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REMANUFACTURING STRATEGY WITH DESIGN FOR THE ENVIRONMENT UNDER ASYMMETRIC DEMAND INFORMATION

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Abstract. The encroachment of a remanufacturer not only intensifies market competition but also affects the manufacturer's adoption of Design for the Environment (DfE) in its product manufacturing process. Although the manufacturer typically holds an information advantage regarding market demand and is therefore expected to respond readily to the remanufacturer's encroachment, the specific interaction mechanisms remain unclear. Motivated by this observation, we examine the implications of remanufacturer encroachment in the presence of both DfE and asymmetric demand information. By developing a signaling game model, we derive several insightful findings. First, contributing to the ongoing debate on the impact of remanufacturing, this study supports the negative view by demonstrating that encroachment by an independent remanufacturer (IR) consistently reduces the profit of the independent manufacturer (IM), irrespective of the information structure. Second, contrary to conventional wisdom, the IR may benefit from being informationally disadvantaged, achieving higher profits than under a full-information scenario. This finding offers a novel perspective for the informed IM: by sharing information, the IM can prevent the IR from making quantity decisions that would inadvertently intensify competition. Third, through numerical analysis with data from parameter values that are in line with reality, we find that the dual signal mechanism may be more beneficial for the IM than the single signal mechanism. Taken together, these findings underscore the need for remanufacturing stakeholders to carefully evaluate the multifaceted effects of DfE on IR behavior and to fully account for the critical role of information structure in strategic interactions.

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1. Introduction

With the rapid advancement of science and technology, remanufacturing has become a widely adopted sustainable production mode across various industries, including automotive parts, electronics, and paper products. As a key strategy for promoting circular economy and improving resource efficiency, remanufacturing enables the recovery of valuable materials from end-of-life products for use in the production of new ones, thereby reducing resource waste and alleviating environmental burdens. For instance, each recycled iPhone 14 contains approximately \$3.5 worth of recoverable gold, silver, and rare earth elements, while an older MacBook Pro can

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yield nearly $12 in precious metals. When scaled to millions of devices, the total recoverable value embedded in these materials amounts to several hundred million dollars[1]. Another case is United Microelectronics Corporation (UMC), which, through its Circular Economy and Recycling Innovation Centre, converts waste into economically valuable recycled resources. This initiative is expected to reduce waste by 15,000 metric tonnes annually and generate approximately NT$100 million in economic value[2]. Furthermore, remanufacturing is also recognized for its contribution to carbon neutrality [93], attracting an increasing number of firms to adopt this circular model – particularly in a context where governments are placing greater emphasis on corporate carbon emissions [65].

Despite the well-documented environmental and cost advantages of remanufacturing, its competitive implications remain a subject of ongoing scholarly debate. Remanufacturing activities are typically undertaken by specialized independent remanufacturers. Some scholars argue that the introduction of remanufactured products intensifies market competition with original products, thereby reducing the profitability of original equipment manufacturers (OEMs) [69, 74]. In response to such competitive pressure, many OEMs have considered entering the remanufacturing market themselves [38]. However, due to steep learning curves and the operational complexities stemming from a lack of remanufacturing expertise, such strategic initiatives have often yielded unsatisfactory outcomes. For example, Ford ultimately withdrew from remanufacturing, citing prohibitive initial costs associated with inexperience, and chose to refocus its resources on its core original production activities [20]. In contrast, other researchers contend that the presence of remanufactured products may expand the overall addressable market, enhance consumer awareness of the product, and ultimately benefit OEMs [23, 77]. These divergent findings suggest that the impact of remanufacturer encroachment on OEMs warrants further investigation.

In addition, in light of mounting environmental concerns and increasingly stringent regulatory pressures, a growing number of manufacturers are integrating environmental considerations into the product design phase by adopting Design for the Environment (DfE) strategies, thereby enhancing product sustainability [43, 63]. Currently, DfE has been widely adopted across various industries. For instance, Inditex systematically adopts green materials in its production processes and strategically sources its raw materials from regenerative agriculture, organic farming practices, and recycling technologies in response to consumers' growing demand for environmentally friendly products[3]. In Canon's product design, reusable and recyclable materials are being incorporated into production. Similarly, Hewlett-Packard has integrated recyclability into its product design phase. As a design philosophy encompassing the entire product lifecycle, DfE aims to reduce resource consumption and production costs. However, the implementation of DfE also presents manufacturers with a novel strategic dilemma. On the one hand, DfE improves resource efficiency and reduces the carbon emissions of production through optimized product design [18]; On the other hand, DfE simultaneously improves recycling efficiency and remanufacturing potential, lowering the technological barriers for remanufacturers [21], thereby potentially intensifying market competition between manufacturers and remanufacturers. Consequently, a key challenge for manufacturers implementing DfE lies in balancing the sustainability gains against the competitive risks posed by remanufacturers. And the role of DfE in the implications of remanufacturer encroachment on OEMs is still unclear.

In practice, manufacturers often possess superior knowledge of market demand compared with remanufacturers because they initiate the production and selling process of the product and hold deeper market insights, and are typically reluctant to share such sensitive information with remanufacturers due to the competition threaten, leading to information asymmetry [70]. Given their information advantages, manufacturers are expected to occupy a dominant position, enabling them to readily address the impacts of remanufacturer encroachment. However, neither prior literature nor industry practice has elucidated the specific coping strategies through which such advantages translate into effective responses. Most studies on remanufacturing have focused on strategic decisions under full information, with some also examining the effects of DfE [21, 80]. Only a limited number of publications address information asymmetry in the remanufacturing context [19, 33]. Our research

[1] https://www.recycleoldtech.com/blog/hidden-gold-rush.
[2] https://www.umc.com/en/Html/latest_newsletters/HasLeftContent/20260205-2.
[3] https://www.inditex.cn/itxcomweb/es/en/sustainability.

is most related to the studies of Wei *et al.* [75], Huang *et al.* [37] and Zhao *et al.* [89]. Wei *et al.* [75] analyzed optimal pricing and collection rate decisions under different information structures in a closed-loop supply chain involving a manufacturer and a retailer. But they do not address the issue of information asymmetry between manufacturers and remanufacturers. Huang *et al.* [37] and Zhao *et al.* [89] considered information asymmetry regarding remanufacturing costs between manufacturers and remanufacturers in contexts where original equipment manufacturers (OEMs) outsource remanufacturing activities to third-party remanufacturers (3PRs). With the rapid development of the remanufacturing industry, a substantial number of professional remanufacturers independent of OEMs have emerged [60]. These independent remanufacturers autonomously handle the collection, disassembly, remanufacturing, and resale of end-of-life products. The issue of demand information asymmetry between independent manufacturers and such independent remanufacturers has yet to receive adequate academic attention.

In response to this research gap, this study incorporates the independent manufacturer's (IM) DfE decisions into a signaling game framework to systematically investigate the strategic interactions between the IM and the independent remanufacturer (IR) under demand information asymmetry. Specifically, the following research questions are addressed:

(i) How does the IR determine its encroachment strategy under different information structures and signaling modes, and how is the encroachment strategy influenced by the IM's DfE efforts?
(ii) What are the impacts of the remanufacturer encroachment strategy on quantity decisions and profits of the manufacture under varying information structures and signaling modes?
(iii) How do the information structure and signaling mode influence equilibrium quantity decisions and the profitability of supply chain members? What implications can be drawn for information management?

To address these questions, we model the strategic interaction as a signaling game between a manufacturer (the signal sender) and a remanufacturer (the signal receiver). The model incorporates Design for the Environment (DfE) decisions into the signaling game framework, thereby revealing how the manufacturer's quantity decision and sustainability investment influence the remanufacturer's informational inferences. Furthermore, it seeks to provide a theoretical foundation for managers seeking to balance the sustainability gains from DfE against the competitive challenges posed by remanufacturers. Our analysis yields several interesting results.

Conventional wisdom suggests that a higher level of Design for the Environment (DfE) undertaken by the manufacturer may increase the remanufacturer's production and thereby intensify market competition by facilitating product recyclability. However, our results reveal the opposite: due to the marginal effect of DfE[4], an increase in the DfE level can actually reduce the remanufacturer's production. This finding opens up a new pathway for manufacturers to mitigate the negative impacts of remanufacturer encroachment – namely, by leveraging the potential harm that DfE may impose on the remanufacturer and reinforcing their investment in DfE.

We find that a manufacturer can mitigate the profit losses induced by a remanufacturer's competitive encroachment by sharing market information with the remanufacturer. In contrast to Huang and Wang [34], who examine information sharing between an original equipment manufacturer (OEM) and a retailer, the present study extends the context to a co-opetitive relationship between a manufacturer and a remanufacturer. In this setting, the manufacturer's incentive to share information lies in guiding the remanufacturer to reduce excessive production by alleviating the latter's demand uncertainty, which is consistent with the findings of Huang and Wang [34]. However, the effectiveness of information sharing in our study depends on the information transmission cost, consumers' valuation of remanufactured products, and the marginal effect of Design for the Environment (DfE). Thus, our results validate that, as long as competition is taken into account, the operational practice of information sharing – observed in real-world manufacturers and remanufacturers – is moving in the right direction.

Our results further indicate that a manufacturer's private information may unintentionally benefit the remanufacturer at the expense of the manufacturer's own profit during the information transmission process, particularly as the marginal effect of DfE intensifies. To address this dilemma, this study examines the moderating

[4] The Marginal Effect of DfE: The marginal change in manufacturing cost per unit increase in the Design for Environment level.

role of a dual-signal mode, which enables the manufacturer to more accurately separate demand types, thereby preventing the remanufacturer from misinterpreting the quantity signal and reducing inefficient production expansion. Our findings caution manufacturers to carefully leverage private information as a tool to cope with remanufacturer encroachment.

The subsequent sections of this paper are arranged as follows. Section 2 reviews the related literature. Section 3 shows the basic model setup and assumptions. Section 4 analyzes the remanufacturer's entry strategies under both complete and asymmetric information scenarios. In Section 5, the case of asymmetric information with dual signal is explored. Finally, Section 6 presents conclusions and research prospects. The proofs are provided in the appendix.

2. Literature review

Our literature review revolves around the following streams: closed-loop supply chain management, DfE within recycling channel structures, and information asymmetry among supply chain members.

2.1. Closed-loop supply chain management

Closed-loop supply chains have emerged as a significant research topic in the field of sustainable operations management. The existing literature primarily focuses on reverse channel coordination [31, 78], pricing for remanufactured products [2, 40, 44], the impacts of remanufacturing activities [9, 32], and closed-loop supply chain network design [24,26]. In addition, remanufacturing strategies have attracted considerable attention. Lin *et al.* [51] analyzed the impact of lifecycle dynamics of new products and after-sales service demand on firms' remanufacturing strategies. Lin *et al.* [52] further introduced delayed network effects to explore the underlying mechanisms influencing the selection of remanufacturing strategies. Zhang *et al.* [84] investigated manufacturers' investments in smart manufacturing and their subsequent choices of remanufacturing strategies. Reimann *et al.* [64] examined the effectiveness of product process innovation in reducing variable remanufacturing costs. Our research is most closely related to the studies by Zhang *et al.* [84] mentioned above; however, remanufacturing is conducted by the manufacturer to some extent but not by the independent remanufacturer, in these studies; moreover, information asymmetry is not considered.

A growing body of recent literature has also integrated low-carbon considerations into closed-loop supply chain management [47, 55, 81, 88]. For instance, Li *et al.* [49] examined the synergistic effects of carbon taxes and tariffs in cross-border closed-loop supply chains. Li *et al.* [48] discussed optimal decisions for hybrid manufacturing and remanufacturing systems under carbon tax and trade-in scheme scenarios. Liu *et al.* [54] analyzed operational decisions for authorized remanufacturing in leasing models under carbon cap-and-trade regulations. Shokouhifar *et al.* [67] applied the exergy accounting method to closed-loop food supply chain management, offering a novel perspective for assessing resource utilization efficiency and environmental impact. This research stream typically assumes that manufacturers and remanufacturers possess the same information regarding consumer demand. In reality, however, manufacturers – who usually bring products to market first – often have superior market forecasting capabilities and thus enjoy a first-mover advantage through private knowledge of true market demand. Our research contributes to this literature by explicitly modeling this information asymmetry. Specifically, we develop a signaling game in which a manufacturer can use its new product quantity and DfE level as signals to either reveal or conceal market information from a remanufacturer. Our model captures the manufacturer's information advantage and demonstrates that asymmetric information indeed exerts a non-negligible impact on the manufacturing strategies of both new and remanufactured products.

2.2. DfE within recycling channel structures

DfE has garnered increasing scholarly attention [25, 61, 66, 73]. Conceptually, the DfE is similar to product green design or production process innovation [13,63]. Zhu and He [94] argued that supply chain structure, green product attributes, and product demand competition are the factors affecting the degree of product greenness. Cai *et al.* [10] examined the environmental taxes' effect on the DfE and production decisions. Jackson *et al.*

[39] further studied DfE's effect on environmental and economic performance. A subset of the literature has integrated DfE into remanufacturing contexts. Subramanian *et al.* [68] considered the related decisions in two cases where the remanufacturing is carried out by the manufacturer and the remanufacturer respectively. Liu *et al.* [53] further conducted a comparative analysis of the impacts of process innovation and recycling innovation on firms' sustainable operations. Li *et al.* [46] and Atasu and Souza [4] studied how new product design can be influenced by the remanufacturing strategy.

Our research is most similar to the study of Feng *et al.* [21], who considered the effect of DfE on production decisions in a remanufacturing setting. However, their paper investigates the DfE and remanufacturing strategies under full information. Different from Feng *et al.* [21], our research demonstrates that the influence of DfE on remanufacturing strategies varies significantly under different information structures. Besides, our research is also related to the study of Raz *et al.* [63], who incorporated demand uncertainty in their model of production and DfE decisions. But their work did not account for remanufacturing. Our work makes contributions to this stream by explicitly incorporating asymmetric demand information in a closed-loop supply chain. More significantly, this paper makes a substantial contribution by showing that the DfE can be a weapon for manufacturers to resist competition from remanufacturers.

2.3. Information asymmetry among supply chain members

Information asymmetry among supply chain members represents a prominent stream of research in operations management. Existing studies have extensively examined this issue, particularly between manufacturers/suppliers and retailers [16,36,57,59] or between retailers and consumers [6,29]. In recent years, scholars have extended the discussion of information asymmetry to the remanufacturing context. The impact of information asymmetry on remanufacturing strategies has abtained a thorough discussion. Wang *et al.* [72] treated manufacturers' fairness concerns as private information, revealing its impact on closed-loop supply chain performance. Bin *et al.* [8] examined how information opacity in remanufacturing processes influences consumer purchase intentions. Zhao *et al.* [91] analyzed the impact of information asymmetry in remanufacturing green advertising on third-party recycling pricing and collection volume.

To address the negative impacts caused by information asymmetry, previous literature mainly focuses on two perspectives: operation strategy or optimization method. On the operation strategy side, Li *et al.* [50] considered the problem of stable service portfolio composition and optimal selection under quality uncertainty in the context of cloud remanufacturing; Zhao and Zhou [87] developed a game-theoretic model to analyze remanufacturing strategies for green defective products under output information asymmetry. On the optimization method side, Guo *et al.* [30] employed deep learning to cope with uncertainty and optimize closed-loop remanufacturing supply chain operation under government incentives; Nadar *et al.* [58] modeled remanufacturing systems as a Markov decision process to address quality uncertainty in used parts procurement; Goli *et al.* [27] proposed a robust framework combining possibilistic programming and simulation optimization to handle demand and time fuzziness in organ transplant supply chain design using credibility theory. However, none of the existing research has paid attention to information asymmetry regarding demand between independent manufacturers and independent remanufacturers.

Furthermore, few studies have incorporated DfE – a critical strategy – into the analytical framework of the closed-loop supply chain with information asymmetry. While Wei *et al.* [75] and Zhao *et al.* [90] analyzed the impact of information asymmetry on equilibrium pricing and recycling decisions within the context of closed-loop supply chains, neither study considered DfE factors. Therefore, this study characterizes information asymmetry as the disparity in demand information between independent manufacturers and independent remanufacturers, and incorporates the independent manufacturer's DfE decisions into a signaling game framework to reveal the strategic behaviors between the two parties.

In summary, the existing literature has typically investigated remanufacturing strategies with DfE under complete information or explored the impacts of information asymmetry between manufacturer/retailer and consumers in closed-loop supply chain, while this study incorporates both the product's DfE level and asymmetric demand information into a unified remanufacturing model. Our results provide managerial implications through delving into the impacts of remanufacturer encroachment on the decisions and profitability of supply chain members. Furthermore, we provide a nuanced analysis of the distinct effects of DfE. Crucially, by examining how different information structures and signaling modes influence the production quantities and profits of both the IM and the IR, this study also offers valuable insights for information management.

3. Model setup

Asymmetric demand information is prevalent in supply chains [71,83]. As a classical theoretical framework for analyzing dynamic interactions under information asymmetry, signaling games characterize how the informed party (the signal sender) strategically transmits private information through observable actions, and how the uninformed party (the signal receiver) updates its beliefs and responds optimally based on observed signals. This framework thus reveals the patterns of strategic interaction under incomplete information and shows information transmission. Adopting this theoretical perspective, we model market demand size as the manufacturer's private information and examine the quantity decisions of both the independent manufacturer (IM) and the independent remanufacturer (IR) under different information structures.

Meanwhile, design for the environment has also received considerable attention in the field of sustainable operations [28]. In line with this, we take green design as the starting point and consider the production decisions of IM and IR with the awareness of design for the environment. DfE contributes to lowering the production costs for both parties, thereby playing a critical role throughout the manufacturing and remanufacturing processes. Our model includes the most indispensable factors in the real production process in practice involving remanufacturing and puts forward meaningful and reasonable advice on production for IM and IR.

We consider a decentralized decision-making framework with an independent manufacturer (IM, referred to as "she") and an independent remanufacturer (IR, referred to as "he"). The exclusion of a retailer simplifies the analytical process without altering the qualitative insights. Both the IM and the IR sell their products to consumers directly in a single period. To analyze the IR's market encroachment decisions, we set that the remanufactured product can be produced after the IM sells the new products. This is consistent with the study of Agrawal *et al.* [1]. Thus, the IR can enter the market once the IM makes the quantity decision (We assume the new products will be sold immediately after the quantity decision). The new product quantity produced by the IM is q_n. The DfE level of new product e is decided by the IM, and $0 < e < 1$[5]. The investment cost in product's DfE is quadratic and satisfies $F(0) = 0$, $\frac{\mathrm{d}F(e)}{\mathrm{d}e} > 0$, and $\frac{\mathrm{d}^2F(e)}{\mathrm{d}e^2} > 0$. We assume $F(e) = \frac{ke^2}{2}$ and $k > 0$ to represent the scale coefficient therein. This assumption and the quadratic function form have been widely used in the literature [63,76]. To exclude the impossible case that the IM set an excessively high DfE level, we let $k > \frac{(-2c_n\beta_1+c_r\beta_2)^2}{4(2-\phi)}$. Besides, we let c_n be the new product's unit production cost and c_r be the remanufactured product's unit production cost[6], where $c_n > c_r$. This is consistent with Ferguson and Toktay [22] and Xiong *et al.* [79]. Given that the DfE of products can decrease all products' marginal production costs, we assume the production costs after environmental design are inversely proportional to e, *i.e.*, $\tilde{c}_n(e) = (1 - \beta_1 e)c_n$ and $\tilde{c}_r(e) = (1 - \beta_2 e)c_r$, where $\beta_1, \beta_2 > 0$ and $\beta_1 > \beta_2$[7]. β_1 and β_2 represent the marginal effect of DfE on the costs of new and remanufactured products, respectively. This cost reduction assumption aligns with the setting of Raz *et al.* [63].

In reality, due to different perceived values of consumers, consumers usually pay higher prices for new products than for remanufactured ones. To capture the differential consumer valuation for new and remanufactured products, we let p_n and p_r denote the prices of new and remanufactured products, respectively, with $p_n > p_r$, consistent with Xiong *et al.* [79] and Ferguson and Toktay [22]. We set v as willingness of consumers to purchase one unit of the new product and to be distributed uniformly over $[0, \alpha_i]$, *i.e.*, $v \sim U(0, \alpha_i)$, and ϕv as consumers'

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[5] e also can be explained as the environment-friendly rate of the product. e approaching 1 means the product is nearly 100% environment-friendly; e approaching 0 means the product is totally environmentally harmful.

[6] Here, remanufactured cost c_r includes the cost of recycling.

[7] DfE is determined by IM according to new products, so DfE will reduce the cost of new products to a greater extent than remanufactured products.

Table 1. Notations.

Symbol	Definition
v	Consumers' valuation to new products.
ϕv	Consumers' valuation to remanufactured products, $0 < \phi < 1$ is a discount factor.
c_n	New product's unit production cost.
c_r	Remanufactured product's unit production cost.
β_1	The marginal reduction of new products' production cost due to DfE, $0 < \beta_1 < 1$.
β_2	The marginal reduction of remanufactured products' production cost due to DfE, $0 < \beta_2 < 1$.
$\tilde{c}_n$	New product's unit production cost with the DfE.
$\tilde{c}_r$	Remanufactured product's unit production cost with the DfE.
e	DfE level, $0 < e < 1$.
k	The investment function's scale parameter.
q_n	Quantity of new product decided by manufacturer.
q_r	Quantity of remanufactured product decided by remanufacturer.
α_i	$i = h, l$. The market size, with probability λ being a high type ($\alpha = \alpha_h$) and with probability $1 - \lambda$ being a low type ($\alpha = \alpha_l$), where $0 < \alpha_l < \alpha_h$.

willingness to purchase one unit remanufactured product, where ϕ is a discount factor and $0 < \phi < 1$ [74]. Consequently, the utility of consumers with purchasing one unit of new product is $v - p_n$, and that from purchasing one-unit remanufactured product is $\phi v - p_r$. It's only at $v - p_n > \phi v - p_r$ and $v - p_n \geq 0$ that consumers prefer to buy the new products, and at $\phi v - p_r > v - p_n$ and $\phi v - p_r > 0$ that consumers tend to purchase remanufactured products. Thus, the inverse demand functions for new and remanufactured products can be derived as follows:

$$p_n = \alpha_i - q_n - \phi q_r, \tag{1}$$

$$p_r = \phi(\alpha_i - q_n - q_r), \tag{2}$$

where $\alpha_i (i = h, l)$ is the market size. Owing to its established market presence, the IM is typically better equipped to ascertain the true market size, whereas the IR has access only to its prior distribution. Following the literature on signaling games [3, 41, 42, 45], we consider that the market size α is random and ex-ante uncertain, with probability of λ being a high type ($\alpha = \alpha_h$) and probability of $1 - \lambda$ being a low type, where $\alpha_h > \alpha_l > 0$. So $\mu = \lambda\alpha_h + (1 - \lambda)\alpha_l$ is the expected market size. Table 1 summarizes the key notations used in our analysis.

The sequence of the game is illustrated in Figure 1. First, the IM decides the level of DfE. Then, the IM decides new products' quantity q_n before the selling season begins. After that, IR can know q_n through observing new products' quantity on the market, based on which he will update the belief of the market size and decide whether to encroach on the market and remanufactured product's quantity q_r if choosing to encroach. Finally, each consumer decides to purchase a new product, a remanufactured product, or nothing.

4. Analysis

To explore the influence of remanufacturing in different information structures, we first establish a benchmark scenario in Section 4.1, where both the IM and the IR have complete information about the market size. Then, in Section 4.2, we analyze the asymmetric information scenario, in which the IM possesses private information about the market size, while the IR has access only to its prior distribution.

4.1. Full information

When both the IM and IR know the true market size, they can make decisions according to this size. We use superscript "f" to represent this scenario. Given the real market size α_i, the manufacturer decides the new

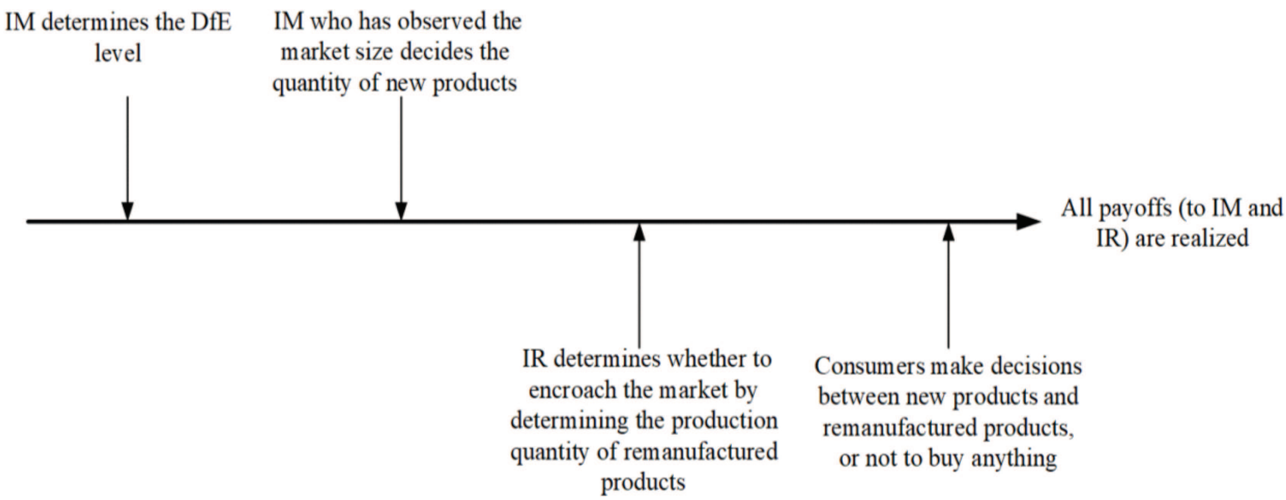

FIGURE 1. Sequence of events.

product quantity q_n to maximize her profit

$$\pi_M = q_n((\alpha_i - q_n - \phi q_r) - (1-\beta_1 e)c_n) - \frac{ke^2}{2}, \qquad i = h, l, \tag{3}$$

at the beginning of the selling season. Then the remanufacturer decides his optimal product quantity with his profit

$$\pi_R = q_r(\phi(\alpha_i - q_n - q_r) - (1-\beta_2 e)c_r), \qquad i = h, l. \tag{4}$$

Our analysis is based on backward induction to get the solutions of the above models. Therefore, we first get the equilibrium quantities q_r as

$$q_r^f = \frac{-c_r + c_r e\beta_2 - q_n\phi + \phi\alpha_i}{2\phi}, \qquad i = h, l. \tag{5}$$

First, we consider the case where IR does not encroach, that is, $q_r^f = 0$. We can get the optimal quantities, and the outcome is given in Lemma 1.

Lemma 1. *Without the encroachment of IR, the optimal quantity decision of the IM is* $q_n = \frac{1}{2}(-c_n + c_n e\beta_1 + \alpha_i)$.

Next, we consider the case of the IR encroaching the market. The equilibrium outcomes are expressed in Lemma 2.

Lemma 2. *Under full information, the IM's optimal quantity is* $q_n^f = \frac{2c_n - c_r - 2c_n e\beta_1 + c_r e\beta_2 - (2-\phi)\alpha_i}{2(-2+\phi)}$, *and the IR's optimal quantity is* $q_r^f = \frac{c_r(-1+e\beta_2)(-4+\phi) + 2c_n(-1+e\beta_1)\phi + (-2+\phi)\phi\alpha_i}{4(-2+\phi)\phi}$, *where* $i = h, l$.

Lemma 2 shows that the optimal quantities decided by the IM and IR are both related to the true market size. The different market sizes have the same effect on the optimal quantities of new and remanufactured products. Furthermore, the analysis indicates that encroachment is more beneficial for the IR than the non-encroachment scenario, albeit at the expense of the IM's profits. To illustrate these findings graphically, Figures 2 and 3 depict the impact of IR market entry on the IM's production quantity and profit, respectively, under full information with reasonable parameter values $\alpha_h = 0.9$, $\alpha_l = 0.7$, $\phi = 0.9$, $\beta_1 = 0.7$, and $\beta_2 = 0.5$. These parameter

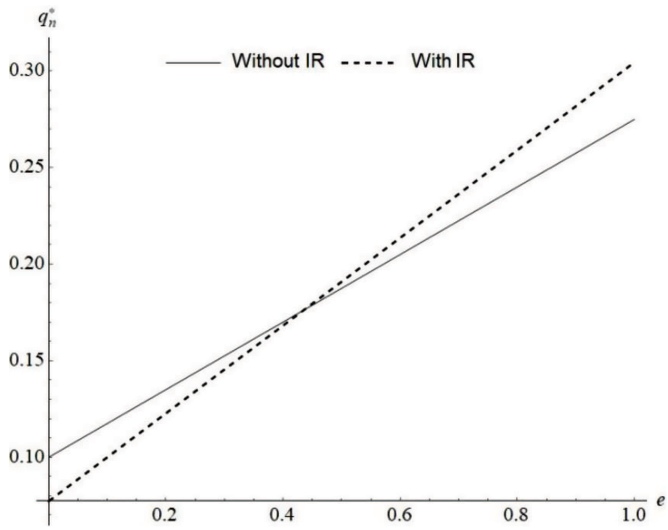

FIGURE 2. IM's production quantity under full information.

values satisfy the basic assumptions of the model, namely that the high-demand market size is greater than the low-demand market size, and that the marginal cost reduction effect of DfE on new products is stronger than that on remanufactured products. Moreover, the values of α_h, α_l, β_1 and β_2 all lie within reasonable ranges commonly adopted in the supply chain game literature, *e.g.*, Sun *et al.* [70], Cai *et al.* [11] and Feng *et al.* [21]. Although the production quantity and profit of the IM both increase with the DfE level e, the market is eaten away, and the profit of the IM is always hurt by the IR's encroachment. Moreover, the marginal effect of DfE is more pronounced under encroachment. Figure 2 shows that the optimal new product production quantity rises more steeply with e under encroachment and even surpasses the quantity under the scenario without encroachment. The reason is that the DfE can excavate potential markets and decrease the production cost, and the competition between the IM and IR will further increase the production quantity under full information. Although DfE also lowers the production cost of remanufactured products, the intensified competitive pressure ultimately erodes the IM's profitability.

4.2. Asymmetric information

We mainly discuss the situation in which only the independent manufacturer knows the true market size in this part. Under asymmetric information, although the independent remanufacturer has no information about the true market size, he can formulate his production decisions by inferring market conditions from the IM's quantity of new products. From the IM's perspective, remanufactured products cannibalize a portion of her original market share. Therefore, for any given q_n, a lower selling quantity q_r decided by the IR would benefit the IM. However, the IR will set a larger number of remanufactured products if he infers a high market size. This strategic interaction gives rise to a signaling game between the IM and the IR. On one side, the high-type IM (who finds $\alpha = \alpha_h$) has a motivation to imitate a low-type (who finds $\alpha = \alpha_l$) one to misdirect the IR into underestimating market demand. On the other side, the IM of low-type would wish to credibly distinguish herself from a high-type to induce a lower quantity from the IR. To achieve this separation, the low-type IM will distort her new product quantity downward to a level that makes it unprofitable for a high-type IM to imitate her. Alternatively, the IM can set the same quantity of new products under both the high and low market sizes. At this point, the IR cannot identify the market size according to the IM's quantity decision.

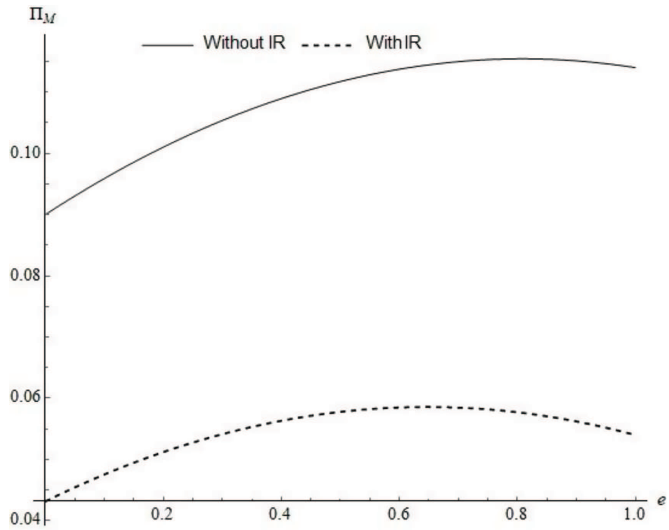

FIGURE 3. IM's optimal profit under full information.

The two cases above respectively represent the separating and the pooling outcomes in a signaling game. Under separating equilibrium, the low-type IM distorts its new product quantity downward to credibly differentiate itself from the high-type. Under pooling equilibrium, each type IM makes the same quantity decision of new products regardless of a high or low market size. We separately discuss the two kinds of equilibria in the following subsections, followed by the equilibrium refinement and the IR's quantity strategy.

4.2.1. Separating outcome

First, we consider the case of the separating equilibrium, which is represented by the superscript "s". As we mentioned earlier, for any given q_n, the IM hopes that the IR can choose a low q_r to keep the new product's high price. Following the principle of backward induction, we begin by examining the IR's production decision. From the inference based on the IM's quantity decision, the IR obtains the information about the market size and then decides q_r to maximize

$$\pi_R = q_r(\phi(\alpha_i - q_n - q_r) - (1 - \beta_2 e)c_r), \qquad i = h, l. \tag{6}$$

We generate remanufactured products' equilibrium quantity from the first-order condition of the equation (6) as

$$q_r^{i(q_n)} = \frac{-c_r + c_r e\beta_2 - q_n\phi + \phi\alpha_{i(q_n)}}{2\phi}, \qquad i = h, l. \tag{7}$$

We use $q_r^{i(q_n)}$ to denote the IR's updated belief of the remanufactured product's quantity after observing the q_n, which follows the belief structure with a threshold as below

$$i(q_n) = \begin{cases} h, & q_n > q_n^s \\ l, & q_n \le q_n^s \end{cases}. \tag{8}$$

Under this structure of belief, the IR thinks that the market size is low if he finds that the quantity of new products is no more than the threshold q_n^s. Therefore, after considering the reaction of IR, the IM decides her new product quantity q_n to maximize

$$\pi_M = q_n((\alpha_i - q_n - \phi q_r) - (1 - \beta_1 e)c_n) - \frac{ke^2}{2}, \qquad i = h, l. \tag{9}$$

In the separating equilibrium, when and only when the IM's production quantity q_n meets

$$\max \pi_M(q_n > q_n^s|\alpha_h) \geq \max \pi_M(q_n \leq q_n^s|\alpha_h), \tag{10}$$

$$\max \pi_M(q_n \leq q_n^s|\alpha_l) \geq \max \pi_M(q_n > q_n^s|\alpha_l), \tag{11}$$

$$q_n^s \geq 0, \tag{12}$$

a Perfect Bayesian Equilibrium (PBE) exists. The inequalities above describe the conditions of separating equilibrium. If the market size is high, Inequality (10) ensures that IM can obtain more profits by transmitting real information instead of pretending to be the low type IM. Inequality (11) shows that, when the market size is low, the IM would get lower profits if she signals a high market size to the IR. Inequality (12) ensures a non-negative product quantity for the IM. We can get the lemma as follows by solving inequalities (10)–(12).

Lemma 3. *The separating equilibrium is: when $\alpha = \alpha_h$, the IM sets $q_n = q_n^h = \frac{c' - (2-\phi)\alpha_h}{2(-2+\phi)} > q_n^s$; when $\alpha = \alpha_l$, the IM's product quantity $q_n = q_n^s$, where $c' \equiv 2c_n - c_r - 2c_n e\beta_1 + c_r e\beta_2$,*

$$q_n^s \equiv \begin{cases} \frac{c' - (2-\phi)\alpha_l}{2(-2+\phi)}, & \text{if } e < \tilde{e}, \\ \frac{c' - 2\alpha_h + \phi\alpha_l + \sqrt{\phi(-\alpha_h + \alpha_l)(2c' + (-4+\phi)\alpha_h + \phi\alpha_l)}}{2(-2+\phi)}, & \text{otherwise,} \end{cases}$$

and $\tilde{e} \equiv \frac{4c_n\phi - 2c_r\phi + 4\alpha_h - 4\phi\alpha_h + \phi^2\alpha_h - 4\alpha_l + \phi^2\alpha_l}{2(2c_n\beta_1 - c_r\beta_2)\phi}$.

Lemma 3 shows that when the DfE level is small, *i.e.*, $e < \tilde{e}$, the low-type IM could signal the actual market size to the IR without distorting her first-best product quantity $\frac{c' - (2-\phi)\alpha_l}{2(-2+\phi)}$[8]; when the DfE level is large enough, *i.e.*, $e \geq \tilde{e}$, the low-type IM must downward distort the product quantity to impede the high-type IM's imitation. In this way, the information of market size is effectively transmitted; in other words, the IR can always infer the information of market size from the IM's product quantity and determine remanufactured product quantity correspondingly.

To provide an intuitive understanding of Lemma 3, Figure 4 below shows the changes in possible IM's profit under different cases with q_n. Among them, q_n^l and q_n^h represent the first-order conditions under the two types, and q_n^s is the equilibrium solution given in Lemma 3. Figure 4 shows their relationship and downward distortion trend. We can see the IM's imitation motivation for any given product quantity q_n: the IM of high-type can gain a higher profit through imitating the IM of low-type; If low-type IM is regarded as high-type IM, her profit will suffer a loss.

4.2.2. Pooling outcome

Now we consider the case of pooling equilibrium, which is represented by superscript "o". In this case, the IM chooses the same quantity decision regardless of the market size type. Lemma 3 shows that a low-type IM may downward distort the product quantity q_n and incur a cost of signaling if she intends to separate from a high-type IM. If the signaling cost is excessively high, the low-type IM will instead opt to set the uniform q_n to pool with the high-type IM. If both types of the IM choose the equal quantity, the IR cannot update his belief about the market size. Consequently, the IR can only make the remanufacturing quantity decision q_r based on the common knowledge about the market size to maximize

$$\pi_R = \mathbb{E}[q_r(\phi(\alpha - q_n - q_r) - (1 - \beta_2 e)c_r)], \tag{13}$$

8 $\frac{c' - (2-\phi)\alpha_i}{2(-2+\phi)}$ is the optimal quantity of IM under full information.

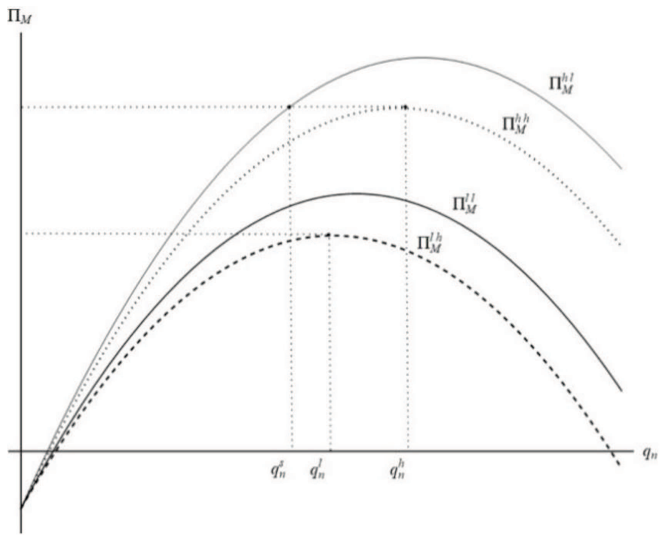

FIGURE 4. IM's optimal profit functions.

which renders

$$q_r^o = \frac{-c_r + c_r\beta_2 e - q_n\phi + \lambda\phi\alpha_h + (\phi - \lambda\phi)\alpha_l}{2\phi}. \tag{14}$$

In the pooling case, if $q_n \leq q_n^o$, the belief of the IR is identical with his prior belief, and the belief is $\alpha = \alpha_h$ if $q_n > q_n^o$. That is, there exists a product quantity threshold q_n^o such that the IR's belief on the market size is α_h if he observes $q_n > q_n^o$, and the IR would not update his belief if $q_n \leq q_n^o$. At this time, if and only if the new product production quantity of IM satisfies

$$\max \pi_M(q_n \leq q_n^o|\alpha_h) = \pi_M(q_n = q_n^o|\alpha_h), \tag{15}$$
$$\max \pi_M(q_n \leq q_n^o|\alpha_l) = \pi_M(q_n = q_n^o|\alpha_l), \tag{16}$$
$$\max \pi_M(q_n \leq q_n^o|\alpha_h) \geq \max \pi_M(q_n > q_n^o|\alpha_h), \tag{17}$$
$$\max \pi_M(q_n \leq q_n^o|\alpha_l) \geq \max \pi_M(q_n > q_n^o|\alpha_l), \tag{18}$$
$$q_n^o \geq 0, \tag{19}$$

a perfect Bayesian pooling equilibrium exists. Equalities (15) and (16) indicate that: If the IM wants to keep the IR from knowing the market size, her product quantity must satisfy $q_n \leq q_n^o$, and she will get the maximum profit when $q_n = q_n^o$ regardless of the market size type. Compared with the situation where the IR think the market size is high, inequalities (17) and (18) ensure that choosing pooling at q_n and keep the IR uninformed is more profitable for the IM. By solving (15)–(19) we can generate the following lemma.

Lemma 4. *If* $e > \tilde{\tilde{e}}(\lambda)$, *a perfect Bayesian pooling equilibrium exists as* $q_n = q_n^o = \frac{c' + \lambda\phi\alpha_h + (-2+\phi-\lambda\phi)\alpha_l}{2(-2+\phi)}$ *no matter what type the market size is, where* $\tilde{\tilde{e}}(\lambda) \equiv \frac{-4c_n\phi + 2c_r\phi + 4c_n\lambda\phi - 2c_r\lambda\phi - 4\alpha_h + 4\phi\alpha_h - 4\lambda\phi\alpha_h - \phi^2\alpha_h + \lambda^2\phi^2\alpha_h + 4\alpha_l - \phi^2\alpha_l + 2\lambda\phi^2\alpha_l - \lambda^2\phi^2\alpha_l}{2(2c_n\beta_1 - c_r\beta_2)(-1+\lambda)\phi}$.

Lemma 4 shows that the IM always tends to keep the IR uninformed and chooses $q_n = q_n^o$ to make the most profit in the pooling equilibrium.

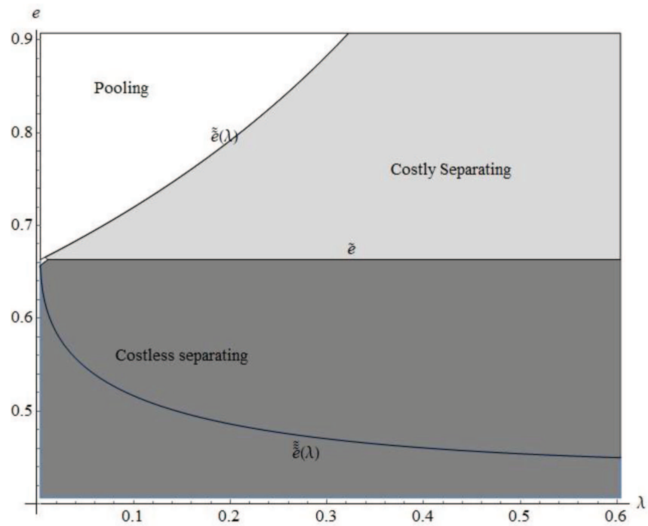

FIGURE 5. LMSE under asymmetric information.

4.2.3. LMSE refinement

Lemmas 3 and 4 show two types of equilibrium and their existing conditions. To refine the multiple equilibria, the intuitive criterion is commonly employed [15]. However, as discussed by Mailath *et al.* [56], the intuitive criterion may inappropriately exclude pooling equilibria due to its incomplete logical structure. The lexicographically maximum sequential equilibrium (LMSE) outcome can just make up for this shortcoming. The concept of LMSE has been increasingly adopted to refine the equilibria in recent works about signaling games (*e.g.*, [14, 29]). In our analysis, we use the intuitive criterion first but find the intuitive criterion cannot refine our two types of equilibrium. Thus, we adopt the LMSE concept to refine the multiple equilibria. This principle of LMSE is to select the most beneficial outcome for the type that intends to separate from the other type. Specifically, LMSE refinement selects the unique and most efficient outcome for the low-type IM. The intuitive rationale for this refinement is that since the low-type IM wants to reveal its identity, if the low-type IM finds the pooling outcome more profitable than the separating outcome, the pooling outcome should be selected and *vice versa*. In our model, given that the low-type IM would like to isolate from the high-type IM who has imitative motivation, the results of LMSE can be obtained by comparing profits of low-type IM under the two equilibria as shown in Proposition 1.

Proposition 1. *A unique LMSE outcome exists under asymmetric information. Specifically, the IM achieves a costless separating equilibrium when* $0 < e \le \tilde{e}$*, a costly separating equilibrium when* $\tilde{e} < e \le \tilde{\tilde{e}}(\lambda)$*, and a pooling equilibrium when* $\tilde{\tilde{e}}(\lambda) < e < 1$.

Proposition 1 demonstrates that with e increasing, the pooling equilibrium is gradually better than the separating equilibrium. This is because a higher DfE level imposes greater separation costs on the low-type manufacturer. When e is relatively low, the low-type IM can afford to distort its quantity downward to deter imitation by the high-type, thereby sustaining separation. However, as e rises, the marginal cost of such signaling distortion increases, making separation prohibitively costly and inducing the low-type IM to instead opt for pooling. For further understanding of Proposition 1, Figure 5 depicts the IM's LMSE according to the variation of the high market size probability λ and the DfE level e.

With the LMSE concept, we can obtain that the pooling equilibrium is better than the separating at $e > \tilde{\tilde{e}}(\lambda)$ but the pooling equilibrium only exists at $e > \tilde{e}(\lambda)$, where $\tilde{\tilde{e}}(\lambda)$ is shown in the Proposition 3's proof in

Appendix E. Combining Lemma 3 with Lemma 4, we can get that: if $e > \tilde{\tilde{e}}(\lambda)$, the pooling and the separating equilibria coexist but the IM of low-type could obtain higher profit under pooling case, which makes the IM of low-type choose to pool; if $\tilde{e} < e \leq \tilde{\tilde{e}}(\lambda)$, the low-type IM will select a costly separating because the low-type IM needs to warp the production quantity downward to impede the high-type IM's imitation; if $e \leq \tilde{e}$, pooling equilibrium will not exist and separating equilibrium is the unique equilibrium, thereby yielding the resulting costless separating.

When $e \leq \tilde{e}$, the IR's recycling cost is extremely high, rendering its production decisions insensitive to the manufacturer's product quantity signal. As a result, the high-type IM lacks the incentive to mimic the low-type IM's product quantity to convey a false signal of market demand, and the low-type IM can achieve natural separation from the high-type IM without distorting its product quantity downward. When $\tilde{e} < e \leq \tilde{\tilde{e}}(\lambda)$, the IR's recycling cost decreases, enhancing its sensitivity to the product quantity signal. The high-type IM's incentive to imitate the low-type IM's product quantity increases substantially, forcing the low-type IM to incur signaling costs by distorting its product quantity downward below the optimal level to deter imitation, resulting in a costly separating equilibrium. When e further increases to $e > \tilde{\tilde{e}}(\lambda)$, the IR's recycling cost becomes sufficiently low that its production decisions rely less on the manufacturer's product quantity signal. It has no necessity for the high-type IM to mimic and the high-type IM's gain from imitation declines significantly, making the pooling equilibrium more favorable.

4.2.4. IR's quantity strategy

Based on each of the new product quantity equilibrium of IM under different cases, we can get the corresponding remanufactured product quantity equilibrium of IR. By substituting each equilibrium quantity q_n into equations (7) and (14), we have Lemma 5.

Lemma 5. *Under asymmetric information, the IR's remanufactured product equilibrium quantity is*

$$q_r^* = \begin{cases} \frac{c_r(-1+e\beta_2)(-4+\phi)+2c_n(-1+e\beta_1)\phi+(-2+\phi)\phi\alpha_i}{4(-2+\phi)\phi}, & \text{if } e \leq \tilde{e}, \\ \frac{(c_r(-1+e\beta_2)(-4+\phi)+2c_n(-1+e\beta_1)\phi+2\phi\alpha_h+(-4+\phi)\phi\alpha_l}{4(-2+\phi)\phi} \\ -\frac{\phi\sqrt{\phi(-\alpha_h+\alpha_l)(4c_n-2c_r-4c_ne\beta_1+2c_re\beta_2+(-4+\phi)\alpha_h+\phi\alpha_l)}}{4(-2+\phi)\phi}, & \text{if } \tilde{e} < e \leq \tilde{\tilde{e}}(\lambda), \\ \frac{c_r(-1+e\beta_2)(-4+\phi)+2c_n(-1+e\beta_1)\phi+\lambda(-4+\phi)\phi\alpha_h+\phi(-2-\lambda(-4+\phi)+\phi)\alpha_l}{4(-2+\phi)\phi}, & \text{if } \tilde{e} > \tilde{\tilde{e}}(\lambda). \end{cases}$$

Lemma 5 shows that the IR's decision on remanufactured product quantity depends on the LMSE is separating or pooling. Figure 6 shows the variation of q_r^* with the DfE level.

Figure 6 illustrates that q_r^* increases with e under asymmetric information. The IR will set a larger remanufacturing product quantity with a higher DfE level. This result aligns with the practical understanding that a higher DfE level substantially lowers remanufacturing costs, thus incentivizing greater production. In addition, q_r^* is bigger in the pooling case than that in the separating case and is the lowest under the costless separating equilibrium, thereby implying that the high separating cost of the manufacturer promotes remanufactured products' production.

4.3. Impacts of information structure

We discuss the role of information in equilibrium quantities and profits of the IM and the IR in this part. We still employ the following reasonable parameters, which are $\alpha_h = 0.9$, $\alpha_l = 0.7$, and $\lambda = 0.3$, to make the numerical analysis. As noted above, the parameter values employed in this study are primarily based on commonly used benchmarks established in the literature, such as Cai *et al.* [11] and Zhang *et al.* [85]. Furthermore, to verify the rationality of the chosen parameter value for λ, we examined the robustness of our results by assigning alternative values to λ within a reasonable range and found that our main conclusions remain unchanged. For the purpose of clarity and illustration, we present the results using $\lambda = 0.3$. Figures 7 and 8 illustrate how the optimal quantities of new and remanufactured products vary with the DfE level under different information structures. It can be observed that the information asymmetry does not change the increasing or decreasing trend of new or remanufactured product's

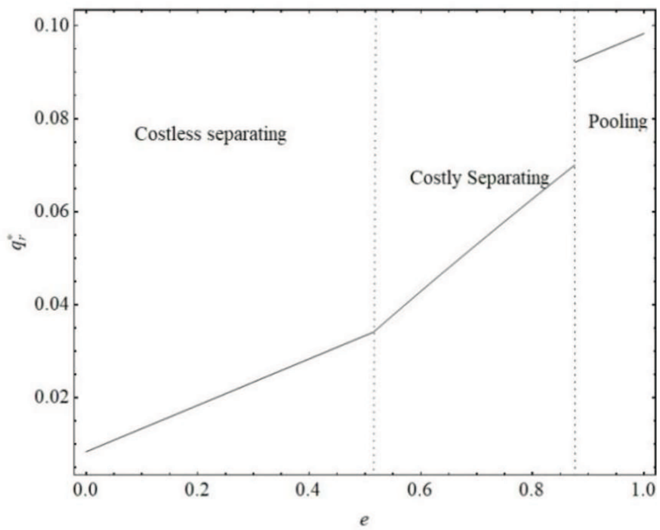

FIGURE 6. Remanufactured product quantity with the DfE level.

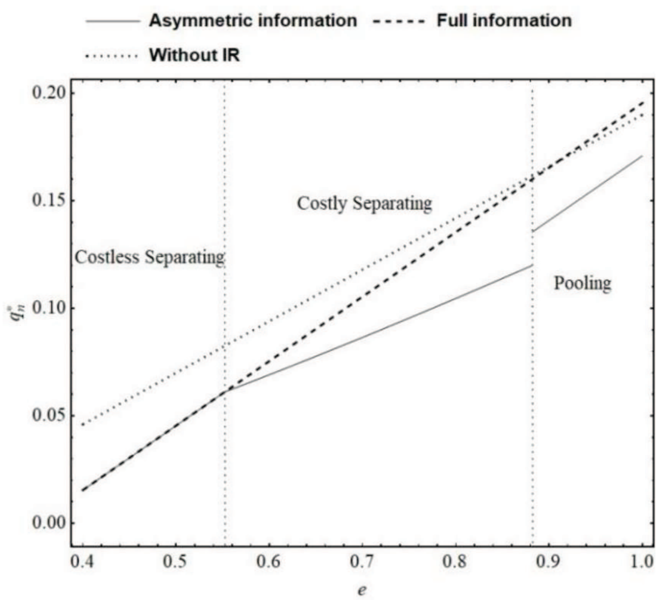

FIGURE 7. IM's product quantity under different information structures.

optimal quantity with the DfE's effect but changes the increase rate or decrease rate. Specifically, under the pooling equilibrium – where the IR lacks clear information – the ambiguous signal slows the rate of increase in the optimal quantity of new products and, simultaneously, moderates the rate of decrease in the optimal quantity of remanufactured products as the DfE level rises. Moreover, by comparing the profit of the IM or the IR under different information structures, we obtain Proposition 2 as summarized below.

Proposition 2. *The information advantage is not always beneficial for the IM in competition with the IR.*

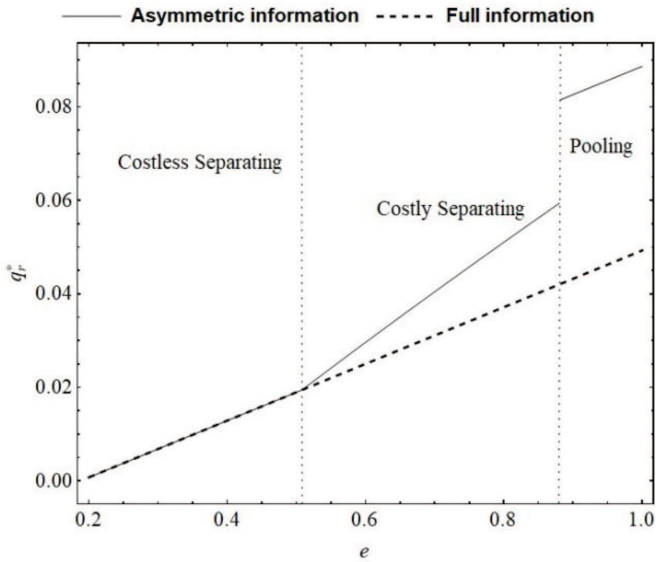

FIGURE 8. IR's product quantity under different information structures.

Proposition 2 reveals a counterintuitive finding in the remanufacturing market: the information advantage held by an IM does not necessarily translate into a competitive edge when competing with an independent remanufacturer; under certain conditions, it may instead become a factor that undermines its market position. To understand Proposition 2 more directly, Figures 9 and 10 separately depict the profits of the IM and IR under different information structures. Obviously, the IR's entry consistently erodes the IM's profitability under asymmetric information. It is generally recognized that the information advantage about the market could help the IM to reduce the negative impact of IR's encroachment. But interestingly, our results reveal that the information advantage may sometimes make the IM suffer more. This counterintuitive result can be explained by the interaction between information asymmetry and the production decision of the IR. As shown in Figure 8, the optimal quantity of remanufactured products is higher under asymmetric information than under full information. Facing incomplete demand information, the IR makes its production decision based on its rational beliefs about market conditions, leading to overproduction relative to the full-information benchmark. This overproduction intensifies market competition, ultimately harming the IM.

As revealed by Banerjee *et al.* [7], in the context of financial communication, the "curse of knowledge" experienced by information senders may, under certain conditions, lead to more information output and improved decision-making, yet it may also intensify conflicts of interest. Analogously, in a remanufacturing supply chain, a manufacturer that fails to effectively manage its information advantage may instead find itself at a competitive disadvantage due to the curse of knowledge. This finding suggests to managers that an information advantage is not immutable; its value hinges on how the information-advantaged party perceives and responds to the strategic reactions of the information-disadvantaged party.

4.4. IM's ex-ante DfE level

In this subsection, we decide the IM's ex-ante DfE level based on the LMSE. From Figure 5, we can see that the manufacturer has different LMSE under different DfE levels. The expected ex-ante profit of IM is $\mathbb{E}\Pi_M^{ij}(e)$, where the posterior belief j of the IR can be "o" under pooling equilibrium or "i" under separating equilibrium. Hence, the IM's optimal DfE level is given as $e^* = \arg\max \mathbb{E}\Pi_M^{ij}(e)$. Because the analytical solution is too complex to derive, we use numerical analysis to illustrate the optimal e. We still consider the following

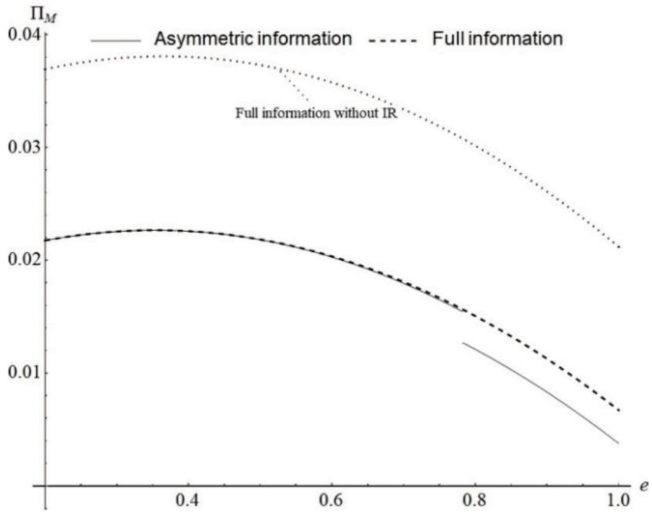

FIGURE 9. IM's profits under different information structures.

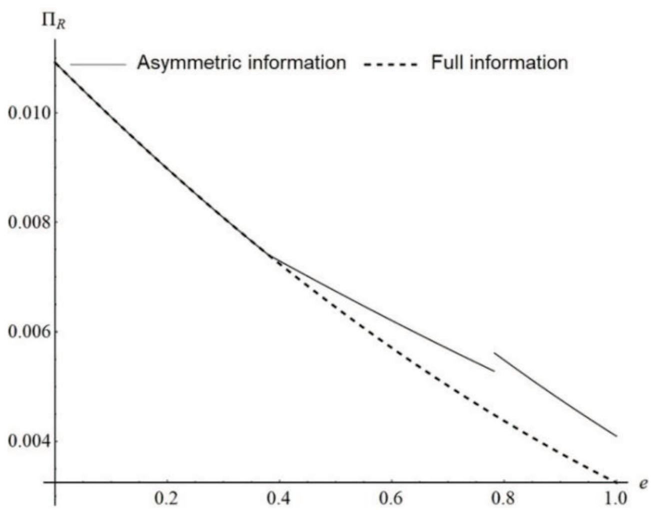

FIGURE 10. IR's profits under different information structures.

reasonable parameters: $\alpha_h = 0.9$, $\alpha_l = 0.7$, and $\phi = 0.5$. For more intuitively illustrating the impact of the DfE, the results are presented using $\phi = 0.5$. We can verify that the results are robust by assigning other alternative values to ϕ in the range $0 < \phi < 1$. From Figure 11, we can see the optimal value of e in three different cases under given parameter values: Under costless separating, *i.e.*, $\tilde{e} < \arg\max \mathbb{E}\Pi_M^{ii}(e)$, the optimal value of the first-order condition cannot be obtained and thus $e^* = \tilde{e}$; Under costly separating, the first-order optimal value can always be obtained, *i.e.*, $e^* = \arg\max \mathbb{E}\Pi_M^{ii}(e)$; Under pooling equilibrium, there is a threshold $\overline{\lambda}$, thereby resulting in $e^* = \arg\max \mathbb{E}\Pi_M^{ii}(e)$ if $\lambda < \overline{\lambda}$ and $e^* = \tilde{\tilde{e}}(\lambda)$ otherwise.

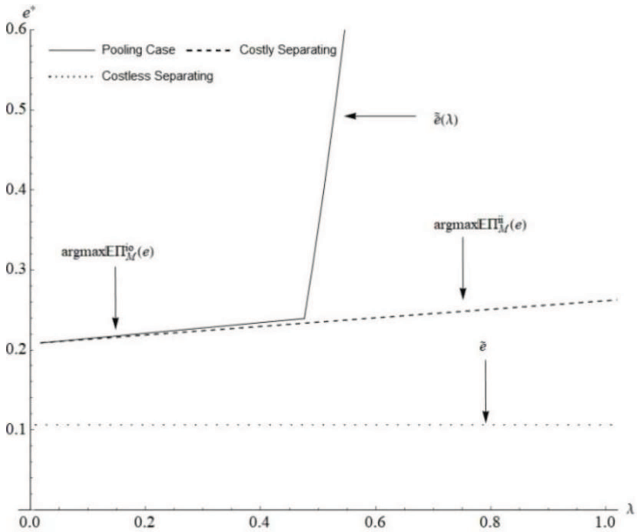

FIGURE 11. The optimal value of DfE level e.

5. Extension – Dual signal transmission

Section 4 examines the equilibrium strategies of the IM under different information structures, assuming the DfE level is unknown to the IR – a premise grounded in the fact that DfE levels are less directly observable than production quantities. In this section, we discuss the scenario where the IM or the IR can use new information technology, such as blockchain, to release or access the real DfE level, which is consistent with reality. Due to the visibility and verifiability of blockchain, every member of the supply chain can access any information in the production process [5, 17]. In addition, firms are usually willing to make more efforts to improve the DfE level when they find their products are marketable. A high DfE level means a large market size [63]. Thus, we let the DfE level be another signal besides the new product quantity, and the two signals are employed by the IR to infer the market size in the following analysis.

Lemma 6. *In dual signal mode, the equilibrium strategies for the low-type IM are*

$$(q_n^*, e^*) = \begin{cases} \left(\frac{2k(2c_n - c_r + \phi\alpha_l - 2\alpha_l)}{-8k+4c_n^2\beta_1^2-4c_nc_r\beta_1\beta_2+c_r^2\beta_2^2+4k\phi}, \frac{(2c_n\beta_1 - c_r\beta_2)(2c_n-c_r+\phi\alpha_l-2\alpha_l)}{-8k+4c_n^2\beta_1^2-4c_nc_r\beta_1\beta_2+c_r^2\beta_2^2+4k\phi}\right), & \text{if } \phi < \tilde{\phi}, \\ \left(A + \frac{4k^2(-2\alpha_h+\phi\alpha_l)}{2k((-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi))} + \frac{(2c_n\beta_1-c_r\beta_2)T}{2k((-2+\phi)(\alpha_h-\alpha_l))}, B - \frac{T}{k(\alpha_h-\alpha_l)}\right), & \text{otherwise,} \end{cases}$$

where $A \equiv \frac{4c_nk-2c_rk}{(-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi)} + \frac{\sqrt{-\phi(\alpha_h-\alpha_l)(4c_n-2c_r+(-4+\phi)\alpha_h+\phi\alpha_l)}}{2(-2+\phi)}$, $B \equiv \frac{(2c_n\beta_1-c_r\beta_2)(2c_n-c_r-2\alpha_h+\phi\alpha_l)}{(-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi)}$, $T \equiv \sqrt{-\frac{k^2(-2c_n\beta_1+c_r\beta_2)^2\phi(\alpha_h-\alpha_l)^3(4c_n-2c_r+(-4+\phi)\alpha_h+\phi\alpha_l)}{((-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi))^2}}$, *and* $\tilde{\phi} \equiv \frac{-2c_n+c_r+2\alpha_h-\sqrt{4c_n^2-4c_nc_r+c_r^2-8c_n\alpha_h+4c_r\alpha_h+4\alpha_l^2}}{\alpha_h+\alpha_l}$.

When $\phi < \tilde{\phi}$, the low-type IM can be separated from the one of high-type naturally, *i.e.*, the costless separating equilibrium exists. When $\phi \geq \tilde{\phi}$, costly separating equilibrium emerges, which means the low-type IM incurs signaling cost to separate herself. Figure 12 shows the change of IM's DfE level decision with ϕ, where a high value of ϕ implies consumers' preferences are higher for remanufactured products. By the sensitivity analysis, we find the IM's optimal DfE level decreases with consumers' preference for remanufactured product ϕ (see Fig. 12), which is consistent with reality that the DfE of IM is also beneficial for the competitive remanufactured product and the IM must decrease the DfE level to reduce IR's benefits when the remanufactured products are popular.

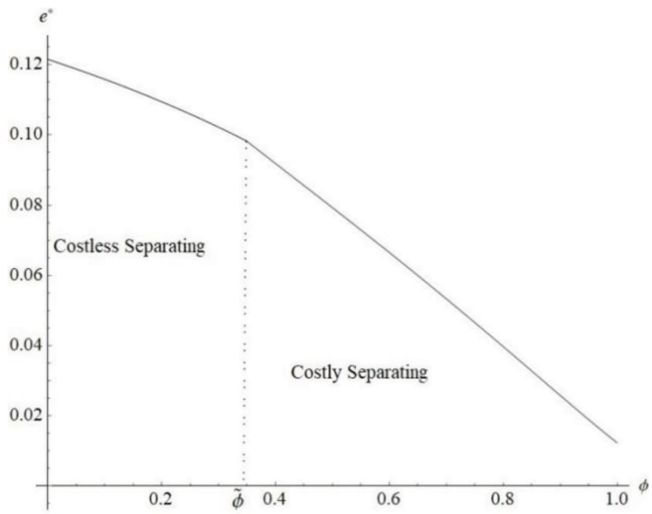

FIGURE 12. The equilibrium DfE level of dual signal transmission.

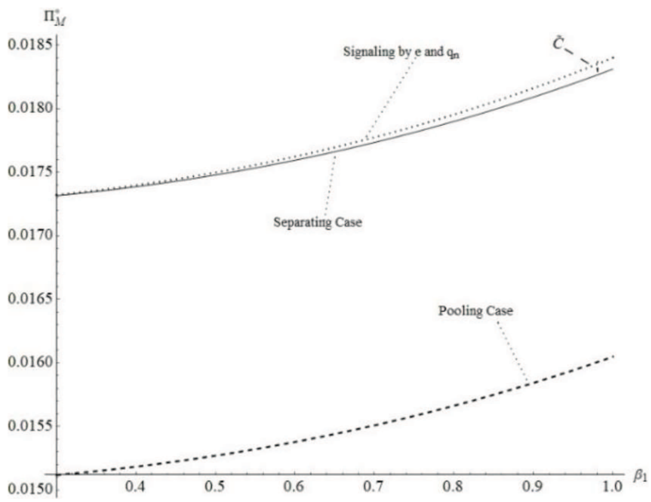

FIGURE 13. IM's profits under different signal model.

In dual signal mode, the IM can adopt blockchain to disclose the DfE level to the IR. Given the complexity of IM's or IR's profit functions, we resort to numerical analysis rather than an analytical method to compare the equilibrium strategies of the two signal modes and derive managerial insights. Figure 13 shows the profits of the IM under sole signal mode and dual signal mode. The outcome is summarized in Proposition 3.

Proposition 3. *Dual signal mode is better for the IM if and only if the cost that releases information is less than* $\tilde{C}$.

The specific form of $\tilde{C}$ is shown in the proof of Proposition 3 in Appendix G. Intuitively, under any equilibrium scenario shown in Figure 13, the independent manufacturer's profit increases with the marginal impact of DfE. Moreover, the profit of the IM is higher under dual signal mode than in sole signal mode if the cost of releasing information about the DfE level is less than $\tilde{C}$. This threshold characterizes the maximum information disclosure cost that the IM can bear while still attaining higher profitability under the dual-signal mode. As described in Section 4, greater information precision helps guide the remanufacturer to make production decisions that align more closely with actual market conditions, thereby alleviating the overproduction problem identified in Proposition 2. Therefore, it is imperative for members in the supply chain to be concerned about the effect of new emerging information technology (such as blockchain) applications, which can serve as effective tools for enhancing information transparency and optimizing operational strategies [12, 82].

6. Conclusion

Against the backdrop of global commitments to peak carbon emissions and carbon neutrality, remanufacturing has gained significant traction among firms seeking sustainable practices. While remanufacturing enables the recovery of maximum value from end-of-life products, it also introduces market competition between original manufacturers and remanufacturers. To address this, the original manufacturers usually adopt the DfE in new products to decrease carbon emissions throughout the product lifecycle and increase competitiveness. Paradoxically, the DfE not only improves environmental performance but also is supposed to facilitate remanufacturing, thereby indirectly benefiting the remanufacturer – the manufacturer's competitor. In addition, the manufacturer often has information advantage about the market but the new entrant – remanufacturer – does not. Motivated by these observations, we consider the remanufacturer's encroachment strategy with the IM's DfE under various information structures to explore the impacts of the remanufacturer's encroachment on the DfE level and profits of IM and IR in differentiated information strategies. The main conclusions are as follows.

6.1. Results and discussion

First, we study the production decision of manufacturers and remanufacturers under different information structures. By comparing the product quantity of remanufactured products, we find that the IR is more inclined to encroach on the market under full information. In this case, IM may choose not to share information to avoid the competition caused by IR's encroachment. Under the scene of complete information, the IR can accurately assess market prospects and thus exhibit a stronger entry inclination. In contrast, in an information asymmetric scene, the IM can strategically conceal demand information, thereby weaken the IR's encroachment incentive. In addition, a higher level of DfE increases the production quantities of both the manufacturer and the remanufacturer. However, the marginal effect of DfE has a divergent impact: it further boosts the manufacturer's production while conversely reducing that of the remanufacturer. When the marginal effect of DfE increases, both the manufacturing costs of the manufacturer and the remanufacturer decrease, but that of the manufacturer decreases more, which intensifies the competitive advantage of the manufacturer. Not only that, because DfE has a stronger marginal cost reduction effect on new products than on remanufactured ones, the economic incentive for the IR is weakened: when the product itself already achieves a high level of environmental performance, the necessity of remanufacturing diminishes accordingly. This is consistent with Zhao *et al.* [91]'s study, who point out that under a high DfE level, manufacturers tend to adopt an outsourcing remanufacturing strategy to obtain higher profits at the expense of environmental benefits. Further, the manufacturer will expand its production scale to dilute the costs incurred by DfE investment, compressing the market share of remanufacturer. With these three effects, the product quantity of manufacturer increases and that of the remanufacturer decreases to avoid more fierce competition. Our results extend Zhang *et al.* [86]'s study, who focus on the relationship between investment in design for remanufacturing and output under recycling regulations, by demonstrating that the IM's DfE efforts reshape the output structure of new products and remanufacturing products in the market.

Second, this study summarizes the encroachment effect of IR on the IM. We reveal that no matter what the information structure is, the IR's encroachment always erodes the market and reduces the profit of IM – a finding that echoes the conclusion of Feng *et al.* [21] under competitive market, which further reinforces the IM's intrinsic motivation to adopt a defensive information concealment strategy. These results further support

Huang and Wang [35]'s study, who examine the interaction between a retailer's information sharing and a manufacturer's encroachment strategy, finding that encroachment always increases the manufacturer's profit, regardless of whether the manufacturer engages in self-remanufacturing or authorizes a third party to do so. But different from them, this paper focuses on the manufacturer's defensive information concealment strategy in the face of remanufacturer's encroachment, thereby complementing the theoretical understanding of the interaction mechanism between information asymmetry and competition in the closed-loop supply chain.

Third, this study challenges the conventional paradigm that "information superiority equates to competitive advantage". The unexpected outcomes show that the information advantage of IM about the market is not always the weapon for the IM to compete with the IR and may hurt the IM more under certain conditions. More specific information can make remanufacturers decide the number of remanufactured products more reasonable and relieve the competition with the IM under asymmetric information. This finding echoes the conclusion of Sun *et al.* [70], who find concealing demand information from an independent remanufacturer is not always beneficial for the original equipment manufacturer; when the market size is small, information hiding may backfire by causing the OEM to over-reduce its own output, thereby harming its own profit. But they don't consider the role of DfE. Besides, unlike Sun *et al.* [70], who only discuss a single production-quantity signal, our research introduces the DfE level as the second signal to convey demand information. We provide an extension to study the dual signal mode that can be realized by the newly emerging information technology – blockchain. Numerical analysis shows that when the cost of disclosing the DfE signal is low, compared to a single signal mode, the dual signal mode can serve as an effective strategy for IM to mitigate the negative impact caused by IR's encroachment. greater information transparency reduces the IR's belief bias and brings its output decision closer to the first-best level under full information, thus mitigating the efficiency loss induced by asymmetric information. This effect is theoretically isomorphic with the finding of Ran and Duan [62], that transparency enabled by blockchain technology can improve supply chain performance, but only when the operating cost is below about 12% of profit.

6.2. Management implications

The main findings of this study offer the following management implications for different stakeholders.

For the IM, they should drive a fundamental shift in strategic positioning, moving from passively responding to market competition to proactively designing strategic layouts. Specifically, the independent manufacturer (IM) needs to carefully formulate information sharing strategies in order to proactively avoid competitive risks induced by increased information transparency in potentially competitive markets. At the same time, the IM should actively leverage emerging technologies such as blockchain and digital twins to enhance the effectiveness of signal transmission, reduce profit erosion caused by information spillovers, and guide competitors toward rational decision-making. In doing so, the IM can safeguard its own core interests while shaping a favorable market game structure. For example, Mitsubishi Chemical Corporation collaborated with Chaintope to conduct a demonstration test of a traceability system for chemical recycling. By leveraging blockchain technology, the company built a transparent and trustworthy supply chain information platform that actively controls the scope of information sharing while enhancing transparency, prevents the leakage of core data, and thereby effectively guides the rational decision-making of upstream and downstream partners[9].

For the IR, they should strengthen their ability to actively scrutinize market information, transitioning from passive reception to critical evaluation. By carefully interpreting the intent and credibility behind the strategic signals released by the IM, the IR can improve the accuracy of its strategic decisions, effectively avoid misjudgment risks in complex game situations, and ultimately optimize its own profits. Especially in an environment of information asymmetry, the IR should establish a multi-source information cross-validation mechanism to prevent belief bias from leading to overproduction.

For supply chain coordinators, they should actively promote collaboration among firms in pre-competitive areas such as product design or recycling technology adoption, and establish authoritative information coordi-

[9] https://www.mcgc.com/english/news_release/02103.html.

nation mechanisms. Such measures would internalize the negative externalities arising from information asymmetry, guide the remanufacturing industry away from zero-sum competition toward a positive-sum game, and achieve overall efficiency optimization in resource circulation. In 2023, CATL, GEM and Mercedes-Benz signed a tripartite memorandum of cooperation on battery recycling[10]. By sharing information on battery retirement schedules and capacity, they effectively avoided redundant investment and overcapacity, thereby transforming potential competition into value co-creation. This case clearly demonstrates that firms can turn competitive pressure into cooperative gains through information coordination mechanisms in the closed-loop supply chain.

6.3. Limitations

Although this study offers valuable managerial insights into remanufacturer encroachment in relation to the IM's DfE and information strategy, it still has several limitations that point to future research directions. First, we analyze a decentralized decision-making framework consisting of an IM and an IR, both of which are responsible for production and sales. Future research can introduce retailers or other intermediaries to examine these issues within a more complex and realistic supply chain setting. Second, we assume that DfE is implemented solely by the IM and that its benefits are shared by both the IM and IR. It is also interesting to study the subject where the DfE is conducted by IR and only benefits the IR. Third, our model restricts the manufacturer from engaging in remanufacturing. It would be worthwhile to relax this assumption and investigate settings where the IM also has remanufacturing capability, thereby intensifying competition with the IR.

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Conflicts of interest

The authors report there are no competing interests to declare.

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Appendix A. Proof of Lemma 1

Without the encroachment of IR, *i.e.*, $q_r = 0$ in equation (3), we can obtain the optimal production decision of IM from the first-order condition.

Appendix B. Proof of Lemma 2

Substituting the optimal decision of IR in equation (5) into equation (3), we can obtain the profit function of IM under full information as follows:

$$\pi_M = -\frac{e^2k}{2} + q_n\left(-q_n - c_n(1-e\beta_1) + \alpha_i + \frac{1}{2}(c_r(1-e\beta_2) + q_n\phi - \phi\alpha_i)\right). \tag{B.1}$$

The optimal decision of IM can be obtained according to the first-order conditions:

$$q_n^f = \frac{2c_n - c_r - 2c_ne\beta_1 + c_re\beta_2 - (2-\phi)\alpha_i}{2(-2+\phi)}, \qquad i = h, l. \tag{B.2}$$

Appendix C. Proof of Lemma 3

The manufacturer will set different production quantities if she intends to separate under different market sizes. The IR's belief is $\alpha = \alpha_h$ if $q_n > q_n^s$ and $\alpha = \alpha_l$ if $q_n \leq q_n^s$ as shown in (7) and (8). In order to satisfy the conditions for the existence of separating equilibrium, we will solve the constraints (10)–(12) respectively. When $\alpha = \alpha_h$, from (7) and (9), we obtain the high-type IM's profit function as follows:

$$\pi_M(q_n > q_n^s \mid \alpha_h) = -\frac{e^2k}{2} + q_n\left(-q_n - c_n(1-e\beta_1) + \alpha_h + \frac{1}{2}(c_r(1-e\beta_2) + \phi(q_n - \alpha_h))\right), \tag{C.1}$$

$$\pi_M(q_n \leq q_n^s \mid \alpha_h) = -\frac{e^2k}{2} + q_n\left(-q_n - c_n(1-e\beta_1) + \alpha_h + \frac{1}{2}(c_r(1-e\beta_2) + \phi(q_n - \alpha_l))\right). \tag{C.2}$$

To satisfy inequality constraint (10), we need $q_n^s \leq \tilde{q}_n = \left(\frac{c' - 2\alpha_h + \phi\alpha_l + \sqrt{\phi(-\alpha_h+\alpha_l)(2c' + (-4+\phi)\alpha_h + \phi\alpha_l)}}{2(-2+\phi)}\right)$. For convenience, here $c' \equiv 2c_n - c_r - 2c_ne\beta_1 + c_re\beta_2$. We also use this symbol in the following proof. When $\alpha = \alpha_h$, the optimal for the IM is the first-best order quantity as

$$q_n = q_n^h = \frac{c' - (2-\phi)\alpha_h}{2(-2+\phi)}. \tag{C.3}$$

Next, for low-type cases, the low-type IM's profit function as follows:

$$\pi_M(q_n \le q_n^s \mid \alpha_l) = \frac{1}{2}(-e^2k + q_n(c_r - 2q_n + 2c_n(-1 + e\beta_1) - c_re\beta_2 + q_n\phi - (-2 + \ \phi)\alpha_l)), \tag{C.4}$$

$$\pi_M(q_n > q_n^s \mid \alpha_l) = \frac{1}{2}(-e^2k + q_n(c_r - 2q_n + 2c_n(-1 + e\beta_1) - c_re\beta_2 + q_n\phi - \phi\alpha_h + 2\alpha_l)). \tag{C.5}$$

The manufacturer's first-best production quantity can be clearly obtained as $q_n = \frac{c' - (2-\phi)\alpha_l}{2(-2+\phi)}$ when $\alpha = \alpha_l$. Then, we can get the most profitable production quantity when $\alpha = \alpha_l$ as

$$q_n^s = \min\left\{\tilde{q}_n, \frac{c' - (2-\phi)\alpha_l}{2(-2+\phi)}\right\}. \tag{C.6}$$

Obviously, when $q_n^s = \frac{c'-(2-\phi)\alpha_l}{2(-2+\phi)}$, constraint (11) is satisfied; when $q_n^s = \tilde{q}_n$, constraint (11) can also be satisfied. To compare these two values, denoting $\Delta \equiv \frac{c'-(2-\phi)\alpha_l}{2(-2+\phi)} - \tilde{q}_n$, we can find that

$$\frac{\partial \Delta}{\partial e} = \frac{(-4c_n\beta_1 + 2c_r\beta_2)\phi(\alpha_h - \alpha_l)}{4(-2+\phi)\sqrt{\phi(-\alpha_h + \alpha_l)(2c' + (-4+\phi)\alpha_h + \phi\alpha_l)}}, \tag{C.7}$$

$$\frac{\partial^2 \Delta}{\partial e^2} = \frac{2c_n^2e^2\phi^2(-\alpha_h + \alpha_l)^2}{(-2+\phi)(\phi(-\alpha_h + \alpha_l)(2c' + (-4+\phi)\alpha_h + \phi\alpha_l))^{\frac{3}{2}}}. \tag{C.8}$$

Equations (C.7) and (C.8) show that Δ is monotonically increasing in e. Solving $\Delta = 0$, we can get $\tilde{e} = \frac{4c_n\phi - 2c_r\phi + 4\alpha_h - 4\phi\alpha_h + \phi^2\alpha_h - 4\alpha_l + \phi^2\alpha_l}{2(2c_n\beta_1 - c_r\beta_2)\phi}$. Thus, when $e < \tilde{e}$, $\Delta \le 0$, $q_n^s = \frac{c'-(2-\phi)\alpha_l}{2(-2+\phi)}$; otherwise, $\Delta > 0$ holds, and $q_n^s = \tilde{q}_n$.

Appendix D. Proof of Lemma 4

In the pooling case, to prevent the IR from obtaining real market size, the two types of IMs will set the same quantity. As shown in (15)–(19), the IR has no information on market size if $q_n \le q_n^o$, and the IR's belief is $\alpha = \alpha_h$ if $q_n > q_n^o$. Given that

$$\begin{aligned}\pi_M(q_n \le q_n^o \mid \alpha_h) = \frac{1}{2}(&-e^2k + q_n(-2c_n + c_r - 2q_n + 2c_ne\beta_1 - c_re\beta_2 + q_n\phi \\ &+ (2 - \lambda\phi)\alpha_h + (-1+\lambda)\phi\alpha_l)).\end{aligned} \tag{D.1}$$

And

$$\begin{aligned}\pi_M(q_n \le q_n^o \mid \alpha_l) = \frac{1}{2}(&-e^2k + q_n(-2c_n + c_r - 2q_n + 2c_ne\beta_1 - c_re\beta_2 + q_n\phi - \lambda\phi\alpha_h \\ &+ (2 + (-1+\lambda)\phi)\alpha_l)),\end{aligned} \tag{D.2}$$

to satisfy constraints (15) and (16), we need

$$q_n^o \le \frac{(c' + \lambda\phi\alpha_h + (-2 + \phi - \lambda\phi)\alpha_l)}{(2(-2+\phi))}. \tag{D.3}$$

This inequality ensures that both (D.1) and (D.2) increase with q_n. We set

$$q_n^o = \frac{(c' + \lambda\phi\alpha_h + (-2 + \phi - \lambda\phi)\alpha_l)}{(2(-2+\phi))}. \tag{D.4}$$

Under these conditions, q_n^o has satisfied (18). To satisfy (17), we can obtain the following inequality as the condition

$$\begin{aligned}q_n^o > \tilde{q}_n^o = &\frac{c' + (-2 + \lambda\phi)\alpha_h + \phi\alpha_l - \lambda\phi\alpha_l}{2(-2+\phi)} \\ &+ \frac{\sqrt{(-1+\lambda)\phi(\alpha_h - \alpha_l)(2c' + (-4 + \phi + \lambda\phi)\alpha_h + (\phi - \lambda\phi)\alpha_l)}}{2(-2+\phi)}.\end{aligned} \tag{D.5}$$

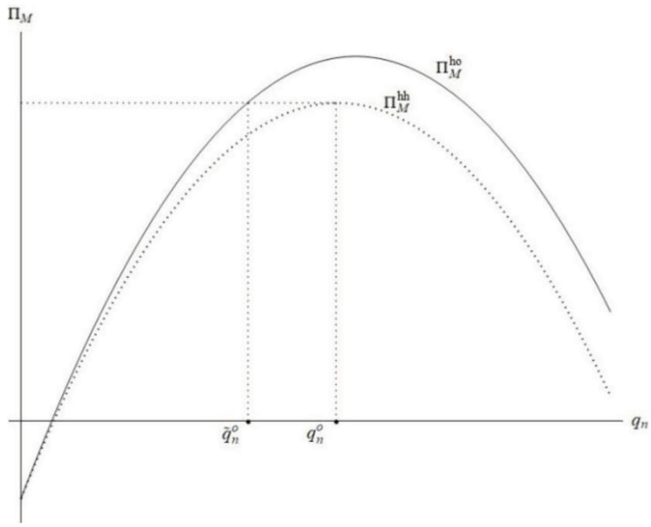

FIGURE D.1. High-type's profit under pooling case.

Figure D.1 shows the specific conditions that $q_n^o > \tilde{q}_n^o$.
Denoting $\Delta' \equiv q_n^o - \tilde{q}_n^o$. Through the Δ''s first-order condition, we can find that

$$\frac{\partial \Delta'}{\partial e} = \frac{(2c_n\beta_1 - c_r\beta_2)(-1+\lambda)\phi(\alpha_h - \alpha_l)}{(-2+\phi)\sqrt{(-1+\lambda)\phi(\alpha_h-\alpha_l)(2c' + (-4+\phi+\lambda\phi)\alpha_h + (\phi - \lambda\phi)\alpha_l)}}. \tag{D.6}$$

Obviously, Δ' is monotonically increasing in e. We can obtain the range of e when (D.5) is satisfied:

$$\begin{aligned} &e > \tilde{\tilde{e}}(\lambda) \\ &\equiv \frac{-4c_n\phi + 2c_r\phi + 4c_n\lambda\phi - 2c_r\lambda\phi - 4\alpha_h + 4\phi\alpha_h - 4\lambda\phi\alpha_h - \phi^2\alpha_h + \lambda^2\phi^2\alpha_h + 4\alpha_l - \phi^2\alpha_l + 2\lambda\phi^2\alpha_l - \lambda^2\phi^2\alpha_l}{2(2c_n\beta_1 - c_r\beta_2)(-1+\lambda)\phi}. \end{aligned} \tag{D.7}$$

APPENDIX E. PROOF OF PROPOSITION 1

For manufacturers, there are pooling and separating equilibrium. LMSE chooses a more profitable equilibrium for low-type manufacturer. Therefore, in order to prove Proposition 1, it is only necessary to prove that the manufacturer can obtain more profits when she chooses pooling, if and only if $e > \tilde{\tilde{e}}(\lambda)$.

Consider a low-type manufacturer. We use the superscript ij to represent the profit function, where i represents the true IM's type and $j = o, h, l$, which represents the IR's belief. That is, from Lemma 2, the pooling profit under pooling equilibrium is

$$\pi_M^{lo} = \frac{1}{4}\left(-2e^2k - \frac{(-c' - \lambda\phi\alpha_h + (2 + (-1+\lambda)\phi)\alpha_l)^2}{2(-2+\phi)}\right); \tag{E.1}$$

and from Lemma 3, the separating profit is

$$\begin{aligned} \pi_M^{ll} = \frac{1}{8(-2+\phi)}\Big(&8e^2k - c'^2 - 4e^2k\phi + (4 - (-4+\phi)\phi)\alpha_h^2 - 2\alpha_h\Big(c'\phi + 2(2+\phi)\alpha_l \\ &+ 2\sqrt{-\phi(\alpha_h-\alpha_l)(2c' + (-4+\phi)\alpha_h + \phi\alpha_l)}\Big) \\ &+ 4\alpha_l\Big(c' + \phi\alpha_l + \sqrt{\phi(-\alpha_h+\alpha_l)(2c' + (-4+\phi)\alpha_h + \phi\alpha_l)}\Big)\Big). \end{aligned} \tag{E.2}$$

Through analyzing $\pi_M^{lo} - \pi_M^{ll}$, we can obtain which equilibrium is better. Note that

$$\frac{\partial^2\left(\pi_M^{lo} - \pi_M^{ll}\right)}{\partial e^2} = -\frac{(-2c_n\beta_1 + c_r\beta_2)^2\phi^2(\alpha_h - \alpha_l)^3}{2(-2+\phi)(-\phi(\alpha_h - \alpha_l)(2c' + (-4+\phi)\alpha_h + \phi\alpha_l))^{3/2}}, \tag{E.3}$$

which shows that $\pi_M^{lo} - \pi_M^{ll}$ is convex in e. Solving $\pi_M^{lo} - \pi_M^{ll} = 0$, and $e \in (0,1)$, we can obtain a unique solution:

$$\begin{aligned}\tilde{\tilde{e}}(\lambda) \equiv\ & \frac{1}{2(-2c_n\beta_1 + c_r\beta_2)^2(-1+\lambda)^2\phi^2}\Big(2(2c_n - c_r)(2c_n\beta_1 - c_r\beta_2)(-1+\lambda)^2\phi^2 \\ & - 4\sqrt{(-2c_n\beta_1 + c_r\beta_2)^2\lambda\phi^2(2+(-1+\lambda)\phi)^2(\alpha_h - \alpha_l)^2} + (2c_n\beta_1 - c_r\beta_2)\phi((4(1+\lambda) + 4(-1+\lambda)\phi \\ & + (-1+\lambda)^2(1+\lambda)\phi^2)\alpha_h - (2+(-1+\lambda)\phi)(2+\phi+\lambda(2+(-2+\lambda)\phi))\alpha_l)\Big).\end{aligned} \tag{E.4}$$

Therefore, the condition of $\pi_M^{lo} - \pi_M^{ll} > 0$ is satisfied when $e > \tilde{\tilde{e}}(\lambda)$.

However, the pooling equilibrium only exists in a certain range. Next, we will prove Proposition 1 by comparing $\tilde{\tilde{e}}(\lambda)$ and $\tilde{e}(\lambda)$. Denote that

$$\begin{aligned}\gamma &\equiv \tilde{e}(\lambda) - \tilde{\tilde{e}}(\lambda) \\ &= \frac{2\left(\sqrt{(-2c_n\beta_1 + c_r\beta_2)^2\lambda\phi^2(2+(-1+\lambda)\phi)^2(\alpha_h - \alpha_l)^2} + (2c_n\beta_1 - c_r\beta_2)\lambda\phi(2+(-1+\lambda)\phi)(-\alpha_h + \alpha_l)\right)}{(-2c_n\beta_1 + c_r\beta_2)^2(-1+\lambda)^2\phi^2}.\end{aligned} \tag{E.5}$$

Because of $\lambda \in (0,1)$, we can obviously obtain that $\gamma > 0$, that is, $\tilde{e}(\lambda) > \tilde{\tilde{e}}(\lambda)$. Thus, when pooling equilibrium exists, it is always better than the separating one.

Appendix F. Proof of Lemma 5

We substitute the optimal production quantity q_n under different equilibria of the previous solution into equation (7), and thus we can get q_r^* in the corresponding case. The high-type remanufacturer's situation is similar to the previous proof process, and thus it is omitted.

Appendix G. Proof of Lemma 6

After observing the market size α, the IM determines the DfE level e and the quantity of new product q_n simultaneously; after that, the IR decides the quantity of remanufactured product q_r based on the IM's decisions. As mentioned above, there is still information asymmetry in the market size during the whole process of decision-making. The adoption of blockchain technology will generate corresponding fixed cost C for IM. In dual signal mode, the high-type IM still has an incentive to disguise herself as the low-type to enable the IR to set a low quantity of remanufactured products. The IR updates his belief about market size according to the DfE level e and the new product quantity q_n decided by the IM. The IR's belief update principle is as follows [14, 29]: in the separating case, the IR believes that the market size is low if $(q_n, e) \in \Omega$ and high otherwise, where Ω represents the set of strategies in which the high-type IM will not mimic; in the pooling case, the IR's belief is the same as his prior belief if $(q_n, e) = (q_n^o, e^o)$ and otherwise, he believes that the market is high. Similar to the sole signal mode, we also use backward induction to obtain the existence conditions of separating equilibrium and pooling equilibrium.

In the separating equilibrium, there exists a PBE when and only when the IM's strategy quantity q_n satisfies

$$\max \pi_M((q_n, e) \notin \Omega \mid \alpha_h) \geq \max \pi_M((q_n, e) \in \Omega \mid \alpha_h), \tag{G.1}$$

$$\max \pi_M((q_n, e) \in \Omega \mid \alpha_l) \geq \max \pi_M((q_n, e) \notin \Omega \mid \alpha_l). \tag{G.2}$$

By solving the above inequalities, we can obtain the solution of separation equilibrium in the dual signal mode.

Then a PBE pooling equilibrium exists if and only if the IM's strategy satisfies

$$\pi_M((q_n^o, e^o) \mid \alpha_l) \geq \max_{q_n,e}\ \pi_M((q_n, e) \neq (q_n^o, e^o) \mid \alpha_l), \tag{G.3}$$

$$\pi_M((q_n^o, e^o) \mid \alpha_h) \geq \max_{q_n,e}\ \pi_M((q_n, e) \neq (q_n^o, e^o) \mid \alpha_h). \tag{G.4}$$

We find that the existing conditions (*i.e.*, the inequalities (G.3) and (G.4)) of pooling equilibrium cannot be satisfied within the given parameter range[11]. Thus, pooling equilibrium does not exist and the only equilibrium is the separating one given in Lemma 6.

The proof of Lemma 6 is similar to Lemmas 3 and 4. It is also the equilibrium solution of a signal game problem. We prove it through the following two steps. Step 1: Find the separating equilibrium solution and its existence conditions. Step 2: Prove that the pooling equilibrium does not exist.

Step 1. In the separating equilibrium, there exists a PBE when and only when the manufacturer's strategy quantity q_n satisfies

$$\max \pi_M((q_n, e) \notin \Omega \mid \alpha_h) \geq \max \pi_M((q_n, e) \in \Omega \mid \alpha_h), \tag{G.5}$$

$$\max \pi_M((q_n, e) \in \Omega \mid \alpha_l) \geq \max \pi_M((q_n, e) \notin \Omega \mid \alpha_l). \tag{G.6}$$

The High-type manufacturer's profit function is as follows:

$$\pi_M((q_n, e) \notin \Omega \mid \alpha_h) = -\frac{e^2 k}{2} + q_n\left(-q_n - c_n(1 - e\beta_1) + \alpha_h + \frac{1}{2}(c_r(1 - e\beta_2) + \phi(q_n - \alpha_h))\right) - C, \tag{G.7}$$

$$\pi_M((q_n, e) \in \Omega \mid \alpha_h) = -\frac{e^2 k}{2} + q_n\left(-q_n - c_n(1 - e\beta_1) + \alpha_h + \frac{1}{2}(c_r(1 - e) + \phi(q_n - \alpha_l))\right) - C. \tag{G.8}$$

Different from the sole signal mode, the profit function in dual signal mode is a binary function about q_n and e. Due to the existence of imitation motivation, there is a region composed of q_n and e, such that equation (G.5) is satisfied in this region. We record this region as region A. By comparing the maximum values of equations (G.7) and (G.8), we can get the white part of region A, as shown in Figure G.1. This figure is a cross-sectional view of the IM's profit function, in which the expressions of the two boundaries are as follows:

$$q_n^1 = \frac{2c_n - c_r - 2c_n e\beta_1 + c_r e\beta_2 - 2\alpha_h + \phi\alpha_l}{2(-2+\phi)} - \frac{\sqrt[2]{-\frac{-2k(1-\frac{\phi}{2})(c_n^2(4-4e^2\beta_1^2)+4c_n c_r(-1+e^2\beta_1\beta_2)+c_r^2(1-e^2\beta_2^2)-4e^2k(-2+\phi)}{(-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi)} + \frac{(-2+\phi)\alpha_h(4c_n-2c_r+(-2+\phi)\alpha_h))-\frac{1}{4}((-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi))(2c_n-c_r-2c_n e\beta_1+c_r e\beta_2-2\alpha_h+\phi\alpha_l)^2}{(-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi)}}}{2(-2+\phi)}, \tag{G.9}$$

$$q_n^2 = \frac{2c_n - c_r - 2c_n e\beta_1 + c_r e\beta_2 - 2\alpha_h + \phi\alpha_l}{2(-2+\phi)} + \frac{\sqrt[2]{-\frac{-2k(1-\frac{\phi}{2})(c_n^2(4-4e^2\beta_1^2)+4c_n c_r(-1+e^2\beta_1\beta_2)+c_r^2(1-e^2\beta_2^2)-4e^2k(-2+\phi)}{(-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi)} + \frac{(-2+\phi)\alpha_h(4c_n-2c_r+(-2+\phi)\alpha_h))-\frac{1}{4}((-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi))(2c_n-c_r-2c_n e\beta_1+c_r e\beta_2-2\alpha_h+\phi\alpha_l)^2}{(-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi)}}}{2(-2+\phi)}. \tag{G.10}$$

Next, for the low-type IM, the profit function as follows:

$$\pi_M((q_n, e) \in \Omega \mid \alpha_l) = \frac{1}{2}\left(-e^2 k + q_n(c_r - 2q_n + 2c_n(-1 + e\beta_1) - c_r e\beta_2 + q_n\phi - (-2+\phi)\alpha_l)\right) - C, \tag{G.11}$$

$$\pi_M((q_n, e) \notin \Omega \mid \alpha_l) = \frac{1}{2}\left(-e^2 k + q_n(c_r - 2q_n + 2c_n(-1 + e\beta_1) - c_r e\beta_2 + q_n\phi - \phi\alpha_h + 2\alpha_l)\right) - C. \tag{G.12}$$

The manufacturer's first-best production quantity can be clearly obtained that $(q_n, e) = \left(\frac{2k(2c_n-c_r+\phi\alpha_l-2\alpha_l)}{-8k+4c_n^2\beta_1^2-4c_n c_r\beta_1\beta_2+c_r^2\beta_2^2+4k\phi}, \frac{(2c_n\beta_1-c_r\beta_2)(2c_n-c_r+\phi\alpha_l-2\alpha_l)}{-8k+4c_n^2\beta_1^2-4c_n c_r\beta_1\beta_2+c_r^2\beta_2^2+4k\phi}\right)$ when $\alpha = \alpha_l$. Next, we need to judge whether the solution under the first-order condition is in region A. If this solution in region A, the costless separating equilibrium arises; otherwise, low-type needs to deviate these decisions downward, and thus the costly separating equilibrium arises.

[11] The scale parameter of the investment function $k > \frac{(-2c_n\beta_1+c_r\beta_2)^2}{4(2-\phi)}$, which ensures the existence condition of the optimal solution.

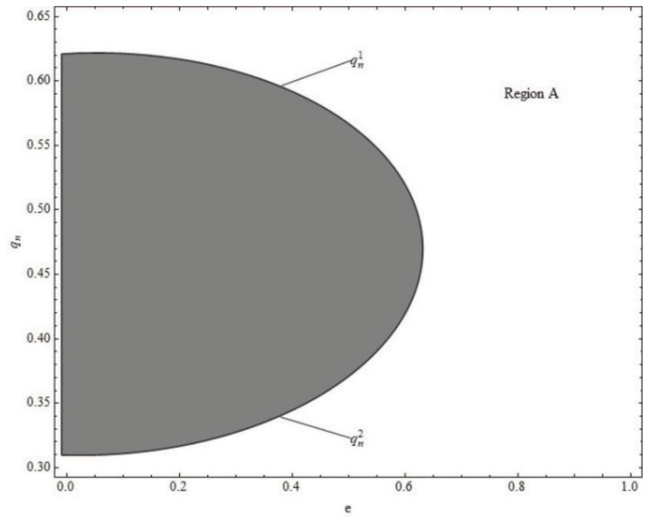

FIGURE G.1. Cross section of high-type profit function.

In region A, the value of (G.8) is less than the maximum value of (G.7). The judgment can be completed by substituting the first-order optimal (q_n, e) into (G.8) and comparing with the maximum value of (G.7).

The result as is that, when $\phi \geq \frac{-2c_n+c_r+2\alpha_h-\sqrt{4c_n^2-4c_nc_r+c_r^2-8c_n\alpha_h+4c_r\alpha_h+4\alpha_l^2}}{\alpha_h+\alpha_l}$, the first-order optimal solution is not in region A. In this case, to meet the condition of equilibrium existence, the low-type IM can only set q_n and e on the boundary of region A. In this way, by substituting q_n^1 and q_n^2 into (G.11), the optimal solution can be obtained by comparing the optimal profit. Thus, we obtain the optimal solution of downward distortion:

$$(q_n^*, e^*) = \left(\frac{4c_nk - 2c_rk}{(-2c_n\beta_1 + c_r\beta_2)^2 + 4k(-2+\phi)} + \frac{\sqrt{-\phi(\alpha_h-\alpha_l)(4c_n - 2c_r + (-4+\phi)\alpha_h + \phi\alpha_l)}}{2(-2+\phi)} + \frac{\frac{4k^2(-2\alpha_h+\phi\alpha_l)}{(-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi)} + \frac{(-2c_n\beta_1+c_r\beta_2)\mathrm{T}}{(-2+\phi)(\alpha_h-\alpha_l)}}{2k}, \frac{(2c_n\beta_1 - c_r\beta_2)(2c_n - c_r - 2\alpha_h + \phi\alpha_l)}{(-2c_n\beta_1 + c_r\beta_2)^2 + 4k(-2+\phi)} - \frac{T}{k(\alpha_h - \alpha_l)}\right), \tag{G.13}$$

where $T \equiv \sqrt{-\frac{k^2(-2c_n\beta_1+c_r\beta_2)^2\phi(\alpha_h-\alpha_l)^3(4c_n-2c_r+(-4+\phi)\alpha_h+\phi\alpha_l)}{((-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi))^2}}$.

Step 2. The proof of this step is supported by the IR's belief: if $(q_n, e) = (q_n^o, e^o)$, the IR's belief keep unchanged, otherwise, his belief is $\alpha = \alpha_h$. Therefore, when the following conditions are met, a pooling equilibrium exists.

$$\pi_M((q_n^o, e^o) \mid \alpha_l) \geq \max_{q_n,e}\pi_M((q_n, e) \neq (q_n^o, e^o) \mid \alpha_l), \tag{G.14}$$

$$\pi_M((q_n^o, e^o) \mid \alpha_h) \geq \max_{q_n,e}\ \pi_M((q_n, e) \neq (q_n^o, e^o) \mid \alpha_h). \tag{G.15}$$

Under this situation, the low-type manufacturer will decide her product quantity and effort level as $q_n^o = \frac{2k(2c_n-c_r+\lambda\phi\alpha_h-2\alpha_l+\phi\alpha_l-\lambda\phi\alpha_l)}{((-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi))^2}$, $e^o = \frac{(2c_n\beta_1-c_r\beta_2)(2c_n-c_r+\lambda\phi\alpha_h-2\alpha_l+\phi\alpha_l-\lambda\phi\alpha_l)}{((-2c_n\beta_1+c_r\beta_2)^2+4k(-2+\phi))^2}$. For the high-type IM, $\pi_M((q_n, e) \neq (q_n^o p, e^o) \mid \alpha_h)$ is maximized by her first-best solution, which renders $(q_n, e) = (\frac{2k(2c_n-c_r+\phi\alpha_h-2\alpha_h)}{-8k+4c_n^2\beta_1^2-4c_nc_r\beta_1\beta_2+c_r^2\beta_2^2+4k\phi}, \frac{(2c_n\beta_1-c_r\beta_2)(2c_n-c_r+\phi\alpha_h-2\alpha_h)}{-8k+4c_n^2\beta_1^2-4c_nc_r\beta_1\beta_2+c_r^2\beta_2^2+4k\phi})$. Substituting this solution into the profit function, and comparing to $\pi_M((q_n^o, e^o)|\alpha_h)$, we can obtain the following equation:

$$\pi_M((q_n^o, e^o) \mid \alpha_h) - \max_{q_n,e}\ \pi_M((q_n, e) \neq (q_n^o p, e^o) \mid \alpha_h) \tag{G.16}$$

$$= \frac{k\big((2c_n - c_r + (-2+\phi)\alpha_h)^2 - (2c_n - c_r + \lambda\phi\alpha_h + (-2+\phi-\lambda\phi)\alpha_l)(2c_n - c_r + (-4+\lambda\phi)\alpha_h + (2+\phi-\lambda\phi)\alpha_l)\big)}{2\big((-2c_n\beta_1 + c_r\beta_2)^2 + 4k(-2+\phi)\big)}.$$

Due to the assumption of $(-2c_n\beta_1 + c_r\beta_2)^2 + 4k(-2+\phi) < 0$, the value of (G.16) is always less than zero. In other words, under given conditions, the pooling equilibrium does not exist.

Appendix H. Proof of Proposition 3

Proposition 3 is the comparison of profits under two information signaling modes. When q_n is used as the signal alone, the value of effort level e is the optimal solution under complete information that $e^* = \frac{(2c_n\beta_1 - c_r\beta_2)(2c_n - c_r + \phi\alpha_i - 2\alpha_i)}{-8k + 4c_n^2\beta_1^2 - 4c_nc_r\beta_1\beta_2 + c_r^2\beta_2^2 + 4k\phi}$. Through this setting, we can ensure that the profits of the two modes are the same under complete information, which is consistent with the actual situation. Through the verification of different values, we can obtain that the profit under dual signal mode is always higher than that under sole signal mode, thereby meaning that there exists a threshold $\tilde{C}$ of the fixed cost.