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Producer information disclosure decision of remanufactured product under licensing

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Abstract : We investigate the impact of information asymmetry regarding the producer of remanufactured products on the decisions of a manufacturer and an authorized remanufacturer (AR) in a competitive closed-loop supply chain. Information asymmetry affects consumers' perceived value of new and remanufactured products, thereby influencing market dynamics. In our model, the manufacturer licenses the AR to remanufacture products, with both parties independently setting prices and deciding on the policy of information disclosure about the remanufactured products' producer. The analysis shows that information symmetry generally results in higher prices for new products and lower prices for remanufactured products. However, when the AR's remanufacturing capacity is bound, there is a threshold in consumer recognition of remanufactured products (net gain value of product perceived value under information symmetry) which alters the price relationship. When the AR employs a partial remanufacturing strategy, information symmetry leads to a reduction in the manufacturer's licensing fee. Additionally, we find that information symmetry can cause the AR to adjust its remanufacturing strategies under certain conditions. Due to the perceived value effects, sometimes there is no threshold for product cost that can cause changes in the information disclosure policies. Furthermore, the independent decision-making of supply chain members sometimes can allow the manufacturer to benefit as a free rider. These findings highlight the complex interplay between information asymmetry, remanufacturing strategies, and remanufacturing licensing.

Keywords : Supply chain management, remanufacturing licensing, information disclosure, free rider, perceived value

1 Introduction

The complexity of the product's characteristics (features, quality, etc.) make consumers uncertain about how well a product matches their personal preferences (Sun et al., 2023), with this uncertainty being more pronounced for experiential products, e.g., beauty products, accessories, and apparel (Sun et al., 2022). To help consumer in assessing the product's fit, sellers are providing online information that typically goes beyond basic textual details to include descriptions of technical specifications enhanced through visual effects such as graphics and videos (Sun and Tyagi, 2020). Also, Q&A sessions and customer assessments are made available to allow consumers to evaluate and understand products on the basis of their unique requirements (Hu et al., 2023). Along these lines, retailers have been exploring various product information disclosure strategies. For example, JD.com has a product comparison function that allows for the comparison of detailed parameters of similar styles of products. Moreover, during specific event periods, such as the 2024 Double 11 shopping festival, JD.com also launched the "True Low-Price Challenge" activity, where users can directly compare the prices of products on JD.com and other platforms. Walmart often displays two highly alternative products to consumers in their store at the same time, which allows them to visually compare the performance parameters and appearance attributes of two products.

The market co-presence of new and remanufactured goods significantly amplifies the inherent challenges consumers encounter when evaluating experience-based product attributes. As information affects consumers' perception of quality, some papers have begun to focus on the issue of product information disclosure in closed-loop supply chains (CLSCs). Quality information is the first to receive attention. Interestingly, Zhang et al. (2022) believed that the perception of product quality is influenced by the information disclosure behavior of different supply chain roles. The disclosure of remanufacturers can increase consumers' perception of new products, whereas the disclosure of manufacturers can reduce consumers' perception of remanufactured products. Another product attribute has not yet received research focus. When manufacturers and remanufacturers compete, consumers usually prefer manufacturers' products (Ferrer and Swaminathan, 2006). Majumder and Groenevelt (2001) observed that buyers do not differentiate between products sold by original equipment manufacturers (OEMs), whether they are new or remanufactured. However, customers do differentiate these products from those sold by remanufacturers. Furthermore, Agrawal et al. (2015) examined the dual-channel influence mechanism of remanufactured products and remanufacturer identity on consumer valuation of new products. Their findings revealed that third-party remanufacturing operations create asymmetric perceptual effects: while enhancing consumer valuation of new products, they simultaneously diminish perceived value of remanufactured alternatives.

When manufacturers with a national brand sell products through retailers, the confusion of consumer quality preferences caused by national and store brands has received research attention (Guo et al., 2023). Accordingly, in the remanufacturing industry, the producer of remanufactured products serves as a type of information similar to quality or fit. When consumers grasp this information, their perceived value of new and remanufactured products will inevitably change. We define it as the perceived value change effect caused by producer information. The purpose of our article is to discuss the impact of differences in consumer perceived value arising from different producers of remanufactured goods.

In licensing-based manufacturer-remanufacturer collaborations, the market simultaneously accommodates both product categories, creating unique valuation dynamics. Consumer predisposition toward manufacturer-branded products induces significant shifts in perceived value across new and remanufactured offerings. To provide actionable insights for firms navigating these complex market conditions, our study investigates the following research questions:

RQ1: What are manufacturers' and remanufacturers' optimal responses when the remanufacturer remanufactures used products under a license from the manufacturer? What is the impact of a remanufacturing license on market equilibrium?

RQ2: Is there interaction between information disclosure strategy and remanufacturing entry strategy?

RQ3: Considering the manufacturer and the remanufacturer as decision makers for information disclosure, what are their motivations for disclosing information? Is there consistency in strategy selection between the two players?

To answer these questions, we build a CLSC, including a manufacturer and an authorized remanufacturer (AR) with retail capability. Under this framework, both the manufacturer and AR independently determine the producer information disclosure strategies.

Our contribution can be summarized as follows: (1) We introduce product producers as an attribute into an analytical model for the first time, which is of great significance for supplementing the vertical and horizontal dimensions of product information, especially in the remanufacturing industry. (2) Unlike traditional views, in the coopetition relationship between the manufacturer and the AR, we find that the AR is not always unwilling to disclose information about remanufactured product producer. (3) We add insights into the free riding effect on information disclosure by manufacturers and remanufacturers.

The rest of the paper is organized as follows. We briefly review the literature and position our paper with respect to previous studies in Section 2. The conceptualization and formulation of the model are shown in Section 3. Section 4 presents the analytical results for the benchmark case when there is no information asymmetry. Section 5 presents the analytical results in the presence of information asymmetry and Section 6 examines the information disclosure strategy selection of the manufacturer and AR. We conclude the paper and outline the limitations and possible directions for future research in Section 7. All proofs are in the Online Supplement.

2 Literature review

Our paper draws from, and contributes to, the following three research streams: (1) firm's licensing decision and authorization remanufacturing, (2) product quality and fit information disclosure, and (3) information asymmetry in a closed-loop supply chain.

Licensing decisions are a widely discussed problem in operations management. Hernández-Murillo and Llobet (2006) investigated the technology adoption heterogeneity among downstream licensees in competitive market settings, with particular focus on deriving optimal contractual arrangements between technology licensors and their licensed entities. Jiang and Shi (2018) analyzed how technology licensing agreements between incumbents and entrants influence market competition and quality optimization. Their conclusion revealed a competition-alleviating mechanism between established firms and new market players. Wang et al. (2018) investigated the strategic interplay in technology licensing within emerging multi-agent supply chain ecosystems, where proprietary technologies are licensed to third-party design specialists and subsequently embedded into manufactured products through OEM partnerships. Negoro and Matsubayashi (2021) examined the partner selection strategies of new entrants when introducing new products in foreign markets. Compared to established enterprises, the products offered by new entrants possess either brand or technological advantages, with licensing emerging as a viable alliance option for them. The primary focus of this extensive body of literature lies in determining whether patent holders ought to license their technology to potential competitors, and if so, how to proceed with the licensing process.

A more relevant literature to remanufacturing in licensing issues is authorization for remanufacturing. Oraiopoulos et al. (2012) constructed an analytical framework for durable goods markets where OEMs strategically modulate product residual values through technology relicensing fees imposed on refurbished equipment purchasers. The study characterized the equilibrium conditions between value retention incentives and intra-brand competition effects in secondary markets. Much of the subsequent research has instead focused on manufacturer-to-remanufacturer licensing strategies. Zou et al.

(2016) developed a game-theoretic framework to characterize strategic interactions between OEMs and Third-Party Remanufacturers (TPRs), conducting comparative analysis on outsourcing versus authorization contractual modalities. Their equilibrium analysis quantified differential impacts on market output, pricing, and profits under consumer valuation toward remanufactured goods. Since then, some studies have also compared remanufacturing outsourcing and licensing (Zhang et al., 2020; Zhou et al., 2023). Liu et al. (2018) suggested that remanufactured products from unauthorized TPRs are less preferred by consumers than OEMs' or authorized TPRs'. They examined optimal refurbishing authorization strategy for the OEM. Considering consumer online reviews, Qiao and Su (2021) formulated a dynamic game-theoretic framework to investigate strategic interdependencies between OEMs' technology transfer policies and Independent Remanufacturers' distribution network configurations in closed-loop production systems. Jin et al. (2022) introduced a dealership-integrated remanufacturing paradigm, conducting comparative analysis against conventional TPR operations. They demonstrated that authorization significantly enhance consumer premium valuation for refurbished products. Zhou et al. (2022) modeled OEM-independent remanufacturer technology transfer strategies, comparing royalty-based licensing with in-house R&D, and analyzing their impacts on product quality, pricing, and market competition in closed-loop systems. Li et al. (2023) explored how consumer-perceived value influences OEMs' remanufacturing authorization strategies, demonstrating that licensing TPRs can create mutually beneficial outcomes under specific market conditions. Our research advances this literature by examining a manufacturer's remanufacturing authorization strategy that incorporates both the competitive dynamics between new and remanufactured products and collaborative remanufacturing partnerships. While building upon foundational work on quality disclosure in technology licensing by Hong et al. (2021), we pioneer the investigation of information disclosure policies within the specific context of remanufacturing licensing, focusing on the interplay between technology transfer decisions and supply chain transparency.

Product quality is a vertical attribute, whereas the quality distribution of different categories is a horizontal attribute. The vertical and horizontal dimensions depict most of the attributes of a product (Sun, 2011). In recent research, the latter is called fit (match) attribute (Sun et al. (2021), Sun and Tyagi, 2020). Quality information disclosure in supply chain management has been widely considered, with most studies assuming uncertainty of consumers' preference for product quality (Guo, 2009; Guo and Zhao, 2009; Kuksov and Lin, 2010). Subsequent research investigated the interaction between obtaining information and quality information disclosure strategy (Cao et al., 2019; Guan and Chen, 2017), disclosure strategy in the presence of channel encroachment (Guan et al., 2019), consumer reviews (Guan et al., 2020) or consumer loss aversion (Zhang and Li, 2021). Fit (match) information is closely related to quality information. Sun and Tyagi (2020) investigated the motivation of all supply chain members to disclose information when a manufacturer sells through two competing retailers. They showed that the level of product quality and the degree of retail competition play important roles in a disclosure conflict. On this basis, Sun et al. (2022) considered the information disclosure decision of a retailer selling products from two manufacturers with differentiated quality. Hu et al. (2023) provided a comprehensive summary of the information that may be involved in supply chain operation decisions. They considered product information and market information. Sun et al. (2021) proposed the concept of quality preference information which refers to the information that retailers or manufacturers can provide to help consumers understand and evaluate suitability. They studied the information disclosure strategies of two competing manufacturers and a downstream retailer. Sun et al. (2023) investigated the impact of this information on the outsourcing strategy of a high-quality product manufacturer. Unlike the above literature, we focus on the free-rider effect that may be caused by unilateral information disclosure of an entity in the supply chain environment. Guan et al. (2019) suggested that in a supply chain where a supplier engages in channel encroachment, a retailer may benefit from increased consumer quality expectations brought about by supplier information disclosure and become a free rider. Zhang et al. (2022) investigated the free-rider effect between suppliers on the decision-making of information disclosure. They combine quality information disclosure and free riding issues in remanufacturing, but in our model, we focus more on the competitive relationship formed by manufacturers and remanufacturers through remanufacturing authorization contracts. Both manufacturers and remanufacturers have the motivation to disclose information, and the free riding effect does not always exist when remanufacturers disclose information.

Product quality is a vertical attribute, whereas the quality distribution of different categories is a horizontal attribute. The vertical and horizontal dimensions depict most of the attributes of a product (Sun, 2011). In recent research, the latter is called fit (match) attribute (Sun et al., 2021; Sun and Tyagi, 2020). Quality information disclosure in supply chain management has been widely considered, with most studies assuming uncertainty of consumers' preference for product quality (Guo, 2009; Guo and Zhao, 2009; Kuksov and Lin, 2010). Subsequent research investigated the interaction between obtaining quality information and information disclosure strategy (Cao et al., 2019; Guan and Chen, 2017), disclosure strategy in the presence of channel encroachment (Guan et al., 2019), consumer reviews (Guan et al., 2020) or consumer psychological feelings (Guan and Wang, 2022; Zhang and Li, 2021). Product fit information is intrinsically linked to quality attributes. Sun and Tyagi (2020) examined information disclosure incentives across supply chain participants in a dual-retailer distribution system, revealing that both product quality levels and intensity of retail competition significantly influence disclosure strategy conflicts. On this basis, Sun et al. (2022) considered the information disclosure decision of a retailer selling products from two manufacturers with differentiated quality. Hu et al. (2023) provided a comprehensive summary of the information that may be involved in supply chain operation decisions. They considered product information and market information. Sun et al. (2021) pioneered the conceptualization of quality preference information as a strategic tool for enhancing consumer product suitability evaluation, which can be selectively disclosed through manufacturer or retailer channels. They investigated the complex interplay of information revelation strategies in a vertically differentiated market structure comprising competing manufacturers and their common downstream retailer. Furthermore, Sun et al. (2023) examined how quality preference information influences outsourcing decisions in premium product manufacturing. The strategic management of product fit information has also been discussed (Wu et al., 2018). Diverging from existing research trajectories, our study specifically addresses the strategic implications of free-riding behavior induced by unilateral information disclosure within multi-tier supply chain networks. Guan et al. (2019) suggested that in a supply chain where a supplier engages in channel encroachment, a retailer may benefit from increased consumer quality expectations brought about by supplier information disclosure and become a free rider. Zhang et al. (2022) explored the strategic interdependencies in supplier information disclosure policies, with particular focus on free-riding dynamics in competitive supply networks. They combine quality information disclosure and free riding issues in remanufacturing, but in our model, we focus more on the competitive relationship formed by manufacturers and remanufacturers through remanufacturing authorization contracts. Both manufacturers and remanufacturers have the motivation to disclose information, and the free riding effect does not always exist when remanufacturers disclose information.

Information asymmetry has emerged as a critical research dimension in CLSC management. The operational dynamics of these systems are fundamentally characterized by collection efficiency metrics and cost structures associated with reverse logistics operations. A manufacturer engages in remanufacturing but assigns a third-party (3P) entity to gather used products. Due to asymmetric information, the 3P may experience a reduction in the quantity of products collected, leading to low collection efficiency (Zhao et al., 2022). Zhang et al. (2014) explored the challenge of contract design in a CLSC where the retailer keeps the cost of collection efforts confidential. Suvadarshini et al. (2023) discovered that an OEM can enhance profitability by acquiring information on the cost coefficient of an external recollection agent; however, if the OEM solely relies on external agents for recollection, the information is useless. Demand information transparency has emerged as a significant research stream. Huang and Wang (2017a) established an analytical framework to evaluate information sharing benefits in triadic closed-loop systems involving manufacturers, distributors, and licensed third-party operators. Their subsequent research trajectory (2017b, 2020, 2023) systematically investigated demand information sharing mechanisms across diverse closed-loop configurations, providing foundational insights into optimal disclosure strategies. Complementing this line of inquiry, Nie et al. (2021) examined the strategic implications of retailer-initiated demand information sharing during manufacturer-led product line extensions into remanufactured goods markets. Through the above research, we have found that in studies involving remanufacturing, more attention is given to the issue of asymmetric information on the collection cost, efficiency, and demand information sharing. A few studies have focused on the quality information (Hong et al., 2021; Liu et al., 2023; Zhang et al., 2022), but the product fit information derived from quality information has not yet been studied. Our article first focuses on this focal point.

Table 1 shows the relationships between our article and related articles concerning product information disclosure in supply chain.

Table 1: Key articles on information disclosure in the supply chain

	Coopetition supply chain	Licensing strategy	Consumer uncertainty about product	CLSC
Sun et al. (2023)	√		√	
Guan et al. (2019)	√		√	
Hong, Cao, et al. (2021)			√	√
Hong, Zhou, and Gong (2021)	√	√	√	
Zhang et al. (2022)			√	√
This paper	√	√	√	√

3 Assumptions and notation

We consider a model incorporating a manufacturer and an authorized remanufacturer with retail function. The manufacturer produces new products and subcontracts remanufacturing to the AR at the same time. The AR is responsible for selling new products while also producing and selling remanufactured products, and it must pay a licensing fee to the manufacturer.

Focusing on the core business and outsourcing or licensing the remanufacturing business to a TP is a common choice for OEMs. In addition to third parties dedicated to remanufacturing, some entities with retail functions are also involved in the remanufacturing industry. Some companies operate as partners of manufacturing enterprises in the initial stages of establishment, primarily assuming the role of retailers. As business development continues to mature, they gradually expand their business scope, not only manufacturing products, but also being able to act as authorized partners for product remanufacturing. For example, the well-known Chinese engineering machinery company SEVALO and its Korean partner DOOSAN have such a relationship (Yi et al., 2016). There is another case where some upstream OEMs sell their products through downstream distributors. To cover a wider market, downstream distributors provide a wider range of services, which benefits both OEMs and distributors. The US truck industry exemplifies this trend, where independent distributors are expanding their service portfolios to capitalize on the lucrative truck parts market. Emerging market entrants are addressing dual consumer demands for both cost-effective replacement parts and premium refurbished components. Notably, Daimler Trucks North America has strategically positioned its Alliance Truck Parts brand across new and remanufactured product lines, implementing innovative logistics solutions like dedicated delivery services to optimize parts distribution efficiency for repair facilities and end-users (Jin et al., 2022). Meanwhile, some new companies have entered the industry. For example, LKQ Corp. sells parts from recycled cars and trucks. LKQ is headquartered in Chicago and operates multiple factories producing heavy trucks in the US and Canada. It purchases many cars, some of which are dismantled into parts, and some are resold. Some parts have also been remanufactured and sold. In addition, some high-tech enterprises that integrate design, R&D, production, and sales are entering the remanufacturing industry, and their emergence has made the role of remanufacturers more diverse and abundant. For example, the Ministry of Industry and Information Technology of

China announced two batches of Electromechanical Products Remanufacturing Pilot Enterprises in 2009 and 2016, e.g., Kangyue Technology Co., Ltd. Therefore, the participation of these entities with retail functions in remanufacturing has led to the sustained growth of the remanufacturing industry.

In this paper, the manufacturer (M) produces new products and authorizes the AR to remanufacture. M produces a new product at a constant cost c_n, and sells it through the AR. The new products are used and become cores (used products) for remanufacturing. The AR collects cores and recovers their residual value to produce a remanufactured product at cost c_r. We consider the interaction between M and AR in a single period, which could be interpreted as a representation of the steady state of the product's life cycle where all decisions are unchanging in different periods. We assume that each product can be used for one period and remanufactured at most once. Therefore, the remanufactured product quantity in the current period is constrained by the new product quantity in the previous period, which equals the new product quantity in the current period, i.e., $q_n \geq q_r \geq 0$. We assume that all cores are available for remanufacturing. In the benchmark case, we assume that both M and AR have common knowledge of the demand and cost information. Therefore, the manufacturer decides on the new product wholesale price w_n, and then the AR decides on the new and remanufactured products selling price supplied to the market. The variables and parameters are defined in Table 2, and the game sequence in the closed-loop supply chain system is depicted in Figure 1.

Table 2: Notation

Variables	Definitions
w_n	Wholesale price per unit of the new product
p_n	Retail price per unit of the new product
p_r	Retail price per unit of the remanufactured product
q_n	Quantity of the new product
q_r	Quantity of the remanufactured product
Parameters	Definitions
c_n	Unit production cost of the new product
c_r	Unit production cost of the remanufactured product
r	Licensing fee
ρ	Consumer recognition of remanufactured products $(0 < \rho < 1)$
δ	Coefficient of influence of non-manufacturer production on consumer recognition of remanufactured products $(0 < \delta < 1)$
θ	Coefficient of influence of non-manufacturer production on consumer recognition of new products $(\theta > 1)$
C	Fixed cost for the manufacturer to disclose information
Symbols	Definitions
φ	Consumer valuation of new products
U	Consumer utility
M, R	Subscripts denote the manufacturer and the AR, respectively
B, A, MD, RD	Superscripts indicating that the base case with full information, when neither the manufacturer nor the AR disclose information, when the manufacturer disclose information and when the AR disclose information, respectively
π_M	Manufacturer's profit
π_R	AR's profit

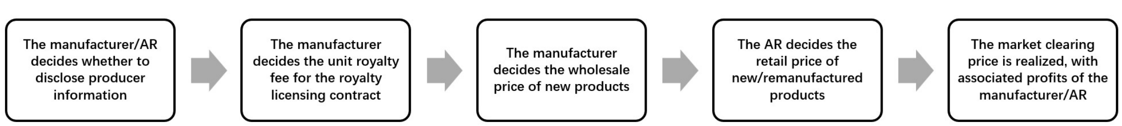


Figure 1: Sequence of events

First, the manufacturer and the AR engage in authorized remanufacturing cooperation model and decide their disclosure strategies, respectively. Also, the manufacturer decides on its unit licensing fee. Second, the manufacturer and the AR make price decisions successively. Next, the manufacturer and the AR set prices, which also determine the quantities of the new and remanufactured products. Finally, consumers make purchase choices according to disclosure strategies and prices.

Drawing on Agraval et al. (2015), we characterize information asymmetry through consumers' willingness-to-pay, in our settings, also known as consumer recognition of products. The real producer of remanufactured products is known by both the manufacturer and the AR.

Each consumer's willingness-to-pay for a remanufactured product is a fraction ρ of their willingness-to-pay for the new product. We assume that consumers' willingness-to-pay (valuation) is distributed uniformly in the interval $[0, 1]$ and that in any period, each consumer uses at most one unit. The market size is normalized to 1. A consumer of type $\varphi \in [0, 1]$ has a valuation of φ for a new product and $\rho\varphi$ for a remanufactured product, with $\rho \in (0, 1)$. The utility that each consumer derives from purchasing a product is given by the difference in their valuation and price. As in Ferguson and Tokay (2006), the net utility of the new and remanufactured units is $U_N = \varphi - p_n$ and $U_R = \rho\varphi - p_r$, respectively. The consumer has three purchasing strategies: (i) buy a new unit (N); (ii) buy a remanufactured unit (R); or (iii) be inactive (X). In terms of consumer utility, if all three strategies are observed in equilibrium, then consumers who follow an N strategy value the product more (i.e., have a higher φ) than consumers who follow an R strategy, who value it more than consumers who follow an X strategy. Now consider the lowest valuation consumer who adopts an R strategy. This consumer is located at a point $\varphi = 1 - q_n - q_r$ and is indifferent between R and X, so the utility from following an R strategy equals an X strategy, i.e., $0 = \rho(1 - q_n - q_r) - p_r$. Considering the lowest valuation of the consumer who adopts an N strategy, this consumer is located at a point $\varphi = 1 - q_n$ and is indifferent between following an N and R strategy, so the utility from following an N strategy equals an R strategy, i.e., $(1 - q_n) - p_n = \rho(1 - q_n) - p_r$. Combining these two equations yields the following inverse demand functions:

$$\begin{cases} p_n &= 1 - q_n - \rho q_r, \\ p_r &= \rho(1 - q_n - q_r), \end{cases}$$

i.e.,

$$\begin{cases} q_n &= 1 - \frac{p_n - p_r}{1-\rho} = \frac{1-\rho-p_n+p_r}{1-\rho}, \\ q_r &= \frac{p_n-p_r}{1-\rho} - \frac{p_r}{\rho} = \frac{\rho p_n - p_r}{\rho(1-\rho)}. \end{cases} \tag{1}$$

Consumers value differently the producers of remanufactured goods. If the manufacturer licenses remanufacturing to a remanufacturer, a consumer of type $\varphi \in [0, 1]$ has a valuation of $\theta\varphi$ for a new product produced by the manufacturer and $\delta\rho\varphi$ for a remanufactured product produced by the remanufacturer. The net utility of the new and remanufactured units changes to $U_N = \theta\varphi - p_n$ and $U_R = \delta\rho\varphi - p_r$, respectively. Similarly, we have the two equalities $\theta(1 - q_n) - p_n = \delta\rho(1 - q_n) - p_r$ and $\delta\rho(1 - q_n - q_r) - p_r = 0$, which can be combined to obtain the inverse demand function:

$$\begin{cases} p_n &= \theta(1 - q_n) - \delta\rho q_r, \\ p_r &= \delta\rho(1 - q_n - q_r), \end{cases}$$

i.e.,

$$\begin{cases} q_n &= 1 - \frac{p_n-p_r}{\theta-\delta\rho} = \frac{\theta-\delta\rho-p_n+p_r}{\theta-\delta\rho} \\ q_r &= \frac{p_n-p_r}{\theta-\delta\rho} - \frac{p_r}{\delta\rho} = \frac{\delta\rho p_n - \theta p_r}{\delta\rho(\theta-\delta\rho)}. \end{cases} \tag{2}$$

4 The benchmark case

As a benchmark, we consider the case where there is no information asymmetry between the manufacturer, the AR, and consumers. To determine a subgame-perfect equilibrium, we solve the multistage game backward.

The manufacturer's and AR's profit functions are as follows:

$$\underset{w_n}{Max}\pi_M^B = (w_n - c_n)\,q_n + rq_r, \tag{3}$$

$$\underset{p_n,p_r}{Max}\pi_R^B = (p_n - w_n)\,q_n + (p_r - c_r - r)\,q_r, \tag{4}$$

where the superscript B stands for benchmark.

Let $c_{r1}^B = \frac{2\delta\rho w_n - \delta\rho(\theta-\delta\rho)-(\theta+\delta\rho)r}{\theta+\delta\rho}$ and $c_{r2}^B = \frac{\delta\rho w_n - \theta r}{\theta}$. The equilibrium results are summarized in the following proposition.

Proposition 1. *When there is no information asymmetry, the manufacturer's and AR's equilibrium pricing strategies are as follows:*

- *If $c_r > c_{r2}^B$, then $w_n^B = \frac{c_n+\theta}{2}$, $p_n^B = \frac{c_n+3\theta}{4}$ and $p_r^B = \frac{\delta\rho(c_n+3\theta)}{4\theta}$.*
- *If $c_{r1}^B \leq c_r \leq c_{r2}^B$, then $w_n^B = \frac{c_n+\theta}{2}$, $p_n^B = \frac{c_n+c_r+3\theta-\delta\rho+2r}{4}$ and $p_r^B = \frac{c_r+\delta\rho+r}{2}$.*
- *If $c_r < c_{r1}^B$, then $w_n^B = \frac{c_n-c_r+\theta+\delta\rho}{2} - r$, $p_n^B = \frac{(\theta+\delta\rho)(c_n+c_r)+3\theta-\delta\rho+10\theta\delta\rho}{4(\theta+3\delta\rho)}$ and $p_r^B = \frac{\delta\rho(c_n+c_r+\theta+5\delta\rho)}{2(\theta+3\delta\rho)}$.*

Next, we investigate the manufacturer's royalty fee decision. In anticipation of the AR's pricing decisions, the manufacturer determines the unit royalty fee that maximizes its profit when a licensing contract is implemented.

Proposition 2. *When there is no information asymmetry, the manufacturer's optimal royalty fee is as follows:*

- *When $c_{r1}^B \leq c_r \leq c_{r2}^B$, the optimal royalty fee is $r_{PR}^B = \frac{\delta\rho - c_r}{2}$.*
- *When $c_r < c_{r1}^B$ or $c_r > c_{r2}^B$, the manufacturer's profit is independent of the royalty fee, so there is no equilibrium royalty fee.*

To shed a light on this result, we look at production of new and remanufactured products for the different interval values of c_r that show up in Propositions 1 and 2. It can be easily verified that we have the following cases:

No-Remanufacturing (NR): If $c_r > c_{r2}^B$, then $q_r^B = 0$ and $q_n^B = \frac{\theta - c_n}{4\theta}$, i.e., the AR stays out of the remanufacturing market, and the manufacturer serves the whole market.

Partial-Remanufacturing (PR): If $c_{r1}^B \leq c_r \leq c_{r2}^B$, then $q_r^B = \frac{\delta\rho c_n - \theta c_r}{4\delta\rho(\theta-\delta\rho)}$ and $q_n^B = \frac{c_r - c_n + \theta - \delta\rho}{4(\theta-\delta\rho)}$, $q_r^B < q_n^B$, i.e., the AR enters the market and remanufactures part of the available cores.

Full-Remanufacturing (FR): If $c_r < c_{r1}^B$, then $q_r^B = \frac{-(c_n+c_r-\theta-\delta\rho)}{4(\theta+3\delta\rho)}$ and $q_n^B = \frac{-(c_n+c_r-\theta-\delta\rho)}{4(\theta+3\delta\rho)}$, $q_r^B = q_n^B$, i.e., the AR enters and remanufactures all available cores.

The results can be easily interpreted. if c_r is low enough, remanufacturing is profitable, and the AR remanufactures as many units as possible making the quantity constraint binding ($q_r^B = q_n^B$). Huang et al. (2019) and Zhang et al. (2022) refer to the quantity constraint as a salient feature in remanufacturing. When $c_r > c_{r2}^B$, remanufacturing is not profitable, and any license agreement is immaterial. When $c_r < c_{r1}^B$, due to the high cost of manufacturer's new products ($c_r < c_{r1}^B$ is equivalent to c_n is greater than a threshold), the quantity of new products is limited implying that authorized remanufacturing is less attractive. Therefore, for the manufacturer, the impact of the new product production cost and wholesale revenue makes the profits of remanufacturing authorization negligible in equilibrium. This result is different from that of Zhou et al. (2022) who showed that the manufacturer always has the optimal royalty fee decision in the *PR* and *FR* scenarios. Here, we show that there is no optimal royalty fee if the quantity constraint is binding.

5 Information asymmetry

In this section, we analyze the setup where consumers value differently the producers of remanufactured goods and neither the manufacturer nor the AR discloses information, which means that consumers do not know who produced the remanufactured product. The consumers' valuation for a new product will follow a uniform distribution in the interval of $[\varphi, \theta\varphi]$, and a uniform distribution in the interval of $[\delta\rho\varphi, \rho\varphi]$ for a remanufactured product, i.e., consumers will update their prior belief to the expected willingness-to-pay conditional on no disclosure. The net utility of the new and remanufactured units changes to $U_N = \frac{\theta+1}{2}\varphi - p_n$ and $U_R = \frac{\delta+1}{2}\rho\varphi - p_r$. Similarly, we can get two utilities equations $\frac{\theta+1}{2}(1-q_n) - p_n = \frac{\delta+1}{2}\rho(1-q_n) - p_r$ and $\frac{\delta+1}{2}\rho(1-q_n-q_r) - p_r = 0$. These two equations are combined to obtain the inverse demand functions:

$$\begin{cases} p_n &= \frac{\theta+1}{2}(1-q_n) - \frac{\delta+1}{2}\rho q_r \\ p_r &= \frac{\delta+1}{2}\rho(1-q_n-q_r) \end{cases}$$

i.e.,

$$\begin{cases} q_n &= 1 - \frac{p_n - p_r}{\frac{\theta+1}{2} - \frac{\delta+1}{2}\rho} = \frac{\frac{\theta+1}{2} - \frac{\delta+1}{2}\rho - p_n + p_r}{\frac{\theta+1}{2} - \frac{\delta+1}{2}\rho} \\ q_r &= \frac{p_n - p_r}{\frac{\theta+1}{2} - \frac{\delta+1}{2}\rho} - \frac{p_r}{\frac{\delta+1}{2}\rho} = \frac{\frac{\delta+1}{2}\rho p_n - \frac{\theta+1}{2}p_r}{\frac{\delta+1}{2}\rho\left(\frac{\theta+1}{2} - \frac{\delta+1}{2}\rho\right)} \end{cases} \tag{5}$$

The manufacturer's and AR's profit functions are as follows:

$$\underset{w_n}{Max}\pi_M^A = (w_n - c_n)\,q_n + rq_r \tag{6}$$

$$\underset{p_n, p_r}{Max}\pi_R^A = (p_n - w_n)\,q_n + (p_r - c_r - r)\,q_r \tag{7}$$

We refer to the situation in this section as Model A.

Let $c_{r1}^A = \frac{(\delta+1)\rho^2 - (\delta+1)(\theta+1)\rho - 2(\theta+1)r - 2(\delta+1)\rho r + 4(\delta+1)\rho w_n}{2(\theta+1+(\delta+1)\rho)}$ and $c_{r2}^A = \frac{(\delta+1)\rho w_n - (\theta+1)r}{\theta+1}$. The equilibrium results are summarized in the following proposition.

Proposition 3. *In Model A, the manufacturer's and AR's optimal pricing results are as follows:*

- *If $c_r > c_{r2}^A$, then $w_n^A = \frac{2c_n+\theta+1}{4}$, $p_n^A = \frac{2c_n+3(\theta+1)}{8}$ and $p_r^A = \frac{(\delta+1)\rho(2c_n+3(\theta+1))}{8(\theta+1)}$.*
- *If $c_{r1}^A \le c_r \le c_{r2}^A$, then $w_n^A = \frac{2c_n+\theta+1}{4}$, $p_n^A = \frac{2c_n+2c_r+3(\theta+1)-(\delta+1)\rho+4r}{8}$ and $p_r^A = \frac{2c_r+(\delta+1)\rho+2r}{4}$.*
- *If $c_r < c_{r1}^A$, then $w_n^A = \frac{2c_n-2c_r+(\theta+1)+(\delta+1)\rho}{4} - r$, $p_n^A = \frac{((\theta+1)+(\delta+1)\rho)(c_n+c_r)+3(\theta+1)-(\delta+1)\rho+5(\theta+1)(\delta+1)\rho}{4((\theta+1)+3(\delta+1)\rho)}$ and $p_r^A = \frac{(\delta+1)\rho(2c_n+2c_r+(\theta+1)+5(\delta+1)\rho)}{4((\theta+1)+3(\delta+1)\rho)}$.*

The manufacturer's optimal royalty fee is as follows:

- *If $c_{r1}^A \le c_r \le c_{r2}^A$, then $r^A = \frac{(\delta+1)\rho-2c_r}{4}$.*
- *If $c_r < c_{r1}^A$ or $c_r > c_{r2}^A$, then the manufacturer's profit is independent of the royalty fee, i.e., there is no optimal royalty fee.*

Like Propositions 1 and 2, Proposition 3 characterizes the manufacturer's and AR's equilibrium decisions and the conditions for the AR to implement different remanufacturing strategies. The AR will not engage in remanufacturing when the cost of remanufacturing is high enough (i.e., $c_r > c_{r2}^A$), whereas it will collect and remanufacture all the used products when the cost of remanufacturing is relatively low ($c_r < c_{r2}^A$). When the cost of remanufacturing is at a medium level ($c_{r1}^A \le c_r \le c_{r2}^A$), the AR will collect and remanufacture some but not all the used products.

5.1 Comparison with information symmetry

We describe the boundary conditions of models A and B in Figure 2. Comparing the boundary conditions and the manufacturer's and AR's optimal decisions in the three remanufacturing quantity strategies in the two cases, we find that in the vast part of the regions, c_r is less than both c_{r2}^A and c_{r2}^B, which means that remanufacturing licensing behavior always occurs in these situations. Therefore, in the lower right corner region of curve c_{r2}^B (because c_{r2}^A is greater than c_{r2}^B, AR will always choose PR or FR strategy in cases of information symmetry or asymmetry), the issue of remanufactured products producer information disclosure caused by remanufacturing licensing behavior always exists. However, in Region R_4, if there is information asymmetry, the AR will engage in remanufacturing, i.e., AR will choose PR strategy in model A. It is interesting that if consumers obtain information about the producer of remanufactured products through certain ways, the optimal strategy for AR becomes not to enter remanufacturing anymore, i.e., AR will choose NR strategy in model B. In conclusion, information disclosure has led to changes in AR's remanufacturing strategies.

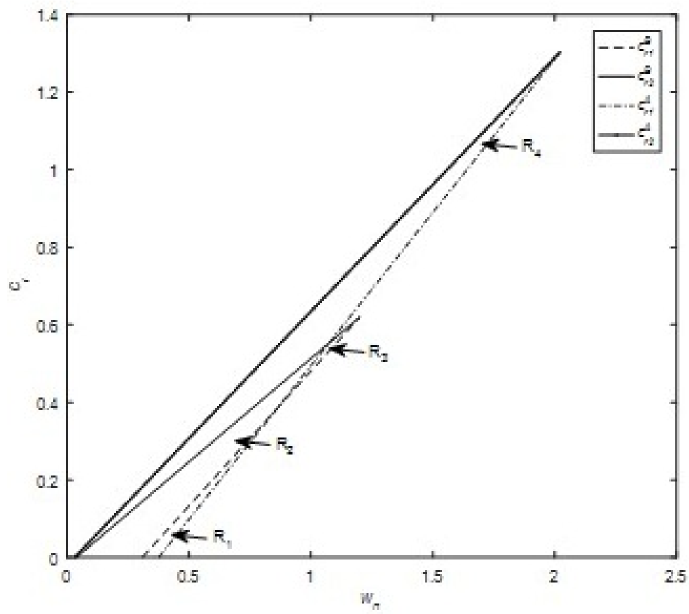


Figure 2: The impact of information disclosure on AR's remanufacturing strategies

In Lemma 1, we compare the equilibrium prices in the three remanufacturing strategies of models A (information asymmetry) and B (information symmetry), first assuming that the license fee is exogenous (we add a tilde to the subscript in this scenario), and next considering an endogenous license fee. Let $\rho_1 = \frac{\theta-1}{1-\delta}$.

Lemma 1. *If the license fee is exogenous, then the equilibrium prices compare as follows:*

1. *In strategy NR,* $w_{\tilde{n}}^B > w_{\tilde{n}}^A$, $p_{\tilde{n}}^B > p_{\tilde{n}}^A$.
2. *In strategy PR,* $w_{\tilde{n}}^B > w_{\tilde{n}}^A$, $p_{\tilde{n}}^B > p_{\tilde{n}}^A$ *and* $p_{\tilde{r}}^B < p_{\tilde{r}}^A$.
3. *In strategy FR:*
   (a) *if* $0 < \rho < \rho_1$ *and* $0 < \rho_1 < 1$, *then* $w_{\tilde{n}}^B > w_{\tilde{n}}^A$; *otherwise,* $w_{\tilde{n}}^B < w_{\tilde{n}}^A$. *If* $\rho_1 > 1$, $w_{\tilde{n}}^B > w_{\tilde{n}}^A$ *for any* $\rho \in (0, 1)$.
   (b) *if* $c_r < c_{r1}^{BA}$, *then* $p_{\tilde{n}}^B < p_{\tilde{n}}^A$; *otherwise,* $p_{\tilde{n}}^B > p_{\tilde{n}}^A$.
   (c) *if* $c_r < c_{r2}^{BA}$, *then* $p_{\tilde{r}}^B > p_{\tilde{r}}^A$; *otherwise,* $p_{\tilde{r}}^B < p_{\tilde{r}}^A$.

If the licensing fee is endogenous, then we obtain exactly the same price rankings as in the exogenous license fee case.

A comparison of the manufacturer's and AR's pricing decisions in the two remanufacturing strategies (PR and FR) of the two cases (B and A), Lemma 1 implies that information symmetry induces the manufacturer to increase its wholesale price on most occasions. Only when the AR adopts the FR remanufacturing strategy, i.e., when the remanufacturing cost is low enough and consumer recognition of remanufactured products ρ exceeds $\rho_1 = \frac{\theta-1}{1-\delta}$ (with $0 < \rho_1 < 1$), will the wholesale price of new products in the information symmetry case be less than those in the information asymmetry case. Note that $\rho_1 = \frac{\theta-1}{1-\delta}$ represents the ratio of the added value of consumer recognition of new products to the discount value of recognition of remanufactured products in the case of (remanufactured product producer) information symmetry. Therefore, the threshold ρ_1 is the net gain of perceived value under information symmetry. Lemma 1 indicates that only when $\rho > \rho_1$ information symmetry leads to a lower manufacturer's equilibrium wholesale price strategy.

For the AR's, information symmetry increases the optimal retail price of new products and decreases the retail price of remanufactured products on most occasions. Only when the AR adopts the FR strategy, i.e., when the remanufacturing cost is low enough and the remanufacturing cost is less is than the thresholds c_{r1}^{BA} and c_{r2}^{BA}, respectively, does the ranking of retail prices change.

Interestingly, we additionally find that both exogenous and endogenous licensing fees lead to the same ranking of price decisions.

The next lemma compares the gap in new and remanufactured products prices under information symmetry and asymmetry and an exogenous license fee, that is, $p_{\tilde{n}}^B - p_{\tilde{r}}^B$ versus $p_{\tilde{n}}^A - p_{\tilde{r}}^A$. The results are the same when we consider an endogenous license fee, so we will not repeat them.

Lemma 2. *If the license fee is exogenous, the price gaps of new and remanufactured products in the information asymmetry and symmetry compare as follows:*

1. *In strategy PR,* $p_{\tilde{n}}^B - p_{\tilde{r}}^B > p_{\tilde{n}}^A - p_{\tilde{r}}^A$.
2. *In strategy FR,* $p_{\tilde{n}}^B - p_{\tilde{r}}^B < p_{\tilde{n}}^A - p_{\tilde{r}}^A$ *if* $c_r < c_{r3}^{BA}$*; otherwise,* $p_{\tilde{n}}^B - p_{\tilde{r}}^B > p_{\tilde{n}}^A - p_{\tilde{r}}^A$.

Lemma 2 provides a comparison of the equilibrium prices of the two cases (information asymmetry and symmetry) from another perspective than Lemma 1. Lemma 2 shows that the price increase of new products is always greater than that of remanufactured products from the information asymmetry case to the symmetry case in the PR strategy. Compared with new products in the information symmetry case, remanufactured products will become more competitive with a relatively lower price if the quantity constraint is not binding ($0 < q_r < q_n$). However, in the FR strategy, i.e., the quantity constraint is binding ($q_r = q_n$), compared with the information asymmetry case, product competition does not always intensify in the information symmetry case. Only when c_r exceeds the threshold c_{r3}^{BA} will the price difference between new and remanufactured products increase. If $c_r < c_{r3}^{BA}$, information symmetry actually softens product competition. The above results indicate that whether the quantity constraint is binding is a crucial factor affecting the relationship between information symmetry and product competition.

According to Lemmas 1 and 2, the quantity constraint is also expressed as threshold intervals for the cost of remanufactured products (c_{r1}^B, c_{r2}^B, c_{r1}^A,c_{r2}^A) in this article. Therefore, for Lemma 2, a more concise conclusion is that when $c_{r3}^{BA} < c_r < \min\left\{c_{r2}^B, c_{r2}^A\right\}$, information symmetry intensifies competition between new and remanufactured products. Correspondingly, for Lemma 1, except for the optimal pricing of the manufacturer, when $c_r < c_{r1}^{BA}$, information symmetry decreases the optimal retail price of new products and increases the optimal retail price of remanufactured products.

By observing the royalty fee under strategy PR in Propositions 2 and 3, we can easily obtain:

Corollary 1. *Information symmetry leads to a decrease in the remanufacturing royalty fee.*

The reason for Corollary 1 is that information symmetry leads to a decrease in the perceived value of remanufactured products, resulting in a decrease in sales revenue for remanufactured products. The manufacturer accordingly reduces its licensing fee.

6 Information disclosure

Producer information disclosure influences consumers' perceptions of new and remanufactured products, and consumers' perceptions influence supply chain members' profits. Therefore, information disclosure decisions are important to all product suppliers (manufacturer and AR). We analyze producer information disclosure decisions and the influence of the free-rider effect next.

6.1 When the manufacturer discloses the information

Compared with disclosure by ARs, disclosure information by manufacturers incurs higher costs. Manufacturers do not directly interact with consumers, which excludes ways of disclosing information such as labeling.

The manufacturer's and AR's profit functions are as follows:

$$\underset{w_n}{Max}\pi_M^{MD} = (w_n - c_n)\, q_n + r q_r - C \tag{8}$$

$$\underset{p_n,p_r}{Max}\pi_R^{MD} = (p_n - w_r)\, q_n + (p_r - c_r - r)\, q_r \tag{9}$$

Similarly, the manufacturer's and AR's optimal decisions can be obtained by solving the KKT necessary conditions, and the equilibrium results are provided in Proposition 4. The remanufacturing cost thresholds for different remanufacturing strategies are exactly the same as those in Model B. In addition, we consider that the royalty fee is determined endogenously by the manufacturer in this section. We refer to the situation in this subsection as Model MD.

Proposition 4. *In Model MD with information disclosure by the manufacturer, the manufacturer's and AR's equilibrium pricing strategies are as follows:*

- *When $c_r > c_{r2}^B$, $w_n^{MD} = \frac{c_n+\theta}{2}$, $p_n^{MD} = \frac{c_n+3\theta}{4}$ and $p_r^{MD} = \frac{\delta\rho(c_n+3\theta)}{4\theta}$.*
- *When $c_{r1}^B \le c_r \le c_{r2}^B$, the optimal pricing decisions for the manufacturer and the AR are $w_n^{MD} = \frac{c_n+\theta}{2}$, $p_n^{MD} = \frac{c_n+c_r+3\theta-\delta\rho+2r}{4}$ and $p_r^{MD} = \frac{c_r+\delta\rho+r}{2}$.*
- *When $c_r < c_{r1}^B$, the optimal pricing decisions for the manufacturer and the AR are $w_n^{MD} = \frac{c_n-c_r+\theta+\delta\rho}{2} - r$, $p_n^{MD} = \frac{(\theta+\delta\rho)(c_n+c_r)+3\theta-\delta\rho+10\theta\delta\rho}{4(\theta+3\delta\rho)}$ and $p_r^{MD} = \frac{\delta\rho(c_n+c_r+\theta+5\delta\rho)}{2(\theta+3\delta\rho)}$.*

The manufacturer's optimal royalty fee is as follows:

- *When $c_{r1}^B \le c_r \le c_{r2}^B$, $r_{PR}^{MD} = \frac{\delta\rho-c_r}{2}$.*
- *When $c_r < c_{r1}^B$ or $c_r > c_{r2}^B$, the manufacturer's profit is not related to royalty fee, so there is no optimal royalty fee.*

With Propositions 3 and 4, the impact on profit of the consumer perceived value effect on the information disclosure of the supply chain under different remanufacturing strategies is summarized in Lemmas 3 to 5 and Figures 3 to 7.

Define $\pi_M^{MA} = \pi_M^{MD} - \pi_M^A$ and $\pi_R^{MA} = \pi_R^{MD} - \pi_R^A$ in different remanufacturing strategies, where $\pi_M^{MA}$and π_R^{MA} are quadratic functions in $c_n$and c_r.

Lemma 3. *When the AR does not remanufacture, considering the conditions of production cost (new product cost) under which the manufacturer has incentives to disclose information, changes in perceived value do not affect the disclosure decision (i.e., positivity and negativity of $\frac{\partial^2\pi_M^{MA}}{\partial {c_n}^2}$ and $\frac{\partial^2\pi_R^{MA}}{\partial {c_n}^2}$ are not related to δ and θ).*

Figure 3 and Corollary 2 further investigate how new product costs affect supply chain members' profits in scenario MD and A.

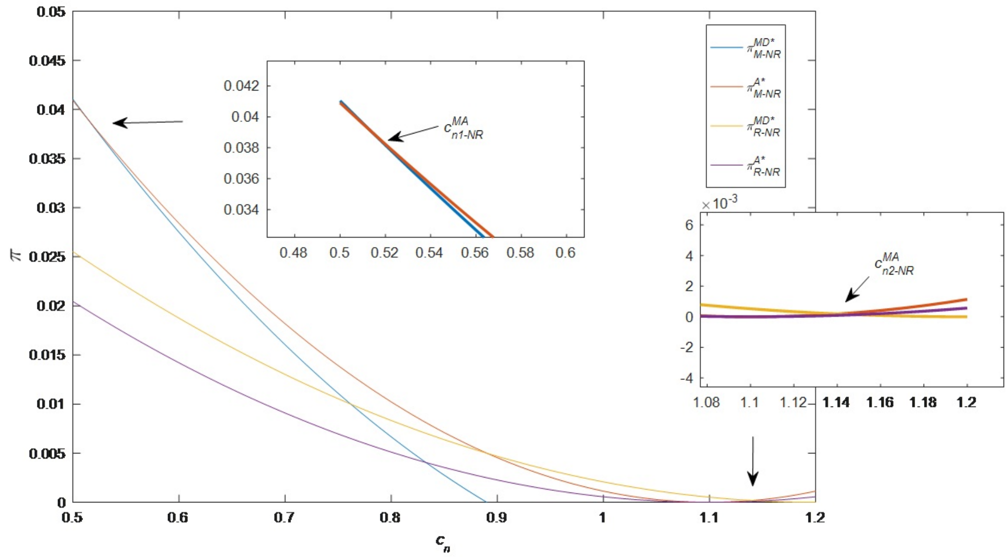


Figure 3: Profit as a function of c_n under the NR strategy

Corollary 2.

- $\pi_M^{MD} < \pi_M^A$ *if* $c_n > c^{MA}_{n1-NR}$*; otherwise,* $\pi_M^{MD} > \pi_M^A$.
- $\pi_R^{MD} < \pi_R^A$ *if* $c_n > c^{MA}_{n2-NR}$*; otherwise,* $\pi_R^{MD} > \pi_R^A$*, where* c^{MA}_{n1-NR} *and* c^{MA}_{n2-NR} *are defined in the Online Supplement.*

We use P to represent the disclosure strategy of the manufacturer or AR, whereas D and U represent the choices to disclose and conceal, respectively. With Corollary 2, we can obtain the manufacturer's information strategy:

$$P_M = \begin{cases} D, \ if \ c_n < c^{MA}_{n1} \\ U, \ otherwise \end{cases}$$

From Corollary 2, when the cost of a new product is high, the manufacturer chooses to conceal the information of the remanufactured producer. When the cost of a new product is low, the manufacturer discloses the information, which is contrary to intuition. In the absence of remanufactured products in the market, remanufactured product producer information sharing should have no impact on profits according to conventional wisdom. The possible reason is that, recall the model settings, the perceived value gain of new products caused by remanufactured product producer information sharing always exists, which means that when the production cost of new products is below the threshold, the benefits brought by the perceived value gain of new products are greater than the sales loss caused by uncertainty in the consumer valuation of new products under information asymmetry. This explanation is reasonable for both the manufacturer and the AR. From the comparison of the threshold for the production cost of new products, c^{MA}_{n1} less than c^{MA}_{n2} means that the manufacturer will choose to disclose information only at a lower production cost, as the manufacturer also needs to bear an additional information disclosure cost.

Comparing the manufacturer's and AR's profits with respect to production cost (new product cost and remanufactured product cost), we obtain Lemma 4.

Lemma 4. *In strategy PR,*

1. *As a function of new product cost, for any* $\theta \in (1, +\infty)$*,* $\delta \in (0,1)$ *and* $\rho \in (0,1)$*,* $\frac{\partial^2 \pi_M^{MA}}{\partial {c_n}^2} < 0$ *and* $\frac{\partial^2 \pi_R^{MA}}{\partial {c_n}^2} < 0$.

2. *As a function of remanufactured product cost, we have:*
   (a) *When* $0 < \delta < \frac{1}{3}$, *for any* $\theta \in (1, +\infty)$, $\rho \in (0, 1)$, $\frac{\partial^2 \pi_M^{MA}}{\partial {c_r}^2} > 0$ *and* $\frac{\partial^2 \pi_R^{MA}}{\partial {c_r}^2} > 0$;
   (b) *When* $\frac{1}{3} < \delta < 1$,
      i. *if* $1 < \theta < \theta_1$,
         A. *for* $0 < \rho < \rho_2$, $\frac{\partial^2 \pi_M^{MA}}{\partial {c_r}^2} > 0$ *and* $\frac{\partial^2 \pi_R^{MA}}{\partial {c_r}^2} > 0$;
         B. *for* $\rho_2 < \rho < 1$, $\frac{\partial^2 \pi_M^{MA}}{\partial {c_r}^2} < 0$ *and* $\frac{\partial^2 \pi_R^{MA}}{\partial {c_r}^2} < 0$;
      ii. *if* $\theta > \theta_1$, *for any* $\rho \in (0, 1)$, $\frac{\partial^2 \pi_M^{MA}}{\partial {c_r}^2} > 0$ *and* $\frac{\partial^2 \pi_R^{MA}}{\partial {c_r}^2} > 0$.

Here, $\theta_1 = \frac{2\delta}{1-\delta}$ *and* $\rho_2 = \frac{(1-\delta)(\theta+1)\theta}{\theta(1-\delta)(1+\delta)+2\delta(\theta-\delta)}$.

Similarly, Figure 4 and Figure 5 illustrate how the costs of new products and remanufactured products affect the profits of supply chain members in Scenarios MD and A.

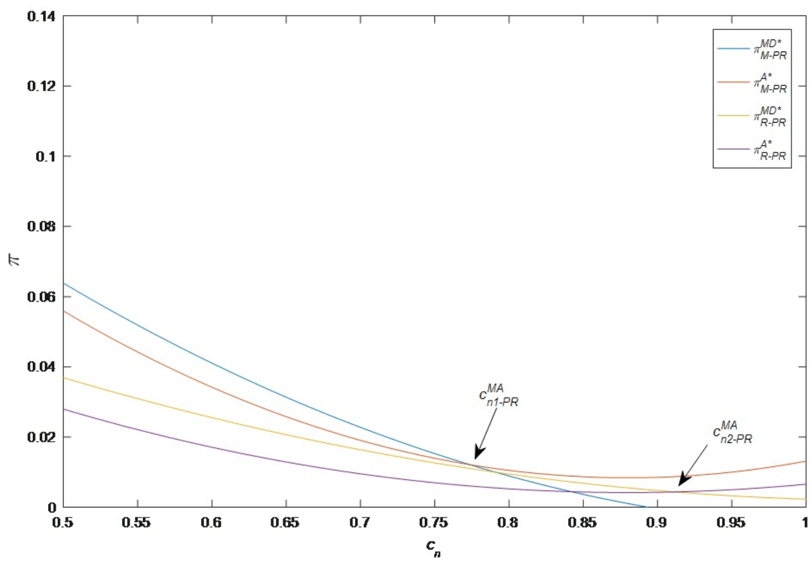


Figure 4: Profit as a function of c_n under the PR strategy

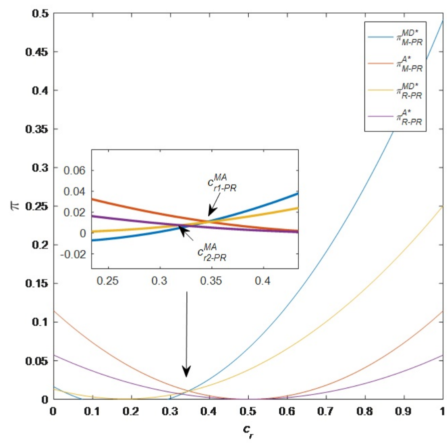
Combining Lemma 4 with Figures 4 and 5, we can derive Corollary 3.

Corollary 3.

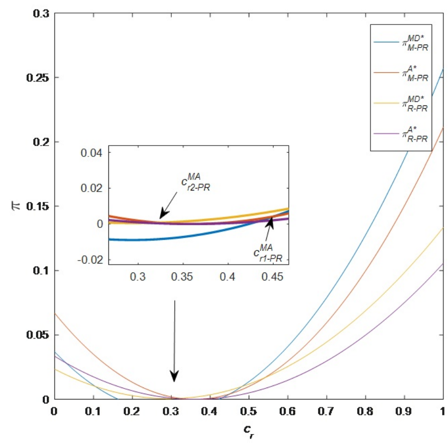
- $\pi_M^{MD*} > \pi_M^{A*}$ *if* $c_n < c_{n1-PR}^{MA}$; *otherwise,* $\pi_M^{MD*} < \pi_M^{A*}$.
- $\pi_R^{MD*} > \pi_R^{A*}$ *if* $c_n < c_{n2-PR}^{MA}$; *otherwise,* $\pi_R^{MD*} < \pi_R^{A*}$.
- $\pi_M^{MD*} > \pi_M^{A*}$ *always hold if* $\frac{1}{3} < \delta < 1$ *and* $\theta > \theta_1$; *otherwise, when* $c_r > c_{r1-PR}^{MA}$, $\pi_M^{MD*} > \pi_M^{A*}$, *and when* $c_r < c_{r1-PR}^{MA}$, $\pi_M^{MD*} < \pi_M^{A*}$.
- $\pi_R^{MD*} > \pi_R^{A*}$ *always hold if* $\frac{1}{3} < \delta < 1$ *and* $\theta > \theta_1$; *otherwise, when* $c_r > c_{r2-PR}^{MA}$, $\pi_R^{MD*} > \pi_R^{A*}$; *and when* $c_r < c_{r2-PR}^{MA}$, $\pi_R^{MD*} < \pi_R^{A*}$.

We can derive the conditions where the manufacturer has incentives to disclose the remanufactured product producer information from Corollary 3. The conclusions are summarized as follows.

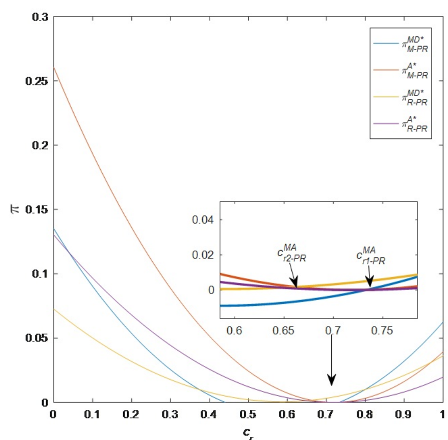
$$P_M = \begin{cases} D, \begin{cases} if\ \frac{1}{3} < \delta < 1\ and\ \theta > \theta_1, \\ or\ c_r > c_{r1}^{MA}\ and\ \frac{1}{3} < \delta < 1\ or\ \theta > \theta_1, \\ or\ c_n < c_{n1}^{MA}. \end{cases} & U,\ otherwise. \end{cases}$$



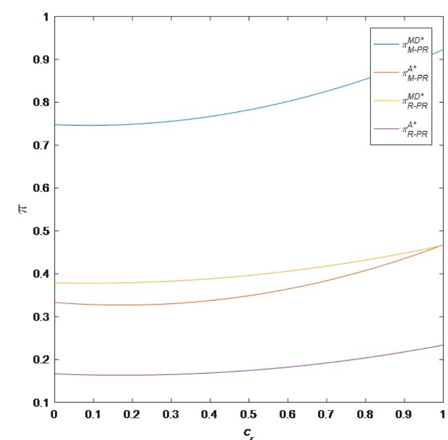
(a) $0 < \delta < \frac{1}{3}$, $\theta > 1$, $0 < \rho < 1$



(b) $\frac{1}{3} < \delta < 1$, $1 < \theta < \theta_1$, $0 < \rho < \rho_2$



(c) $\frac{1}{3} < \delta < 1$, $1 < \theta < \theta_1$,$\rho_2 < \rho < 1$



(d) $\frac{1}{3} < \delta < 1$,$\theta > \theta_1$, $0 < \rho < 1$

Figure 5: Profit as a function of c_r under FR strategy

When the cost of new products is considered, a lower cost makes the manufacturer willing to disclose information. When considering the cost of remanufactured products, when the perceived value loss of the remanufactured product caused by information symmetry is small or moderate $(0 < (1-\delta) < \frac{2}{3})$ and the perceived value gain of new products is relatively large $(\theta > \theta_1)$, whether the cost of the remanufactured product changes, it does not have an effect on the manufacturer's information policy. The manufacturer always adopts a disclosure strategy. Otherwise, there is also a cost threshold for remanufactured products, which makes the manufacturer willing to disclose information when the cost of remanufactured products exceeds this threshold.

Similar to the analysis under NR and PR strategies, we obtain Lemma 5, figs. 6 and 7, and corollary 4 in sequence.

Lemma 5. *In strategy FR,*

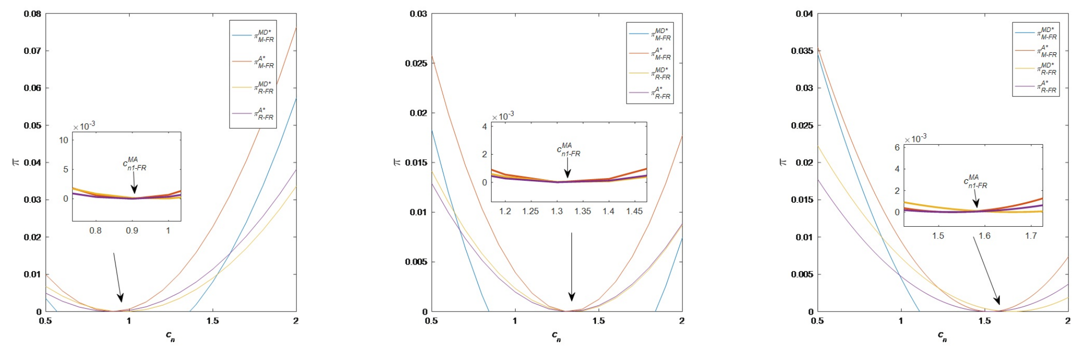
1. *When* $0 < \frac{\theta-1}{1-\delta} < 3$,
   (a) *for* $0 < \rho < \frac{1}{3}\rho_1$, $\frac{\partial^2 \pi_M^{MA}}{\partial {c_n}^2} < 0$, $\frac{\partial^2 \pi_R^{MA}}{\partial {c_n}^2} < 0$, $\frac{\partial^2 \pi_M^{MA}}{\partial {c_r}^2} < 0$ *and* $\frac{\partial^2 \pi_R^{MA}}{\partial {c_r}^2} < 0$.
   (b) *for* $\frac{1}{3}\rho_1 < \rho < 1$, $\frac{\partial^2 \pi_M^{MA}}{\partial {c_n}^2} > 0$, $\frac{\partial^2 \pi_R^{MA}}{\partial {c_n}^2} > 0$, $\frac{\partial^2 \pi_M^{MA}}{\partial {c_r}^2} > 0$ *and* $\frac{\partial^2 \pi_R^{MA}}{\partial {c_r}^2} > 0$.
2. *When* $\frac{\theta-1}{1-\delta} > 3$, *for any* $\rho \in (0,1)$, $\frac{\partial^2 \pi_M^{MA}}{\partial {c_n}^2} < 0$, $\frac{\partial^2 \pi_R^{MA}}{\partial {c_n}^2} < 0$, $\frac{\partial^2 \pi_M^{MA}}{\partial {c_r}^2} < 0$ *and* $\frac{\partial^2 \pi_R^{MA}}{\partial {c_r}^2} < 0$.

Corollary 4.

- $\pi_M^{MD*} < \pi_M^{A*}$ *always holds for any* c_n *and* c_r.
- $\pi_R^{MD*} < \pi_R^{A*}$ *if* $c_n > c_{n1-FR}^{MA}$, *otherwise,* $\pi_R^{MD*} > \pi_R^{A*}$.
- $\pi_R^{MD*} < \pi_R^{A*}$ *if* $c_r > c_{r1-FR}^{MA}$, *otherwise,* $\pi_R^{MD*} > \pi_R^{A*}$.

Combining Lemma 5 and Corollary 4, we get the information policies of the manufacturer: $P_M = U$.

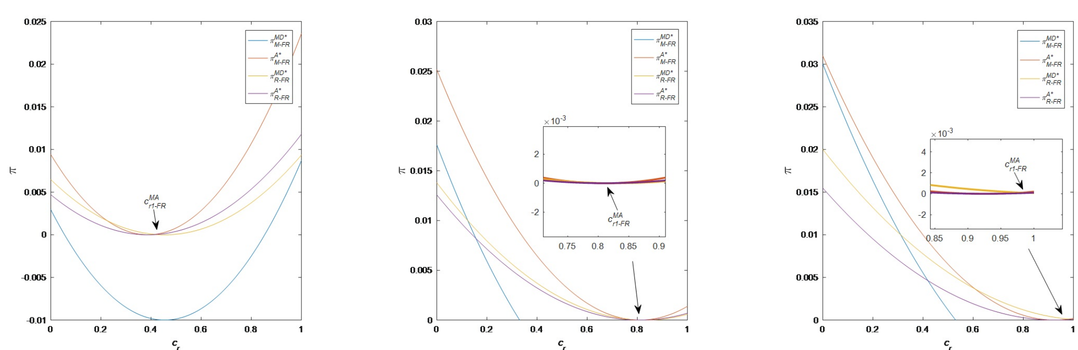
Interestingly, under FR strategy, the impact of information symmetry on supply chain members' profit is stable. Regardless of how the cost of new and remanufactured products changes, the manufacturer always chooses to conceal information. The reason behind this phenomenon could be that the cost of disclosing information and the loss of profit from remanufacturing license fees are always greater than the increase in sales revenue of new products. From the perspective of the AR, there are still two thresholds for the cost of new products and remanufactured products, which make the AR prefer information symmetry. Therefore, in Figures 6 and 7, $c_n > c_{n1-FR}^{MA}$ and $c_r > c_{r1-FR}^{MA}$ are Pareto improvement intervals, where concealing information becomes a more preferred information strategy for both the manufacturer and the AR.



(a) $0 < \frac{\theta-1}{1-\delta} < 3, 0 < \rho < \frac{1}{3}\rho_1$ **(b)** $0 < \frac{\theta-1}{1-\delta} < 3, \frac{1}{3}\rho_1 < \rho < 1$ **(c)** $\frac{\theta-1}{1-\delta} > 3, 0 < \rho < 1$

Figure 6: Profit as a function of c_n under FR strategy

From the perspective of the manufacturer, it will disclose the producer of remanufactured products if and only if the profit under disclosure is higher than that under nondisclosure. Considering that disclosing information can increase consumers' perceived value of new products, intuitively, the manufacturer should always disclose information. Manufacturers are only responsible for the production and sales of new products. However, combining Corollaries 2 to 4, the manufacturer does not always voluntarily disclose information.



(a) $0 < \frac{\theta-1}{1-\delta} < 3, 0 < \rho < \frac{1}{3}\rho_1$ **(b)** $0 < \frac{\theta-1}{1-\delta} < 3, \frac{1}{3}\rho_1 < \rho < 1$ **(c)** $\frac{\theta-1}{1-\delta} > 3, 0 < \rho < 1$

Figure 7: Profit as a function of c_r under FR strategy

6.2 When the AR discloses the information

When we consider information disclosure by ARs, we believe it is costless (Guo, 2009). Because in our model setting, the AR produces remanufactured products, it is easy for the AR to transmit the information of remanufactured product producers to consumers through packaging and other methods.

The manufacturer's and AR's profit functions are as follows:

$$\underset{w_n}{Max}\pi_M^{RD} = (w_n - c_n)\, q_n + r q_r \tag{10}$$

$$\underset{p_n,\ p_r}{Max}\pi_R^{RD} = (p_n - w_n)\, q_n + (p_r - c_r - r) q_r \tag{11}$$

We refer to the situation in this subsection as Model RD.

Proposition 5. *In Model RD with information disclosure by the AR, the manufacturer's and AR's optimal pricing results are as follows:*

- *When $c_r > c_{r2}^B$, the optimal pricing decisions for the manufacturer and the AR are $w_n^{RD*} = \frac{c_n+\theta}{2}$, $p_n^{RD*} = \frac{c_n+3\theta}{4}$ and $p_r^{RD*} = \frac{\delta\rho(c_n+3\theta)}{4\theta}$.*
- *When $c_{r1}^B \le c_r \le c_{r2}^B$, the optimal pricing decisions for the manufacturer and the AR are $w_n^{RD*} = \frac{c_n+\theta}{2}$, $p_n^{RD*} = \frac{c_n+c_r+3\theta-\delta\rho+2r}{4}$ and $p_r^{RD*} = \frac{c_r+\delta\rho+r}{2}$.*
- *When $c_r < c_{r1}^B$, the optimal pricing decisions for the manufacturer and the AR are $w_n^{RD*} = \frac{c_n-c_r+\theta+\delta\rho}{2} - r$, $p_n^{RD*} = \frac{(\theta+\delta\rho)(c_n+c_r)+3\theta-\delta\rho+10\theta\delta\rho}{4(\theta+3\delta\rho)}$ and $p_r^{RD*} = \frac{\delta\rho(c_n+c_r+\theta+5\delta\rho)}{2(\theta+3\delta\rho)}$.*

The manufacturer's optimal royalty fee is as follows:

- *When $c_{r1}^B \le c_r \le c_{r2}^B$, the optimal royalty fee is $r_{PR}^{RD*} = \frac{\delta\rho-c_r}{2}$.*
- *When $c_r < c_{r1}^B$ or $c_r > c_{r2}^B$, the manufacturer's profit is not related to royalty fee, so there is no optimal royalty fee.*

Like in Section 6.1, we provide the following comparative lemma.

Lemma 6. *When model RD and model A are compared, the equilibrium profit behaves as follows:*

1. *In strategy NR, $\pi_M^{RD*} < \pi_M^{A*}$ and $\pi_R^{RD*} < \pi_R^{A*}$ if $c_n > c_{n1-NR}^{RA}$ ($c_{n1-NR}^{RA} = c_{n2-NR}^{MA}$); otherwise, $\pi_M^{RD*} > \pi_M^{A*}$ and $\pi_R^{RD*} > \pi_R^{A*}$.*
2. *In strategy PR:As functions of new product cost, $\pi_M^{RD*} > \pi_M^{A*}$ and $\pi_R^{RD*} > \pi_R^{A*}$ if $c_n < c_{n1-PR}^{RA}$; otherwise, $\pi_M^{RD*} < \pi_M^{A*}$ and $\pi_R^{RD*} < \pi_R^{A*}$.*
   As functions of the remanufactured product cost,
   (a) *When $0 < \delta < \frac{1}{3}$, for any $\theta \in (1, +\infty)$, $\rho \in (0, 1)$, $\pi_M^{RD*} > \pi_M^{A*}$ and $\pi_R^{RD*} > \pi_R^{A*}$ if $c_r > c_{r1-PR}^{RA}$; otherwise, $\pi_M^{RD*} < \pi_M^{A*}$ and $\pi_R^{RD*} < \pi_R^{A*}$.*
   (b) *When $\frac{1}{3} < \delta < 1$,*
      i. *if $1 < \theta < \theta_1$,*
         A. *for $0 < \rho < \rho_2$, $\pi_M^{RD*} > \pi_M^{A*}$ and $\pi_R^{RD*} > \pi_R^{A*}$ if $c_r > c_{r1-PR}^{RA}$; otherwise, $\pi_M^{RD*} < \pi_M^{A*}$ and $\pi_R^{RD*} < \pi_R^{A*}$;*
         B. *for $\rho_2 < \rho < 1$, $\pi_M^{RD*} < \pi_M^{A*}$ and $\pi_R^{RD*} < \pi_R^{A*}$ if $c_r > c_{r1-PR}^{RA}$; otherwise, $\pi_M^{RD*} > \pi_M^{A*}$ and $\pi_R^{RD*} > \pi_R^{A*}$;*
      ii. *if $\theta > \theta_1$, for any $\rho \in (0, 1)$, $\pi_M^{RD*} > \pi_M^{A*}$ and $\pi_R^{RD*} > \pi_R^{A*}$ always hold.*
3. *In strategy FR:As functions of new product cost, $\pi_M^{RD*} > \pi_M^{A*}$ and $\pi_R^{RD*} > \pi_R^{A*}$ if $c_n > c_{n1-FR}^{RA}$, otherwise, $\pi_M^{RD*} < \pi_M^{A*}$ and $\pi_R^{RD*} < \pi_R^{A*}$.*
   As functions of remanufactured product cost, $\pi_M^{RD*} > \pi_M^{A*}$ and $\pi_R^{RD*} > \pi_R^{A*}$ if $c_r > c_{r1-FR}^{RA}$; otherwise, $\pi_M^{RD*} < \pi_M^{A*}$ and $\pi_R^{RD*} < \pi_R^{A*}$.

Similarly, according to Lemma 6, observing the information policies of the AR under three remanufacturing strategies when it is the subject of information disclosure decisions is not difficult.

Corollary 5. *The AR's information disclosure policies under NR strategy are as follows:*

$$P_{R-NR} = \begin{cases} D, & if\ c_n < c_{n1-NR}^{RA} \\ U, & otherwise \end{cases}$$

The AR's information disclosure policies under PR strategy are as follows:

$$P_{R-PR} = \begin{cases} D, & \begin{cases} if\ \frac{1}{3} < \delta < 1\ and\ \theta > \theta_1, \\ or\ c_r > c_{r1-PR}^{RA}\ and\ \frac{1}{3} < \delta < 1\ or\ \theta > \theta_1, \\ or\ c_n < c_{n1-PR}^{RA}. \end{cases} & U,\ otherwise. \end{cases}$$

The AR's information disclosure policies under FR strategy are as follows:

$$P_{R-FR} = \begin{cases} D, & if\ c_n > c_{n1-FR}^{RA} \\ U, & otherwise \end{cases}$$

Comparing Corollary 5 with Corollaries 2 to 4, we find that the perceived value effect caused by information symmetry has no effect on the subject of information disclosure decisions from manufacturer to AR. Under the three remanufacturing strategies, only the threshold of the product cost changes.

Intuitively, suppliers may be reluctant to disclose the unfavorable quality of low-quality products. Previous studies also show that low-quality suppliers prefer not to disclose unfavorable quality (Board, 2009; Kuksov and Lin, 2010). Of course, some studies suggest that remanufacturers are always willing to disclose their quality information (Zhang et al., 2022). However, according to Corollary 5, the AR does not always choose to disclose or conceal information similar to that of the manufacturer. In particular, the optimal information decisions of the manufacturer and the AR are consistent, which means that there is no possibility of Pareto improvement when the AR makes disclosure decisions.

In addition, the manufacturer may be a free rider when the AR discloses information and the manufacturer does not. Comparing the conditions in Corollaries 2 to 4 and Lemma 6, we have the following result, which is different from those of previous studies (Zhang et al., 2022).

Corollary 6. *The manufacturer is not always a free rider when the AR discloses information about remanufactured product producers.*

We use the conclusion part of strategy NR in Corollary 2 and Lemma 6 to illustrate this finding. When $c_n > c_{n2-NR}^{MA}$, both the manufacturer and the AR choose to conceal information when making information disclosure decisions. When $c_{n1-NR}^{MA} < c_n < c_{n2-NR}^{MA}$, the manufacturer chooses to conceal information, but the AR chooses to disclose information. In both of these scenarios, there is no free-riding effect. However, when $c_n < c_{n1-NR}^{MA}$, if the manufacturer and the AR are independent decision-makers in information disclosure, both prefer to choose to disclose information. For the manufacturer, owing to the additional cost of disclosing information, the information symmetry achieved through the AR's disclosure makes it a free rider.

Recalling the boundary conditions given in Figure 2 for the symmetric and asymmetric information cases, there are some areas where the manufacturer or the AR adopts different remanufacturing strategies in situations of information symmetry and asymmetry, i.e., R_1, R_3 and R_4. In the R_1 region, under information symmetry, the AR adopts the FR strategy, whereas under information asymmetry, the AR adopts the PR strategy. The subscript *FP* is added to describe this situation. Similarly, there are *PF* and *NP*. With each member's profit in Propositions 1 to 5, we can summarize the results, as shown in Lemmas 7 to 9.

Lemma 7. *When the manufacturer/AR adopt the FR strategy in information symmetry and the PR strategy in information asymmetry, when the model MD/RD and model A are compared, the equilibrium profit behaves as follows:*

- *When the manufacturer discloses information,* $\pi^{MD*}_{M-FR} < \pi^{A*}_{M-PR}$ *always holds.* $\pi^{MD*}_{R-FR} < \pi^{A*}_{R-PR}$ *if* $c_n > c^{MA}_{n1-FP}$ *or* $c_n < \bar{c}^{MA}_{n1-FP}$*; otherwise,* $\pi^{MD*}_{R-FR} > \pi^{A*}_{R-PR}$.
- *When the AR discloses information,* $\pi^{RD*}_{M-FR} < \pi^{A*}_{M-PR}$ *and* $\pi^{RD*}_{R-FR} < \pi^{A*}_{R-PR}$ *if* $c_n > c^{RA}_{n2-FP}$ *or* $c_n < \bar{c}^{RA}_{n2-FP}$*; otherwise,* $\pi^{RD*}_{M-FR} > \pi^{A*}_{M-PR}$ *and* $\pi^{RD*}_{R-FR} > \pi^{A*}_{R-PR}$.

Lemma 8. *When the manufacturer or the AR adopts the PR strategy in information symmetry and the FR strategy in information asymmetry, comparing model MD/RD and model A, the equilibrium profit behaves as follows:*

When the manufacturer discloses information,

1. *if* $\theta < \theta_2$,
   (a) *for* $0 < \rho < \rho_3$, $\pi^{MD*}_{M-PR} > \pi^{A*}_{M-FR}$ *and* $\pi^{MD*}_{R-PR} > \pi^{A*}_{R-FR}$ *always hold.*
   (b) *for* $\rho_3 < \rho < 1$, $\pi^{MD*}_{M-PR} > \pi^{A*}_{M-FR}$*, if* $c_n > c^{MA}_{n1-PF}$ *or* $c_n < \bar{c}^{MA}_{n1-PF}$*; otherwise,* $\pi^{MD*}_{M-PR} < \pi^{A*}_{M-FR}$. $\pi^{MD*}_{R-PR} > \pi^{A*}_{R-FR}$ *always holds.*
2. *if* $\theta > \theta_2$*, for any* $\rho \in (0,1)$, $\pi^{MD*}_{M-PR} > \pi^{A*}_{M-FR}$ *and* $\pi^{MD*}_{R-PR} > \pi^{A*}_{R-FR}$ *always hold.*

When the AR discloses information,

1. *if* $\theta < \theta_2$,
   (a) *for* $0 < \rho < \rho_3$, $\pi^{RD*}_{M-PR} > \pi^{A*}_{M-FR}$ *and* $\pi^{RD*}_{R-PR} > \pi^{A*}_{R-FR}$ *always hold.*
   (b) *for* $\rho_3 < \rho < 1$, $\pi^{RD*}_{M-PR} > \pi^{A*}_{M-FR}$ *and* $\pi^{RD*}_{R-PR} > \pi^{A*}_{R-FR}$ *always hold.*
2. *if* $\theta > \theta_2$*, for any* $\rho \in (0,1)$, $\pi^{RD*}_{M-PR} > \pi^{A*}_{M-FR}$ *and* $\pi^{RD*}_{R-PR} > \pi^{A*}_{R-FR}$ *always hold.*
   Here, $\rho_3 = \frac{\theta-1}{5\delta+3}$, $\theta_2 = 5\delta + 4$.

Lemma 9. *When the manufacturer or the AR adopts strategy NR in information symmetry and strategy PR in information asymmetry, comparing model MD/RD and model A, the equilibrium profit behaves as follows:*

- *When the manufacturer discloses information,* $\pi^{MD*}_{M-NR} < \pi^{A*}_{M-PR}$ *always holds.* $\pi^{MD*}_{R-NR} < \pi^{A*}_{R-PR}$ *if* $c_n > c^{MA}_{n1-NP}$ *or* $c_n < \bar{c}^{MA}_{n1-NP}$*; otherwise,* $\pi^{MD*}_{R-NR} > \pi^{A*}_{R-PR}$.
- *When the AR discloses information,* $\pi^{RD*}_{M-NR} < \pi^{A*}_{M-PR}$ *and* $\pi^{RD*}_{R-NR} < \pi^{A*}_{R-PR}$ *if* $c_n > c^{RA}_{n2-NP}$ *or* $c_n < \bar{c}^{RA}_{n2-NP}$*; otherwise,* $\pi^{RD*}_{M-NR} > \pi^{A*}_{M-PR}$ *and* $\pi^{RD*}_{R-NR} > \pi^{A*}_{R-PR}$.

Compared with Lemmas 3 to 9, we obtain insight into disclosure incentives. Considering the impact of product costs on information disclosure decisions by the manufacturer or the AR, the product perceived value effect has an effect only in extreme situations, for example, $\theta > \theta_1$ in Corollary 5 and Lemma 6 and $\theta > \theta_2$ in Lemma 9. Excluding these extreme situations, regardless of the perceived value effect, the impact of product costs on information disclosure decisions is stable and consistent.

With respect to the free rider effect, Lemmas 7 to 9 indicate that when the AR adopts different remanufacturing strategies under information symmetry and asymmetry, only when the product cost is moderate, can the manufacturer become a free rider.

7 Conclusion

ConclusionIn this work, we establish a closed-loop supply chain model that includes one manufacturer and one authorized remanufacturer. The manufacturer signs a remanufacturing license contract with the AR to authorize it to remanufacture, while each supply chain member independently makes decisions on remanufactured product producer information disclosure and products pricing. We provide several new insights into the issue of information asymmetry in remanufacturing. First, regarding the manufacturer's remanufacturing license fee, we compare licensing fee decisions under information symmetry and asymmetry, when the AR adopts a partial remanufacturing strategy, information symmetry leads to a decrease in the optimal remanufacturing license fee. When the AR is constrained by remanufacturing cost or the quantity of new products and chooses no remanufacturing or full remanufacturing strategies, license fee no longer has an effect on the manufacturer's profits. Second, by comparing the boundary conditions of remanufacturing strategies under information symmetry and asymmetry, we find that under most conditions, the AR adopts consistent remanufacturing strategies. However, there are still some remanufacturing cost conditions that cause the AR to change from one remanufacturing strategy under information asymmetry to another under information symmetry, which means that information symmetry can change the AR's remanufacturing strategy. Third, regarding pricing decisions, when the AR adopts no remanufacturing and partial remanufacturing strategies, the impact of information symmetry on the pricing decisions of the manufacturer and the AR is stable. However, when the AR adopts full remanufacturing strategy, there is a threshold (net gain value of product perceived value under information symmetry) for consumer recognition of remanufactured products, which changes this impact. The endogeneity of remanufacturing license fee does not change this impact. Fourth, considering that the manufacturer and the AR independently make information disclosure decisions, we find that in the presence of the consumer perceived value effect, regardless of the AR's remanufacturing strategy (even the no remanufacturing strategy), both the manufacturer and the AR are motivated to conceal or disclose information about the remanufactured product producer. Furthermore, unlike previous studies, we find that the manufacturer is not always the free rider if the AR makes information disclosure decisions.

A potential extension of current research is to consider that information disclosure by ARs is also cost-effective and different from that of manufacturers. Consumer heterogeneity is currently an issue not considered in this article, and the presence of green consumers who prefer remanufactured products is a potential setting. In addition, this study verifies the partial existence of the free-riding effect of manufacturers in remanufacturing when considering changes in consumer perceived value, and further exploration of the impact of this effect on AR information decision-making can be considered.

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