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IMPACT OF REMANUFACTURING OPTIMISM ON COMPETITIVE QUALITY CHOICE AND PRODUCT-DESIGN STRATEGY*

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Abstract. Research has shown that managers typically display optimistic expectations for the future. In a competitive market, remanufacturers may overestimate consumers' willingness to pay (WTP) for remanufactured products. We develop a game-theoretic model of competition between an original equipment manufacturer (OEM) and an independent remanufacturer (IR), where the OEM determines interchangeability in product design, and the IR may have an optimistic bias about remanufacturing market demand and adopt different quality strategies. We find that the OEM is always strategic about the interchangeability design of its products. Interestingly, remanufacturing optimism triggers more significant changes in the degree of interchangeability. In some cases, the IR's optimistic bias can lead to a win–win outcome for both firms. In addition, we find that a moderate increase in the quality of remanufactured products alleviates the weak situation in consumer quality perception. But when the WTP of remanufactured products is generally low, it is more profitable for the optimistic IR to keep the quality of remanufactured products equivalent to new products than to blindly upgrade the product quality. Our findings suggest that applying bounded rationality to issues in remanufacturing may yield new insights into the determinants of product design and quality management.

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1. Introduction

Remanufacturing[1] restores the quality and performance of used products to "like-new" or "better-than-new" conditions through a comprehensive and rigorous industrial process [1]. For example, Hitachi[2] and Aoke[3] have developed processing and repair techniques that allow the remanufactured construction machinery and parts to maintain or exceed the quality provided by new products. Compared to new products, remanufactured products can reduce emissions by 80%, energy by 60%, and raw materials by 70% [2]. For example, toner and

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[1] https://remanstandard.us/.
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cartridges can save oil by developing remanufacturing technology while reducing the consumption of plastic, metal, and other accessories [3]. Because of these benefits, the government is working to promote remanufacturing in industries such as automotive parts, engineering apparatuses, and electronics [4, 5]. Many remanufacturers such as Recycle Assist, Foxconn, and Gazelle have also joined the remanufacturing market [6]. Some studies indicate that the remanufacturing industry in the United States has exceeded $53 billion [7]. With the active expansion of the remanufacturing market, more remanufactures than ever are pleasantly looking ahead to a bright future for the remanufacturing industry.

One concern, however, is that remanufacturers may be overly optimistic about the market potential for remanufacturing. Although some remanufactured products are upgraded with new technology or features that make them more desirable or of higher quality than the original, consumers may not be aware of such efforts [8]. Because consumers are often unaware of the procedures used for remanufacturing, the details of replacement or upgrade components, and the quality testing specifications and practices established by remanufacturers [9, 10]. Remanufacturers may overestimate consumers' reliance on the quality of remanufactured products or misjudge consumers' subjective knowledge or cognition about remanufactured products [11]. In addition, many remanufacturers see remanufacturing as a possible marketing opportunity related to growing consumer concern about environmental issues. This is also reflected in many environmental surveys, such as one that shows that 80% of EU citizens are willing to buy products with low environmental impact [12]. However, White *et al.* [13] demonstrate that only about 26% do so. Michaud and Llerena [14] even find no evidence that consumers are willing to pay a premium for remanufactured products. Due to the green gap between consumers' positive environmental commitments and actual purchase decisions [11], remanufacturers are likely to overestimate the market potential. The optimism bias is a common psychological sentiment [15], and the impact of such emotions by remanufacturers on supply chain members' decisions in a competitive market is not insignificant.

In the actual competitive market, third-party independent remanufacturers (IR) are a significant threat to original equipment manufacturers (OEM). Due to concerns about resources, knowledge, loss of goodwill, etc., not all OEMs have remanufacturing capability or intention [16]. In the United States, most of the remanufacturing is done by IRs, with OEMs accounting for only 6% of the more than 2000 remanufacturing firms [1]. To curb the encroachment of remanufactured products on new products, the OEM may reduce the interchangeability in its product design. This interchangeability involves material selection, process design, disassembly, and cleaning [17, 18]. Recovering products that cannot be efficiently disassembled is difficult and costly for the IR [19]. In the printer industry, for example, some OEMs try to prevent IRs from remanufacturing by applying ultrasonic welding technology to reduce product interchangeability during the assembly process [20]. Ecorica even sues Canon for changing the design of the IC chip resulting in the inability to remanufacture cartridges. However, some OEMs choose to improve the interchangeability of their products. On the one hand, a high level of interchangeability facilitates inspection, handling, and cleaning by OEMs [21]. On the other hand, OEMs can save on inventory holding or shortage costs [22].

It is interesting to discuss the interaction between the IR's optimism and the OEM's product design. Economic models usually assume that beliefs are correct on average. But there is very limited research on how the IR's optimistic beliefs about remanufacturing affect the decisions of supply chain members. In this paper, we consider the competitive market of an OEM and an IR. Since consumers have lower perceived quality for remanufactured products, the classical approach to model willingness-to-pay (WTP) for remanufactured products is to multiply the WTP of his/her corresponding new product by a discount factor, *i.e.*, a remanufacturing discount factor (RDF). But there is significant consumer uncertainty about the discount factor for remanufactured products [23]. Thus, we assume that a realistic IR makes an objective assessment of the remanufacturing market demand, while an optimistic IR has biased beliefs about the RDF, *i.e.*, overestimates the number of consumers that have high valuations for the quality of remanufactured products. To counter the threat from the IR, the OEM determines the level of product interchangeability. They competitively choose their quality and price. Since there is the minimum quality standard required by law, many scholars assume that the quality of remanufactured and new products is always the same and is determined solely by the OEM. In our paper, however, the IR can determine a higher level of quality for remanufactured products to reflect improvements that have occurred since the product was originally made.

Based on the above argument, we address the following research questions. How does the IR's optimism about remanufacturing affect the competitive quality choice and product-design strategy? Does remanufacturing optimism trigger higher profits for firms than when the IR is realistic about remanufacturing? We find that the OEM's choice of product design is strategic. Interestingly, influenced by changes in product prices, remanufacturing optimism triggers greater changes in the level of interchangeability. Another finding is that although remanufacturing optimism is not always beneficial to firms, in some cases, the IR's optimistic belief can lead to a win–win outcome in a competitive market. The reason that remanufacturing optimism benefits both firms is the change in the IR's quality strategy. Finally, we find it profitable for the IR to improve the quality of remanufactured products, because it alleviates the weakness of remanufactured products in consumer perception. But when the IR is optimistic about RDF, it is counterproductive to blindly improve the quality of remanufactured products. This is mainly related to the general attitude of consumers towards remanufactured products and the cost efficiency of firms.

The rest of this paper is structured as follows. Section 2 reviews the related literature. In Section 3, we describe the model. Section 4 presents the equilibrium results. In Section 5, we analyze the sensitivity of related parameters. In Section 6, we analyze the impact of interchangeability and remanufacturing optimism. Section 7 considers the OEM's optimistic belief bias. Section 8 concludes the paper. All proofs are provided in appendices.

2. Literature review

We review the literature most relevant to our study in three streams: remanufacturing and its competition, product design, and behavioral operations management.

2.1. The supply chain of remanufacturing and its market competition

Some scholars focus on the heterogeneity between new and remanufactured products and hypothesize that consumers perceive higher quality in new products [24]. Quality knowledge, cost information, and environmental attitudes can influence consumer perception differences [2, 25, 26]. However, due to the lack of remanufacturing capabilities and experience of OEMs, most remanufacturing activities are operated by IRs [66]. In general, most scholars confirm that the entry of IRs reduces the profits of OEMs [27, 28]. Facing the threat from IRs, what strategies OEMs can adopt is an important research question. Zhang *et al.* [29] compare OEMs' remanufacturing operations through outsourcing or licensing. Majumder and Groenevelt [30] confirm that the OEM can influence remanufacturing activities through its production (quantity) decision. Atasu and Souza [31] and Örsdemir *et al.* [7] explore the impact of OEMs on competitive markets by capturing their endogenous quality and quantity decisions. Chen and Chen [32] examine the competition in the remanufacturing industry under exogenous product quality. However, the above literature on quality assumes that the objective quality of remanufactured products is equivalent to that of new products, where objective quality refers to the performance, features, reliability, durability, and esthetics of the product [33]. Remanufacturing requires producers to make systemic changes to traditional products, business models, and processes [19]. Genovese *et al.* [34] argue that remanufacturing represents an upgrade or even a departure from traditional production and consumption systems. Therefore, in this paper, we explore the impact of different quality strategies of the IR on the competitive market under the quality standards required by law.

2.2. Product design strategy in the supply chain

Manufacturing process-oriented product design is a common strategy used by OEMs in competitive markets. If products are not properly designed for remanufacturing, there are increased barriers and costs for remanufacturers [35]. For example, Ijomah *et al.* [36] point out that welding and strong adhesive designs during assembly significantly increase the difficulty of remanufacturing. The goals geared towards product design are diverse and include modularity [37], commonality [22], interchangeability [20], disassembly [21], and durability

[38]. Mukhopadhyay and Setoputro [39] find that products with modular design are easy to assemble and disassemble, thus increasing the retainability value of products. Product design also leads to a higher degree of interchangeability [40] and achieves economies of scale by using common product modules for multiple products, thereby reducing assembly and inventory holding costs [41]. In recent years, scholars have focused on the interaction of product-design strategies with other decisions. Atasu and Souza [31] explore the impact of forms of product recycling, collecting cost structures, and legislation on product design. Reimann *et al.* [42] discuss the link between remanufacturing and opportunities to reduce variable remanufacturing costs through process innovation. Wu [20] considers the impact of the product-design strategy of the OEM on pricing decisions.

2.3. Behavioral operations management and optimism

Behavioral operations management aims to understand managers' decisions and uses this understanding to generate interventions to improve supply chain operations [43, 44]. The literature on behavioral operations management has successfully incorporated deviations from rational assumptions into the model. In terms of consumer behavior factors, Su and Zhang [45] examine the impact of strategic consumers, *i.e.*, consumers who can anticipate future sales and choose purchase timing, on supply chain performance. Papanastasiou and Savva [46] discuss the interaction between consumers' social learning and strategic behavior. Other factors such as low-carbon awareness [47] and impulse buying [48] are also taken into account. With respect to the study of managerial behavior, factors such as strategic inventory [49], visibility [50], loss-averse [51], and fairness [52] are discussed.

There is ample evidence from applied psychology that managers typically overestimate their capabilities and often display optimistic expectations for the future. Optimism due to cognitive biases can induce sub-optimal decisions, and many scholars confirm that optimistic managers do not deliver optimal profits [53, 54]. Jin *et al.* [55] find that green optimism is always detrimental to manufacturers. But some scholars argue that optimism can also be a strategic advantage. Galasso and Simcoe [56] find that optimism leads to more citation-weighted patents. Jiang and Liu [57] show that an optimistic manager in a competitive market can make the firm better off because managerial optimism mitigates intense market competition. Considering the prevailing optimism in competitive markets, we introduce the IR's optimistic beliefs about the remanufacturing market into the product design issue to examine its impact.

This paper makes the following contributions to the existing literature. First, the existing research mainly examines managers' optimism about their own abilities, whereas we focus on the IR's optimism about remanufacturing market demand in a competitive market and its impact on corporate decisions. Second, considering the practices of the remanufacturing industry, we extend the assumption that the quality of new and remanufactured products is always consistent. We therefore additionally discuss the competitive market dynamics when the IR applies remanufacturing technology to determine higher product quality levels. Finally, we clarify the interaction between the OEM's interchangeability in product design and the IR's optimism in a competitive environment and their impact on quality and pricing decisions.

3. Modeling framework

In this section, we consider an OEM selling the new product and an IR selling the remanufactured product. Consumers make decisions between the two types of products to maximize utility. We define the consumer's WTP for new product quality as θ. Consistent with Wu [20], we normalize the consumer valuation (θ) of the new product to 1. The consumer's valuation for new products is θs_a, where s_a is the quality of new products. We assume that quality is observable [32], for example, the quality of an automobile transmission can be explained as a combination of heat dissipation, stability, durability and fuel consumption. China's National Development and Reform Commission requires remanufacturers to provide quality assurance for remanufactured products that is not lower than the quality level of corresponding new products[4]. So, we assume that $s_b \geq s_a$, where s_b is

[4]https://www.ndrc.gov.cn/xxgk/zcfb/ghxwj/202104/t20210423_1277190_ext.html.

the quality of remanufactured products. However, in reality, consumers perceive the quality of remanufactured products to be inferior to that of new products. Many studies in closed-loop supply chains capture this by modeling consumers' WTP for remanufactured products as a δ fraction for new products [22, 31, 58]. The consumer's valuation for remanufactured product is $\delta\theta s_b$, where δ is the remanufacturing discount factor (RDF).

A major contribution of our paper is that we explore the impact of remanufacturing optimism on corporate decisions. There is heterogeneity in remanufacturers' perceptions of the remanufacturing discount factor [25]. Therefore, based on the belief in the uncertainty of the remanufacturing market, we assume that IRs are either realistic or optimistic. Referring to Jiang and Liu [57] and Jin *et al.* [55], we assume that a realistic IR has an unbiased belief about the RDF, *i.e.*, $\bar{\delta} \in (0, 1)$. An optimistic IR that overestimates the level of the RDF has a biased belief, *i.e.*, $\hat{\delta} \geq \bar{\delta}$. $\delta_j (j \in \{H, L\})$ denotes the discount factor of type-j consumer's WTP for the quality of remanufactured products. Let α denote the fraction of consumers having high RDF for remanufactured products, and $1 - \alpha$ denotes the fraction of consumers having low RDF. An optimistic IR will overestimate the probability of a high value of δ as $\hat{\alpha}(\hat{\alpha} \in (\alpha, 1])$. By focusing on the boundary case of $\hat{\alpha} = 1$, the biased belief of an optimistic IR for the RDF is $\hat{\delta} = \hat{\alpha}\delta_H + (1 - \hat{\alpha})\delta_L = \delta_H$. Similar to Xu and Xiao [59], we consider that each manager's type is common knowledge. The optimistic IR knows that her/his belief about RDF is different from that of her/his opponent, but (s)he does not think that her/his belief is biased [57]. Therefore, the IR's profit-maximization decision is based on her/his own belief and her/his knowledge about the opponent's belief [55].

To consider the price sensitivity and horizontal preferences of consumers for new and remanufactured products, we use a Hotelling-type model [20, 60, 67]. In this horizontal preference dimension, the OEM is located at 0 and the IR at 1. Therefore, a consumer's net utility from a new product is $U_n = s_a - tx - p_n$, and the utility from a remanufactured product is $U_r = \delta_j s_b - t(1 - x) - p_r$. x represents the ideal distance of a consumer's horizontal preference to a new product. t is the sensitivity of consumers to horizontal mismatch, and tx represents the mismatch cost. Similar to Pazoki and Zaccour [60], we assuming full coverage of the market, which makes it possible to capture cannibalization. Consumers compare the two products and choose the one that offers higher non-negative utility value.

The unit cost of producing a new product with quality s_a is $c_m = ks_a^2$, $k > 0$. Giutini and Gaudette [61] find that the unit remanufacturing cost is about 40–65% of that of a new product. Therefore, we set ρ to denote the degree of cost savings of remanufacturing. The unit cost of producing a remanufactured product with quality s_b is $c_r = \rho ks_b^2$. Interchangeability refers to the cores and parts that can make the product achieve the specified performance without repair or adjustment. Following Wu [20], we let $\tau(-1 < \tau < 1)$ represents the interchangeability in the OEM's product-design strategy. When the OEM chooses an interchangeability of τ, the unit production costs of the OEM and the IR are $c_m - \eta_n\tau$ and $c_r - \eta_r\tau$, respectively. η_n and η_r refer to the degree of influence of interchangeability on the production cost of new and remanufactured products, and $\eta_n \neq \eta_r$. When $\tau = 0$, the OEM does not adopt a product-design strategy. When $0 < \tau < 1$, the OEM adopts a high level of interchangeability design, which makes the production cost of the OEM and IR benefit from the improvement of assembly efficiency and recyclability. When $-1 < \tau < 0$, the low level of interchangeability leads to an increase in the production cost of the OEM and IR. Moreover, product-design strategy is accompanied by fixed costs such as technology investment and equipment upgrades. We denote the fixed cost as a quadratic form of τ, *i.e.*, $\beta\tau^2$. This cost structure is widely used by other studies [62, 63]. Table 1 summarizes the notations used in this manuscript.

4. The models

4.1. Model-R: the IR is realistic for the remanufacturing discount factor (RDF)

Under Model-R, the IR has unbiased belief about RDF. A consumer who is indifferent between the new and remanufactured product has a horizontal preference x^* that is determined by $s_a - tx - p_n = \delta_j s_b - t(1 - x) - p_r$. Therefore, $x^* = (t + (s_a - \delta_j s_b) - (p_n - p_r))/2t$. Thus, the demand functions for new products and remanufactured

TABLE 1. Summary of related notations.

Symbol	Definition
δ	Level of remanufacturing discount factor (RDF)
$\bar{\delta}$	Unbiased belief about RDF
$\hat{\delta}$	Biased belief about RDF, and in this paper, $\hat{\delta} = \delta_H$
s_a/s_b	Quality of a new/remanufactured product
p_n/p_r	Price of a new/remanufactured product
t	Transportation cost or competition intensity
D_n/D_r	Production quantity of new/remanufactured products
k	Marginal cost of production per unit of quality for the new product
ρ	Per unit of cost savings from remanufacturing
τ	The OEM's choice of interchangeability in its product design
η_n/η_r	Impact factors of the degree of interchangeability on the production costs of a new/remanufactured product
β	Scale parameter of the investment function
Π_i^{h-l}	Profit function of firm i under scenario $h-l$, where i = OME(IR) denotes the OEM (IR), $h = R(O)$ denotes the IR's unbiased (biased) beliefs about remanufacturing, $l = A(B)$ denotes the high-quality (quality-following) strategy adopted by the IR
WTP	Willingness to pay
OEM	Original equipment manufacturer
IR	Independent remanufacturer
RDF	Remanufacturing discount factor

products are:

$$D_r = \frac{t - \left(s_a - \bar{\delta} s_b\right) - (p_r - p_n)}{2t} \tag{1}$$

$$D_n = \frac{t + \left(s_a - \bar{\delta} s_b\right) - (p_n - p_r)}{2t}. \tag{2}$$

Note that $\bar{\delta} = \alpha\delta_H + (1-\alpha)\delta_L$ and $\bar{\delta}$ represents the average RDF $D_r = \alpha D_{r-H} + (1-\alpha) D_{r-L}$. D_{r-H} and D_{r-L} denote the quantities when δ_j is of high and low type, respectively. Accordingly, $D_n = \alpha D_{n-H} + (1-\alpha) D_{n-L}$. The quality level of the OEM, the degree of interchangeability in the product design, and the quality level of the IR are first determined simultaneously. Next, the OEM and the IR both choose the unit sale prices. The timeline of events is summarized in Figure 1. We derive the equilibrium by backward induction. According to equations (1) and (2), we obtain the profit-maximization problem as follows:

$$\max_{\tau, s_a, p_n} \Pi_{\text{OEM}}^{R} = \left(p_n - \left(k s_a^2 - \eta_n \tau\right)\right) D_n - \beta \tau^2 \tag{3}$$

$$\max_{s_b, p_r} \Pi_{\text{IR}}^{R} = \left(p_r - \left(\rho k s_b^2 - \eta_r \tau\right)\right) D_r$$

$$\text{s.t. } 0 < D_r; 0 < D_n; s_b \geq s_a. \tag{4}$$

This solution approach is the same as in Örsdemir *et al.* [7]. To ensure a unique interior solution, as in Yan *et al.* [64] and Qiao and Su [6], we impose the condition of $0 < D_r, 0 < D_n$. Note that we use the superscript R to denote optimal values.

Proposition 1. *The optimal decisions for the OEM and IR are as follows:*

(a) *If $\rho_a < \rho < \bar{\delta}$ and $k > k_a$, the IR adopts a high-quality strategy.*

$$s_a^{R-A} = \frac{1}{2k}, \quad s_b^{R-A} = \frac{\bar{\delta}}{2k\rho}, \quad \tau^{R-A} = \frac{\left(\rho + 12kt\rho - \bar{\delta}^2\right)(\eta_n - \eta_r)}{4k\rho A},$$

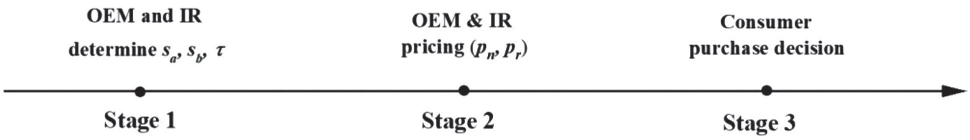

FIGURE 1. Timeline of events.

$$p_n^{R-A} = \frac{\left(4\rho + 12kt\rho - \bar{\delta}^2\right)A - \left(\rho + 12kt\rho - \bar{\delta}^2\right)B}{12k\rho A}, \quad p_r^{R-A} = \frac{\left(12kt\rho + 4\bar{\delta}^2 - \rho\right)A - \left(\rho + 12kt\rho - \bar{\delta}^2\right)B}{12k\rho A}.$$

(b) *If $\bar{\delta} < \rho < 1$ and $k > k_b$, the IR adopts a quality -following strategy.*

$$s_a^{R-B} = s_b^{R-B} = \frac{1}{2k}, \quad \tau^{R-B} = \frac{\left(1 + 12kt + \rho - 2\bar{\delta}\right)(\eta_n - \eta_r)}{4kA},$$
$$p_n^{R-B} = \frac{\left(4 + 12kt + \rho - 2\bar{\delta}\right)A - \left(1 + 12kt + \rho - 2\bar{\delta}\right)B}{12kA}, \quad p_r^{R-B} = \frac{\left(2(6kt + \rho + \bar{\delta}) - 1\right)A - \left(1 + 12kt + \rho - 2\bar{\delta}\right)B}{12kA}$$

where $A = 18t\beta - (\eta_n - \eta_r)^2$, $B = (\eta_n - \eta_r)(2\eta_n + \eta_r)$, $\rho_a = \frac{3\beta\bar{\delta}^2}{3\beta + 2k(\eta_n - \eta_r)^2}$, $k_a = \frac{3\beta\left(\rho - \bar{\delta}^2\right)}{4\rho(A - 9t\beta)}$, $k_b = \frac{3\beta\left(1 + \rho - 2\bar{\delta}\right)}{4(A - 9t\beta)}$.

The range of k value reflects the constraints on the quantity of remanufactured products and the conditions for full market coverage. The relevant proofs, optimal quantities and profits are derived and summarized in Appendix A.

Proposition 1 suggests that the IR's quality strategy is influenced by remanufacturing cost savings. The IR tends to adopt a high-quality strategy when ρ is small. In this case, the increase of the average RDF and the decrease of ρ will enhance the quality level of remanufactured products. A large average RDF implies a reduction in the difference in consumer perception of quality between new and remanufactured products, which promotes the IR to upgrade product quality. If the degree of cost savings in remanufacturing decreases, the incentive for the IR to improve product quality weakens. When ρ is large, remanufacturing activities do not provide a large cost advantage to the IR. However, due to the regulation of quality standards for remanufacturing, the IR will adopt a quality-following strategy. In this case, the quality level of the new and remanufactured products is related only to the cost coefficient. A larger cost coefficient means that for a high-quality product, the OEM costs more to produce. As a result, the new product quality decreases as k increases. Due to the quality-following strategy, k has the same effect on the quality of remanufactured products.

4.2. Model-O: the IR is optimistic for the remanufacturing discount factor (RDF)

Under Model-O, the IR has optimistic biased belief about RDF. Due to the OEM's realism about RDF, the demand function for the OEM is the same as equation (2). The IR believes that all consumers have high RDF for remanufactured products. Therefore, from the optimistic IR's perspective, the demand function of remanufactured products is

$$D_r = \frac{t - (s_a - \delta_H s_b) - (p_r - p_n)}{2t}. \tag{5}$$

According to equations (2) and (5), we obtain the profit-maximization problem as follows:

$$\max_{\tau, s_a, p_n} \Pi_{\text{OEM}}^O = \left(p_n - \left(ks_a^2 - \eta_n\tau\right)\right)\frac{t + \left(s_a - \bar{\delta}s_b\right) - (p_n - p_r)}{2t} - \beta\tau^2 \tag{6}$$
$$\max_{s_b, p_r} \Pi_{\text{IR}}^O = \left(p_r - \left(\rho ks_b^2 - \eta_r\tau\right)\right)\frac{t - (s_a - \delta_H s_b) - (p_r - p_n)}{2t}$$

$$\text{s.t. } 0 < D_r; 0 < D_n;\ \ s_b \geq s_a. \tag{7}$$

Note that when deriving the optimal decision, we use the profit function of the optimistic IR based on the biased belief about the RDF. However, since the biased beliefs cannot directly change the expected profit of the IR, we calculate the expected profit of the optimistic IR based on unbiased belief.

Proposition 2. *The optimal decisions for the OEM and IR are as follows:*

(a) *If* $\rho_b < \rho < 2\delta_H - \bar{\delta}$ *and* $k > k_c$*, the IR adopts a high-quality strategy.*

$$s_a^{O-A} = \frac{1}{2k},\quad s_b^{O-A} = \frac{2\delta_H - \bar{\delta}}{2k\rho},\quad \tau^{O-A} = \frac{(\rho + 12kt\rho - C)(\eta_n - \eta_r)}{4k\rho A},$$

$$p_n^{O-A} = \frac{(4(\rho + 3kt\rho) - C)A - (\rho + 12kt\rho - C)B}{12k\rho A},\quad p_r^{O-A} = \frac{\left((12kt-1)\rho + 4\left(\bar{\delta} - 2\delta_H\right)^2\right)A - (\rho + 12kt\rho - C)B}{12k\rho A}.$$

(b) *If* $2\delta_H - \bar{\delta} < \rho < 1$ *and* $k > k_d$*, the IR adopts a quality -following strategy.*

$$s_a^{O-B} = s_b^{O-B} = \frac{1}{2k},\quad \tau^{O-B} = \frac{\left(1 + 12kt + \rho - 4\bar{\delta} + 2\delta_H\right)(\eta_n - \eta_r)}{4kA},$$

$$p_n^{O-B} = \frac{\left(4 + 12kt + \rho - 4\bar{\delta} + 2\delta_H\right)A - (1 + 12kt + \rho - 4\delta_a + 2\delta_H)B}{12kA},$$

$$p_r^{O-B} = \frac{\left(12kt + 2\rho - 1 - 2\bar{\delta} + 4\delta_H\right)A - \left(1 + 12kt + \rho - 4\bar{\delta} + 2\delta_H\right)B}{12kA}$$

where $C = \left(5\bar{\delta} - 4\delta_H\right)\left(2\delta_H - \bar{\delta}\right)$, $\rho_b = \frac{3\beta C}{3\beta + 2k(\eta_n - \eta_r)^2}$, $k_c = \frac{3\beta(\rho - C)}{4\rho(A - 9t\beta)}$, $k_d = \frac{3\beta\left(1 + \rho - 4\bar{\delta} + 2\delta_H\right)}{4(A - 9t\beta)}$.

Similar to Model-R, the relevant proofs, optimal quantities and profits are derived and summarized in Appendix A.

Proposition 2 shows that the IR's quality strategy is also influenced by remanufacturing cost savings. In addition, the IR's optimism about RDF increases the interval for the IR to adopt a high-quality strategy and induces a higher quality of remanufactured products ($s_b^{O-A} > s_b^{R-A}$). But when the IR adopts a quality-following strategy, the IR's optimism does not affect product quality. Note that the quality of remanufactured products decreases with the increase of the average RDF. Because a large average RDF indicates an increase in the valuation of remanufactured products, thus narrowing the gap between $\bar{\delta}$ and δ_H. Conversely, if δ_H increases, the IR upgrades product quality. As in Proposition 1, the quality level of remanufactured and new products is only related to the cost coefficient when the IR adopts a quality-following strategy.

Proposition 3. *The OEM's product-design strategy is as follows. The OEM chooses high interchangeability if* $\eta_n > \eta_r$*, and low interchangeability otherwise.*

In Proposition 3, we explore the OEM's attitude toward interchangeability in its product-design strategy. We find that the OEM's product-design strategy relies on the extent to which interchangeability affects product production costs. When $\eta_n > \eta_r$, the OEM chooses high interchangeability. While high interchangeability also benefits the IR, product-design strategy can lead to greater cost reduction for the OEM. But when $\eta_n < \eta_r$, the IR is more susceptible to product design. In this case, the OEM chooses low-level interchangeability to increase the difficulty of remanufacturing. Because the low level of interchangeability forces the IR to incur more unit production costs than the OEM. The low level of interchangeability also reduces the OEM's fixed investment in product design.

5. Analysis of the equilibrium solutions

In this section, we focus on the impact of the cost structure of firms and the remanufacturing discount factor on the equilibrium results. We denote the interchangeability of different models as τ^{h-l}, where $h = R, O$ represents Model-R and Model-O. $l = A, B$ denotes the high-quality and quality-following strategies.

Proposition 4. *The effect of k on equilibrium decisions in different models is as follows.*

(a) $\frac{\partial s_a^{h-l}}{\partial k} < 0$, $\frac{\partial s_b^{h-l}}{\partial k} < 0$. $\frac{\partial \tau^{h-l}}{\partial k} < 0$ *if* $\eta_n > \eta_r$; $\frac{\partial \tau^{h-l}}{\partial k} > 0$ *if* $\eta_n < \eta_r$.

(b) *When* $\rho > \rho_i^{h-l}$, $\frac{\partial p_n^{h-l}}{\partial k} < 0$, $\frac{\partial p_r^{h-l}}{\partial k} > 0$, *otherwise*, $\frac{\partial p_n^{h-l}}{\partial k} > 0$, $\frac{\partial p_r^{h-l}}{\partial k} < 0$.

(c) *When* $\rho > \bar{\delta}^2$, $\frac{\partial D_n^{h-A}}{\partial k} < 0$, $\frac{\partial D_r^{h-A}}{\partial k} > 0$, *otherwise*, $\frac{\partial D_n^{h-A}}{\partial k} > 0$, $\frac{\partial D_r^{h-A}}{\partial k} < 0$. $\frac{\partial D_n^{h-B}}{\partial k} < 0$ *and* $\frac{\partial D_r^{h-B}}{\partial k} > 0$.

Where $\rho_i^{h-l} (i = n, r)$ are detailed in the Appendix B.

Proposition 4 suggests that the increase in the cost coefficient weakens the incentive for firms to improve product quality. Regarding product-design strategy, the level of interchangeability increases as the cost coefficient decreases when interchangeability results in greater cost reductions for the OEM. This indicates that in the case of low production costs, the OEM weakens the IR's competitiveness by increasing the level of interchangeability. Intuitively, the price of a new product increases as the cost coefficient increases. But this holds only if the remanufacturing cost savings are small. A possible explanation for this might be that the increase in cost coefficient forces the OEM and the IR to reduce product quality, which causes the price of new products to fall. When cost savings are large, the reduction of remanufactured product quality by the cost coefficient dominates the improvement of product quality by the cost savings, and the price of remanufactured products decreases. The impact of cost coefficient on the product demand is different under different quality strategies. Specifically, when the IR adopts a quality-following strategy, the increase in the cost coefficient has a greater negative impact on the demand for new products. When the IR adopts a high-quality strategy, the effect of the cost coefficient on quantities changes in the case where ρ is large.

Proposition 5. *The effect of ρ on equilibrium decisions in different models is as follows.*

(a) $\frac{\partial p_n^{R-l}}{\partial \rho} > 0$, $\frac{\partial p_r^{R-A}}{\partial \rho} < 0$, $\frac{\partial p_r^{R-B}}{\partial \rho} > 0$, $\frac{\partial D_n^{R-l}}{\partial \rho} > 0$, $\frac{\partial D_r^{R-l}}{\partial \rho} < 0$.

(b) $\frac{\partial p_r^{O-A}}{\partial \rho} < 0$, $\frac{\partial p_r^{O-B}}{\partial \rho} > 0$. *When* $\bar{\delta} > \frac{4}{5}\delta_H$, $\frac{\partial p_n^{O-A}}{\partial \rho} > 0$, $\frac{\partial D_n^{O-A}}{\partial \rho} > 0$, $\frac{\partial D_r^{O-A}}{\partial \rho} < 0$. *Otherwise,* $\frac{\partial p_n^{O-A}}{\partial \rho} < 0$, $\frac{\partial D_n^{O-A}}{\partial \rho} < 0$, $\frac{\partial D_r^{O-A}}{\partial \rho} > 0$. *The influence of ρ on the equilibrium decisions in Model O–B is the same as the sensitivity in Model R–B.*

In Proposition 5, we interestingly find that the impact of remanufacturing cost savings on the price of remanufactured products varies depending on the quality strategy. This discrepancy could be attributed to the effect of ρ on the quality of remanufactured products. When the IR adopts a high-quality strategy, the quality of remanufactured products decreases as ρ increases. The decreasing effect of quality on price dominates the increasing effect of ρ on price. When the IR adopts a quality-following strategy, the increased ρ directly increases the unit production cost of remanufactured products. Moreover, the sensitivity varies under different beliefs about RDF. When the IR is realistic, the new product price and demand always increase with ρ. On the one hand, the increase of ρ under the high-quality strategy reduces the quality of remanufactured products. The increased relative quality of new products drives the OEM to set a higher product price. On the other hand, although the quality of remanufactured products is independent of ρ in Model R–B, the positive effect of higher remanufactured product prices on the quantity of new products dominates the negative effect of higher new product prices on the quantity of new products.

Proposition 5(b) shows that when the IR is optimistic and adopts a high-quality strategy, the effect of ρ on equilibrium solutions depends on the average RDF. We clearly explain the effect of ρ on prices and profits numerically. We provide Figure 2 in which $k = 1$ [7], $t = 0.12$ [20], $\beta = 1$ [65], $\eta_r = 0.14$ and $\eta_n = 0.24$ [4]. In

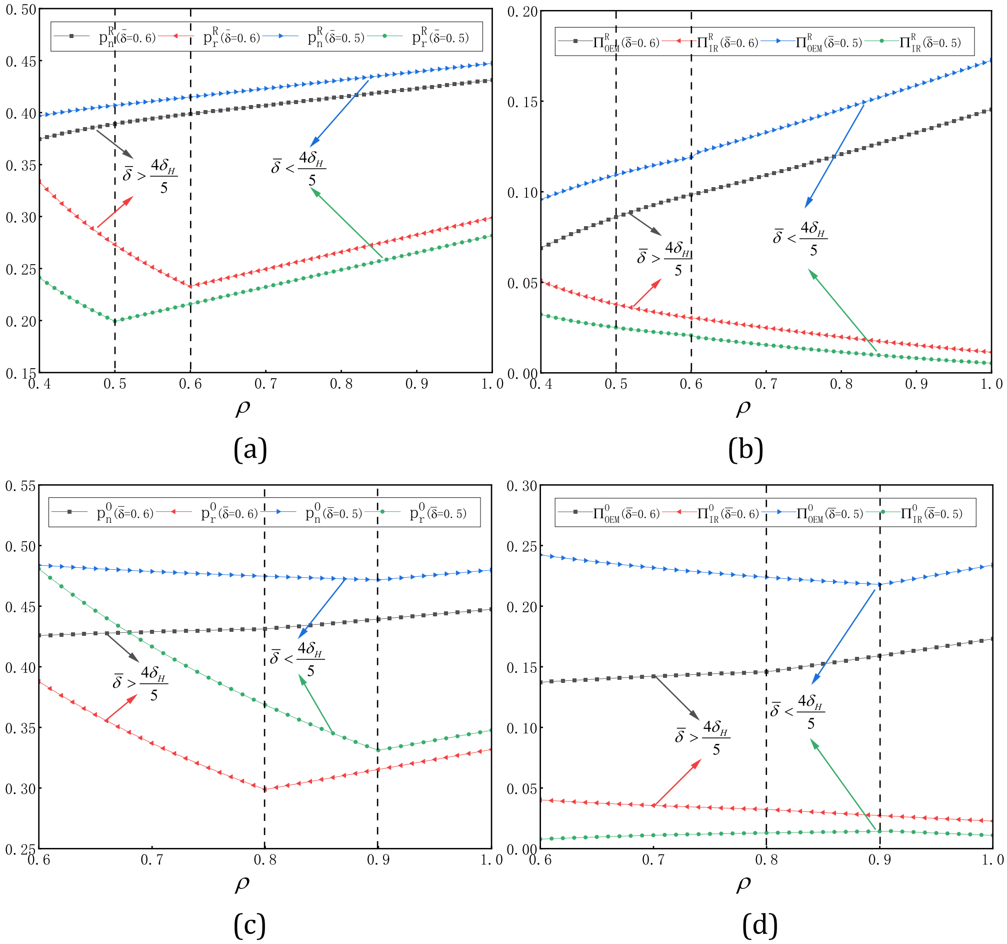

FIGURE 2. Effect of ρ on the equilibrium prices and profits. (a) Effect of ρ on price in Model-R. (b) Effect of ρ on profit in Model-R. (c) Effect of ρ on price in Model-O. (d) Effect of ρ on profit in Model-O.

addition, we set $\delta_H = 0.7$ and $\bar{\delta} = 0.5, 0.6$ to show the variation of sensitivity under different average RDFs. As shown in Figure 2, when the average RDF is large, the effect of ρ on the new product price and profit is the same as that when the IR has an unbiased belief, *i.e.*, both are a steadily increasing curve. However, when the average RDF is small, the effect of ρ on the price of new products changes. The reason is that the low average RDF keeps the quality of remanufactured products at a high level. Fierce competition for quality between new and remanufactured products is forcing the OEM to lower product price even as ρ increases. A small average RDF implies a significant belief bias for the optimistic IR. This leads to a mismatch between the IR's excessive upgrading of product quality and actual market demand. Thus, as Figure 2 shows, in the case of low average RDF, the declining quality of remanufactured products instead generates more profit for the optimistic IR. As the price of remanufactured products decreases more than the price of new products, the IR attracts more consumers causing a decrease in the OEM profits. In addition, we visually observe from Figure 2 that when the IR is realistic, a high-quality strategy always leads to larger profits for the IR compared to a quality-following strategy. However, when the IR is optimistic, the high-quality strategy does not always generate greater profits for the IR.

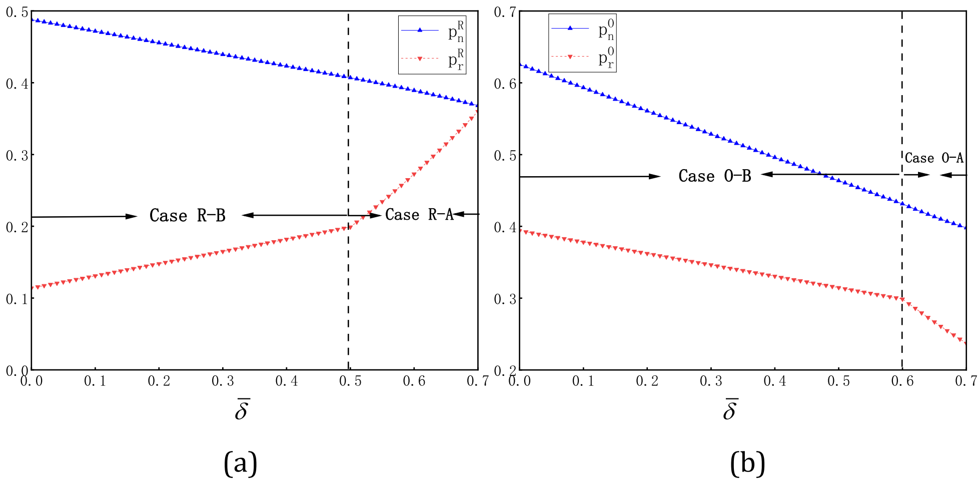

FIGURE 3. Effect of $\bar{\delta}$ on the equilibrium prices. (a) Model-R. (b) Model-O.

Proposition 6. *The effect of $\bar{\delta}$ on equilibrium decisions in different models is as follows.*

(a) $\frac{\partial s_a^{h-l}}{\partial \bar{\delta}} = 0$, $\frac{\partial s_b^{h-A}}{\partial \bar{\delta}} < 0$, $\frac{\partial s_b^{h-B}}{\partial \bar{\delta}} = 0$. $\frac{\partial \tau^{h-l}}{\partial \bar{\delta}} < 0$ *if* $\eta_n > \eta_r$*;* $\frac{\partial \tau^{h-l}}{\partial \bar{\delta}} > 0$ *if* $\eta_n < \eta_r$*;*

(b) $\frac{\partial p_n^{R-l}}{\partial \bar{\delta}} < 0$, $\frac{\partial p_r^{R-l}}{\partial \bar{\delta}} > 0$, $\frac{\partial D_n^{R-l}}{\partial \bar{\delta}} < 0$, $\frac{\partial D_r^{R-l}}{\partial \bar{\delta}} > 0$*;*

(c) $\frac{\partial p_n^{O-l}}{\partial \bar{\delta}} < 0$, $\frac{\partial p_r^{O-l}}{\partial \bar{\delta}} < 0$, $\frac{\partial D_n^{O-l}}{\partial \bar{\delta}} < 0$, $\frac{\partial D_r^{O-l}}{\partial \bar{\delta}} > 0$.

In Proposition 6, the quality of remanufactured products decreases as the average RDF increases when the IR adopts a high-quality strategy. In terms of interchangeability, the level of interchangeability decreases as the average RDF increases when the product design results in greater cost reductions for the OEM. When the IR is realistic about RDF, the price of remanufactured products increases as the average RDF increases. Because an increase in the average RDF implies that consumers gain more utility from purchasing remanufactured products. Although the decrease in remanufactured product quality, the positive impact of rising average RDF on the demand for remanufactured products dominates the negative impact of declining quality on the demand for remanufactured products. In this case, the price and quantity of new products decrease as the average RDF increases.

When the IR is optimistic, different sensitivities emerge in the price of remanufactured products. We numerically discuss this effect of average RDF on the price. The parameters are the same as those in Figure 2. As shown in Figure 3, we unexpectedly find that the IR's belief bias leads to a decrease in the remanufactured price as the average RDF increases. On the one hand, the observed decrease in price could be attributed to the increased average RDF reducing the quality of remanufactured products. On the other hand, the optimistic IR incorrectly believes in an increase in the perceived quality of remanufactured products due to a biased belief in market uncertainty. The lower the average level of RDF, the more significant the belief bias of the IR. Thus, as the average RDF increases, the easing of the IR's belief bias drives down the price of remanufactured products. The positive impact of the lower remanufactured product price and higher average RDF on the demand for remanufactured products outweighs the negative impact of the lower new product price and lower remanufactured product quality on the demand for remanufactured products. The demand for remanufactured products gradually increases with the average RDF.

6. Analysis with interchangeability and remanufacturing optimism

6.1. The choice of product-design strategy for the OEM

In this section, we explore the product design choices under different quality strategies and remanufacturing beliefs. To compare the profits of the OEM and the IR under different product-design strategies, we also calculate equilibrium solutions when there is no product design ($\tau = 0$). We use superscript $j = \text{NR}, \text{NO}$ to indicate that the IR is realistic and optimistic about the RDF in this case, respectively.

Proposition 7. *The impact of product-design strategy on corporate profits is as follows.*

(a) $\Pi_{\text{OEM}}^{R-l} > \Pi_{\text{OEM}}^{\text{NR}-l}$, $\Pi_{\text{OEM}}^{O-l} > \Pi_{\text{OEM}}^{\text{NO}-l}$.

(b) $\Pi_{\text{IR}}^{R-l} < \Pi_{\text{IR}}^{\text{NR}-l}$. *When* $k_c < k < k_e$, $\Pi_{\text{IR}}^{O-A} > \Pi_{\text{IR}}^{\text{NO}-A}$, *otherwise,* $\Pi_{\text{IR}}^{O-A} < \Pi_{\text{IR}}^{\text{NO}-A}$. *When* $k_d < k < k_f$, $\Pi_{\text{IR}}^{O-B} > \Pi_{\text{IR}}^{\text{NO}-B}$, *otherwise,* $\Pi_{\text{IR}}^{O-B} < \Pi_{\text{IR}}^{\text{NO}-B}$.

Where k_e *and* k_f *are detailed in the Appendix B.*

Proposition 7 suggests that regardless of the IR's attitude toward RDF, it is always profitable for the OEM to adopt product-design strategy. As shown in Proposition 3, when $\eta_n > \eta_r$, the OEM chooses to increase the level of interchangeability to bring greater cost reduction to the production of new products. When $\eta_n < \eta_r$, the barriers for the IR to participation in remanufacturing increase, *i.e.*, the unit production cost of the IR increases more than the unit production cost of the OEM.

When the IR is optimistic, the IR can benefit from the product-design strategy in some cases. Specifically, when the product cost coefficient is large, the product-design strategy is effective in reducing competition for the IR. When the product cost coefficient is small, the optimistic IR is able to make more profit in the product-design strategy compared to the realistic IR. A possible explanation for this might be that remanufacturing optimism triggers greater changes in the level of interchangeability. When the product-design strategy is designed to make the IR more difficult to remanufacture ($\eta_n < \eta_r$), the OEM reduces the level of interchangeability due to remanufacturing optimism $\left(\tau^{O-l} < \tau^{R-l}\right)$. In this case, compared to Model-R, the unit production cost of the IR in Model-O increases more. When the product-design strategy aims to reduce the production cost ($\eta_n > \eta_r$), the IR's optimism encourages the OEM to increase the level of interchangeability $\left(\tau^{O-l} > \tau^{R-l}\right)$. Thus, the IR is able to obtain a greater degree of cost reduction.

6.2. Effect of optimism on firm's price decisions and profits

When the IR adopts a different quality strategy, remanufacturing optimism has a different impact on price decisions and profits. We first discuss the effect of optimism when the IR adopts a quality-following strategy.

Proposition 8. *When the IR adopts a quality-following strategy, the equilibrium solutions of Model-O and Model-R are compared as follows.*

(a) $s_a^{O-B} = s_a^{R-B} = s_b^{O-B} = s_b^{R-B} \cdot \tau^{O-B} > \tau^{R-B}$ *if* $\eta_n > \eta_r$; $\tau^{O-B} < \tau^{R-B}$ *if* $\eta_n < \eta_r$.

(b) $p_n^{O-B} > p_n^{R-B}$, $p_r^{O-B} > p_r^{R-B}$, $D_n^{O-B} > D_n^{R-B}$, $D_r^{O-B} < D_r^{R-B}$, $\Pi_{\text{OEM}}^{O-B} > \Pi_{\text{OEM}}^{R-B}$. *If* $k_d < k < k_g$, $\Pi_{\text{IR}}^{O-B} < \Pi_{\text{IR}}^{R-B}$, *if* $k > k_g$, $\Pi_{\text{IR}}^{O-B} > \Pi_{\text{IR}}^{R-B}$.

Where k_g *are detailed in the Appendix B.*

As a result of overestimating the number of consumers with high valuations of remanufactured products, the optimistic IR chooses higher product prices. In Proposition 8, an increase in the price of remanufactured products induces the OEM to raise the price of new products. Although the price of remanufactured and new products increases, the quality of remanufactured products remains the same. The quantity of remanufactured products is reduced. The OEM is able to make a higher profit in this case. We next analyze the impact of optimism on the IR's decisions. Intuitively, an optimistic IR that overestimates the level of RDF sets a higher price than a realistic IR. Therefore, when the IR adopts a quality-following strategy, remanufacturing optimism creates two opposite effects on the IR's profits. On the one hand, since the quality level of remanufactured and new products is the same, the higher remanufactured price amplifies the marginal profit of the IR. On the other hand, the optimistic IR's belief bias about the RDF ignores the actual price preferences of low-valuation consumers. The IR's optimism leads to a decline in demand for remanufactured products, negatively impacting the IR's profits.

Proposition 9. *When the IR adopts a high-quality strategy, the optimal decisions of Model-O and Model-R are compared as follows.*

(a) $s_a^{O-A} = s_a^{R-A}$, $s_b^{O-A} > s_b^{R-A} \cdot \tau^{O-A} > \tau^{R-A}$ *if* $\eta_n > \eta_r$; $\tau^{O-A} < \tau^{R-A}$ *if* $\eta_n < \eta_r$.

(b) $p_n^{O-A} > p_n^{R-A}$. *When* $\eta_n > \eta_r$, $p_r^{O-A} > p_r^{R-A}$. *When* $\eta_n < \eta_r$, $p_r^{O-A} < p_r^{R-A}$ *if* $\bar{\delta} > \bar{\delta}_a$; $p_r^{O-A} > p_r^{R-A}$ *if* $\bar{\delta} < \bar{\delta}_a$. $D_n^{O-A} > D_n^{R-A}$, $D_r^{O-A} < D_r^{R-A}$.

Where $\bar{\delta}_a$ *are detailed in the Appendix B.*

We move on to discuss the effect of optimism on equilibrium solutions when the IR adopts a high-quality strategy. In Proposition 9, remanufacturing optimism stimulates quality upgrades in remanufactured products when the IR chooses a high-quality strategy. One might intuitively assume that the improved quality would drive the IR to choose a higher price. However, this intuition may not be correct. Because the possible interference of product quality and product-design strategy cannot be ruled out. Although the low interchangeability of the OEM choices increases the unit production cost of remanufactured products when $\eta_n < \eta_r$, the increase in quality of remanufactured products shrinks when $\bar{\delta} > \bar{\delta}_a$. And as confirmed by Proposition 6, $\bar{\delta}$ has a completely different effect on the price of remanufactured products with different RDF attitudes. Therefore, in this case, the optimistic IR chooses a lower price. But when $\bar{\delta} < \bar{\delta}_a$, the quality improvement of remanufactured products becomes larger. The greater degree of quality upgrades and low interchangeability of remanufactured products are forcing the optimistic IR to choose a higher price. When $\eta_n > \eta_r$, the optimistic IR always chooses the higher price. Rising interchangeability reduces the IR's production costs, but the product-design strategy is limited in its role in reducing costs due to $\eta_r < \eta_n$. Affected by the quality upgrade of remanufactured products, the price of remanufactured products increases. In addition, the quantity of new products benefits from remanufacturing optimism, while the quantity of remanufactured products does not. It depends on the price and quality competition between different products.

Proposition 10. *When the IR adopts a high-quality strategy, the equilibrium profits of Model-O and Model-R are compared as follows.*

(a) *When* $0 < \bar{\delta} < \bar{\delta}_b$, $\Pi_{\text{OEM}}^{O-A} > \Pi_{\text{OEM}}^{R-A}$; *otherwise,* $\Pi_{\text{OEM}}^{O-A} < \Pi_{\text{OEM}}^{R-A}$.

(b) *When* $0 < \bar{\delta} < \bar{\delta}_c$, $\Pi_{\text{IR}}^{O-A} < \Pi_{\text{IR}}^{R-A}$. *When* $\bar{\delta}_c < \bar{\delta} < \delta_H$, $\Pi_{\text{IR}}^{O-A} > \Pi_{\text{IR}}^{R-A}$ *if* $k > k_h$; $\Pi_{\text{IR}}^{O-A} < \Pi_{\text{IR}}^{R-A}$ *if* $k_c < k < k_h$.

Where $\bar{\delta}_b$, $\bar{\delta}_c$ *and* k_h *are detailed in the Appendix B.*

Having discussed the impact of optimism on equilibrium decisions, let us now turn to explore its impact on the profits of firms. For the OEM, the IR's optimism triggers higher profits for the OEM when the average RDF is low. If the average RDF is high, lower OEM profits occur. This change in the OEM's profit is mainly related to the IR's product competition under different RDFs. Moving on now to consider the profits of the IR. When $\bar{\delta}$ is sufficiently large, the degree to which the optimistic IR improves the quality of remanufactured products decreases. Accordingly, the comparison of the IR's profits is similar to the comparison of profits when the IR adopts a quality-following strategy. When $\bar{\delta}$ is small, an optimistic IR will significantly upgrade the quality of remanufactured products. However, since the quantity of low-valuation consumers, in this case, occupies the majority of the market, the IR's beliefs distort the perceived quality signals of consumers in the market for remanufactured products. The upgrade of product quality not only fails to significantly improve product competitiveness but also increases the unit cost and unit price of remanufactured products. As a result, the rapidly declining demand for remanufactured products induces a reduction in the IR's profits.

Figure 4 explains the impact of remanufacturing optimism on corporate profits. We set $\rho = 0.3, 0.4, 0.5$ to indicate that the IR adopts a high-quality strategy. Area E indicates invalid solutions and we exclude from consideration. Area A1 and A2 are cases where remanufacturing optimism makes the OEM better off and the IR worse off. Area A1 highlights that a small average RDF always reduces the IR's profits. Area B is the worst scenario, where optimism drives down profits for both firms. Area C implies a decline in the OEM's profits and an increase in the IR's profits. We focus on area D, where both the OEM and the IR can benefit from remanufacturing optimism when the average RDF and cost coefficient are large. The win–win outcome can occur because of the influence of remanufacturing optimism on quality decisions for remanufactured products. A large average RDF mitigates the optimism bias of the IR. The large cost coefficient inhibits the optimistic IR from over-upgrading the quality of remanufactured products, and maintains a moderate level of product heterogeneity among firms. In addition, it can be observed from Figures 4b and 4c that area D increases significantly as ρ increases, *i.e.*, the region where remanufacturing optimism leads to an increase in the win–win situations. Because similar to the mechanism of k, large remanufacturing costs can also constrain the IR to excessively improve the quality of remanufactured products.

7. Extension

In this section, we further consider the effect of the OEM's optimistic biased belief on the equilibrium solution. We use superscript OR to indicate that the manufacturer is optimistic. Under Model-OR, the manufacturer has optimistic biased belief about RDF. The manufacturer believes that all consumers have high RDF for remanufactured products. Therefore, from the optimistic manufacturer's perspective, the demand function of products is $D_n = \frac{t+(s_a-\delta_H s_b)-(p_n-p_r)}{2t}$. The relevant results are summarized in Appendix C.

We find that the OEM's optimism about RDF induces a lower quality of remanufactured products $\left(s_b^{\mathrm{OR}-A} < s_b^{O-A}\right)$. But when the IR adopts a quality-following strategy, the OEM's optimism does not affect product quality. Note that the quality of remanufactured products increases with the increase of the average RDF. Conversely, if δ_H decreases, the IR upgrades product quality.

Proposition 11. *When the IR adopts a quality-following strategy, the equilibrium solutions of Model-OR and Model-R are compared as follows.*

(a) $s_a^{\mathrm{OR}-B} = s_a^{R-B} = s_b^{\mathrm{OR}-B} = s_b^{R-B} \cdot \tau^{\mathrm{OR}-B} > \tau^{R-B}$ *if* $\eta_n > \eta_r$; $\tau^{\mathrm{OR}-B} < \tau^{R-B}$ *if* $\eta_n < \eta_r$.

(b) $p_n^{\mathrm{OR}-B} < p_n^{R-B}$, $p_r^{\mathrm{OR}-B} < p_r^{R-B}$, $D_n^{\mathrm{OR}-B} > D_n^{R-B}$, $D_r^{\mathrm{OR}-B} < D_r^{R-B}$, $\Pi_{\mathrm{OEM}}^{\mathrm{OR}-B} < \Pi_{\mathrm{OEM}}^{R-B}$, $\Pi_{\mathrm{IR}}^{\mathrm{OR}-B} < \Pi_{\mathrm{IR}}^{R-B}$.

We first analyze the impact of the OEM's optimism on decision making when the IR adopts a quality-following strategy. We find that due to the OEMs' optimism about the remanufacturing market, the manufacturer sees more competition between new and remanufactured products. The OEM chooses to lower the price of new products in response to this perceived competition, which forces the IR to lower the price of products. In contrast to the IR's optimism, the OEM's optimism always hurts the performance of supply chain members when the IR chooses a quality-following strategy.

Proposition 12. *When the IR adopts a high-quality strategy, the equilibrium profits of Model-OR and Model-R are compared as follows.*

(a) *When* $\bar{\delta} > \bar{\delta}_2 = \frac{2\delta_H}{3}$, $\Pi_{\mathrm{OEM}}^{\mathrm{OR}-A} > \Pi_{\mathrm{OEM}}^{R-A}$ *if* $k < k_m$; *otherwise*, $\Pi_{\mathrm{OEM}}^{\mathrm{OR}-A} > \Pi_{\mathrm{OEM}}^{R-A}$ *if* $k > k_m$.

(b) *When* $\bar{\delta} > \bar{\delta}_g$, $\Pi_{\mathrm{IR}}^{\mathrm{OR}-A} < \Pi_{\mathrm{IR}}^{R-A}$. *When* $\bar{\delta} < \bar{\delta}_1$, $\Pi_{\mathrm{IR}}^{\mathrm{OR}-A} > \Pi_{\mathrm{IR}}^{R-A}$ *if* $k > k_n$; $\Pi_{\mathrm{IR}}^{\mathrm{OR}-A} < \Pi_{\mathrm{IR}}^{R-A}$ *if* $k < k_n$.

Where $k_m = \frac{-6\rho\bar{\delta}+33\bar{\delta}^3+4\rho\delta_H-55\bar{\delta}^2\delta_H+29\delta_a\delta_H^2-5\delta_H^3}{24t\rho\left(3\bar{\delta}-2\delta_H\right)}$, $k_n = \left(-\frac{2\bar{\delta}^2-3\bar{\delta}\delta_H+\delta_H^2}{t} + \frac{3\beta\left(\bar{\delta}^2-5\bar{\delta}\delta_H+2\left(\rho+\delta_H^2\right)\right)}{9t\beta-(\eta_n-\eta_r)^2}\right)/8\rho$.

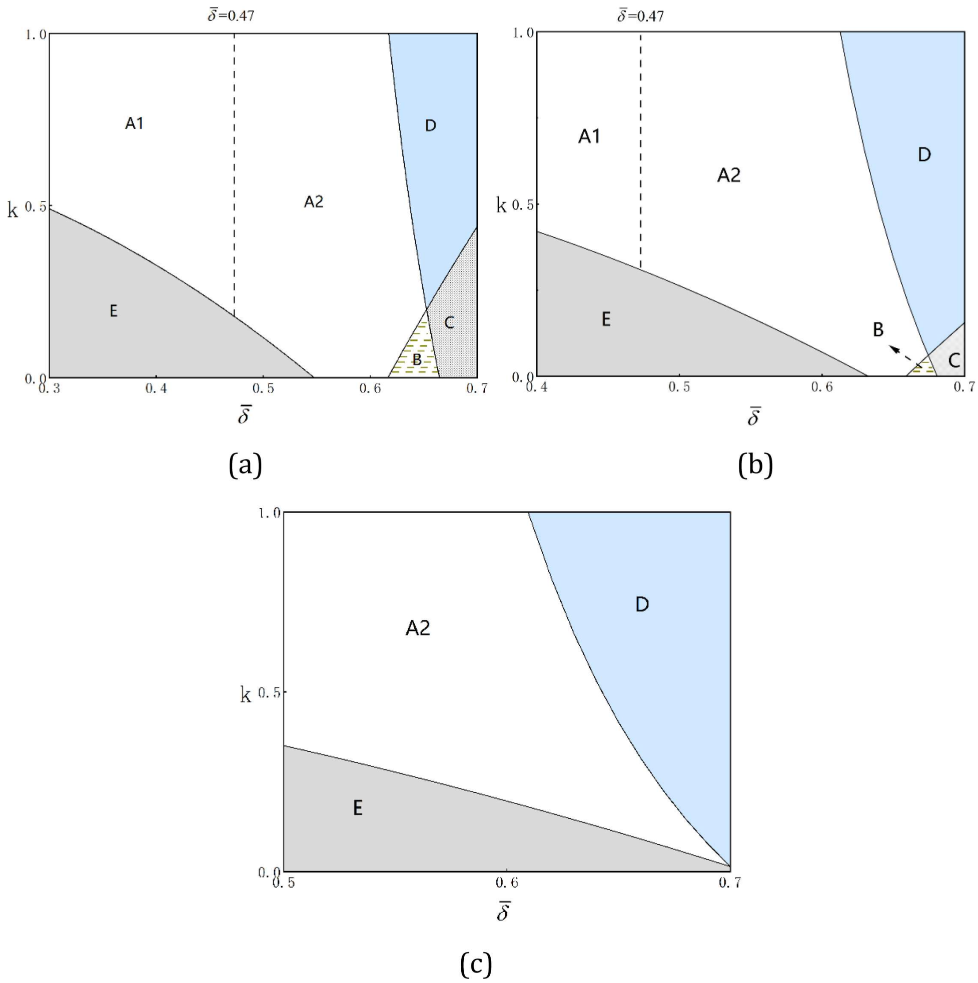

FIGURE 4. Effect of RDF optimism on the IR's profits in a high-quality strategy. (a) $\rho = 0.3$. (b) $\rho = 0.4$. (c) $\rho = 0.5$.

Proposition 12 shows a comparison of firm performance when the IR adopts a high-quality strategy. For the OEM, the OEM's optimism triggers higher profits when the average RDF is large and the cost coefficient is small. Because a larger average RDF reduces the degree of belief bias for the OEM, while a smaller cost factor helps the OEM reduce the manufacturing cost. Therefore, the OEM's optimism does not always hurt the OEM profits. For the IR, the OEM's optimism always makes the IR less profitable when the average RDF is larger.

Figure 5 explains the impact of OEM's remanufacturing optimism on corporate profits. Similar to the impact of IR's optimism, the OEM's optimism about remanufacturing can lead to a win–win situation in the supply chain (in area A of Fig. 5). However, unlike the comparative results resulting from IR optimism, the OEM optimism can benefit all supply chain members when the average RDF is small and the cost coefficient is large.

8. Conclusions

Optimism in management decisions is widespread. There is evidence that optimism often reduces business performance, but sometimes it can be a strategic advantage. We introduce an optimism bias, where the IR

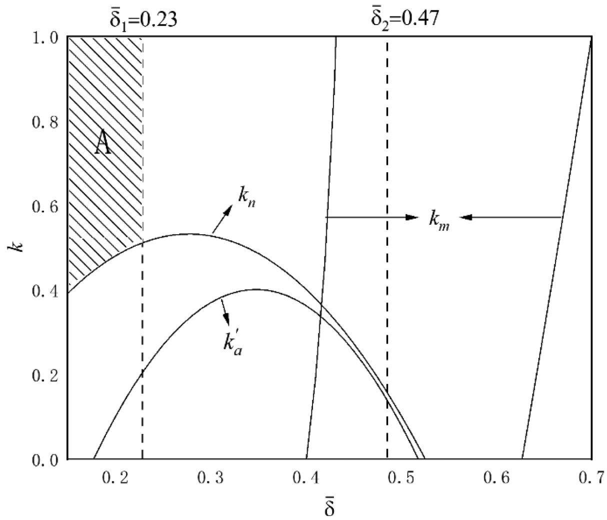

FIGURE 5. Effect of OEM's optimism on the profits in a high-quality strategy.

overestimates the level of RDF, into a competitive market consisting of an OEM and an IR. We develop a game model that combines the OEM's product-design strategy and the IR's quality strategy to investigate the interaction of remanufacturing optimism with product interchangeability and its impact on product quality, pricing, and profit. Our analysis provides several interesting findings and management insights.

First, we find that when the unit production cost of the IR is more significantly affected by product design, the OEM reduces interchangeability to make remanufacturing more difficult. This implies that the pivotal strategic deployment before OEMs can determine the degree of interchangeability is to identify and anticipate the extent to which product design affects competitors' cost structures. Interestingly, in some cases, remanufacturing optimism enables IR to benefit more from product design. Therefore, when OEMs increase product interchangeability, the IR hiring an optimistic manager can reduce more remanufacturing costs. This finding builds a bridge between the remanufacturing market and human resource management.

Second, when the IR adopts a quality-following strategy, the optimistic IR always raises product prices due to overestimating the number of consumers with high valuations of remanufactured products. Unexpectedly, an optimistic IR may choose a lower price when the IR determines a higher quality product. In some cases, the IR's optimism can lead to a win–win outcome for the competitive market. Both firms benefited because of the impact of optimism on product design and quality decisions.

Finally, although consumer perceptions of remanufactured products differ from reality, our findings provide evidence that it is profitable for remanufacturers to upgrade product quality. It should be noted, however, that when the perceived quality of remanufactured products is low for most consumers, the optimistic IR blindly updating the quality of remanufactured products may be counterproductive. We suggest that in such cases, it may be more effective to provide or promote knowledge about remanufacturing to consumers, such as advertisements and exhibitions. Because it helps to open the ambiguous black box of the remanufacturing process for consumers, thus alleviating their general concerns.

Future research could continue to explore the following limitations of this paper. First, expanding the problem to the competition between new products and other types of products such as refurbished and repaired products, or competition among enterprises in a decentralized channel environment, may yield new insights. Second, studying the relationship between multi-period products and their remanufacturing decisions may be an interesting research question. Finally, consistent with most modeling approaches, the level of the remanufacturing discount factor is an exogenous parameter. In the future, it may be promising to discuss the impact of the dynamic interaction between educational mechanisms and RDF on decision making.

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