1 - q_N^N - \delta q_{OR}^N$ and $p_{OR}^N = \delta(1 - q_N^N - q_{OR}^N)$.

In Scenario A, a consumer buys i) N if $U_N^A > \max\{0, U_{OR}^A, U_{MR}^A\}$, i.e., $V \in (\frac{p_N^A - p_{MR}^A}{1-\theta}, 1]$, ii) MR if $U_{MR}^A \geq \max\{0, U_{OR}^A, U_N^A\}$, i.e., $(\frac{p_{MR}^A - p_{OR}^A}{\theta-\delta}, \frac{p_N^A - p_{MR}^A}{1-\theta}]$, iii) OR if $U_{OR}^A \geq \max\{0, U_{MR}^A, U_N^A\}$, i.e., $V \in (\frac{p_{OR}^A}{\delta}, \frac{p_{MR}^A - p_{OR}^A}{\theta-\delta}]$, and iv) nothing otherwise. To avoid trivial cases in which no consumer buys MR or OR, we restrict $\frac{\theta}{\delta} p_{OR}^A \leq p_{MR}^A \leq \frac{(\theta-\delta)p_N^A + (1-\theta)p_{OR}^A}{1-\delta}$. Using the same approach as in Scenario N, we obtain the inverse demand functions: $p_N^A = 1 - \theta q_{MR}^A - q_N^A - \delta q_{OR}^A$, $p_{MR}^A = \theta - \theta(q_{MR}^A + q_N^A) - \delta q_{OR}^A$, and $p_{OR}^A = \delta(1 - q_{MR}^A - q_N^A - q_{OR}^A)$.

The inverse demand functions in Scenario L are the same as in Scenario A.

Appendix C-2. Derivations of optimal solutions

(1) In Scenario N, the maximization problem of the OEM is shown in Eq. (4-1). From $\frac{\partial^2 \pi_O^N(q_N^N, q_{OR}^N)}{\partial q_N^N^2} = -2 < 0$ and the Hessian matrix (**H**) of $\pi_O^N(q_N^N, q_{OR}^N)$ (**H**=4(1- δ) δ > 0), we know that $\pi_O^N(q_N^N, q_{OR}^N)$ is jointly concave in q_N^N and q_{OR}^N . Additionally, the OEM's problem is characterized by Karush-Kuhn-Tucker (KKT) conditions. Let n denote the Lagrangian multiplier, then we have the Lagrangian function of the OEM's optimization problem, i.e. Eq. (4-1), as follows:

$$L(q_N^N, q_{OR}^N, n) = q_N^N(p_N^N - c_N - t_e) + q_{OR}^N(p_{OR}^N - c_{OR}) + n q_{OR}^N$$

With the first conditions $\frac{\partial L}{\partial q_N^N} = 1 - c_N - 2q_N^N - 2\delta q_{OR}^N - t_e = 0$, $\frac{\partial L}{\partial q_{OR}^N} = -c_{OR} - \delta q_N^N + \delta(1 - q_N^N - q_{OR}^N) - \delta q_{OR}^N = 0$ and the constraint $n q_{OR}^N = 0$, we have the following optimal solutions:

Case N1. When $n > 0$ and $q_{OR}^N = 0$, we have $q_N^{N*} = \frac{1}{2}(1 - c_N - t_e)$, $q_{OR}^{N*} = 0$, and $n^* =$

$c_{OR} - \delta(c_N + t_e)$. The relative profits are $\pi_O^{N*} = \frac{1}{4}(1 - c_N - t_e)^2$. The conditions to ensure $n^* > 0$ is $t_e < \tilde{t}_e^{N1}$, where $\tilde{t}_e^{N1} = \frac{-\delta c_N + c_{OR}}{\delta}$.

Case N2. When $n = 0$ and $q_{OR}^N > 0$, we have $q_N^{N*} = \frac{1 - c_N - t_e + \delta - c_{OR}}{2(1 - \delta)}$, $q_{OR}^{N*} = \frac{\delta(c_N + t_e) - c_{OR}}{2\delta(1 - \delta)}$, and $n^* = 0$. The relative profits are $\pi_O^{N*} = \frac{\delta(1 - c_N - e_N t_e)^2 - (\delta - c_{OR})(\delta + c_{OR} - 2\delta(c_N + t_e))}{4(1 - \delta)\delta}$. The conditions to ensure $q_{OR}^{N*} > 0$ is $t_e > \tilde{t}_e^{N1}$.

(2) In Scenario A, the maximization problems of the OEM and the MNR are shown in Eq. (4-2). Because the second derivative of the MNR's profit with respect to its remanufacturing quantity is less than zero, i.e., $\frac{\partial^2 \pi_M^A(q_{MR}^A)}{\partial q_{MR}^{A2}} = -2\theta < 0$, π_M^A is concave in q_{MR}^A . Meanwhile, from $\frac{\partial^2 \pi_O^A(q_N^A, q_{OR}^A)}{\partial q_N^{A2}} = -2 < 0$ and the Hessian matrix **(H)** of $\pi_O^A(q_N^A, q_{OR}^A)$ (**H** = $4(1 - \delta)\delta > 0$), we know that $\pi_O^A(q_N^A, q_{OR}^A)$ is jointly concave in q_N^A and q_{OR}^A . Additionally, the OEM's problem is characterized by Karush-Kuhn-Tucker (KKT) conditions. Let a denote the Lagrangian multiplier, then we have the Lagrangian function of the OEM's optimization problem, i.e. Eq. (4-2), as follows:

$$L(q_N^A, q_{OR}^A, a) = q_N^A(p_N^A - c_N - t_e) + q_{OR}^A(p_{OR}^A - c_{OR}) + a q_{OR}^A$$

With the first conditions $\frac{\partial L}{\partial q_N^A} = 1 - c_N - \theta q_{MR}^A - 2q_N^A - 2\delta q_{OR}^A - t_e = 0$, $\frac{\partial L}{\partial q_{OR}^A} = -c_{OR} - \delta q_N^A + \delta(1 - q_{MR}^A - q_N^A - q_{OR}^A) - \delta q_{OR}^A = 0$ and the constraint $a q_{OR}^A = 0$, solving the OEM's and the MNR's problem simultaneously, we have the following optimal solutions:

Case A1. When $a > 0$ and $q_{OR}^A = 0$, we have $q_N^{A*} = \frac{2 - \theta + c_{MR} - 2c_N - 2t_e + t_r}{4 - \theta}$, $q_{OR}^{A*} = 0$, $q_{MR}^{A*} = \frac{\theta(1 + c_N + t_e) - 2(c_{MR} + t_r)}{(4 - \theta)\theta}$ and $a^* = \frac{-2\delta(-1 + \theta)c_{MR} + 3\delta\theta c_N + (-4 + \theta)\theta c_{OR} + \delta\theta(-1 + \theta + 3t_e) - 2\delta(-1 + \theta)t_r}{(-4 + \theta)\theta}$. The relative profits are $\pi_O^{A*} = \frac{(2(1 - c_N - t_e) + c_{MR} - \theta + t_r)^2}{(4 - \theta)^2}$ and $\pi_{MR}^{A*} = \frac{(\theta(1 + c_N + t_e) - 2(c_{MR} + t_r))^2}{(4 - \theta)^2\theta}$. The conditions to ensure $a^* > 0$ is $t_e < \tilde{t}_e^{A1}$, where $\tilde{t}_e^{A1} = \frac{\delta\theta(1 - \theta) + \theta c_{OR}(4 - \theta) - 2\delta(1 - \theta)(t_r + c_{MR}) - 3\delta\theta c_N}{3\delta\theta}$.

Case A2. When $a = 0$ and $q_{OR}^A > 0$, we have $q_{MR}^{A*} =$

$$\begin{aligned}
& \frac{(\theta-\delta)(c_N+t_e)-2(1-\delta)(t_r+c_{MR})+\theta(1-\delta)+(1-\theta)c_{OR}}{(4\theta-\delta)-2\delta\theta-\theta^2}, \quad q_N^{A*} = \\
& \frac{(4\theta-\delta)(1-c_N-t_e)+2(\theta-\delta)(\theta+c_{MR}+t_r)+\theta(\delta-4\theta+3c_{OR})}{2((4\theta-\delta)-2\delta\theta-\theta^2)}, \quad q_{OR}^{A*} = \\
& \frac{\delta(1-\theta)(2c_{MR}-\theta+2t_r)+3\delta\theta(c_N+t_e)-\theta c_{OR}(4-\theta)}{2\delta((4\theta-\delta)-2\delta\theta-\theta^2)}, \text{ and } \alpha^* = 0. \text{ The relative profits are } \pi_O^{A*} = \\
& -\frac{1}{4\delta(\delta+2\delta\theta-(4-\theta)\theta)^2} ((\delta(\delta+(-3+\delta)\theta+\theta^2)+2(-1+\delta)\delta c_{MR}+\delta(-\delta+\theta)c_N+ \\
& 4\theta c_{OR}-3\delta\theta c_{OR}-\theta^2 c_{OR}-\delta^2 e_N t_e+\delta\theta t_e+2(-1+\delta)\delta t_r)(-2\delta(-1+\theta)c_{MR}+ \\
& 3\delta\theta c_N+(-4+\theta)\theta c_{OR}+\delta\theta(-1+\theta+3t_e)-2\delta(-1+\theta)t_r)+\delta(2(-2+\theta)\theta+\delta(1+ \\
& \theta)+2(\delta-\theta)c_{MR}-(\delta-4\theta)c_N-3\theta c_{OR}-\delta t_e+4\theta t_e+2(\delta-\theta)t_r)(-2(-2+\theta)\theta+ \\
& \delta(-1+(-2+\theta)\theta)-2(-1+\delta)\theta c_{MR}+(\delta-4\theta+3\delta\theta)c_N+\delta t_e+\theta((-1+\theta)c_{OR}+ \\
& (-4+3\delta)t_e-2(-1+\delta)t_r))) \text{ and } \pi_{MR}^{A*} = \frac{\theta((2c_{MR}+2t_r-\theta)(1-\delta)-(\theta-\delta)(c_N+t_e)-(1-\theta)c_{OR})^2}{(\delta+2\delta\theta-(4-\theta)\theta)^2}. \text{ The} \\
& \text{conditions to ensure } q_{OR}^{A*} > 0 \text{ is } t_e > \tilde{t}_e^{A1}.
\end{aligned}$$

(3) In Scenario L, the maximization problems of the OEM and the MNR are shown in Eq. (4-3). Because the second derivative of the MNR's profit with respect to its remanufacturing quantity is less than zero, i.e., $\frac{\partial^2 \pi_M^L(q_{MR}^L)}{\partial q_{MR}^{L2}} = -2\theta < 0$, π_M^L is concave in q_{MR}^L . Meanwhile, from $\frac{\partial^2 \pi_O^L(q_N^L, q_{OR}^L)}{\partial q_N^{L2}} = -2 < 0$ and the Hessian matrix (**H**) of $\pi_O^L(q_N^L, q_{OR}^L)$ (**H**= $4(1-\delta)\delta > 0$), we know that $\pi_O^L(q_N^L, q_{OR}^L)$ is jointly concave in q_N^L and q_{OR}^L . Following the same optimization approach, we directly present the optimal solutions as follows:

Case L1. When $t_e \leq \tilde{t}_e^{L1}$, $q_N^{L*} = \frac{2(1-c_N-t_e)-\Delta-\theta+c_{MR}+t_{rL}}{4-\theta}$, $q_{OR}^{L*} = 0$, and $q_{MR}^{L*} = \frac{\theta(1+c_N+t_e)-2(c_{MR}+t_r)}{(4-\theta)\theta}$. The relative profits are $\pi_O^{L*} = \frac{(2(1-c_N-t_e)+c_{MR}-\theta+t_{rL}+\Delta)^2}{(4-\theta)^2}$ and $\pi_{MR}^{L*} = \frac{(\theta(1+c_N+t_e)-2(c_{MR}+t_{rL}-\Delta))^2}{(4-\theta)^2\theta}$, where $\tilde{t}_e^{L1} = \frac{\delta\theta(1-\theta)+\theta c_{OR}(4-\theta)-2\delta(1-\theta)(t_r+c_{MR})-3\delta\theta c_N}{3\delta\theta} + \frac{2\delta(1-\theta)(\Delta+t_r-t_{rL})-\beta(4-\theta)\theta c_{OR}}{3\delta\theta}$.

Case L2. When $t_e > \tilde{t}_e^{L1}$, $q_N^{L*} = \frac{(4\theta-\delta)(1-c_N-t_e)+2(\theta-\delta)(\theta+c_{MR}-\Delta+t_{rL})-3\theta(\theta-c_{OR}(1-\beta))}{2((4\theta-\delta)-2\delta\theta-\theta^2)}$, $q_{OR}^{L*} = \frac{2\delta(1-\theta)(\theta+c_{MR}-\Delta+t_{rL})-3\delta\theta(1-c_N-t_e)-\theta c_{OR}(1-\beta)(4-\theta)+3\delta\theta^2}{2\delta((4\theta-\delta)-2\delta\theta-\theta^2)}$, and $q_{MR}^{L*} = \frac{(\theta-\delta)(1+c_N+t_e)-2(1-\delta)(\theta+c_{MR}-\Delta+t_{rL})+(1-\theta)(\delta+(1-\beta)c_{OR})+2\theta(1-\delta)}{(4\theta-\delta)-2\delta\theta-\theta^2}$. The relative profits are $\pi_O^{L*} =$

$$\frac{1}{2(\delta+2\delta\theta+(-4+\theta)\theta)}(\delta(\delta+2\Delta-2\delta\Delta+(-3+\delta)\theta+\theta^2)+2(-1+\delta)\delta c_{MR}+\delta(-\delta+\theta)c_N+2\delta c_{OR}-2\beta\delta c_{OR}-4\theta c_{OR}+4\beta\theta c_{OR}+\delta\theta c_{OR}-\beta\delta\theta c_{OR}+\theta^2 c_{OR}-\beta\theta^2 c_{OR}-\delta^2 t_e+\delta\theta t_e+2(-1+\delta)\delta t_{rL}) \quad \text{and} \quad \pi_{MR}^{L*} = \frac{1}{2(\delta+2\delta\theta+(-4+\theta)\theta)}(\delta+2\theta(-2+\Delta+\theta)-\delta\theta(-2+2\Delta+\theta)+2(-1+\delta)\theta c_{MR}+(2(-2+\theta)\theta+\delta(1+\theta))c_N+\delta t_e+\theta((-1+\beta)(-1+\theta)c_{OR}+(-4+\delta+2\theta)t_e+2(-1+\delta)t_{rL})).$$

Appendix C-3. Expressions of thresholds and consumer surplus

(1) Thresholds of Proposition C-1.

Scenario N: $\tilde{t}_e^{N1} = \frac{c_{OR}-\delta c_N}{\delta}$, $\tilde{t}_e^{N2} = 1 - \delta - c_N + c_{OR}$.

Scenario A: $\tilde{t}_r^{AN} = \frac{\delta\theta-2\delta c_{MR}+\theta c_{OR}}{2\delta}$, $\tilde{t}_r^{A1} = \frac{2\theta c_{OR}-\delta(\theta+c_{MR})}{\delta}$, $\tilde{t}_r^{A2} = \frac{\delta\theta-2\delta c_{MR}+\theta c_{OR}}{2\delta}$, $\tilde{t}_e^{A0} = \frac{(2c_{MR}-\theta+2t_r)(1-\delta)-c_N(\theta-\delta)-c_{OR}(1-\theta)}{\theta-\delta}$, $\tilde{t}_e^{A1} = \frac{\delta\theta(1-\theta)+\theta c_{OR}(4-\theta)-2\delta(1-\theta)(t_r+c_{MR})-3\delta\theta c_N}{3\delta\theta}$, $\tilde{t}_e^{A2} = \frac{(4\theta-\delta)(1-c_N)+2(c_{MR}+t_r)(\theta-\delta)+\theta(3c_{OR}-\delta-2\theta)}{4\theta-\delta}$, $\tilde{t}_e^{A3} = \frac{2(1-c_N)-\theta+c_{MR}+t_r}{2}$, $\tilde{t}_e^{AN} = \frac{2(c_{MR}+t_r)-\theta(1+c_N)}{\theta}$.

Scenario L: $\tilde{t}_{rL}^{L1} = \frac{\delta(\Delta-\theta-c_{MR})+2\theta c_{OR}(1-\beta)}{\delta}$, $\tilde{t}_{rL}^{L2} = \frac{1}{2}(2(\Delta+\theta-c_{MR})+c_{OR}(1-\beta)-\delta)$, $\tilde{t}_{rL}^{LN} = \frac{2\delta\Delta+\delta\theta-2\delta c_{MR}+\theta c_{OR}-\beta\theta c_{OR}}{2\delta}$, $\tilde{t}_e^{L0} = \frac{(2(c_{MR}+t_{rL}-\Delta)-\theta)(1-\delta)-(\theta-\delta)c_N-c_{OR}(1-\beta)(1-\theta)}{\theta-\delta}$, $\tilde{t}_e^{L1} = \frac{\delta\theta(1-\theta)+\theta c_{OR}(4-\theta)-2\delta(1-\theta)(t_r+c_{MR})-3\delta\theta c_N}{3\delta\theta} + \frac{2\delta(1-\theta)(\Delta+t_r-t_{rL})-\beta(4-\theta)\theta c_{OR}}{3\delta\theta}$, $\tilde{t}_e^{LN} = \frac{2(c_{MR}+t_{rL}-\Delta)-\theta(1+c_N)}{\theta}$, $\tilde{t}_e^{L1} = \frac{\delta\theta(1-\theta)+\theta c_{OR}(4-\theta)-2\delta(1-\theta)(t_r+c_{MR})-3\delta\theta c_N}{3\delta\theta} + \frac{2\delta(1-\theta)(\Delta+t_r-t_{rL})-\beta(4-\theta)\theta c_{OR}}{3\delta\theta}$, $\tilde{t}_e^{L2} = \frac{2(c_{MR}+t_{rL}-\Delta)(\theta-\delta)+3\theta c_{OR}(1-\beta)+4\theta(1-c_N)-\delta(1+\theta-c_N)-2\theta^2}{4\theta-\delta}$.

(2) Thresholds of Proposition C-2.

$$t_{rL}^L = \frac{-2\Delta+2\delta\Delta+c_{OR}-\theta c_{OR}-2t_r+2\delta t_r}{-2+2\delta}, \beta^L = \frac{-2\Delta+2\delta\Delta-2t_r+2\delta t_r+2t_{rL}-2\delta t_{rL}}{-c_{OR}+\theta c_{OR}}$$

$$\beta^P = \frac{(1-\delta)(2\Delta+\theta)-2(1-\delta)c_{MR}-(\delta-\theta)c_N+(1-\theta)c_{OR}+\theta e_N t_e-\delta(t_e-2t_{rL})-2t_{rL}}{(1-\theta)c_{OR}}$$

(3) Thresholds of Proposition C-3

$$\beta^{M1} = \frac{c_{OR}-\delta(c_N+t_e)}{c_{OR}}, t_{rL}^{M1} = \frac{1}{2}(2\Delta+\theta-2c_{MR}+\frac{\theta(-(-1+\beta)(-4+\theta)c_{OR}+3\delta(c_N+t_e))}{\delta(-1+\theta)}),$$

$$t_{rL}^{M2} = \frac{(1-\delta)(2\Delta+\theta)-2(1-\delta)c_{MR}-(\delta-\theta)c_N-(1-\beta)(-1+\theta)c_{OR}-\delta e_N t_e + \theta t_e}{2(1-\delta)}.$$

(4) Thresholds of Proposition C-4

$$t_{rL}^{Q1} = \frac{1}{2}(2\Delta + \theta - 2c_{MR} + \frac{\delta(\delta-\theta)(-1+\theta)c_N+(\delta+\beta(-4+\theta)\theta+\delta\theta(-2+4\beta+\theta-\beta\theta))c_{OR}+\delta(\delta-\theta)(-1+\theta)t_e}{(1-\delta)\delta(1-\theta)}),$$

$$\beta^{Q1} = \frac{2\delta(1-\theta)(\Delta+t_r-t_{rL})}{(4-\theta)\theta c_{OR}}, \beta^{Q2} = \frac{2(1-\delta)(\Delta+t_r-t_{rL})}{(1-\theta)c_{OR}}.$$

(5) Thresholds of Proposition 5

Given $t_e \geq \tilde{t}_e^{i1}$ ($i \in \{N, A, L\}$), the consumers surplus in the three scenarios are as following:

$$CS_R^N = \frac{\delta - \delta^2 + \delta c_N^2 + c_{OR}^2 - 2\delta(1-\delta+c_{OR})t_e + \delta t_e^2 - 2\delta c_N(1-\delta+c_{OR}-t_e)}{8(1-\delta)\delta}, \quad CS_R^A =$$

$$\frac{1}{8\delta(\delta+2\delta\theta+(-4+\theta)\theta)^2} (\delta(4\theta^2(4+\theta-\theta^2) + \delta^2(1+\theta(4+\theta)(1+2\theta)) + \delta\theta(-8+\theta(-19+5(-2+\theta)\theta))) - 4(-1+\delta)\delta((4-3\theta)\theta + \delta(-3+2\theta))c_{MR}^2 + \delta(\delta^2(1-6\theta) + 4(4-3\theta)\theta^2 + \delta\theta(-8+9\theta))c_N^2 - 6\delta^2\theta c_{OR} + 8\delta\theta^2 c_{OR} + 10\delta^2\theta^2 c_{OR} - 14\delta\theta^3 c_{OR} -$$

$$4\delta^2\theta^3 c_{OR} + 6\delta\theta^4 c_{OR} - 12\delta\theta c_{OR}^2 + 16\theta^2 c_{OR}^2 + 9\delta\theta^2 c_{OR}^2 - 8\theta^3 c_{OR}^2 - 6\delta\theta^3 c_{OR}^2 + \theta^4 c_{OR}^2 - 2\delta^3 t_e + 16\delta^2\theta t_e - 2\delta^3\theta t_e - 32\delta\theta^2 t_e + 14\delta^2\theta^2 t_e - 12\delta^3\theta^2 t_e + 24\delta\theta^3 t_e + 2\delta^2\theta^3 t_e -$$

$$8\delta\theta^4 t_e + 22\delta^2\theta c_{OR} t_e - 40\delta\theta^2 c_{OR} t_e - 4\delta^2\theta^2 c_{OR} t_e + 22\delta\theta^3 c_{OR} t_e + \delta^3 t_e^2 - 8\delta^2\theta t_e^2 - 6\delta^3\theta t_e^2 + 16\delta\theta^2 t_e^2 + 9\delta^2\theta^2 t_e^2 - 12\delta\theta^3 t_e^2 + 8\delta(-2(-1+\delta)\theta(\delta + (-2+\theta)\theta) + (-\theta^2 + \delta(-1+2\theta))((-1+\theta)c_{OR} + (\delta-\theta)t_e))t_r - 4(-1+\delta)\delta((4-3\theta)\theta + \delta(-3+2\theta))t_r^2 +$$

$$8\delta c_{MR}(-2(-1+\delta)\theta(\delta + (-2+\theta)\theta) + (-\theta^2 + \delta(-1+2\theta))((\delta-\theta)c_N + (-1+\theta)c_{OR} + (\delta-\theta)t_e) - (-1+\delta)((4-3\theta)\theta + \delta(-3+2\theta))t_r) - 2\delta c_N(4\theta^2(4+(-3+\theta)\theta) + \delta^2(1+\theta+6\theta^2) - \delta\theta(8+\theta(7+\theta)) + \theta((20-11\theta)\theta + \delta(-11+2\theta))c_{OR} +$$

$$(\delta(8-9\theta)\theta + 4\theta^2(-4+3\theta) + \delta^2(-1+6\theta))t_e - 4(\delta-\theta)(-\theta^2 + \delta(-1+2\theta))t_r)) \quad ,$$

$$\text{and } CS_R^L = \frac{1}{8\delta(\delta+2\delta\theta+(-4+\theta)\theta)^2} (\delta(\delta(\delta+12(-1+\delta)\Delta^2) + 4((-2+\delta)\delta + 4(-1+\delta)\delta\Delta - 2(-2+\delta+\delta^2)\Delta^2)\theta + (16+9\delta^2+4(8-3\Delta)\Delta + \delta(1+2\Delta)(-19+6\Delta))\theta^2 + 2(2-8\Delta + \delta(-5+\delta+8\Delta))\theta^3 + (-4+5\delta)\theta^4) - 4(-1+\delta)\delta((4-3\theta)\theta + \delta(-3+2\theta))c_{MR}^2 + \delta(\delta^2(1-6\theta) + 4(4-3\theta)\theta^2 + \delta\theta(-8+9\theta))c_N^2 + (-1+\beta)^2\theta((-4+\theta)^2\theta - 3\delta(4+\theta(-3+2\theta)))c_{OR}^2 - 2\delta(4\theta^2(4+\theta(-3+\Delta+\theta)) - \delta\theta(8+\theta(7+\theta) +$$

$$\begin{aligned}
& 4\Delta(-1+3\theta)) + \delta^2(1+\theta+6\theta^2+\Delta(-4+8\theta)))t_e + 2\delta c_{OR}((-1+\beta)(-1+ \\
& \theta)(-4\delta\Delta + \delta(-3+8\Delta)\theta + 2(2+\delta-2\Delta)\theta^2 - 3\theta^3) + \theta(-11(-1+\beta)\delta - 2(10- \\
& 10\beta+\delta)\theta)t_e) + 4\beta\delta^2\theta^2 c_{OR}t_e + 22\delta\theta^3 c_{OR}t_e - 22\beta\delta\theta^3 c_{OR}t_e + \delta^3 t_e^2 - 8\delta^2\theta t_e^2 - \\
& 6\delta^3\theta t_e^2 + 16\delta\theta^2 t_e^2 + 9\delta^2\theta^2 t_e^2 - 12\delta\theta^3 t_e^2 + 8\delta((-1+\delta)(-3\delta\Delta + 2\delta(-1+\Delta)\theta + \\
& \theta(\Delta(4-3\theta) - 2(-2+\theta)\theta)) + (-\theta^2 + \delta(-1+2\theta))((-1+\beta+\theta-\beta\theta)c_{OR} + (\delta- \\
& \theta)e_N t_e))t_{rL} - 4(-1+\delta)\delta((4-3\theta)\theta + \delta(-3+2\theta))t_{rL}^2 + 8\delta c_{MR}((-1+\delta)(-3\delta\Delta + \\
& 2\delta(-1+\Delta)\theta + \theta(\Delta(4-3\theta) - 2(-2+\theta)\theta)) + (-\theta^2 + \delta(-1+2\theta))((\delta-\theta)c_N - \\
& (-1+\beta)(-1+\theta)c_{OR} + (\delta-\theta)t_e) - (-1+\delta)((4-3\theta)\theta + \delta(-3+2\theta))t_{rL}) - \\
& 2\delta c_N(4\theta^2(4+\theta(-3+\Delta+\theta)) - \delta\theta(8+\theta(7+\theta) + 4\Delta(-1+3\theta)) + \delta^2(1+\theta+6\theta^2+ \\
& \Delta(-4+8\theta)) + (-1+\beta)\theta(11\delta - 2(10+\delta)\theta + 11\theta^2)c_{OR} + (\delta(8-9\theta)\theta + 4\theta^2(-4+ \\
& 3\theta) + \delta^2(-1+6\theta))t_e - 4(\delta-\theta)(-\theta^2 + \delta(-1+2\theta))t_{rL})).
\end{aligned}$$

The relevant thresholds expressions in Proposition C-5 are: $t_e^{CS1} =$

$$\begin{aligned}
& -\frac{1}{\delta(\delta-\theta)^2(-\theta(4+\theta)+\delta(-1+6\theta))}(-\delta((-1+\delta)(\delta-\theta)(-4\delta\Delta + \delta(-3+8\Delta)\theta + 2(2+\delta- \\
& 2\Delta)\theta^2 - 3\theta^3) - 4(-1+\delta)(\delta-\theta)(-\theta^2 + \delta(-1+2\theta))c_{MR} + (\delta-\theta)^2(-\theta(4+\theta) + \\
& \delta(-1+6\theta))c_N + (\delta^2 + (3+11\beta(-1+\delta) - 7\delta)\delta\theta - 2(2+\beta(-1+\delta)(10+\delta) - \\
& \delta(2+3\delta))\theta^2 + (3+11\beta(-1+\delta) - 7\delta)\theta^3 + \theta^4)c_{OR} - 4(-1+\delta)(\delta-\theta)(-\theta^2 + \\
& \delta(-1+2\theta))t_{rL}) + \sqrt{((-1+\delta)\delta(\delta+2\delta\theta + (-4+\theta)\theta)^2(4(-1+\delta)\delta(\delta-\theta)^2 c_{MR}^2 - \\
& \beta\theta((-2+\beta)\theta^2(4+\theta) + \delta\theta(6+\beta(17-18\theta) + 14\theta) + 2\delta^2(1-6\theta+\beta(-6+ \\
& 4\theta)))c_{OR}^2 - 8\delta(\delta-\theta)c_{MR}(-\beta(\delta-2\delta\theta+\theta^2)c_{OR} + (-1+\delta)(\delta-\theta)(\Delta+\theta-t_{rL})) + \\
& 4(-1+\delta)\delta(\delta-\theta)^2(\Delta+\theta-t_{rL})^2 + 2\beta\delta(\delta-\theta)c_{OR}((4-4\Delta-3\theta)\theta^2 + \delta\theta(-3+ \\
& 2\theta) + \delta\Delta(-4+8\theta) + 4(\delta-2\delta\theta+\theta^2)t_{rL})))},
\end{aligned}$$

$$\begin{aligned}
& t_e^{CS2} = -\frac{1}{\delta(\delta-\theta)^2(-\theta(4+\theta)+\delta(-1+6\theta))}(\delta((-1+\delta)(\delta-\theta)(-4\delta\Delta + \delta(-3+8\Delta)\theta + \\
& 2(2+\delta-2\Delta)\theta^2 - 3\theta^3) - 4(-1+\delta)(\delta-\theta)(-\theta^2 + \delta(-1+2\theta))c_{MR} + (\delta- \\
& \theta)^2(-\theta(4+\theta) + \delta(-1+6\theta))c_N + (\delta^2 + (3+11\beta(-1+\delta) - 7\delta)\delta\theta - 2(2+\beta(-1+ \\
& \delta)(10+\delta) - \delta(2+3\delta))\theta^2 + (3+11\beta(-1+\delta) - 7\delta)\theta^3 + \theta^4)c_{OR} - 4(-1+\delta)(\delta- \\
& \theta)(-\theta^2 + \delta(-1+2\theta))t_{rL}) + \sqrt{((-1+\delta)\delta(\delta+2\delta\theta + (-4+\theta)\theta)^2(4(-1+ \\
& \delta)\delta(\delta-\theta)^2 c_{MR}^2 - \beta\theta((-2+\beta)\theta^2(4+\theta) + \delta\theta(6+\beta(17-18\theta) + 14\theta) + 2\delta^2(1- \\
& 6\theta+\beta(-6+4\theta)))c_{OR}^2 - 8\delta(\delta-\theta)c_{MR}(-\beta(\delta-2\delta\theta+\theta^2)c_{OR} + (-1+\delta)(\delta-\theta)(\Delta+ \\
& \theta-t_{rL})) + 4(-1+\delta)\delta(\delta-\theta)^2(\Delta+\theta-t_{rL})^2 + 2\beta\delta(\delta-\theta)c_{OR}((4-4\Delta-3\theta)\theta^2 + \delta\theta(-3+ \\
& 2\theta) + \delta\Delta(-4+8\theta) + 4(\delta-2\delta\theta+\theta^2)t_{rL})))},
\end{aligned}$$

$$\theta - t_{rL})) + 4(-1 + \delta)\delta(\delta - \theta)^2(\Delta + \theta - t_{rL})^2 + 2\beta\delta(\delta - \theta)c_{OR}((4 - 4\Delta - 3\theta)\theta^2 + \delta\theta(-3 + 2\theta) + \delta\Delta(-4 + 8\theta) + 4(\delta - 2\delta\theta + \theta^2)t_{rL}))).$$

$$\begin{aligned} \beta^{CS1} &= \frac{4(\theta - \delta)(-\theta^2 + \delta(-1 + 2\theta))(\Delta + t_r - t_{rL})}{\theta(11\delta - 2(10 + \delta)\theta + 11\theta^2)c_{OR}}, \quad t_e^{CS3} = (4(-1 + \delta)\delta\Delta(3\delta\Delta + 4\delta\theta - \\ &2(2 + \delta)\Delta\theta + (-8 + 3\Delta)\theta^2 + 4\theta^3) - \left((-2 + \beta)\beta\theta \left(-(-4 + \theta)^2\theta + 3\delta(4 + \right. \right. \\ &\left. \left. \theta(-3 + 2\theta)) \right) c_{OR}^2 \right) + 2\delta(-1 + \theta)c_{OR}((4\Delta + \beta(4 - 4\Delta - 3\theta))\theta^2 + \delta(\beta\theta(-3 + 2\theta) + \\ &4(-1 + \beta)\Delta(-1 + 2\theta)) + 4(\delta - 2\delta\theta + \theta^2)t_r) + 4(-1 + \delta)\delta t_r(4\theta(\delta + (-2 + \theta)\theta) + \\ &((4 - 3\theta)\theta + \delta(-3 + 2\theta))t_r) + 8\delta c_{MR}(\beta(-1 + \theta)(\delta - 2\delta\theta + \theta^2)c_{OR} + (-1 + \\ &\delta)(-3\delta + 2(2 + \delta)\theta - 3\theta^2)(\Delta + t_r - t_{rL})) + 2\delta c_N(\beta\theta(-11\delta + 2(10 + \delta)\theta - \\ &11\theta^2)c_{OR} - 4(\delta - \theta)(-\delta + 2\delta\theta - \theta^2)(\Delta + t_r - t_{rL})) + 8\delta((-1 + \delta)(-3\delta\Delta + 2\delta(-1 + \\ &\Delta)\theta + \theta(\Delta(4 - 3\theta) - 2(-2 + \theta)\theta)) + (-1 + \beta)(-1 + \theta)(\delta - 2\delta\theta + \theta^2)c_{OR})t_{rL} - \\ &4(-1 + \delta)\delta((4 - 3\theta)\theta + \delta(-3 + 2\theta))t_{rL}^2)/(2\delta(\beta\theta(11\delta - 2(10 + \delta)\theta + 11\theta^2)c_{OR} + \\ &4(\delta - \theta)(-\theta^2 + \delta(-1 + 2\theta))(\Delta + t_r - t_{rL}))). \end{aligned}$$

(6) Thresholds of Proposition C-9

$$\begin{aligned} \epsilon_1^P &= \frac{\delta^2 + 2\delta(-3 + 2\delta)\theta + (8 - 7\delta)\theta^2 + (\delta + 4\theta)(3(-1 + \delta)c_{MR} + (-\delta + \theta)c_N) + (12 - 7\delta - 5\theta)\theta c_{OR}}{(\delta - \theta)(\delta + 4\theta)} \quad \text{and} \quad \epsilon_2^P = \\ &\frac{\delta(\delta - 2\alpha(1 + \delta) + \Delta - \delta\Delta) + 2(4\alpha - (2 - \delta)\delta - 2(1 - \delta)\Delta)\theta - (4\alpha - \delta)\theta^2 - (\delta - 4\theta)((1 - \delta)c_{MR} + (\delta - \theta)c_N) - 3(1 - \beta)(\delta - \theta)\theta c_{OR}}{(\delta - 4\theta)(\delta - \theta)}. \end{aligned}$$

Appendix C-4. Proof of Proposition C-6 and C-7

We use backward induction to solve policymaking problems in Scenario A and Scenario L, i.e., Eqs. (C-4) and (C-5).

Proof of Proposition C-6. The policymaking problem in Scenario A is shown in Eq. (4-4). We first substitute the optimal solutions shown in Table 5.2 into Eq. (4-4). From $\frac{\partial^2 SW^A}{\partial t_e^2} = \frac{-4(12 - \theta)\theta^2 - \delta^2(3 + 14\theta) + \delta\theta(24 + 37\theta)}{4(\delta + 2\delta\theta - (4 - \theta)\theta)^2} < 0$ and the Hessian matrix (H) of $SW^A(t_e, t_r)$ ($\frac{28\theta(1 - \delta) + 3(\theta - \delta) + \theta - \delta^2 + 4\theta(1 - \theta)}{4(\delta + 2\delta\theta + (4 - \theta)\theta)^2} > 0$), we know that $SW^A(t_e, t_r)$ is jointly concave in t_e and t_r . Meanwhile, the policymaking problem is characterized by Karush-Kuhn-Tucker (KKT) condition. Let g denote the Lagrangian multiplier, then we have the Lagrangian function of

the policymaking problem as follows:

$$L(t_e, t_r, g) = CS^A + t_e q_N^{A*} + t_r q_{MR}^{A*} - \epsilon q_N^{A*} + g(t_e - \tilde{t}_e^{A1}) \quad (C-1)$$

With the first conditions $\frac{\partial L(t_e, t_r, g)}{t_e} = 0$, $\frac{\partial L(t_e, t_r, g)}{t_r} = 0$, and the constraint $g(t_e - \tilde{t}_e^{A1}) =$

0, we have the following cases:

Case PA1: when $g > 0$ and $t_e - \tilde{t}_e^{A1} = 0$, solving Eq. (C-1) and the first conditions simultaneously yields: $t_e^* = \underline{t}_e^A$, $t_r^* = (\delta - 2\theta(2 + \theta) + \delta\theta(2 + 3\theta) + 6(1 - \delta)\theta c_{MR} + (4\theta - \delta)(1 - \theta)c_N 3 - (1 - \theta)\theta c_{OR} - 2\delta\epsilon - 2\epsilon\theta(-4 + 2\delta + \theta) + (\delta + 5\delta\theta - 2\theta(2 + \theta))t_e)/(2\theta(-11 + 2\theta) + 2\delta(2 + 7\theta))$, and $g^* = \frac{3\theta(\delta(\delta(-1 + \epsilon - 3\theta) + 2\theta(1 + 5\epsilon + \theta) - 2(-3 + \delta + 2\theta)c_{MR} + (\delta + 10\theta)c_N) + (5\delta + 2(-9 + \theta))\theta c_{OR})}{2\delta(3 + 8\theta)(\delta + 2\delta\theta + (-4 + \theta)\theta)}$, where $\underline{t}_e^A = \frac{\delta((3 - 2\theta)\theta - 1) + (\delta - 10\delta\theta)c_N + (11 - 2\theta)\theta c_{OR} + 2\delta(1 - \theta)(\epsilon - 2c_{MR})}{\delta(1 + 8\theta)}$. Let $g^* > 0$, we get $\epsilon \leq \bar{\epsilon}_1^A$, where $\bar{\epsilon}_1^A = \frac{\delta(\delta + 3\delta\theta + 2(-3 + \theta)\theta + 2(1 + \delta - 2\theta)c_{MR} - (\delta - 10\theta)c_N) + \theta(-6 - 5\delta + 2\theta)c_{OR}}{\delta(\delta - 10\theta)}$. Substituting t_e^* and t_r^* into the OME's optimal remanufacturing quantity, we get $q_{OR} = 0$. Therefore, when $\epsilon \leq \bar{\epsilon}_1^A$, the government cannot simultaneously reach the targets of ensuring the local OEM engages in remanufacturing and maximizing the utility. To ensure the local OEM engages in remanufacturing, $t_e^{A*} > \underline{t}_e^A$, $t_r^{A*} = \frac{\theta(11\delta - 2(6 + \theta))}{2\theta(-13 + 2\theta) + 2\delta(2 + 9\theta)} t_e^{A*} + \frac{2(2 - \delta)(1 + 2\epsilon)\theta - \delta(1 + 2\epsilon) + (5\delta - 2(3 + \epsilon))\theta^2 + 10(1 - \delta)\theta c_{MR} + (\delta + 7\delta\theta - 4\theta(1 + \theta))c_N - 5(1 - \theta)\theta c_{OR} + 3\delta t_e}{2\theta(-13 + 2\theta) + 2\delta(2 + 9\theta)}$.

Case PA2: when $g = 0$ and $t_e - \tilde{t}_e^{A1} > 0$, solving Eq. (C-1) and the first conditions simultaneously yields: $t_r^* = \frac{(\theta - \delta)((4\theta - \delta)(c_N + \epsilon) - 3\theta c_{OR}) - \delta(\delta + 2\delta\theta - (4 - \theta)\theta) - (1 - \delta)(4\theta - \delta)c_{MR}}{4(3 - \theta)\theta - \delta(3 + 4\theta) - \delta^2}$ and $t_e^* = \frac{(1 - \delta)(4(-3 + \theta)\theta + \delta(3 + 5\theta) + 4(\delta - \theta)c_{MR} - 3(\delta - 4\theta)c_N - 9\theta c_{OR}) - 2\epsilon(\delta^2 - 2(-6 + \theta)\theta - \delta(3 + 8\theta))}{(\delta^2 + 4(-3 + \theta)\theta + \delta(3 + 4\theta))}$. Let $t_e^* > \tilde{t}_e^{A1}$, we get $\epsilon > \bar{\epsilon}_1^A$. The optimal remanufacturing and production quantities are: $q_{OR}^{A*} = \frac{-\delta(\delta + 3\delta\theta + 2(-3 + \theta)\theta) - 2\delta(1 + \delta - 2\theta)c_{MR} + \delta(\delta - 10\theta)c_N + (6 + 5\delta - 2\theta)\theta c_{OR} + \delta\epsilon(\delta - 10\theta)e_N}{\delta(\delta^2 + 4(-3 + \theta)\theta + \delta(3 + 4\theta))}$, $q_{MR}^{A*} = \frac{(-1 + \delta)\delta - 4(-1 + \delta)c_{MR} + 4(\delta - \theta)c_N - (3 + \delta - 4\theta)c_{OR} + 4\epsilon(\delta - \theta)}{\delta^2 + 4(-3 + \theta)\theta + \delta(3 + 4\theta)}$ and $q_N^{A*} = \frac{4(-3 + \theta)\theta + \delta(3 + 5\theta) + 4(\delta - \theta)c_{MR} - 3((\delta - 4\theta)c_N + 3\theta c_{OR} + \epsilon(\delta - 4\theta))}{\delta^2 + 4(-3 + \theta)\theta + \delta(3 + 4\theta)}$. Let $q_N^{A*} > 0$ and $q_{MR}^{A*} > 0$, we get

$$c_{OR} > \frac{1}{3}(3\delta - 4\theta + 4c_{MR}) \quad \text{and} \quad \bar{\epsilon}_2^A < \epsilon < \bar{\epsilon}_3^A, \quad \text{where} \quad \bar{\epsilon}_2^A =$$

$$\frac{(1-\delta)\delta+4(-1+\delta)c_{MR}-4(\delta-\theta)c_N+(3+\delta-4\theta)c_{OR}}{4(\delta-\theta)}$$

and

$$\bar{\epsilon}_3^A =$$

$$\frac{\delta(3+5\theta)-4(3-\theta)\theta+4(\delta-\theta)c_{MR}-3(\delta-4\theta)c_N-9\theta c_{OR}}{3(\delta-4\theta)}.$$

Proof of Proposition C-7. The policymaking problem in Scenario L is shown in Eq. (4-5). Following the same optimization approach used in Proof of Proposition C-7, we directly present the optimal value of t_e and t_{RL} as follows:

Case PL1: when $\epsilon \leq \bar{\epsilon}_1^L$, the government cannot simultaneously reach the targets of ensuring the local OEM engages in remanufacturing and maximizing the utility. To ensure the local OEM engages in remanufacturing, $t_e^{L*} > \underline{t}_e^L$, where $\underline{t}_e^L = \frac{\delta(1-\theta)(4(a+\Delta-c_{MR})+2(\theta+\epsilon e_N)-1)-(10\delta\theta-\delta)c_N+(1-\beta)\theta(11-2\theta)c_{OR}}{\delta(1+8\theta)}$. Additionally, $t_{rL}^{L*} = \frac{(4\theta-\delta)(1-4a-2\epsilon-(1-\theta)c_N)-6\theta(1-\delta)(c_{MR}-\Delta)+3\theta c_{OR}(1-\beta)(1-\theta)+2\theta(\theta-\delta)+(4a\theta+2\epsilon\theta)(2\delta+\theta)-3\delta\theta^2}{2\theta(11-2\theta)-2\delta(2+7\theta)} + \frac{(2\theta(2+\theta)-\delta(1+5\theta))}{2\theta(11-2\theta)-2\delta(2+7\theta)} t_e^{L*}.$

Case PL2: When $\epsilon > \bar{\epsilon}_1^L$, $t_e^{L*} = \frac{((3\delta-12\theta)(1-c_N)+4(a+\theta-c_{MR}+\Delta)(\theta-\delta)+9\theta(\delta-c_{OR}(1-\beta))-2\epsilon(\delta-8\theta))(1-\delta)+4\epsilon(\theta-\delta)+4\epsilon\theta(1-\theta)}{4\theta(3-\delta)-\delta(3+\delta)-4\theta^2}$, $t_{rL}^{L*} = \frac{(\delta+(1-\delta)(\Delta-c_{MR})-2a)(4\theta-\delta)-3\theta c_{OR}(1-\beta)(\theta-\delta)+4\theta^2(a+c_N+\epsilon)-5\delta\theta(c_N+\epsilon)+\delta^2(2a-2\theta+c_N+\epsilon)-\delta\theta^2}{4\theta(3-\delta)-\delta(3+\delta)-4\theta^2}$, $q_N^{A*} = \frac{4\theta(-3+a+\Delta+\theta)+\delta(3-4a-4\Delta+5\theta)+4(\delta-\theta)c_{MR}-3(\delta-4\theta)c_N+9(-1+\beta)\theta c_{OR}-3\epsilon(\delta-4\theta)}{\delta^2+4(-3+\theta)\theta+\delta(3+4\theta)}$, $q_{MR}^{A*} = \frac{(-1+\delta)(4a+\delta+4\Delta)-4(-1+\delta)c_{MR}+4(\delta-\theta)c_N+(-1+\beta)(3+\delta-4\theta)c_{OR}+4\epsilon(\delta-\theta)e_N}{\delta^2+4(-3+\theta)\theta+\delta(3+4\theta)}$, and $q_{OR}^{A*} = \frac{1}{\delta(\delta^2+4(-3+\theta)\theta+\delta(3+4\theta))}(\delta(\delta(-1+2\Delta-3\theta)+2a(1+\delta-2\theta)-2\theta(2\Delta+\theta)+2(\Delta+3\theta))-2\delta(1+\delta-2\theta)c_{MR}+\delta(\delta-10\theta)c_N+(-1+\beta)\theta(-6-5\delta+2\theta)c_{OR}+\delta\epsilon(\delta-10\theta))$. Let $q_N^{A*} > 0$ and $q_{MR}^{A*} > 0$, we get $\Delta > \frac{1}{4}(-4a+3\delta-4\theta+4c_{MR}-3c_{OR}+3\beta c_{OR})$ and $\bar{\epsilon}_L^2 < \epsilon < \bar{\epsilon}_L^3$, where $\bar{\epsilon}_L^2 = \frac{(-1+\delta)(4a+\delta+4\Delta)-4(-1+\delta)c_{MR}+4(\delta-\theta)c_N+(-1+\beta)(3+\delta-4\theta)c_{OR}}{4(\theta-\delta)}$ and $\bar{\epsilon}_L^3 = \frac{4\theta(-3+a+\Delta+\theta)+\delta(3-4a-4\Delta+5\theta)+4(\delta-\theta)c_{MR}-3(\delta-4\theta)c_N+9(-1+\beta)\theta c_{OR}}{3(\delta-4\theta)}.$

The proof is completed.

6. Conclusions

6.1 Conclusion

As a key activity in CLSCs, remanufacturing delivers significant benefits — including reducing waste, cutting costs, and enhancing environmental protection — by restoring used products to near-new condition through component replacement or reprocessing. It has attracted widespread attention from industry, government, and academia. However, one commonly occurring yet often overlooked factor in remanufacturing systems is the presence of multiple spillover effects — externalities arising from the non-contractual spread of resources, particularly knowledge and technology, between firms ([Kohpaiboon, 2006](#); [Crespo and Fontoura, 2007](#)). These effects are significant because they drive innovation, improve cost efficiencies, and reshape competitive dynamics. Moreover, government policies impose regulatory pressures that further influence firms' production, remanufacturing, and coopetition decisions. Accordingly, this dissertation investigates how these multiple spillovers interact with policy interventions and cost structures to shape firms' production (e.g., new product production and remanufacturing) and coopetition strategies in remanufacturing systems. Through three distinct but interrelated studies examining interactions between an OEM and a TPR (or an MNR), this dissertation reveals the mechanisms by which firms optimize their decision-making in three key areas: production and coopetition, used product management outsourcing and product recovery strategies, and remanufacturing location decisions. In doing so, this dissertation provides valuable managerial insights for firms aiming to optimize profitability, mitigate market cannibalization, and respond to government policies. It also offers policy guidance for regulators seeking to promote more sustainable industrial operations.

Study 1 investigates the role of knowledge spillovers — both general and innovation-related — in shaping the decisions of an OEM and a TPR within a remanufacturing system. General knowledge spillovers occur during the remanufacturing of the OEM's used products and enable the TPR to expand into new product production. This intensifies market competition and may cannibalize both the TPR's remanufactured products and the OEM's

new offerings. In contrast, innovation spillovers — facilitated through remanufacturing authorization cooperation — enhance the TPR's capacity to produce more innovative products, thereby posing a further challenge to the OEM's market position. Nevertheless, remanufacturing authorization cooperation generates benefits for the OEM: he can offset profit losses through authorization fees. To explore the two firms' decisions, game-theoretic models are developed to capture the firms' strategic choices under competition and cooperation scenarios. By analytically solving these models, this study examines how the OEM and TPR determine production quantities (of new and remanufactured products) and choose between pure competition and coopetition strategies. The results reveal that under conditions such as moderate remanufacturing costs and relatively high fixed authorization fees, coopetition outperforms pure competition by yielding higher profits for both firms. The results also prove that coopetition benefits consumers and reduces negative environmental impacts under certain conditions. For example, when the unit authorization fee in coopetition is low, consumer surplus increases; when the emissions from remanufacturing a used product are low, the negative environmental impact decreases. These findings underscore the critical importance of strategic knowledge sharing and cooperation in mitigating competitive threats and maximizing the economic benefits of remanufacturing.

Study 2 examines how environmental policies — emission taxes and waste management regulations — influence used product management outsourcing and production decisions in a CLSC. This supply chain consists of an OEM and a TPR. In handling used products sold by the OEM, he must either pay waste management taxes or outsource used product management to the TPR, who recovers used products by remanufacturing or recovering materials. Furthermore, the TPR may produce new products using recovered materials. Because both firms sell products in the same market, market cannibalization occurs. To analyze the OEM's used product management outsourcing strategy and the TPR's used product recovery and production strategies, this study uses analytical models to describe the two firms' decision-making problems in three scenarios: (i) no outsourcing, (ii) outsourcing without the TPR's new product production, and (iii) outsourcing with the TPR's new product production. The analysis shows that these policies compel the OEM to weigh the costs of

waste management taxes against outsourcing used product management to the TPR, with the latter often emerging as a cost-effective alternative despite the risk of market cannibalization from the TPR's remanufactured and new products. Specifically, the OEM is more likely to outsource used product management when waste management taxes are moderate. Similarly, for the TPR, the decision to prioritize remanufacturing, material recovery, or new product production depends on balancing used product management outsourcing revenues, emission tax burdens, and market competition dynamics. The TPR opts for new product production when waste management taxes are either high or low. Notably, the introduction of the TPR's new products can encourage the OEM's outsourcing when emission taxes are low and waste management taxes are moderate.

Study 3 shifts focus to a global supply chain context. It examines how government policies and technology spillovers influence remanufacturing strategies. In the supply chain considered, a local OEM is subject to environmental taxes on new products and may consider engaging in remanufacturing. Meanwhile, an MNR faces two strategic options: exporting remanufactured products to the domestic market or establishing a local remanufacturing center. When the MNR chooses to establish a local remanufacturing center, she benefits from lower labor and logistics costs and exemption from import tariffs. However, it also incurs domestic taxes and generates technology spillovers that reduce the local OEM's remanufacturing costs by enhancing his remanufacturing capability. To guide the two firms' decision-making, game-theoretic models are developed to capture the strategic interactions between the OEM and the MNR under the two location scenarios: Scenario A where the MNR exports remanufactured products and Scenario L where the MNR establishes local remanufacturing centers. The results show that the local OEM is more likely to engage in remanufacturing when environmental taxes on new products are high. Whether or not the MNR establishes a local remanufacturing center depends on the trade-off between tariff levels and the extent of technology spillovers. Moderate tariffs combined with limited spillovers tend to make local production more attractive, whereas high tariffs or significant spillovers shift the preference toward exporting.

6.2 Contributions

This dissertation makes several contributions to theoretical and practical domains. On the theoretical side, first, **Studies 1 and 2** introduce the strategic implications of TPRs' engagement in new product production — an issue largely overlooked in prior literature, which has mainly focused on competition between OEMs' new and/or remanufactured products and TPRs' remanufactured offerings. Second, **Studies 1 and 3** incorporate the role of spillover effects in remanufacturing systems, including knowledge spillovers arising from authorization-based cooperation between OEMs and TPRs, and technology spillovers resulting from MNRs' FDI in local remanufacturing. To the best of the author's knowledge, such spillover mechanisms have not been formally modeled in the existing remanufacturing literature. Third, by integrating endogenous production, used product recovery, and location decisions with spillover dynamics and environmental policy interventions, this dissertation develops a more comprehensive analytical framework for strategic interaction in CLSCs.

On the practical side, this dissertation provides decision-making insights for firms in CLSCs to optimize decisions in new product production, remanufacturing, and coopetition. It also guides policymakers in policy design. The managerial implications of each study are detailed as follows:

Study 1 offers a practical framework for OEMs and TPRs to manage production, remanufacturing, and coopetition in remanufacturing settings where knowledge spillovers are present. For TPRs, remanufacturing serves as both a revenue source and a learning opportunity that enables them to expand into new product production. The study identifies cost thresholds under which TPRs should focus on remanufacturing, switch to new products, or adopt a mixed strategy. It also shows that engaging in authorization cooperation with OEMs can enhance remanufacturing quality and facilitate access to innovation. For OEMs, simply deterring TPRs is not always optimal. Instead, offering remanufacturing authorization at an appropriate fee enables them to share profits with TPRs. The study provides guidance on setting such fees to balance new product profits and authorization revenue.

Study 2 helps OEMs decide whether to outsource used product management, and assists

TPRs in choosing outsourcing fees and recovery strategies, as well as determining whether or not to use recovered materials to produce new products. OEMs are advised to weigh waste management taxes, outsourcing costs, and market risks from TPRs' self-branded products. Specifically, when waste management taxes are moderate, OEMs should outsource if TPRs do not produce their own new products. If they do, outsourcing is discouraged, especially when emission taxes are low. For TPRs, the study outlines how to select between remanufacturing and material recovery based on collection costs and tax conditions, and when to reuse recovered materials for new products. It also clarifies under what conditions TPRs should end cooperation with OEMs.

Study 3 provides strategic recommendations for OEMs and MNRs on adjusting production and location decisions under policy changes, and offers policymakers actionable guidance on tax and tariff design. OEMs are encouraged to adopt remanufacturing when environmental taxes on new products are high, and to adjust remanufacturing levels based on MNRs' market entry modes. In particular, when an MNR exports remanufactured products, OEMs should reduce their remanufacturing output. Conversely, when the MNR builds a local facility, OEMs should increase their own remanufacturing, especially when MNR products face high environmental taxes. For MNRs, the study advises localization when technology spillovers are low and tax incentives are favorable. For policymakers, the results suggest that well-calibrated environmental taxes and import policies can support remanufacturing while preserving market balance. The study also offers criteria for adjusting tax levels to align environmental and economic goals.

6.3 Limitations and future research

Despite its contributions, this dissertation has several limitations that suggest promising directions for future research. **First**, all models developed in this dissertation rely on the assumption of complete information. That is, all parties are assumed to have full knowledge of cost structures, demand functions, and policy parameters. In practice, however, firms often operate under information asymmetry and uncertainty — such as fluctuating product quality, shifting market demand, or unpredictable policy implementation. Future studies could

incorporate information asymmetry and stochastic elements to more realistically reflect the decision-making environment and identify robust strategies under uncertainty. **Second**, this dissertation assumes that fees — the authorization fee in the first study and the outsourcing fee in the second study — are determined unilaterally by a single firm. In reality, such fees can be determined by negotiation. Future research could examine bilateral or multilateral fee-setting processes and assess how negotiated agreements affect firm strategies and system-level outcomes. **Third**, the current framework assumes a static consumer market and does not consider strategic purchasing behavior. In the real world, consumers may delay purchases in anticipation of future price reductions. Incorporating dynamic consumer expectations and waiting strategies would allow for a richer analysis of price–demand interactions and their implications for firm behavior in remanufacturing markets. **Finally**, the models treat spillover effects as exogenous, whereas in reality, firms may actively manage knowledge flows — for example, through intellectual property protections or restricted information sharing — to maintain competitive advantage. Future research can incorporate these counteractive behaviors to better understand how they affect firms’ production and competition strategies, as well as the overall performance of CLSCs.

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List of Abbreviations

CLSC	Closed-loop supply chain
CM	Contract manufacturer
EPA	Environmental Protection Agency
EPR	Extended producer responsibility
ESG	Environmental, social, and governance
FDI	Foreign direct investment
MNR	Multinational remanufacturer
MNF	Multinational firm
OEM	Original equipment manufacturer
TPR	Third-party remanufacturer
WTP	Willingness to pay

Declaration of AI Use

ChatGPT (OpenAI) was employed exclusively for language refinement and grammatical review. No AI tool was used in the generation of scientific content, analysis, or interpretation. All conceptualization, methodology, and conclusions are the author's own.