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ORIGINAL PAPER

Optimal decisions in a dual-channel remanufacturing supply chain with reference quality effect under WTP differentiation

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Abstract

This study investigates a pricing problem in a dual-channel remanufacturing supply chain consisting of a manufacturer and a retailer with market segmentation and reference quality effects. In the era of e-commerce economy, the reference quality effect plays an increasingly important role in influencing consumers' purchasing behavior, product pricing, and demand changes. It is crucial for manufacturers to develop optimal sales channels of remanufactured products based on consumers' purchasing behavior. To this end, we study the manufacturer's optimal decision problem in two classical business scenarios: selling remanufactured products through retail or direct channels. The objective is to explore the impact of the channel coefficient, remanufactured product acceptance, and the reference quality effect on optimal decisions in the remanufacturing supply chain, as well as their combined impact on profitability. The findings suggest that the reference quality effect has a negative impact on the manufacturer's profit, and the optimal channel choice remains uncertain. Within a specific range, the reference quality effect hurts the profits of supply chain members. In addition, the extended model shows that the manufacturer's profit is highest when the remanufactured product is sold in two channels, but the profits decrease as the reference quality parameter increases.

Keywords Remanufacturing · Dual channel · Reference quality effect · WTP differentiation · Game theory

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1 Introduction

Advances in technology have allowed consumers to assess product quality more easily. For example, E-commerce enterprises such as JD[1] and MI[2] have adopted an online-to-offline sales model to provide a better product experience for consumers and enable them to fully understand the quality of the products that they are interested in (Qiu et al. 2022). The constantly evolving business environment has made consumers' buying behavior more complex and unpredictable. Strong connections with physical retail channels enable consumers to modify their purchasing behavior through multichannel shopping continuously. Hence, it is crucial for manufacturers to design optimal distribution channels for their products based on consumers' purchasing behavior. Most recent literature in the area of operations management and remanufacturing has focused on recycling channel strategies, remanufacturing competition and cooperation, distribution channel decisions, pricing strategy, gaming strategies, and consumer buying behavior (Savaskan et al. 2004; Debo et al. 2005; Atasu et al. 2008; Jiang et al. 2010; Ovchinnikov et al. 2011; Chen et al. 2012; Ma et al. 2013; Zhang et al. 2018; Cao et al. 2022; Cetin et al. 2023; Huang et al. 2023; Zhou et al. 2023).

Remanufacturing refers to the recovery of the value of a used product by replacing parts or reprocessing used parts to make the product in new condition (Atasu et al. 2008). The studies found that consumers are generally less willing to pay for remanufactured products and prefer new products over remanufactured ones (Turki et al. 2018; Zhou et al. 2021). Several scholars have examined the pricing of new and remanufactured products in the remanufacturing supply chain, most of which have forced the assumption that the quality of new and remanufactured products is the same (Zhou et al. 2023). Although the manufacturer has made a commitment to the quality of the remanufactured product, a greater number of consumers perceive the quality difference between the new product and the remanufactured product, which reduces the willingness of consumers to pay for the remanufactured product. In practice, comparing new and remanufactured products, consumers are more concerned about the quality of the latter. The continuous improvement of living standards has led to increased consumers' requirement for product quality. Consumers form general expectations of products based on their previous experience of using them, which largely influences their purchasing behavior and brand recognition. The reality is that the companies involved recognize that there are differences in consumer's willingness to pay (WTP) for products and adopt marketing measures accordingly. For example, Apple[3] puts the user experience at the center of their business. It uses Amazon's cloud service[4] for cloud management and application by analyzing customer preferences. Therefore, companies adopt different distribution channels depending on the products and consumer types to meet different

[1] 1 https://www.jd.com.

[2] 2 https://www.mi.com.

[3] 3 https://www.163.com/dy/article/J4DQKI2Q0519QIKK.html.

[4] 4 https://www.163.com/dy/article/FT8OVSPH05118O92.html.

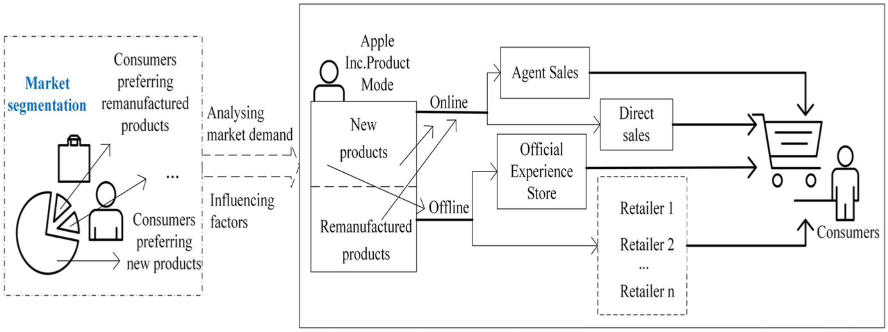

Fig. 1 The main of marketing mode in Apple

consumer needs. Inspired by Apple's marketing mode, this paper mainly examines the pricing decision of a supply chain with reference quality effects in consumer segments. Compared with the marketing model of other companies, Apple is more focused on learning about consumers' needs directly from end-consumers. Then, they design and innovate products to quickly response consumers' needs. Their products are sold through various sales channels, including traditional offline retail, self-operated/ third-party online sales, and experiential shops. The main difference between Apple's multi-channel sales is that offline traditional channels are primarily used to sell new products. Online direct sales, on the other hand, offer both new and remanufactured products. Note that, online shopping makes it easier to provide consumers with more information and services, as well as allows them to compare product information and make purchases. Therefore, considering the advantages of the online platform, Apple does not choose traditional offline retail to sell remanufactured products. The flow of this sales mode is illustrated in Fig. 1.

Quality management is pivotal to business, which has a significant effect on operating results and customer satisfaction. In recent years, due to product quality problems, many companies have suffered severe losses. For example, Samsung Galaxy Note 7[5] cell phone battery explosion has triggered concerns about product quality issues in all walks of life (Yan et al. 2022). Product quality issues affect consumers' purchasing decisions and market demand. Therefore, the reference quality effect has become an important factor affecting consumers' purchasing behavior. Consumers can compare current product quality before making a purchase decision. The theoretical framework suggests that the evaluation of product attributes is related to reference points (Tversky and Kahneman 1991). Empirical studies have shown that the difference between real product quality and reference product quality could significantly affect consumers' purchase probability (Hardie et al. 1993; Kopalle et al. 1996). Specially, reference quality plays a crucial role in business decisions. The reference quality effect is when consumers form expectations of product quality based on previous product quality levels. In other words, consumers form expectations about product attributes through their purchasing experience, thereby affecting

[5] 5 https://tech.huanqiu.com/article/9CaKrnJXWjZ.

their purchasing behavior (Hardie et al. 1993; Xue et al. 2017; Cao et al. 2020; Liu et al. 2021).

Previous portrayals of the mathematical form of the reference quality effect can be classified into two types. The first type is based on a continuous weighted average of past qualities, which is modelled as a weighting function with exponential decay in a continuous time framework (Gavious and Lowengart 2012; Xue et al. 2017). The second is to focus on the current stage and capture the asymmetric effect of the difference between product quality and reference quality on consumer utility in the form of parameters of how consumers perceive reference quality to be higher than observed quality (i.e., the quality assessment of remanufacturing) (Ma et al. 2020). Based on Ma's (2020) work, this study examines the impact of reference quality effects on the pricing decisions of a dual-channel remanufacturing supply chain under the current stage. Based on utility theory and mathematical models, this study explores how the manufacturer can make optimal pricing decisions in different sales situations. Previous research on the reference quality effect has mainly focused on single channels without fully considering the impact of the reference quality effect on dual-channel pricing decisions. On the one hand, if customers have a high acceptance of direct sales channels, independent manufacturers may open direct sales channels to compete with retailers. This may indirectly increase the profit flows of the retail channel and improve the manufacturer's overall profitability by reducing the degree of inefficient price double marginalization (Chiang et al. 2003). It follows that direct selling channels are not always unfavorable to retailers. Thus, the impact of dual channels on the profitability of supply chain members is uncertain. On the other hand, few studies have examined the impact of reference quality behavior on new and remanufactured product decisions in dual-channel supply chains. Ma et al. (2020) explored the impact of dual reference effects on remanufacturing supply chains under a traditional channel. In reality, consumers have concerns about the quality of remanufactured products, which affects their purchasing decisions. Therefore, the multi-channel sales model provides consumers with multiple accessibility, which makes it easier for consumers to compare product quality and allowing them to measure their psychological expectations through a multi-channel platform. In addition, the intricate and fluctuating nature of consumer purchasing behavior renders previous pricing decision-making methods inadequate for current market demand strategies. Besides, there are few studies on the impact of consumer channel preference, acceptance of remanufactured products, and the reference quality effect on the optimal decision-making and profits of dual-channel supply chains. Prior studies have shown that consumer behaviors (including channel preference, acceptance of remanufactured products, and reference behavior) play a crucial role in firms' decision-making (Chiang et al. 2003; Ma et al. 2013; Zhou et al. 2021; Yang et al. 2021). A typical assumption of the above study is that the consumer group is homogeneous. However, in a real business environment, it's normal that there is heterogeneity throughout the sales period. Furthermore, it acknowledges that consumers have different attitudes toward purchasing new and remanufactured products. To address this, motivated by the real case in Apple, game theory and optimal constraint theory are utilized to solve the following problem:

How does reference quality affect the manufacturer's optimal decision under different sales models? What is the threshold of the manufacturer's optimal channel sales decisions? How do the channel coefficient, remanufactured product acceptance, and reference quality parameter affect the price, demand, and profit of supply chain members?

Based on realistic scenarios, a dual-channel remanufactured supply chain structure comprising a manufacturer and a retailer is constructed. The structure includes a traditional channel and an online direct channel. Several models are considered, including the retail channel selling remanufactured products, the direct channel selling remanufactured products, and both channels selling remanufactured products. This structure has been previously discussed in literature, such as Chiang et al. (2003). Different acceptance levels of new and remanufactured products are considered; remanufactured products have a reference quality effect, and the quality of new products in retail channels refers to the reference quality. Previous studies have shown that consumers have different acceptance levels for new and remanufactured products (Zhou et al. 2021) and different levels of acceptance of channel products (Ma et al. 2013). Based on existing research, this study draws some important findings. For example, a high reference quality parameter may increase the demand for new products in the direct channel. The influence of the reference quality effect on optimal decisions is uncertain. The reference quality effect may harm the profits of supply chain members to some extent. A high channel preference coefficient and low acceptance of remanufactured products are more beneficial to the manufacturer than a low channel preference coefficient and high acceptance of remanufactured products.

This paper offers innovative contributions to existing theories on operational management of reference quality in three main ways. First, this paper develops the dual-channel game-theoretic decision model incorporating the reference quality effect into a dual-channel remanufacturing context. This model derives expressions for the optimal price and profit for each supply chain member under consumer heterogeneity. In comparison, most existing literature focuses more on the decision-making problem of new products in different channels (Qiu et al. 2022). However, it is also essential to consider the different sales patterns of new and remanufactured products. Second, using the game form between the members of the dual-channel remanufacturing supply chain, the conditions for achieving the optimal sales choice of supply chain members are analytically derived. Interestingly, unlike Gavious et al. (2012), the manufacturer's optimal channel choice is dynamic. The manufacturer's profit negatively correlates with the reference quality effect within a specific range. Third, we explore the impact of reference quality parameters on supply chain decisions and performance. The investigation is based on theoretical findings from a comparative analysis of equilibrium solutions for remanufactured products, considering the choice of online, offline, or both online and offline sales modes.

The rest of the article is organized as follows. Section 2 provides the literature review. Section 3 presents the model, including the model setting in Sect. 3.1 and the model assumptions in Sect. 3.2. Section 4 discusses the model equilibrium and comparison. Section 5 explores parameter sensitivity analysis. The model extension is in Sect. 6. Section 7 summarizes the conclusions. Proofs are collected in Appendices x.

2 Literature review

Three branches of literature that are closely related to this study are: dual channel supply chains, remanufacturing, and reference quality effects. We present a concise review below.

2.1 Dual channel supply chains

Chiang et al. (2003) examined the influence of direct channels on the retail channel. They found that introducing a direct channel could increase the manufacturer's negotiated share of cooperative profits. In 2005, they proposed a dual-channel inventory model with one traditional retail store and one Internet direct channel. They proved that such a dual-channel inventory model is superior to single channel in most cases. In certain cases, the flexibility of a dual-channel system can significantly reduce operational costs. Dumrongsiri et al. (2008) studied the pricing decision problem of a dual-channel supply chain in which the manufacturer sold products directly to retailers and consumers. They showed that the marginal cost difference between dual channels is a key factor in determining the existence of supply chain equilibrium. Dan et al. (2012) investigated the optimal decision for retail services and prices under centralized and decentralized scenarios by considering both traditional retail channels and online direct channels. They assessed how retail services and customer loyalty to the retail channel affect the pricing behavior of manufacturers and retailers. Liu et al. (2021) analyzed how different return strategies and return rates affect the profitability and pricing of dual-channel retailers. Yang et al. (2021) explored the impact of online consumer reviews (OCR) on products that sold in both retail and internet channels. Their study found that a manufacturer offered OCR in the Internet channel only when the information revealed by OCR was sufficiently favorable. Liu et al. (2022a, b) investigated the effect of consumer overconfidence on demand, pricing decisions, and profits of supply chain members. Their research results suggests that demand in decentralized dual-channel supply chains decreases as consumer overconfidence increases.

Previous research has focused on dual-channel supply chains including direct sales channel and traditional retail channel. They pay more attention on new products management. However, with the improvement of consumers' environmental awareness, it becomes more essential to consider the impact of remanufactured products and reverse logistics in modern enterprise management (Mitra 2016; Liu et al. 2022a, b; Cetin et al. 2023; Zhou et al. 2023). Besides, only some of these studies have addressed the impact of consumer reference behavior on pricing in dual-channel remanufacturing supply chains. Past studies have shown that an increasing number of consumers make purchasing decisions based on their own experiences. This purchasing experience regarding product quality is referred to as reference quality, which results from historical quality levels. If the quality level is lower than the reference level, product demand is negatively affected, and vice versa. This implies that reference quality affects demand and profits. It is worth noting that in-depth research is needed to study the impact of consumer reference behavior from the perspective of dual-channel supply chains. In other words, the influence of reference quality on pricing decisions and profits of dual channel participants requires further attention.

2.2 Remanufacturing

In recent years, remanufacturing gained widespread public attention and attracted the research interest of many scholars. Several scholars have provided comprehensive overviews of remanufacturing supply chains, including Souza (2013), Govindan et al. (2015), and Kumar and Ramachandran (2016). Researchers have studied remanufacturing from various perspectives, including pricing decision, channel coordination and competition between new and remanufactured products. Among them, pricing management involves how manufacturers make optimal pricing decisions when faced with different new and remanufactured products. Following these researches, the topic of market segmentation has been discussed. Scholars focused on how firms can maximize profits by considering product categories and consumers' willingness to pay. This is particularly important for remanufacturing supply chain research when considering that price-sensitive customers may prefer remanufactured products, while quality-sensitive customers may prefer new products. Mitra (2016) discussed whether a manufacturer who sells remanufactured products in a price-sensitive secondary market would gain a competitive advantage over another manufacturer who only sells new products. Although remanufacturing may cannibalize new product sales, they proved that the combined profitability and market share of the manufacturer on account of new and remanufactured product sales would improve over new product sales only. Particularly, under some given assumptions, they show that remanufacturing is almost always more profitable for the manufacturer than when there is no remanufacturing. Zhang et al. (2018) studied the effects of customer purchasing behavior and remanufacturing efficiency on the economic and environmental values of trade-in remanufacturing policy. Their research showed that remanufacturing under a trade-in policy for highly strategic consumers can significantly negatively impact the environment and social welfare. However, for myopic consumers, trade-ins benefit both business and the environment. Tang et al. (2021) explored the optimal choice of supply chain members in a trade-in model comprising a single manufacturer and retailer. They found that the trade-in model can bear higher manufacturing costs and increase sales of new products compared to a benchmark scenario without trade-ins. Ke et al. (2022) developed a two-period model to examine the impact of trade-ins on consumer purchasing behavior. They demonstrated that the more consumers that consider trade-ins, the higher the optimal price of a remanufactured product is. Fang et al. (2023) focused on the choice of remanufacturing strategy between in-house and authorized remanufacturing. Their study found that authorized remanufacturing under the leadership of independent remanufacturers' decisions is inferior to OEM remanufacturing when there are different leadership structures in the market. Liao et al. (2023) developed a mathematical model to quantify the impact of quality-based product categorization of returned products under different return scenarios. The results indicated that optimal purchasing decisions in a multilevel remanufacturing system can save more than 80% of the cost.

There is a large body of literature on remanufacturing, which suggests that there may be differences in consumer purchasing behavior between new and remanufactured products due to differing perceptions of quality. However, previous studies have not addressed the impact of reference quality effects on the pricing decision of a remanufacturing supply chain. In particular, these papers do not plausibly explain the joint effects of consumers' reference quality and willingness to pay on each member's optimal pricing decision.

2.3 Reference quality effects

Kopalle et al. (1996) considered the relationship between expected quality and reference price. They analyzed the problem of a monopolist's price and quality levels when the price exceeds the reference price and the quality of the product is below the expected quality. Gavious et al. (2012) studied the combined effect of price and reference quality on profits. They discovered that the reference quality effect increases firms' profits. Liu et al. (2016) investigated the impact of myopic behavior on product quality and pricing strategies, as well as on the profits of both members in a dynamic supply chain. Such a supply chain involves a manufacturer who produces specialty products and distributes them to consumers through an exclusive retailer. Their study found that reference quality has a significant impact on the supply chain's performance. He et al. (2017) captured the impact of reference quality effects on consumers under different business models based on a modified Nerlove-Arrow model using two different sales functions. Under the quality inflation scenario, Xue et al. (2017) studied the joint pricing and dynamic product quality investment problem with reference quality effects. They found that it is not optimal for firms to continuously increase quality investment throughout the planning horizon. The effect of reference quality on the level of quality investment is more significant. Cao et al. (2020) considered the effect of stochastic reference quality on a monopolist's time-varying policies on price and product quality from a stochastic control theory perspective. The results indicated that the monopolist could benefit from higher prices and higher quality policies compared to the results of a deterministic model. Ma et al. (2020) studied the effects of dual reference parameters and government incentives on pricing strategy, manufacturer's profit, and consumer surplus. Liu et al. (2021) investigated the impact of reference quality level on the service quality of third-party platforms in a manufacturer's oligopoly environment. They found that the selling prices and service levels of online service platforms were significantly affected by the reference quality level of competing platforms. Qiu et al. (2022) studied the coordination of a two-tier decentralized supply chain in which market demand depends on retail prices and reference quality effects. They found that the decisions of supply chain members are dynamic and rely on the consumer's initial reference quality, the strength of the reference quality effect, and the memory parameter. Yan et al. (2022) explored the impact of reference quality on game membership in a dual-channel supply chain. Their study considered Bertrand and Stackelberg games between a manufacturer and a retailer in both centralized and decentralized decision-making scenario. The findings suggested that reference quality has a positive effect on the equilibrium price and profit in a dual-channel supply chain. A substantial body of existing research in this area analyses the impact of specific factors on a single channel in a supply chain that comprises of manufacturers and retailers. In contrast to the existing literature, we develop a dual-channel remanufacturing supply chain consisting of a manufacturer and a retailer to explore the impact of reference quality effects and consumers' willingness to pay on dual channels.

In summary, Table 1 displays the research gaps compared to several closely related works. This study is related to the work by Ma et al. (2020). However, the latter focuses on the impact of reference effects on pricing decisions in traditional two-stage remanufacturing supply chains. In contrast to Gavious et al. (2012), Zhang et al. (2014), and Xue et al. (2017), this study places greater emphasis on the impact of reference quality effects and he difference in consumer payments for new/remanufactured products on dual-channel decisions. As compared to Zhang et al. (2018) and Cetin et al. (2023), we develop a demand-sensitive model with reference quality effects to analyze the pricing decisions of supply chain members in a dual-channel environment.

Table 1 Summary and comparison of the most relevant literature

Related works	Channel structure		Reference effects	Remanf-acturing	WTP	Decision variables
	Single	Dual				
Gavious et al. (2012)	✓		✓			Price; quality
Zhang et al. (2014)	✓		✓			Retail/reference price
Xue et al. (2017)	✓		✓			Product /reference quality
He et al. (2017)		✓	✓			Wholesale/retail price; quality; advertising effort;
Zhang et al. (2018)	✓			✓	✓	Price; quality
Cao et al. (2020)	✓		✓			Product price; reference quality
Ma et al. (2020)	✓		✓	✓	✓	Retail price
Qiu et al. (2022)		✓	✓			Wholesale/ retail price; quality
Cetin et al. (2023)	✓			✓	✓	Product production level; innovation level
This study		✓	✓	✓	✓	Wholesale price; direct price; retail price

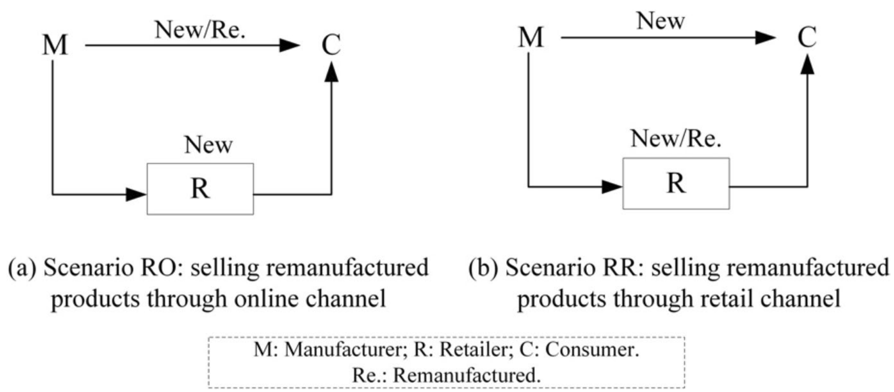

Fig. 2 The structure of Models

3 Models setting and assumptions

In a monopoly market, new and remanufactured products can be sold to consumers by the retailer through the physical channel and by the manufacturer through the online direct channel, respectively. There are no distinct differences in performance between the new and remanufactured products, which are similar in most features (Atasu et al. 2008; Fang et al. 2023). However, consumers' acceptance of new and remanufactured products varies, which causes that the reference quality effect occurs in consumers' purchasing behavior. Note that, environmental consumers' acceptance of remanufactured products may be higher compared to new products. To focus on the major issues, the case where reference quality effects are present is considered in this paper. Here, the retailer is assumed to sell only new products or both new and remanufactured products to the end-consumers. The consumer chooses the product based on the principle of maximizing its utility function.

3.1 Models setting

This study focuses on two sales scenarios in a remanufacturing supply chain: Scenario RO, where the retailer sells only new products in the physical channel, while the manufacturer sells both new and remanufactured products through online direct channel; Scenario RR, the retailer sells both new and remanufactured products in the physical channel, while the manufacturer sells only new products online. Furthermore, to ensure comprehensiveness of the study, above two basic scenarios are extended to a general scenario, in which both new and remanufactured products are sold in the physical channel by the retailer and the direct sales channel by the manufacturer. For each scenario, consumers will choose to purchase new or remanufactured based on the principle of maximizing utility. This study investigates the impact of reference quality effects on the supply chain members' optimal decisions under different models. It is worth noting that consumers are more accessible to products in physical retail channels than that in online direct channel. Hence, offline consumers can be easier to perceive the real quality of product. For example, Apple sets up experience stores to attract consumers and give them a natural feel for the quality of products. The study assumes that consumers form reference quality effects on remanufactured products by comparing them with products in the retail channel. Specially, in this study, the interaction between supply chain members can be modeled as a Stackelberg game, in which the manufacturer is viewed as the leader and the retailer acts as the follower. Based on the retailer's optimal retail price reaction function, the manufacturer determines the optimal prices for both new and remanufactured products. As shown in Fig. 2, two basic sales scenarios in this study are demonstrated.

3.2 Assumptions and description

In this study, the key parameters of the model set are listed in Table 2. In addition, to make the model setup more reasonable, main assumptions are presented as follows.

Table 2 Notations

Notation	Description
Parameters	
w_n^i	Wholesale price for new products (decision variable)
w_r^i	Wholesale price for remanufactured products (decision variable)
p_n^i	Retail price for new products (decision variable)
p_o^i	Direct channel price for new products (decision variable)
p_r^i	Price for remanufactured products (decision variable)
q_n^i	Demand for new products in retail channel
q_o^i	Demand for new products in direct channel
q_r^i	Demand for remanufactured products
v	Quality valuation of new product in the retail channel by consumers
u_z^i	Utility functions for purchasing new and remanufactured products from retail and direct channels
λ	Channel preference coefficient
β	Remanufactured product preference coefficient
ρ	Reference quality effect parameter
π_M^{Rj}	Profit of the manufacturer
π_R^{Rj}	Profit of the retailer
Indexes	
i	Superscript, denoting the models RO, RR and ROR cases, respectively, where $i = ro, rr, ror$
z	Subscript, $z = 1, 2, 3$, used only to distinguish between consumers' expressions of utility for purchasing new and remanufactured products from retail and direct channels
j	Superscript, $j = O, R$
$*$	Superscript, denoting optimal results

Assumption 1. Similar to Savaskan et al. (2004), the unit production cost of new products is higher than that of remanufactured products, i.e., $0 < c_r < c_m$.

Assumption 2. The price of new products in retail channel is higher than that in direct channels, i.e., $p_o^i < \lambda p_n^i$(Ma et al. 2013). In addition, in line with the assumptions of Chiang et al. (2003), consumers prefer traditional channels to direct retail, that is, $0 < \lambda < 1$. Considering that consumers prefer new products to remanufactured products, we assume that the quality of the new product is normalized to 1 and expressing the relative quality of remanufactured products as β, where $0 < \beta < 1$ (Ma et al. 2020).

Assumption 3. Assumed by Chiang et al. (2003), consumers are heterogeneous with respect to their willingness to pay, represented by v, which is uniformly distributed between 0 and 1. The market size is normalized to 1.

Assumption 4. The formation of reference quality effect function is considered as $\rho(v - \beta v)$ (Kopalle et al. 1996; Ma et al. 2020), where ρ is the reference quality parameter, which has an asymmetric effect on consumer utility and thus on market demand, corresponding to how consumers perceive the quality valuation of the reference quality over a remanufactured product. v represents the quality of the new product as a reference quality, and βv denotes the quality of the remanufactured product in the same channel.

Assumption 5. The members participating in the game are all rational and risk neutral. We further assume the information to be symmetric, i.e., the knowledge about the market information is known to both members, and each member is also aware of other member's cost structure. This assumption is consistent with previous studies (Savaskan et al. 2004; Chiang et al. 2005; Ma et al. 2013; Liao et al. 2023).

4 Equilibrium strategies

4.1 Model RO (Scenario RO)

In the RO scenario, the manufacturer only sells new products in the retail channel, and both new and remanufactured products are sold through the online direct channel. For instance, Apple sells new products offline and both new and remanufactured products online (Liu et al. 2022a, b). A consumer gets utility of new products from retail and direct channels are $u_1^{ro} = v - p_n^{ro}$ and $u_2^{ro} = \lambda v - p_o^{ro}$, respectively. The reference quality effect of consumers is considered (new products in the retail channel as the reference quality). The net utility of a consumer purchasing remanufactured products in the direct channel is $u_3^{ro} = \lambda\beta v - p_r^{ro} - \rho(v - \lambda\beta v)$. Without affecting the study, to make the study meaningful and concise, the constraints are as follows, $\lambda\beta - \rho(1 - \lambda\beta) > 0$, $\lambda - \beta + \rho(1 - \beta) > 0$, $\underline{\Delta_p} = \frac{(\lambda(1-\beta)+\rho(1-\lambda\beta))p_o}{\lambda} < p_o - p_r < \frac{(\lambda-\beta+\rho(1-\beta))(p_n-p_r)}{(1-\lambda\beta)(1+\rho)} = \overline{\Delta_p}$. If $u_1^{ro} > u_2^{ro}$, $u_1^{ro} > u_3^{ro}$, $u_1^{ro} > 0$, that is, $v - p_n^{ro} > \lambda v - p_o^{ro}$, $v - p_n^{ro} > \lambda\beta v - p_r^{ro} - \rho(v - \lambda\beta v)$, $v - p_n^{ro} > 0$, then the demand for new products in the retail channel is

$$q_n^{ro} = \int_{\frac{p_n^{ro}-p_o^{ro}}{1-\lambda}}^{1} 1dv = 1 - \frac{p_n^{ro} - p_o^{ro}}{1-\lambda} \tag{1}$$

If $u_2^{ro} > u_1^{ro}$, $u_2^{ro} > u_3^{ro}$, $u_2^{ro} > 0$, that is, $\lambda v - p_o^{ro} > v - p_n^{ro}$, $\lambda v - p_o^{ro} > \lambda\beta v - p_r^{ro} - \rho(v - \lambda\beta v)$, $\lambda v - p_o^{ro} > 0$, then the demand for new products in the direct channel is

$$q_o^{ro} = \int_{\frac{p_o^{ro}-p_r^{ro}}{\lambda(1-\beta)+\rho(1-\lambda\beta)}}^{\frac{p_n^{ro}-p_o^{ro}}{1-\lambda}} 1dv \tag{2}$$

If $u_3^{ro} > u_1^{ro}$, $u_3^{ro} > u_2^{ro}$, $u_3^{ro} > 0$, that is, $\lambda\beta v - p_r^{ro} - \rho(v - \lambda\beta v) > v - p_n^{ro}$, $\lambda\beta v - p_r^{ro} - \rho(v - \lambda\beta v) > \lambda v - p_o^{ro}$, $\lambda\beta v - p_r^{ro} - \rho(v - \lambda\beta v) > 0$, then the demand for remanufactured products in the direct channel is

$$q_r^{ro} = \int_{\frac{p_r^{ro}}{\lambda\beta-\rho(1-\lambda\beta)}}^{\frac{p_o^{ro}-p_r^{ro}}{\lambda(1-\beta)+\rho(1-\lambda\beta)}} 1dv \tag{3}$$

Combining Eqs. (1)–(3), the optimal problems of the retailer and manufacturer are as follows:

$$\begin{aligned} \max \Pi_M^{RO}\left(w_n^{ro}, p_o^{ro}, p_r^{ro}\right) = {} & \left(w_n^{ro} - c_m\right)\left(1 - \frac{p_n^{ro} - p_o^{ro}}{1-\lambda}\right) \\ & + \left(p_o^{ro} - c_m\right)\left(\frac{p_n^{ro} - p_o^{ro}}{1-\lambda} - \frac{p_o^{ro} - p_r^{ro}}{\lambda(1-\beta) + \rho(1-\lambda\beta)}\right) \\ & + \left(p_r^{ro} - c_r\right)\frac{p_o^{ro}(\lambda\beta - \rho(1-\lambda\beta)) - \lambda p_r^{ro}}{(\lambda - \lambda\beta + \rho(1-\lambda\beta))(\lambda\beta - \rho(1-\lambda\beta))} \end{aligned} \tag{4}$$

$$\max \Pi_R^{RO}\left(p_n^{ro}\right) = \left(p_n^{ro} - w_n^{ro}\right)\left(1 - \frac{p_n^{ro} - p_o^{ro}}{1-\lambda}\right) \tag{5}$$

Then, the optimal retail price of new products is obtained from Eq. (5) and $\frac{\partial \Pi_R^{RO}}{\partial p_n^{ro}} = 0$ as follows:

$$p_n^{ro*} = \frac{1 - \lambda + w_n^{ro} + p_o^{ro}}{2} \tag{6}$$

Substituting above optimal retail price p_n^{ro*} into Eq. (4) and solving the optimization problem, the equilibrium values are obtained based on game theory and backward induction, which can be shown in Lemma 1.

Lemma 1 *Under model RO, the optimal results can be summarized as follows*:

$$w_n^{ro*} = \frac{1+c_m}{2}, \quad p_o^{ro*} = \frac{\lambda+c_m}{2}, \quad p_r^{ro*} = \frac{(1+\rho)\lambda\beta+c_r-\rho}{2}, \quad p_n^{ro*} = \frac{2c_m-\lambda+3}{4}, \quad \pi_R^{RO*} = \frac{1-\lambda}{16}$$

$$, \pi_M^{RO*} = \frac{\begin{array}{c}(\beta(1+\rho)-1)\beta(1+\rho)\lambda^3 + \left(\rho-\beta+\beta^2(1+\rho)^2+4\beta c_m(1+\rho)(1-\beta(1+\rho))-\beta\rho(3+2\rho)\right)\lambda^2 + \\ \left(\rho(1+\rho)(1-2\beta)-2\left(2\rho+\beta(1+\rho)\left(c_m-4\rho-2c_r\right)\right)c_m-2c_r^2\right)\lambda+2\rho\left(c_m-2\rho-2c_r\right)c_m+\rho^2\end{array}}{8\left((\beta(1+\rho)-1)\beta(1+\rho)\lambda^2+\rho(1-2\beta(1+\rho))\lambda+\rho^2\right)}.$$

Combining Lemma 1 and Eqs. (1)–(3), the demand for the new and remanufactured product can be derived as follows:

$$q_n^{ro*} = \frac{1}{4}, q_o^{ro*} = \frac{(\beta+\beta\rho-1)\lambda+2\left(c_m-c_r\right)-\rho}{4((\beta+\beta\rho-1)\lambda-\rho)} \text{ and } q_r^{ro*} = \frac{\left(c_r-(\beta+\beta\rho)c_m\right)\lambda+\rho c_m}{2\left(\left(\beta^2(1+\rho)^2-\beta\rho-\beta\right)\lambda^2+(1-2\beta-2\beta\rho)\rho\lambda+\rho^2\right)}.$$

According to Lemma 1, the price of new products in the retail channel is positively related to the cost of remanufactured products but negatively related to the channel coefficient. Besides, the price of remanufactured products in the direct sales channel is affected by factors such as remanufacturing cost, channel preference coefficient, acceptance of remanufactured products, and the reference quality parameter. The price of remanufactured products is positively related to the channel coefficient and remanufactured product acceptance but negatively related to the reference quality effect parameter. This suggests that the price of remanufactured products is positively affected by the acceptance of remanufactured products. This is common in dual-channel supply chains, especially for new and remanufactured products. In contrast, the reference quality effect has a negative effect on the price of the remanufactured product, which does not work on the price of the new product. It is noteworthy that any change in price affects the change in demand. Therefore, it is crucial to consider the acceptance of remanufactured products and reference quality effects when deciding on profit maximization.

Proposition 1 *Under model RO, the effects of β and ρ on price and demand are*

(i) $\frac{\partial p_n^{ro*}}{\partial \beta} = 0, \frac{\partial p_o^{ro*}}{\partial \beta} = 0, \frac{\partial p_r^{ro*}}{\partial \beta} > 0.$

(ii) $\frac{\partial q_n^{ro*}}{\partial \beta} = 0, \frac{\partial q_o^{ro*}}{\partial \beta} < 0, \frac{\partial q_r^{ro*}}{\partial \beta} > 0.$

(iii) $\frac{\partial p_n^{ro*}}{\partial \rho} = 0, \frac{\partial p_o^{ro*}}{\partial \rho} = 0, \frac{\partial p_r^{ro*}}{\partial \rho} < 0.$

(iv) $\frac{\partial q_n^{ro*}}{\partial \rho} = 0, \frac{\partial q_o^{ro*}}{\partial \rho} > 0, \frac{\partial q_r^{ro*}}{\partial \rho} < 0.$

Propositions 1 (i) and (ii) demonstrate the impact of acceptance of remanufactured products on product price and demand. Propositions (iii) and (iv) reveal the changes in the impact of reference quality effects on prices and demand, which tend to exhibit the opposite trend compared to (i) and (ii). These findings indicate that as consumers become more accepting of remanufactured products, the price and demand increase while the demand for new products decreases in the direct channel. Interestingly, the retail price and demand for new products remain constant in the retail channel. However, when consumers have a high reference quality, demand for remanufactured products decreases in the direct channel while the demand for new products increases. One possibility is that consumers have a reference quality effect on remanufactured products, and new products are not affected by the quality reference effect. Overall, in the retail channel, demand for new products is neither affected by the high acceptance of remanufactured products nor the reference quality effect. This implies that a higher reference quality is less favorable to remanufactured products. Therefore, the reference quality effect hurts the sales of remanufactured products to some extent.

4.2 Model RR (Scenario RR)

In scenario RR, the manufacturer sells both new and remanufactured products through the retail channel, while only new products are sold through the direct channel. This structure is also common in real life, for example, Konica Minolta's early remanufactured copier are available in retail stores. In the RR model, the manufacturer determines the wholesale and direct prices. Then, the retailer decides the retail price of the new and remanufactured products. The optimal decision problem is formulated using game theory and backward induction.

A consumer gets utility of new and remanufactured products from the retail channel, which can be characterized as $u_1^{rr} = v - p_n^{rr}$ and $u_2^{rr} = \beta v - p_r^{rr} - \rho(v - \beta v)$. The utility of consumers purchasing new products from the direct channel can be presented as $u_3^{RR} = \lambda v - p_o^{rr}$. The constraints are given as follows, $\hat{\Delta}_p = \frac{\lambda-\beta+\rho(1-\beta)p_o}{\lambda} < p_o - p_r < \frac{(\lambda-\beta+\rho(1-\beta))(p_n-p_r)}{(1-\beta)(1+\rho)} = \breve{\Delta}_p$. If $u_1^{rr} > u_2^{rr}$, $u_1^{rr} > u_3^{rr}$, $u_1^{rr} > 0$; that is, $v - p_n^{rr} > \beta v - p_r^{rr} - \rho(v - \beta v)$, $v - p_n^{rr} > \lambda v - p_o^{rr}$, $v - p_n^{rr} > 0$, then consumers will buy new products from the retail channel. Thus, $q_n^{rr} = \int_{\frac{p_n^{rr}-p_o^{rr}}{1-\lambda}}^{1} 1dv$. If $u_3^{rr} > u_1^{rr}$, $u_3^{rr} > u_2^{rr}$, $u_3^{rr} > 0$, that is, $\lambda v - p_o^{rr} > v - p_n^{rr}$, $\lambda v - p_o^{rr} > \beta v - p_r^{rr} - \rho(v - \beta v)$, $\lambda v - p_o^{rr} > 0$, then consumers will buy remanufactured products from the retail channel. Thus, $q_o^{rr} = \int_{\frac{p_o^{rr}-p_r^{rr}}{\lambda-\beta+\rho(1-\beta)}}^{\frac{p_n^{rr}-p_o^{rr}}{1-\lambda}} 1dv$. If $u_2^{rr} > u_1^{rr}$, $u_2^{rr} > u_3^{rr}$, $u_2^{rr} > 0$; that is, $\beta v - p_r^{rr} - \rho(v - \beta v) > v - p_n^{rr}$, $\beta v - p_r^{rr} - \rho(v - \beta v) > \lambda v - p_o^{rr}$, $\beta v - p_r^{rr} - \rho(v - \beta v) > 0$, then consumers will buy new products from the direct channel. Thus, $q_r^{rr} = \int_{\frac{p_r^{rr}}{\beta-\rho(1-\beta)}}^{\frac{p_o^{rr}-p_r^{rr}}{\lambda-\beta+\rho(1-\beta)}} 1dv$.

Combined with demand functions, the retailer's maximum profit problem can be defined as follows:

$$\max \Pi_R^{RR}\left(p_n^{rr}, p_r^{rr}\right) = \left(p_n^{rr} - w_n^{rr}\right)q_n^{rr} + \left(p_r^{rr} - w_r^{rr}\right)q_r^{rr} \tag{7}$$

Taking the first-order derivative of Π_R^{RR} with respect to p_n^{rr} and p_r^{rr}, the optimal result is given by

$$p_n^{rr} = \frac{p_o^{rr} + w_n^{rr} - \lambda + 1}{2} \tag{8}$$

$$p_r^{rr} = \frac{(\beta - \rho + \beta\rho)p_o^{rr} + \lambda w_r^{rr}}{2\lambda} \tag{9}$$

From Eq. (7), it is observed that p_n^{rr} is proportional to p_o^{rr} and w_n^{rr}. p_r^{rr} increases with the increase in the direct price of the new product and the wholesale price of the remanufactured product.

The profit function of the manufacturer is given as follows:

$$\max \Pi_M^{RR}\left(w_n^{rr}, w_r^{rr}, p_o^{rr}\right) = \left(w_n^{rr} - c_m\right)q_n^{rr} + \left(p_o^{rr} - c_m\right)q_o^{rr} + \left(w_r^{rr} - c_r\right)q_r^{rr} \tag{10}$$

The manufacturer's profit consists of three components: the profit of new products in the retail channel, the profit of remanufactured products in the retail channel, and the profit of new products in the direct sales channel. Combining Eqs. (8) and (9), the equilibrium solution can be derived by applying the Hessian matrix constraint, which is shown in Lemma 2.

Lemma 2 *The equilibrium value of the RR model is* $w_n^{rr*} = \frac{1+c_m}{2}$, $w_r^{rr*} = \frac{c_r+\beta-\rho+\beta\rho}{2}$, $p_n^{rr*} = \frac{2c_m-\lambda+3}{4}$, $p_o^{rr*} = \frac{\lambda+c_m}{2}$, $p_r^{rr*} = \frac{(c_r+2\beta-2\rho+2\beta\rho)\lambda+(\beta-\rho+\beta\rho)c_m}{4\lambda}$. *The optimal profits are*

$$\pi_M^{RR*} = \frac{\begin{array}{c}(\rho - \beta(1+\rho))\lambda^3 - \left(\beta - \rho - \rho^2(1-\beta)^2 + 4c_m(\rho - \beta(1+\rho)) + \beta\rho(3-2\beta) + c_r^2 - \rho^2\right)\lambda^2 - \\ \left(2\beta\rho - \rho^2(1-\beta)^2 + 2c_m\left(2\rho(1+\rho)\beta^2 + 2\rho^2(1-2\beta) + (\rho - \beta(1+\rho))c_r - 4\beta\rho\right) + 2c_m^2(\beta - \rho + \beta\rho) - (1+2\rho)\beta^2\right)\lambda + \\ (\beta(1+\rho)(\beta(1+\rho) - 2\rho) + \rho^2)c_m^2\end{array}}{-8\lambda((\beta(1+\rho) - \rho)\lambda - \beta(1+\rho)(\beta(1+\rho) - 2\rho) - \rho^2)}$$

$$\pi_R^{RR*} = \frac{\begin{array}{c}(\beta(1+\rho) - \rho)\lambda^3 - \left(c_r^2 + \rho^2(1-\beta)^2 + (1+2\rho)\beta^2 - (1+\beta)\rho + \beta\right)\lambda^2 - \\ \left(2\beta\rho - (1-\beta)^2\rho^2 - (1+2\rho)\beta^2 + 2(\rho - \beta - \beta\rho)c_m c_r\right)\lambda - c_m^2\left((1+\rho)(\beta^2(1+\rho) - 2\beta\rho) + \rho^2\right)\end{array}}{-16\left((\beta(1+\rho) - \rho)\lambda^2 + \left(-\beta^2(1+\rho)^2 + \rho(2\beta(1+\rho) - \rho)\right)\lambda\right)}$$

Lemma 2 gives the optimal decision results for the manufacturer and the retailer under the RR model. The findings indicate that as the number of consumers who prefer the direct channel increases, the price of new products in the direct channel increases while the price of new products in the retail channel decreases. The wholesale price of remanufactured products is positively correlated with the acceptance of remanufactured products and negatively related to the reference quality parameter. Unlike traditional channels, the retail price of remanufactured products is uncertain and depends on channel preference, acceptance of remanufactured products, and the reference quality parameter. Previous studies have shown variability in results due to different research environments. For example, Gavious's 2012 found that the reference quality effect increased firms' profits, while Ma'2020 discovered that a higher reference quality effect parameter would hurt the manufacturer's profit. Observing the profit functions of the manufacturer and the retailer reveals that the direct impact of the reference quality effect on the supply chain members cannot be intuitively seen from the expressions compared to the studies of traditional channels.

Proposition 2 *Under model RR, the following relationships hold*:

(i) $\frac{\partial p_n^{rr*}}{\partial \beta} = 0, \frac{\partial p_o^{rr*}}{\partial \beta} = 0, \frac{\partial p_r^{rr*}}{\partial \beta} > 0, \frac{\partial q_n^{rr*}}{\partial \beta} = 0, \frac{\partial q_o^{rr*}}{\partial \beta} < 0, \frac{\partial q_r^{rr*}}{\partial \beta} > 0.$
(ii) $\frac{\partial p_n^{rr*}}{\partial \rho} = 0, \frac{\partial p_o^{rr*}}{\partial \rho} = 0, \frac{\partial p_r^{rr*}}{\partial \rho} < 0, \frac{\partial q_n^{rr*}}{\partial \rho} = 0, \frac{\partial q_o^{rr*}}{\partial \rho} > 0, \frac{\partial q_r^{rr*}}{\partial \rho} < 0.$

Compared with proposition 1, proposition 2 reveals the same trend. This suggests that regardless of whether remanufactured products choose to be sold through retail or direct channels, the acceptance of remanufactured products and the reference quality effect will not change the direction of price and demand. However, the magnitude of the changing trend varies. Differs from Proposition 1, when both new and remanufactured products are sold in the retail channel, consumer acceptance of the remanufactured product affects total demand in the retail channel, resulting in fewer consumers choosing the product in the direct channel. Consequently, the total demand in the direct channel decreases. Furthermore, total demand in the direct channel is also decreasing. As consumers are more willing to buy new products, the price of these products in the direct channel is lower than those in the retail channel as the reference quality parameter increases. This leads to consumers having a greater preference for new products from the direct channel, increasing in demand for this channel. This phenomenon seems counterintuitive because, in the same channel, when the preference for one product increases, the sales of another product will decrease. However, this study shows that different levels of consumer acceptance of remanufactured products do not always affect the price and sales of other products; for example, both models show that the price of the retail channel is not affected by the acceptance of remanufactured products. Since the reference quality effect on the demand function is reflected through the consumer utility function, it is inferred that for the RO and RR models, the remanufactured product acceptance coefficient β is eliminated from the expression for the price of new products in the retail channel. Thus, it can be seen from the expression that $\frac{2c_m-\lambda+3}{4}$ is not directly affected by β. This explains this phenomenon in real companies, such as Apple's new product price, which is almost unaffected by the preference for remanufactured products. Because the quality and reputation of Apple's new products are well known, consumers who prefer new products are less willing to buy remanufactured products. Many consumers who prefer remanufactured products are environmentally conscious, price-sensitive, and less willing to accept new products. Therefore, to a certain extent, the degree of preference for remanufactured products may not be directly influenced by the price setting of new products. The price of new products in the direct channel is inversely proportional to the acceptance of remanufactured products and positively related to the reference quality effect parameter.

Proposition 3 *Compared to the RR model, the threshold Δ_p is higher for the RO model, where* $\underline{\Delta_p} = \frac{(\lambda(1-\beta)+\rho(1-\lambda\beta))(1+c_m)}{2\lambda}$, $\overline{\Delta_p} = \frac{(\lambda(1-\beta)+\rho(1-\lambda\beta))(2c_m-\lambda+3-2((1+\rho)\lambda\beta+c_r-\rho))}{4(1-\lambda\beta)(1+\rho)}$,$\hat{\Delta}_p = \frac{(\lambda-\beta+\rho(1-\beta))(1+c_m)}{2\lambda}$, *and* $\breve{\Delta}_p = \frac{(\lambda-\beta+\rho(1-\beta))(2c_m-\lambda+3-2((1+\rho)\beta+c_r-\rho))}{4(1-\beta)(1+\rho)}$, $\Delta_p = p_o^i - p_r^i$.

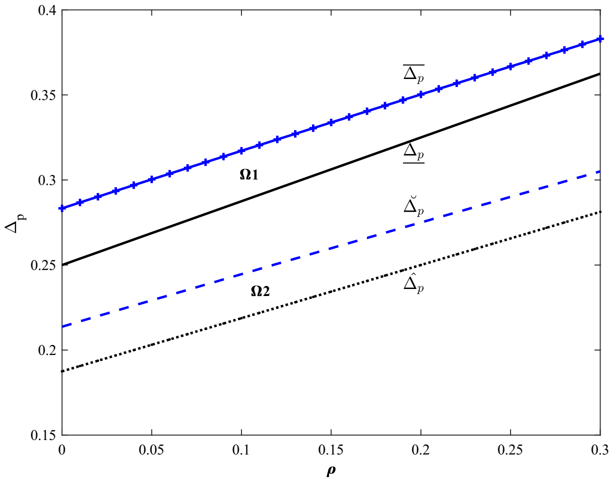

Fig. 3 The effect of ρ on Δ_p

From Proposition 3 and Fig. 3, prices of new and remanufactured products in the direct channel have different boundary values according to the channel preferences under different models. The difference under the RO model is higher than that under the RR model, that is, $\Omega_1 > \Omega_2$. As ρ increases, Δ_p increases to varying degrees, among which $\underline{\Delta}_p$ and $\breve{\Delta}_p$ increase rapidly. The range of boundary values for p_o^i and p_r^i in the RO model is slightly larger. The RO model shows that when the boundary of p_o^i in the direct channel is significantly lower than p_r^i, the manufacturer's profit increases. However, the boundary values do not have a significant impact. This means that even slight differences in the pricing boundary strategies adopted by the manufacturer in different models will ultimately affect the profits of supply chain members. The manufacturer has an optimal response curve that depends on the value of Δ_p. This implies that price boundaries for new and remanufactured products play a vital role in the pricing strategy of the manufacturer. Thus, the reference quality effect brings different impacts on firms' pricing differentials between new and remanufactured products under different models. This suggests that when firms opt to sell remanufactured products online in the direct sales channel, the pricing thresholds between new and remanufactured products under the RO model are narrowed under the high ρ of the direct channel.

4.3 Comparison analysis

In this subsection, decision differences between the retail channel and the online direct channel when selling remanufactured products are compared. Specifically, the optimal pricing strategies of firms under different models for remanufactured products are examined by comparing prices and volumes. Proposition 4 and Figs. 3–4

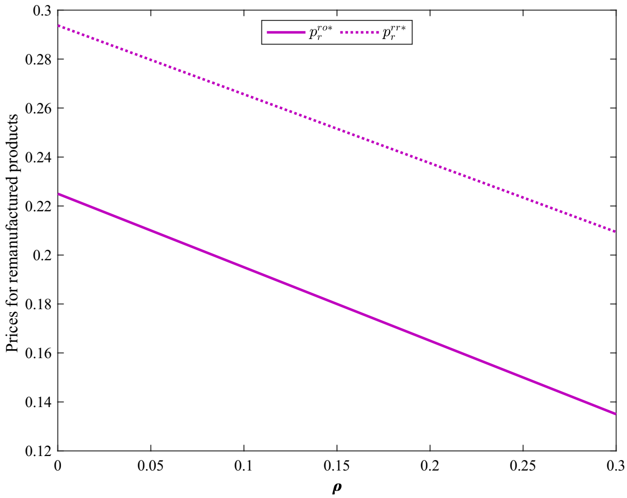

Fig. 4 The effect of ρ on the price of remanufactured products

reveal the relationship between the optimal price and the optimal total demands under different models. In addition, the optimal threshold range of the optimal channel for remanufactured products is derived from Corollary 1.

Proposition 4 *By comparison, the relationship* $p_n^{rr*} = p_n^{ro*}$, $p_o^{rr*} = p_o^{ro*}$, $q_n^{rr*} = q_n^{ro*}$ *holds, and the following relationships hold under certain conditions*:

(i) If $\lambda\beta\rho < \frac{(\beta-\rho+\beta\rho)c_m-2(\lambda-1)\lambda\beta+\lambda c_r}{2(\lambda-1)}$, then $p_r^{ro*} > p_r^{rr*}$; if $\lambda\beta\rho > \frac{(\beta-\rho+\beta\rho)c_m-2(\lambda-1)\lambda\beta+\lambda c_r}{2(\lambda-1)}$, then $p_r^{ro*} < p_r^{rr*}$.

(ii) If $\begin{cases} \lambda\beta\rho > \zeta, \omega > 0 \\ \lambda\beta\rho < \zeta, \omega < 0 \end{cases}$, then $q_o^{ro*} > q_o^{rr*}$; if $\begin{cases} \lambda\beta\rho\langle\zeta, \omega\rangle 0 \\ \lambda\beta\rho > \zeta, \omega < 0 \end{cases}$, then $q_o^{ro*} < q_o^{rr*}$. Where $\omega = (\beta(2+\rho) - \rho - 2\lambda)c_m + (\lambda - 2)c_r$, $\zeta = \frac{-\left((1-\beta)\rho^2+(\lambda-\beta)\rho+\lambda\beta(\beta-2\lambda+1)\right)c_m-\lambda(\lambda+\rho+\beta(\lambda+\lambda\rho-2))c_r}{(\beta(2+\rho)-\rho-2\lambda)c_m+(\lambda-2)c_r}$.

(iii) When $B^2 + 4C(\beta - 1)(1 + \rho)c_m > 0$ is satisfied, if $\lambda\beta\rho < \frac{-B-\sqrt{B^2+4C(\beta-1)(1+\rho)c_m}}{-2(\beta-1)(1+\rho)c_m}$ or $\lambda\beta\rho > \frac{-B+\sqrt{B^2+4C(\beta-1)(1+\rho)c_m}}{-2(\beta-1)(1+\rho)c_m}$, then $q_r^{ro*} < q_r^{rr*}$. When $B^2 + 4C(\beta - 1)(1 + \rho)c_m < 0$ is satisfied, $q_r^{ro*} < q_r^{rr*}$. When $B^2 + 4C(\beta - 1)(1 + \rho)c_m > 0$ is satisfied, if $\frac{-B-\sqrt{B^2+4C(\beta-1)(1+\rho)c_m}}{-2(\beta-1)(1+\rho)c_m} < \lambda\beta\rho < \frac{-B+\sqrt{B^2+4C(\beta-1)(1+\rho)c_m}}{-2(\beta-1)(1+\rho)c_m}$, then $q_r^{ro*} > q_r^{rr*}$.

Proposition 4 shows that under the RO model, the combined effect of remanufactured product acceptance, channel preference, and the reference quality effect parameters causes the manufacturer to lower the price of remanufactured products. Intuitively, on the one hand, the lower the remanufactured product acceptance and channel preference, the lower the consumer interest in remanufactured products. On the other hand, increasing the reference quality parameter will lead to a greater perceived quality difference between remanufactured products and direct channels. This reference quality effect may also make consumers more price sensitive. Therefore, under the RO model, the manufacturer may lower the price to attract more consumers to remanufactured products. As shown in Fig. 4, under both the RO and RR models, the price of remanufactured products decreases with the increase of ρ. At this time, more price-sensitive consumers will choose remanufactured products because of the relatively lower price of p_r^{ro*}, so the demand for the remanufactured product under the RO model increases, while the demand for the new product decreases relatively. The observation of the equilibrium form of the price of new products under two models reveals that the price of new products is closely related to channel preference and the cost of new products. On the contrary, the acceptance of remanufactured products and the reference quality effect will not directly affect the price of new products. Therefore, whether a manufacturer chooses retail or direct channels to sell remanufactured products may not affect the pricing of new products, and further, the price of new products is the same under both models. This implies that whether higher channel preference and remanufactured product acceptance are favorable for sales of remanufactured products also depends on the impact of reference quality effects. A real-world example is Apple, whose online direct sales channel sells remanufactured products such as iPhones and computers, while new products in the retail channel. In relation to the case of Apple, it is found that although the fact that the online direct channel offers lower prices for remanufactured products and even provides more educational discounts for these products, the channel still provides more product quality information for remanufactured products to counteract the impact of quality perception shocks caused by the reference price effect. Therefore, it would be safer for the manufacturer to set a lower price for the remanufactured product because the reference quality effect seems to have some negative impact on remanufactured products.

Corollary 1 *The manufacturer's profit is greater for remanufactured products sold through the retail channel (i.e.,* $\pi_M^{RR*} \geq \pi_M^{RO*}$*)) if and only if* $\overline{M}^*(\rho) > 0$*; the manufacturer is more profitable for remanufactured products sold through the direct channel (i.e.,* $\pi_M^{RO*} \geq \pi_M^{RR*}$*) if and only if* $\overline{M}^*(\rho) < 0$*, where*

$$\overline{M}^*(\rho) = \frac{\begin{array}{c}((\rho - \beta(1+\rho))\vartheta - (\beta(1+\rho) - 1)\beta(1+\rho)\sigma)\lambda^3 - (l\vartheta + h\sigma)\lambda^2 - \\ (\nu\vartheta + \kappa\sigma)\lambda + \left(\beta(1+\rho)(\beta(1+\rho) - 2\rho) + \rho^2\right)\vartheta c_m^2 - 2\sigma\rho\left(c_m - 2\rho - 2c_r\right)c_m + \sigma\rho^2\end{array}}{\sigma\vartheta}.$$

Corollary 1 indicates that when $\overline{M}^*(\rho) > 0$, it is more profitable for the manufacturer to choose the retail channel to sell the remanufactured product. Conversely, when $\overline{M}^*(\rho) < 0$, it is more beneficial for the manufacturer to choose the direct channel to sell the remanufactured product directly. Figure 5 illustrates the effect of the parameter ρ on $\overline{M}^*$. It is found that as ρ increases, $\overline{M}^*$ initially increases and then decreases. This suggests that when the degree of reference quality effect is weighted, the manufacturer is more likely to choose the optimal decision from the two models. The findings reveal that the higher the reference quality parameter, the smaller the profit difference between the two models. It should be noted that reference quality

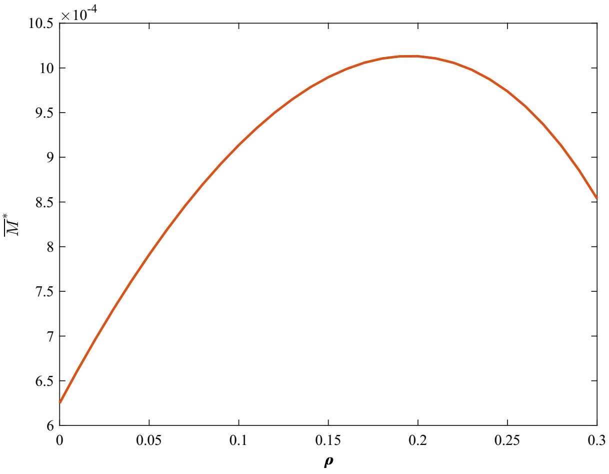

Fig. 5 The effect of ρ on $\overline{M}^*$

effects do not always favor the RO model. In other words, although profitability under the RR model increases, the manufacturer is still negatively affected by reference quality. Nonetheless, when the reference quality parameter is small, the RR model is more favorable than the RO model. Under the RO model, as ρ increases, the price of the remanufactured product decreases, the wholesale price of the remanufactured product decreases, and the demand for the remanufactured product increases. For the manufacturer, the increase in the demand for the remanufactured product offsets the decrease in wholesale price, and therefore the manufacturer's profit increases. A numerical analysis is provided hereafter to explore in detail the impact of the product acceptance coefficient, channel coefficient, and the reference quality effect parameter on the manufacturer's optimal decision and profits.

5 Numerical analysis

In this section, numerical experiments are used to explore the impact of consumer acceptance for remanufactured products (β), consumer acceptance for online direct channel (λ), and the parameter of the reference quality effect (ρ) on the optimal decision and profit of the manufacturer. To validate the proposed pricing problem, similar to previously published studies (Atasu et al. 2008; Ma et al. 2020), the datasets are given as follows.

Examples: $c_m = 0.2,\ c_r = 0.05,\ \lambda = 0.8,\ \beta = 0.3$; $c_m = 0.2,\ c_r = 0.05,\ \lambda = 0.8,\ \beta = 0.4$; $c_m = 0.2,\ c_r = 0.05,\ \lambda = 0.8,\ \beta = 0.5$; $c_m = 0.2,\ c_r = 0.05,\ \lambda = 0.85,\ \beta = 0.3$; $c_m = 0.2,\ c_r = 0.05,\ \lambda = 0.85,\ \beta = 0.4$; $c_m = 0.2,\ c_r = 0.05,\ \lambda = 0.85,\ \beta = 0.5$.

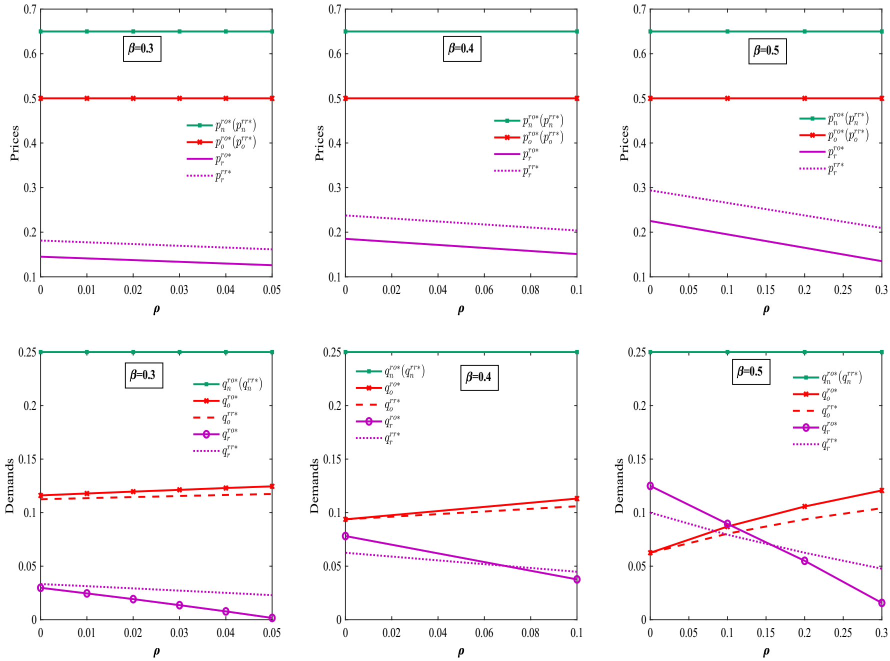

Fig. 6 The effect of ρ on prices and demands ($\lambda = 0.8$)

5.1 The impact of reference quality effect parameter on prices and demands

Figure 6 displays the trend of the reference quality parameter on price and demand under RO and RR models. Under different acceptance levels of remanufactured products, as the reference quality effect parameter increases, the price of new and remanufactured products follows the same trend, but when $\beta = 0.5$, the price of

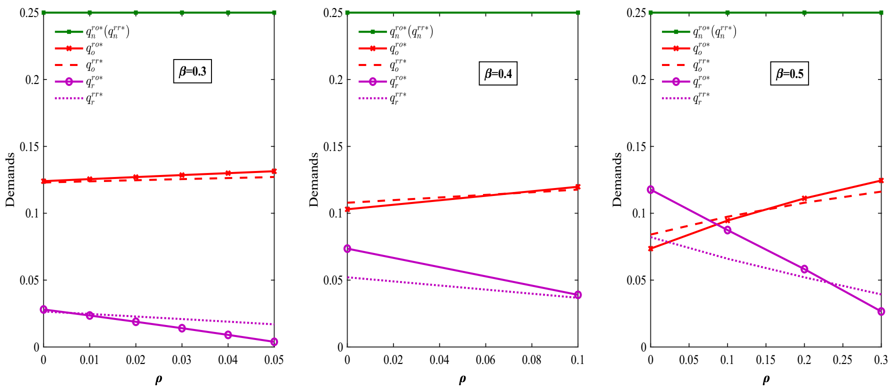

Fig. 7 The effect of ρ on the demands ($\lambda = 0.85$)

remanufactured products is relatively high. Moreover, under different levels of remanufactured product acceptance, as ρ increases, the demand for different products is different. As shown in Fig. 6, when the acceptance of remanufactured products is low, the demand for remanufactured products is higher under the RR model. However, when β is high, and ρ is low, the demand for remanufactured products is higher under the RO model. As β increases, the demand for new products in the direct channel decreases.

Figure 7 plots the demand trends for different products in both models when $\lambda = 0.85$. Compared with Fig. 6, the demand for remanufactured products increases with β and is slightly higher in the RO model, which is independent of λ. The demand for new products is higher under the direct channel when both models have a high channel preference. However, under the RR model, the demand for remanufactured products is uncertain. This is because the acceptance of remanufactured products affects the demand for new products to some extent. The insight gained is that, the demand for new products under the direct channel increases with the increase in the reference quality parameter, and increases rapidly with the acceptance of remanufactured products. Under the RO model, the demand for new products is most favorable when there is a higher channel preference and acceptance of remanufactured products in the direct channel.

5.2 The impact of reference quality effect parameter on the manufacturer's profit

Figure 8 graphs the impact of key parameters on the manufacturer's profit in different models. The profit in the RR model follows the same trend as the RO model. As the value of β increases, the difference in manufacturer's profits between the RR and RO models gradually decreases. When the channel coefficient is large, the manufacturer's profit in both models is higher. Comparing the RR and RO models, the manufacturer's profit is affected by the acceptance of remanufactured products. In this case, the profit of the RO model is greater than that of the RR model. This trend suggests that in the retail channel, the smaller the value of β, the higher the manufacturer's profit of remanufactured products. However, when consumers are more willing

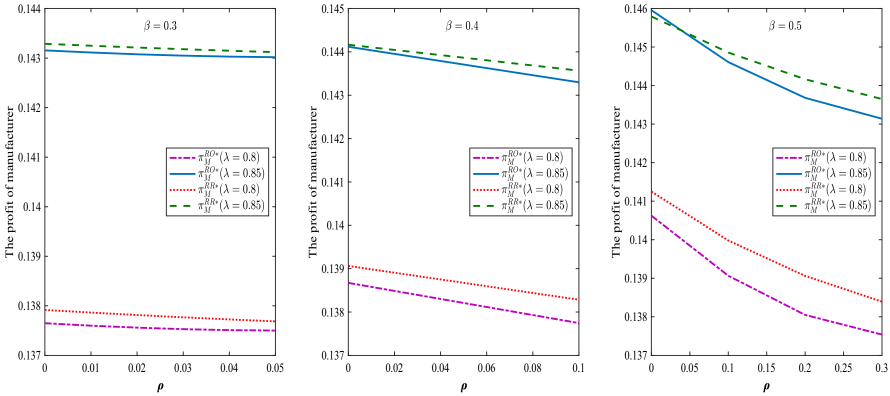

Fig. 8 The effect of ρ on the profits

to buy remanufactured products through direct sales channels, the manufacturer's profit loss can be effectively mitigated. The revelation is that consumer acceptance of remanufactured products does not directly affect the overall profitability of the manufacturer. There is uncertainty in the profitability of the manufacturer choosing retail or direct channels to sell remanufactured products. The profit of both models increases with the increase of channel preference but decreases with the increase of reference quality parameters. Although the reference quality effect creates uncertain dynamic effects to firms, low reference quality parameters generally favor firms that profit from a mixed sales model of new and remanufactured products. Therefore, firms are encouraged to invest in remanufactured products to achieve the balance between cost savings, environmental protection, and business interests. This explains why some real-life companies prefer to sell remanufactured products through direct channels, as Apple does. The manufacturer's profit is negatively affected by the reference quality effect, which somewhat hurts the supply chain members' profits. The manufacturer and the retailer could adjust the reference level of consumers based on product quality information. For example, they can disclose the quality of remanufactured products to improve their perceived quality.

Figure 9 illustrates how the total profit of the RO model is affected by the remanufactured product acceptance, the channel coefficient, and the reference quality effect parameter. The total profit of the RO model decreases as ρ increases, and the trend is independent of remanufactured product acceptance and channel coefficient but is related to the reference quality effect parameter. The study shows that maximum profit is achieved when both the channel coefficient and remanufactured product acceptance are high. However, when λ is high and β is low, profits are higher than when channel coefficients are low and remanufactured product acceptance is high. This trend suggests that when β is low, a higher channel preference can increase total profits (e.g., firms should promote efforts in the direct channel).

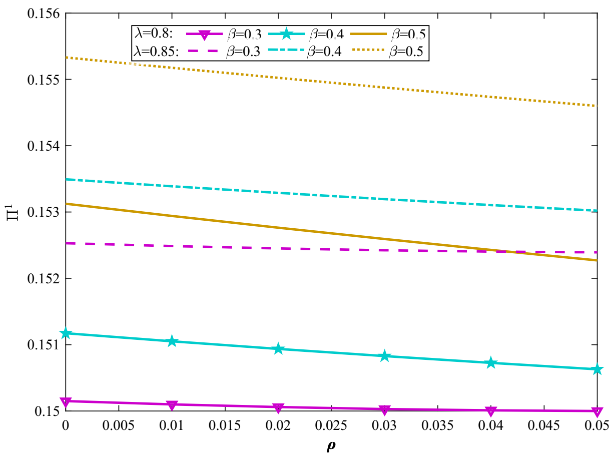

Fig. 9 The effect of ρ on the total profit in model RO

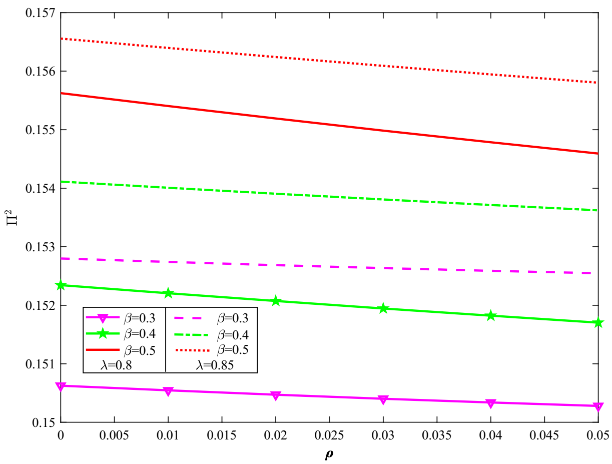

Fig. 10 The effect of ρ on the total profit in model RR

Figure 10 shows the impact of remanufactured product acceptance, the channel coefficient, and the reference quality effect parameter on the total profit of the RR model. The trends are roughly the same as those in the RO model. However, it is worth noting that when β is low, changing the channel preference parameter may not increase total profit. In addition, as ρ increases, the total profit decreases. To improve profits, disclosing the quality of remanufactured products could help mitigate consumers' reference quality behavior. Green development cannot be considered solely on the supply side or only on the demand side. Instead, it should be combined with production patterns on the supply side and the consumption behavior on the demand side. The profitability of the supply chain may be affected by the combined effects of channel preferences, acceptance of remanufactured goods, and reference quality effects. In fact, for a certain range of reference quality parameters, when channel preference is high and remanufactured product acceptance is low, the profitability is higher than that when channel preference is low and remanufactured product acceptance is high.

6 Extensions

In this section, the above questions are expanded to better understand how manufacturers can make the best decisions and improve supply chain profitability when selling remanufactured products in multiple channels. In particular, it examines the sale of remanufactured products in both the retail and direct channels (ROR model). The optimal wholesale price of the product is determined by the manufacturer using the best response function of the retail price of the new or remanufactured product in the retail channel. Similar to the previous discussion in Sect. 4, a consumer could get utility from new and remanufactured products in the retail channel are $u_1^{ror} = v - p_n^{ror}$ and $u_2^{ror} = \beta v - p_{r1}^{ror} - \rho(v - \beta v)$, respectively. Meanwhile, a consumer could get utility from new and remanufactured products in the direct channel are $u_3^{ror} = \lambda v - p_o^{ror}$ and $u_4^{ror} = \lambda\beta v - p_{r2}^{ror} - \rho(v - \lambda\beta v)$, respectively. If $u_1^{ror} > u_2^{ror}$, $u_1^{ror} > u_3^{ror}$, $u_1^{ror} > u_4^{ror}$, $u_1^{ror} > 0$, then consumers will buy new products from the retail channel. If $u_2^{ror} > u_1^{ror}$, $u_2^{ror} > u_3^{ror}$, $u_2^{ror} > u_4^{ror}$, $u_2^{ror} > 0$, then consumers will buy remanufactured products from the retail channel. If $u_3^{ror} > u_1^{ror}$, $u_3^{ror} > u_2^{ror}$, $u_3^{ror} > u_4^{ror}$, $u_3^{ror} > 0$, then consumers will buy new products from the direct channel. If $u_4^{ror} > u_1^{ror}$, $u_4^{ror} > u_2^{ror}$, $u_4^{ror} > u_3^{ror}$, $u_4^{ror} > 0$, then consumers will buy remanufactured products from the direct channel. The constraints are consistent with the above studies, utilizing the consumer utility function and the demand for new products in the retail and direct channels, we have

$$q_n^{ror} = \int_{\frac{p_n^{ror} - p_o^{ror}}{1-\lambda}}^{1} 1dv \tag{11}$$

$$q_o^{ror} = \int_{\frac{p_o^{ror} - p_{r1}^{ror}}{\lambda-\beta+\rho(1-\beta)}}^{\frac{p_n^{ror} - p_o^{ror}}{1-\lambda}} 1dv \tag{12}$$

The demands for remanufactured products in the retail and direct channels are, respectively,

$$q_{r1}^{ror} = \int_{\frac{p_{r1}^{ror} - p_{r2}^{ror}}{\beta(1+\rho)(1-\lambda)}}^{\frac{p_o^{ror} - p_{r1}^{ror}}{\lambda-\beta+\rho(1-\beta)}} 1dv \tag{13}$$

$$q_{r2}^{ror} = \int_{\frac{p_{r2}^{ror}}{\lambda\beta-\rho(1-\lambda\beta)}}^{\frac{p_{r1}^{ror} - p_{r2}^{ror}}{\beta(1+\rho)(1-\lambda)}} 1dv \tag{14}$$

The retailer's expected profit is described as follows

$$\max \Pi_R\left(p_n^{ror}, p_{r1}^{ror}\right) = \left(p_n^{ror} - w_n^{ror}\right)q_n^{ror} + \left(p_{r1}^{ror} - w_r^{ror}\right)q_{r1}^{ror} \tag{15}$$

By taking partial derivatives of the first order of p_n^{ror*} and p_{r1}^{ror*} for the Eqs. (15), it can be observed that
$p_n^{ror*} = \frac{p_o^{ror*}+w_n^{ror*}-\lambda+1}{2}$, $p_{r1}^{ror*} = \frac{\beta(1-\lambda)(1+\rho)p_o^{ror*}+(\lambda+\rho-\beta(1+\rho)p_{r2}^{ror*}+(\lambda+\rho-\lambda\beta(1+\rho))w_r^{ror*}}{2(\lambda+\rho-\lambda\beta(1+\rho))}$.
The manufacturer's optimal profit problem is given as follows,

$$\begin{cases} \max \Pi_M\left(w_n^{ror}, w_r^{ror}, p_o^{ror}, p_{r2}^{ror}\right) = \left(w_n^{ror} - c_m\right)q_n^{ror} + \left(p_o^{ror} - c_m\right)q_o^{ror} \\ +\left(w_r^{ror} - c_r\right)q_{r1}^{ror} + \left(p_{r2}^{ror} - c_r\right)q_{r2}^{ror} \\ S.t.p_{r2}^{ror} < p_{r1}^{ror} < p_o^{ror} < \lambda p_n^{ror} \end{cases} \tag{16}$$

Substituting p_n^{ror*} and p_{r1}^{ror*} into Eqs. (16), the equilibrium values are
$w_n^{ror*} = \frac{1+c_m}{2}$, $w_r^{ror*} = \frac{\beta-\rho+\beta\rho+c_r}{2}$, $p_o^{ror*} = \frac{\lambda+c_m}{2}$, $p_n^{ror*} = \frac{2c_m-\lambda+3}{4}$,

$$p_{r1}^{ror*} = \frac{\begin{array}{c}\left(2\rho - 2\beta - 2c_r + 2\beta^2(1+\rho)^2 + \beta(c_m + c_r) - 2\beta\rho(2+\rho) + \beta\rho(c_m + c_r)\right)\lambda + \\ (\beta - 2\rho + \beta\rho)c_r - (\beta + \beta\rho)c_m - 2\beta\rho(1+\rho) + 2\rho^2\end{array}}{4((\beta+\beta\rho-1)\lambda-\rho)},$$

$p_{r2}^{ror*} = \frac{\lambda\beta(1+\rho)-\rho+c_r}{2}$.

Proposition 5 *Under the ROR model, the optimal profits of supply chain members are*

$$\pi_R^* = \frac{\begin{array}{c}(1-\beta\rho-\beta)\lambda^3 + ((1+\rho)\beta((1+\rho)\beta-\rho) + 2\rho - 1)\lambda^2 + \\ \left(\beta(1+\rho)\left(\left(c_m - c_r\right)^2 - \beta(1+\rho) + 1\right) + \rho^2 - 2\rho\right)\lambda - \beta(1+\rho)\left(c_m - c_r\right)^2 + \beta\rho(1+\rho) - \rho^2\end{array}}{16\left((\beta+\beta\rho-1)\lambda^2 + \left(\left(-\rho^2-2\rho-1\right)\beta^2 + \left(\rho^2+2\rho+1\right)\beta - 2\rho\right)\lambda + \beta\rho(1+\rho) - \rho^2\right)}$$

$$\pi_M^* = \frac{\beta(1+\rho)(\beta(1+\rho)-1)\lambda^4 + \mu\lambda^3 + \varphi\lambda^2 + \varsigma\lambda + \varrho}{\begin{array}{c}8(\beta(1+\rho)((1+\rho)\beta-1)\lambda^3 + \left(\left(\rho^3+3\rho^2+3\rho+1\right)\beta^2(1-\beta) - 3\rho(1+\rho)\beta + \rho\right)\lambda^2 \\ +\rho\left(2(1+\rho)^2\beta^2 - \left(2\rho^2+3\rho+1\right)\beta + 2\rho\right)\lambda + \rho^2(\rho-\beta\rho-\beta))\end{array}}$$

Figure 11 shows how the manufacturer's profit changes with ρ under low channel preference ($\lambda = 0.8$), high channel preference ($\lambda = 0.85$), and low remanufactured product preference ($\beta = 0.3$) or high remanufactured product preference ($\beta = 0.5$). As it can be seen from Fig. 11, the profits of the three models all decrease with ρ. However, under low channel preference, the profit of the remanufactured product

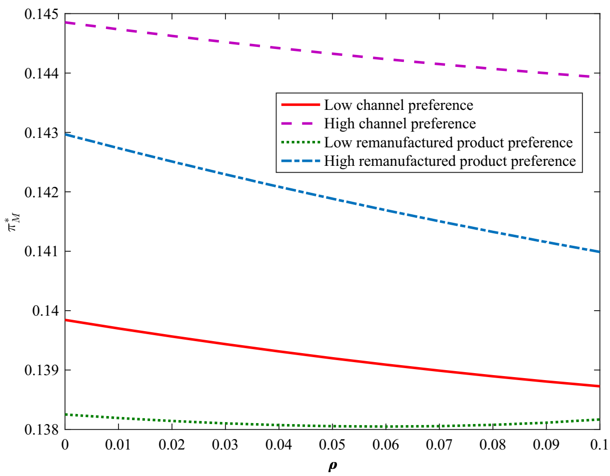

Fig. 11 The effect of ρ on the manufacturer's profit under model ROR

sold through both channels is the highest. Under conditions of low preference for remanufactured products, profits are higher when remanufactured products are sold through both channels. The manufacturer's profit is lowest when the acceptance of the remanufactured product is low, which first decreases and then increases with the reference quality parameter. The possible reason for this is that, when consumers have low acceptance of remanufactured products, the expected quality of the remanufactured product decreases. This leads to aggravated reference quality behavior, which can be detrimental to the sale of the remanufactured product. As a result, sales of new products increase, which leads to an increase in overall profits.

Corollary 2 *When remanufactured products are sold through the dual channel, the manufacturer's profit is highest. The profit of the ROR model is significantly higher than that of the RO model. As the value of ρ increases, the difference in profit between the two models narrows.*

Based on the above analysis, it can be concluded that the manufacturer's profit is the highest in the dual-channel sales model of remanufactured products. This is illustrated in Fig. 12. For example, when $\beta = 0.3$, the profit difference of $\pi_M^* - \pi_M^{RO*}$ is much greater than $\pi_M^* - \pi_M^{RR*}$. That is, the manufacturer's profit is the lowest in the RO model. As ρ increases, the profit difference of $\pi_M^* - \pi_M^{RO*}$ decreases while that of $\pi_M^* - \pi_M^{RR*}$ increases. As β increases, the difference in profit between $\pi_M^* - \pi_M^{RO*}$ and $\pi_M^* - \pi_M^{RR*}$ gradually decreases, which suggests that the RR model gradually dominates. These trends indicate that reference quality effects hurt the profitability of all three models. In the long term, the sales method of remanufactured products tends to be a mixed model of retail and direct sales.

7 Conclusions

The diversity of product consumption among consumers has an impact on their purchasing behavior. Consumer buying behaviors, such as channel preference, acceptance of remanufactured products, and reference quality effects, influence the pricing

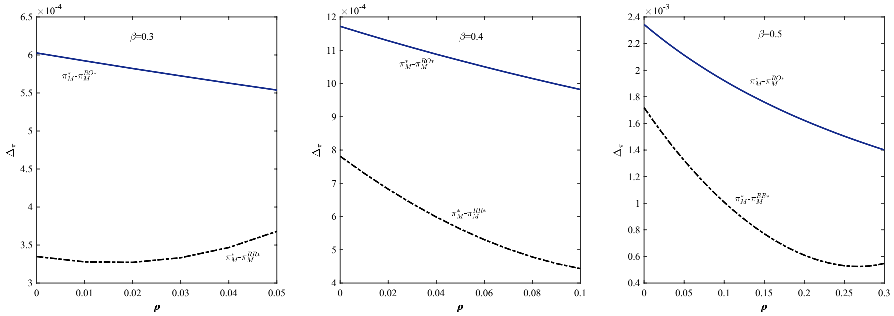

Fig. 12 The effect of ρ on Δ_π

decisions of the manufacturer and retailer on remanufactured products. When consumers purchase these products, they not only consider the acceptability of the remanufactured products, but also compare their quality with new products. They make a purchase decision only after considering all possible factors. The complexity and variability of the business environment and consumer purchasing behavior have created significant challenges for firms when making pricing decisions for new or remanufactured products. It is crucial to consider how firms' pricing decisions would change when consumers have different acceptance of new and remanufactured products in which the impact of the reference quality effect is considered. This study analyses the pricing strategies for remanufactured products which are sold through different channels under the reference quality effect. The main findings and contributions of this study are summarized as follows.

First, there are significant differences in the price and demand of new products in the retail channel under different distribution models. Second, as reference quality parameters increases, the demand and price of remanufactured products decrease. Third, demand for new products in the direct sales channel increases with the reference quality effect parameter and increases even faster with the remanufactured product acceptance. Fourth, the manufacturer's profit depends on the sales mode of remanufactured products, and the manufacturer's profit is negatively related to the reference quality effect. Fifth, the profits of the supply chain are affected by dynamics of channel coefficients and product preference. When the channel preference is high and the remanufactured product acceptance is low, the profit of supply chain members is higher than that when the channel preference is low, and the remanufactured product acceptance is high.

Our research provides two important managerial implications. First, when the reference quality parameter is low, a higher channel preference coefficient within a certain threshold will increase the manufacturer's profit to some extent. Second, when the reference quality parameter is large, and the acceptance of remanufactured products is moderate, the pattern of remanufactured products sold in the direct channel is less profitable and decreases sharply with an increase in the reference quality parameter. When the parameter of the reference quality effect parameter is relatively large, the manufacturer's earnings are relatively high in cases where the remanufactured product is sold in the retail channel. Therefore, the manufacturer can utilize the reference quality effect to adjust the marketing model and improve profitability.

Although this study has presented some useful findings based on realistic assumptions, there are still some limitations. First, owing to the complexity of the model parameters, the model only considers reference quality effects. However, in practice, consumers' purchasing behaviors are usually influenced by both the price and quality of products. In order to make our research more in line with practice, incorporating both the reference price effects and reference quality effects into the dual-channel remanufacturing supply chain decision model will be an interesting topic in future research. Second, to keep consistent with the operations management literature, the study assumes that the consumer utility function follows a uniform distribution. In real life, the consumer utility function may be more complex and variable or even follow a random distribution.

Further research can yield more insights by exploring the possibility of a random distribution of the consumer utility function. Third, for the sake of brevity, this study assumes that the classical dual-channel structure consists of one manufacturer and one retailer. However, in the natural market environment, the structure of one manufacturer and multiple retailers is common, which exists a competitive relationship between retailers. The above content will serve as a subsequent research direction to conduct more in-depth research on related issues so that the research is closer to reality and provides more accurate guidance for the pricing of real enterprises.

Appendix x: Proofs

The following proofs are derived using constraint conditions, the backward induction, and differential partial derivatives methods.

Proof of Lemma 1

Taking Eqs. (6) into the Eqs. (4), the first-order derivative of π_M^{RO} with respect to w_n^{ro}, p_o^{ro}, and p_r^{ro} are respectively

$$\frac{\partial \pi_M^{RO}}{\partial w_n^{ro}} = \frac{\lambda + 2w_n^{ro} - 2p_o^{ro}}{2(\lambda - 1)} \tag{x1}$$

$$\frac{\partial \pi_M^{RO}}{\partial p_o^{ro}} = \frac{\rho(1-\lambda\beta)\left(2w_n^{ro} - 2p_o^{ro} + 1 - \lambda\right) - 2(2-\lambda-\lambda\beta)p_o^{ro} + 4(1-\lambda)p_r^{ro} + \lambda + 2\lambda(1-\beta)w_n^{ro} - \lambda\beta - \lambda^2(1-\beta) + 2(1-\lambda)\left(c_m - c_r\right)}{2(\lambda-1)(\rho(\lambda\beta-1) - \lambda(1-\beta))} \tag{x2}$$

$$\frac{\partial \pi_M^{RO}}{\partial p_r^{ro}} = \frac{\left(2p_r^{ro} - c_r + \beta(1+\rho)\left(c_m - 2p_o^{ro}\right)\right)\lambda + \rho\left(2p_o^{ro} - c_m\right)}{(\beta(1+\rho)-1)\beta(1+\rho)\lambda^2 + (\rho - 2\beta\rho(1+\rho))\lambda + \rho^2} \tag{x3}$$

From the Eqs. (x1)–(x3), we get $\frac{\partial^2(\pi_M^{RO})}{\partial w_n^{ro}\partial w_n^{ro}} = \frac{1}{\lambda-1}$, $\frac{\partial^2(\pi_M^{RO})}{\partial w_n^{ro}\partial p_o^{ro}} = \frac{-1}{\lambda-1}$, $\frac{\partial^2(\pi_M^{RO})}{\partial w_n^{ro}\partial p_r^{ro}} = 0$, $\frac{\partial^2(\pi_M^{RO})}{\partial p_o^{ro}\partial w_n^{ro}} = \frac{-1}{\lambda-1}$, $\frac{\partial^2(\pi_M^{RO})}{\partial p_o^{ro}\partial p_o^{ro}} = \frac{(\rho(\lambda\beta-1)+\lambda(\beta-1))+2(\lambda-1)}{(\lambda-1)(\rho(\lambda\beta-1)+\lambda(\beta-1))}$, $\frac{\partial^2(\pi_M^{RO})}{\partial p_o^{ro}\partial p_r^{ro}} = \frac{-2}{\rho(\lambda\beta-1)+\lambda(\beta-1)}$, $\frac{\partial^2(\pi_M^{RO})}{\partial p_r^{ro}\partial w_n^{ro}} = 0$, $\frac{\partial^2(\pi_M^{RO})}{\partial p_r^{ro}\partial p_o^{ro}} = \frac{-2}{\rho(\lambda\beta-1)+\lambda(\beta-1)}$, $\frac{\partial^2(\pi_M^{RO})}{\partial p_r^{ro}\partial p_r^{ro}} = \frac{2\lambda}{(\rho(\lambda\beta-1)+\lambda(\beta-1))(\lambda\beta+\rho(\lambda\beta-1))}$. The Hessian matrix with respect to π_M^{RO} is

$$H_M^{RO} = \begin{bmatrix} \frac{1}{\lambda-1} & \frac{-1}{\lambda-1} & 0 \\ \frac{-1}{\lambda-1} & \frac{(\rho(\lambda\beta-1)+\lambda(\beta-1))+2(\lambda-1)}{(\lambda-1)(\rho(\lambda\beta-1)+\lambda(\beta-1))} & \frac{-2}{\rho(\lambda\beta-1)+\lambda(\beta-1)} \\ 0 & \frac{-2}{\rho(\lambda\beta-1)+\lambda(\beta-1)} & \frac{2\lambda}{(\rho(\lambda\beta-1)+\lambda(\beta-1))(\lambda\beta+\rho(\lambda\beta-1))} \end{bmatrix}$$

Note that $\frac{1}{\lambda-1} < 0$, $\begin{vmatrix} \frac{1}{\lambda-1} & \frac{-1}{\lambda-1} \\ \frac{-1}{\lambda-1} & \frac{(\rho(\lambda\beta-1)+\lambda(\beta-1))+2(\lambda-1)}{(\lambda-1)(\rho(\lambda\beta-1)+\lambda(\beta-1))} \end{vmatrix} = \frac{-2}{(\lambda-1)(\lambda(1-\beta)+\rho(1-\lambda\beta))} > 0$, $\left|H_M^{RO}\right| = \frac{4}{(\lambda-1)(\lambda\beta-\rho(1-\lambda\beta))(\lambda-(\lambda\beta-\rho(1-\lambda\beta))} < 0$, which indicates that H_M^{RO} is a negative definite matrix. Hence, π_M^{RO} is concave in w_n^{ro}, p_o^{ro} and p_r^{ro}. Using first-order condition, let $\frac{\partial\pi_M^{RO}}{\partial w_n^{ro}} = 0$, $\frac{\partial\pi_M^{RO}}{\partial p_o^{ro}} = 0$ and $\frac{\partial\pi_M^{RO}}{\partial p_r^{ro}} = 0$, the supply chain members' optimal pricing decisions under model RO can be solved as follows: $w_n^{ro*} = \frac{1+c_m}{2}$, $p_o^{ro*} = \frac{\lambda+c_m}{2}$, $p_r^{ro*} = \frac{(1+\rho)\lambda\beta+c_r-\rho}{2}$. Then, substituting w_n^{ro*} and p_o^{ro*} into $p_n^{ro*} = \frac{1-\lambda+w_n^{ro}+p_o^{ro}}{2}$, we have $p_n^{ro*} = \frac{2c_m-\lambda+3}{4}$. Thus, all the optimal results are yielded. Finally, substituting above optimal pricing decisions into π_R^{RO*} and π_M^{RO*}, we have $\pi_R^{RO*} = \frac{1-\lambda}{16}$,

$$\pi_M^{RO*} = \frac{\begin{array}{c}(\beta(1+\rho)-1)\beta(1+\rho)\lambda^3 + \left(\rho-\beta+\beta^2(1+\rho)^2+4\beta c_m(1+\rho)(1-\beta(1+\rho))-\beta\rho(3+2\rho)\right)\lambda^2 + \\ \left(\rho(1+\rho)(1-2\beta)-2\left(2\rho+\beta(1+\rho)\left(c_m-4\rho-2c_r\right)\right)c_m-2c_r^2\right)\lambda+2\rho\left(c_m-2\rho-2c_r\right)c_m+\rho^2\end{array}}{8\left((\beta(1+\rho)-1)\beta(1+\rho)\lambda^2+\rho(1-2\beta(1+\rho))\lambda+\rho^2\right)}.$$

Proof of Proposition 1

Combining Eqs. (1)–(3) and using partial differential theory, we can obtain Proposition 1.

Proof of Lemma 2

Using differential partial derivatives and backward induction to solve the optimization problem in Eqs. (7), the first order derivative of π_R^{RR} with respect to p_n^{rr}, p_r^{rr} can be obtained as follows:

$$\frac{\partial\pi_R^{RR}}{\partial p_n^{rr}} = \frac{\left(2p_n^{rr}-p_o^{rr}-w_n^{rr}\right)+\lambda-1}{\lambda-1} \tag{x4}$$

$$\frac{\partial\pi_R^{RR}}{\partial p_r^{rr}} = \frac{(1-\beta)\rho p_o^{rr}+2\lambda p_r^{rr}-\beta p_o^{rr}-\lambda w_r^{rr}}{(1-\beta)^2\rho^2+(\lambda-\beta(2+\lambda-2\beta))\rho+\beta(\beta-\lambda)} \tag{x5}$$

From the Eqs. (x4)–(x5), we have $\frac{\partial^2(\pi_R^{RR})}{\partial p_n^{rr}\partial p_n^{rr}} = \frac{1}{\lambda-1}$, $\frac{\partial^2(\pi_R^{RR})}{\partial p_n^{rr}\partial p_r^{rr}} = 0$, $\frac{\partial^2(\pi_R^{RR})}{\partial p_r^{rr}\partial p_n^{rr}} = 0$, $\frac{\partial^2(\pi_R^{RR})}{\partial p_r^{rr}\partial p_r^{rr}} = \frac{\lambda}{2(\beta-\lambda+\rho(\beta-1))(\beta+\rho(\beta-1))}$. The Hessian matrix with respect to π_R^{RR} is $H_R^{RR} = \begin{bmatrix} \frac{1}{\lambda-1} & 0 \\ 0 & \frac{\lambda}{2(\beta-\lambda+\rho(\beta-1))(\beta+\rho(\beta-1))} \end{bmatrix}$. Note that $\frac{1}{\lambda-1} < 0$, $\left|H_R^{RR}\right| = \frac{\lambda}{2(\lambda-1)(\beta-\lambda+\rho(\beta-1))(\beta+\rho(\beta-1))} < 0$, which indicates that H_M^{RO} is a negative definite matrix. Hence, π_R^{RR} is concave in p_n^{rr} and p_r^{rr}. Using first-order condition, let $\frac{\partial\pi_R^{RR}}{\partial p_n^{rr}} = 0$ and $\frac{\partial\pi_R^{RR}}{\partial p_r^{rr}} = 0$, we have

$$p_n^{rr} = \frac{p_o^{rr} + w_n^{rr} - \lambda + 1}{2} \tag{x6}$$

$$p_r^{rr} = \frac{(\beta - \rho + \beta\rho)p_o^{rr} + \lambda w_r^{rr}}{2\lambda} \tag{x7}$$

Substituting Eqs. (x6) and (x7) into Eqs. (10), taking partial derivatives of π_M^{RR} with respect to w_n^{rr}, w_r^{rr}, and p_o^{rr}, we get

$$\frac{\partial \pi_M^{RR}}{\partial w_n^{rr}} = \frac{\lambda + 2w_n^{rr} - 2p_o^{rr} - 1}{2(\lambda - 1)} \tag{x8}$$

$$\frac{\partial \pi_M^{RR}}{\partial w_r^{rr}} = \frac{\left(2w_r^{rr} - c_r\right)\lambda + \left(2p_o^{rr} - c_m\right)(\rho - \beta(1+\rho))}{2\left((\rho - \beta(1+\rho))\lambda + \beta(1+\rho)(\beta(1+\rho) - 2\rho) + \rho^2\right)} \tag{x9}$$

$$\frac{\partial \pi_M^{RR}}{\partial p_o^{rr}} = \frac{\begin{array}{c}-\lambda^3 + \left(c_r - 2c_m + 2p_o^{rr} + 2w_n^{rr} - 2w_r^{rr} + \beta - \rho + \beta\rho + 1\right)\lambda^2 + \\ \left(2c_m - c_r - 4p_o^{rr} + 2w_r^{rr} + \left(2w_n^{rr} - c_m + 1\right)(\rho - \beta - \beta\rho)\right)\lambda + \left(c_m - 2p_o^{rr}\right)(\rho - \beta - \beta\rho)\end{array}}{2\left(-\lambda^3 + (\beta(1+\rho) - \rho + 1)\lambda^2 + (\rho - \beta(1+\rho))\lambda\right)} \tag{x10}$$

From Eqs. (x8)–(x10), we get that $\frac{\partial^2(\pi_M^{RR})}{\partial w_n^{rr}\partial w_n^{rr}} = \frac{1}{\lambda-1}$, $\frac{\partial^2(\pi_M^{RR})}{\partial w_n^{rr}\partial w_r^{rr}} = 0$, $\frac{\partial^2(\pi_M^{RR})}{\partial w_n^{rr}\partial p_o^{rr}} = \frac{-1}{\lambda-1}$, $\frac{\partial^2(\pi_M^{RR})}{\partial w_r^{rr}\partial w_n^{rr}} = 0$, $\frac{\partial^2(\pi_M^{RR})}{\partial w_r^{rr}\partial w_r^{rr}} = \frac{\lambda}{(\rho-\beta(1+\rho))\lambda+\beta(1+\rho)(\beta(1+\rho)-2\rho)+\rho^2}$, $\frac{\partial^2(\pi_M^{RR})}{\partial w_r^{rr}\partial p_o^{rr}} = \frac{-1}{\beta-\lambda+\rho(\beta-1)}$, $\frac{\partial^2(\pi_M^{RR})}{\partial p_o^{rr}\partial w_n^{rr}} = \frac{-1}{\lambda-1}$, $\frac{\partial^2(\pi_M^{RR})}{\partial p_o^{rr}\partial w_r^{rr}} = \frac{-1}{\beta-\lambda+\rho(\beta-1)}$, $\frac{\partial^2(\pi_M^{RR})}{\partial p_o^{rr}\partial p_o^{rr}} = \frac{\lambda^2-2\lambda+\beta-\rho+\beta\rho}{-\lambda^3+(\beta-\rho+\beta\rho+1)\lambda^2+(\rho-\beta-\beta\rho)\lambda}$. Then, the Hessian matrix with respect to π_M^{RR} is $H_M^{RR} = \begin{bmatrix} \frac{1}{\lambda-1} & 0 & \frac{-1}{\lambda-1} \\ 0 & \frac{\lambda}{(\rho-\beta(1+\rho))\lambda+\beta(1+\rho)(\beta(1+\rho)-2\rho)+\rho^2} & \frac{-1}{\beta-\lambda+\rho(\beta-1)} \\ \frac{-1}{\lambda-1} & \frac{-1}{\beta-\lambda+\rho(\beta-1)} & \frac{\lambda^2-2\lambda+\beta-\rho+\beta\rho}{-\lambda^3+(\beta-\rho+\beta\rho+1)\lambda^2+(\rho-\beta-\beta\rho)\lambda} \end{bmatrix}$. Note that $\frac{1}{\lambda-1} < 0$, $\begin{vmatrix} \frac{1}{\lambda-1} & 0 \\ 0 & \frac{\lambda}{(\rho-\beta(1+\rho))\lambda+\beta(1+\rho)(\beta(1+\rho)-2\rho)+\rho^2} \end{vmatrix} = \frac{-\lambda}{(\lambda-1)(\beta-\rho+\beta\rho)(\lambda-\beta+\rho-\beta\rho)} > 0$, $\left|H_M^{RR}\right| = \frac{2}{(\lambda-1)(\beta-\rho+\beta\rho)(\lambda-\beta+\rho-\beta\rho)} < 0$, which indicates that H_M^{RR} is a negative definite matrix. Hence, π_M^{RR} is concave in w_n^{rr}, w_r^{rr} and p_o^{rr}. Let $\frac{\partial \pi_M^{RR}}{\partial w_n^{rr}} = 0$, $\frac{\partial \pi_M^{RR}}{\partial w_r^{rr}} = 0$ and $\frac{\partial \pi_M^{RR}}{\partial p_o^{rr}} = 0$, we have $w_n^{rr*} = \frac{1+c_m}{2}$, $w_r^{rr*} = \frac{c_r+\beta-\rho+\beta\rho}{2}$ and $p_o^{rr*} = \frac{\lambda+c_m}{2}$. Then, substituting w_n^{rr*}, w_r^{rr*} and p_o^{rr*} into p_n^{rr} and p_r^{rr}, we have $p_n^{rr*} = \frac{2c_m-\lambda+3}{4}$ and $p_r^{rr*} = \frac{(c_r+2\beta-2\rho+2\beta\rho)\lambda+(\beta-\rho+\beta\rho)c_m}{4\lambda}$. Finally, substituting above optimal pricing decisions into π_M^{RR*} and π_R^{RR*}, we have

$$\pi_M^{RR*}=\frac{\begin{array}{c}(\rho-\beta(1+\rho))\lambda^3-\left(\beta-\rho-\rho^2(1-\beta)^2+4c_m(\rho-\beta(1+\rho))+\beta\rho(3-2\beta)+c_r^2-\rho^2\right)\lambda^2-\\ \left(2\beta\rho-\rho^2(1-\beta)^2+2c_m\left(2\rho(1+\rho)\beta^2+2\rho^2(1-2\beta)+(\rho-\beta(1+\rho))c_r-4\beta\rho\right)+2c_m^2(\beta-\rho+\beta\rho)-(1+2\rho)\beta^2\right)\lambda+\\ (\beta(1+\rho)(\beta(1+\rho)-2\rho)+\rho^2)c_m^2\end{array}}{-8\lambda((\beta(1+\rho)-\rho)\lambda-\beta(1+\rho)(\beta(1+\rho)-2\rho)-\rho^2)}$$

and
$$\pi_R^{RR*}=\frac{\begin{array}{c}(\beta(1+\rho)-\rho)\lambda^3-\left(c_r^2+\rho^2(1-\beta)^2+(1+2\rho)\beta^2-(1+\beta)\rho+\beta\right)\lambda^2-\\ \left(2\beta\rho-(1-\beta)^2\rho^2-(1+2\rho)\beta^2+2(\rho-\beta-\beta\rho)c_mc_r\right)\lambda-c_m^2\left((1+\rho)(\beta^2(1+\rho)-2\beta\rho\right)+\rho^2)\end{array}}{-16\left((\beta(1+\rho)-\rho)\lambda^2+\left(-\beta^2(1+\rho)^2+\rho(2\beta(1+\rho)-\rho)\right)\lambda\right)}$$

Proof of Proposition 2

Combining demand functions and Lemma 2, by applying partial differential theory, the result of Proposition 2 is obtained.

Proof of Proposition 3

Combining the constraints and Lemma 1 and Lemma 2 yields the result.

Proof of Proposition 4

Note that, $p_r^{ro*}-p_r^{rr*}=\frac{\lambda\left((2\lambda-2\rho+2\lambda\rho-2)\beta+c_r\right)-(\beta-\rho+\beta\rho)c_m}{4\lambda}$. When $2(\lambda-1)\lambda\beta+2(\lambda-1)\lambda\beta\rho+\lambda c_r-(\beta-\rho+\beta\rho)c_m>0$, we have $p_r^{ro*}>p_r^{rr*}$, that is, $\lambda\beta\rho<\frac{(\beta-\rho+\beta\rho)c_m-2(\lambda-1)\lambda\beta+\lambda c_r}{2(\lambda-1)}$, if $\lambda\beta\rho>\frac{(\beta-\rho+\beta\rho)c_m-2(\lambda-1)\lambda\beta+\lambda c_r}{2(\lambda-1)}$, then $p_r^{ro*}<p_r^{rr*}$.

Note that, $q_o^{ro*}-q_o^{rr*}=\frac{\left(\lambda\rho+\rho^2+\lambda\beta^2(1+\rho)^2-\beta(1+\rho)\left(\rho-\lambda+\lambda\rho+2\lambda^2\right)\right)c_m+\lambda(\lambda+\rho+\beta(\lambda-2\rho+\lambda\rho-2))c_r}{4\lambda(\lambda-\lambda\beta+\rho(1-\lambda\beta))(\lambda-\beta+\rho(1-\beta))}$. By the constraint $\lambda-\lambda\beta+\rho(1-\lambda\beta)>0$, we get $\lambda-\beta+\rho(1-\beta)>0$, $4\lambda(\lambda-\lambda\beta+\rho(1-\lambda\beta))(\lambda-\beta+\rho(1-\beta))>0$, thus, when $\left(\lambda\rho+\rho^2+\lambda\beta^2(1+\rho)^2-\beta(1+\rho)\left(\rho-\lambda+\lambda\rho+2\lambda^2\right)\right)c_m+\lambda(\lambda+\rho+\beta(\lambda-2\rho+\lambda\rho-2))c_r>0$, we have $q_o^{ro*}>q_o^{rr*}$, that is, if $\left((1-\beta)\rho^2+(\lambda-\beta)\rho+\lambda\beta(\beta-2\lambda+1)\right)c_m+\lambda(\lambda+\rho+\beta(\lambda+\lambda\rho-2))c_r+\left((\beta(2+\rho)-\rho-2\lambda)c_m+(\lambda-2)c_r\right)\lambda\beta\rho>0$, then $q_o^{ro*}>q_o^{rr*}$. In other words, when $\omega>0$, that is, if $\lambda\beta\rho>\frac{-\left((1-\beta)\rho^2+(\lambda-\beta)\rho+\lambda\beta(\beta-2\lambda+1)\right)c_m-\lambda(\lambda+\rho+\beta(\lambda+\lambda\rho-2))c_r}{(\beta(2+\rho)-\rho-2\lambda)c_m+(\lambda-2)c_r}$, then $q_o^{ro*}>q_o^{rr*}$. When $\omega<0$, that is, if $\lambda\beta\rho<\frac{-\left((1-\beta)\rho^2+(\lambda-\beta)\rho+\lambda\beta(\beta-2\lambda+1)\right)c_m-\lambda(\lambda+\rho+\beta(\lambda+\lambda\rho-2))c_r}{(\beta(2+\rho)-\rho-2\lambda)c_m+(\lambda-2)c_r}$, then $q_o^{ro*}>q_o^{rr*}$.

Note that,

$$q_r^{ro*}-q_r^{rr*}=\frac{\begin{array}{c}-(\beta-\rho+\beta\rho)(\lambda\beta-\rho+\lambda\beta\rho)(\lambda-2\beta+\rho+\lambda\beta-2\beta\rho+\lambda\beta\rho)c_m-\\ \lambda c_r\left((-\beta(1+\rho)(\beta+\beta\rho-1))\lambda^2+\left(\left(2\rho^2-2\right)\beta+\rho\right)\lambda+\left(2\rho^2+4\rho+2\right)\beta^2-4\beta\rho(1+\rho)+\rho^2\right)\end{array}}{-4(\lambda\beta(1+\rho)-\rho)(\beta-\rho+\beta\rho)(\lambda-\lambda\beta+\rho(1-\lambda\beta))(\lambda-\beta+\rho(1-\beta))}$$

.

Because $(\lambda\beta(1+\rho)-\rho)(\beta-\rho+\beta\rho)(\lambda-\lambda\beta+\rho(1-\lambda\beta))(\lambda-\beta+\rho(1-\beta))>0$, if $-(\beta-\rho+\beta\rho)(\lambda\beta-\rho+\lambda\beta\rho)(\lambda-2\beta+\rho+\lambda\beta-2\beta\rho+\lambda\beta\rho)c_m-\lambda c_r(-\beta(1+\rho)(\beta+\beta\rho-1)\lambda^2+\left(\left(2\rho^2-2\right)\beta+\rho\right)\lambda+\left(2\rho^2+4\rho+2\right)\beta^2-4\beta\rho(1+\rho)+\rho^2)<0$, then $q_r^{ro*} > q_r^{rr*}$, that is, $-(\lambda\beta\rho)^2(\beta-1)(1+\rho)c_m + \lambda\beta\rho\mathrm{B} + \mathrm{C} < 0$, where

$$\mathrm{B} = c_m(\beta(1-2\beta+\lambda\beta) - (1+\beta+\beta\rho) + \rho(1+\rho) + (\beta-1-\rho+\beta\rho)(\lambda-2\beta+\rho+\lambda\beta-2\beta\rho) + \beta\rho(1+\beta+\beta\rho)) - c_r\left(-(\beta+\beta+\rho\beta-1)\lambda^2 + 2\rho\lambda + 2\rho\beta + 4(\beta-1-\rho)\right)$$

$$\mathrm{C} = -c_m\lambda\beta^2(\lambda-2\beta+\lambda\beta) - \rho\beta(2\beta+\rho-2\beta\rho) + \rho^2(\lambda-2\beta+\rho-2\beta\rho) + \beta\rho(\beta\rho-\rho)(-2\beta+\rho-2\beta\rho) - \lambda c_r\left(-\beta(\beta-1)\lambda^2 - 2\beta\lambda + \rho\lambda + 2\beta^2 + \rho^2\right),$$

. To be specific, when $\mathrm{B}^2 + 4\mathrm{C}(\beta-1)(1+\rho)c_m > 0$, if $\lambda\beta\rho \in \left(\frac{-\mathrm{B}-\sqrt{\mathrm{B}^2+4\mathrm{C}(\beta-1)(1+\rho)c_m}}{-2(\beta-1)(1+\rho)c_m}, \frac{-\mathrm{B}+\sqrt{\mathrm{B}^2+4\mathrm{C}(\beta-1)(1+\rho)c_m}}{-2(\beta-1)(1+\rho)c_m}\right)$, then $q_r^{ro*} > q_r^{rr*}$. When $\mathrm{B}^2 + 4\mathrm{C}(\beta-1)(1+\rho)c_m > 0$, $\lambda\beta\rho < \frac{-\mathrm{B}-\sqrt{\mathrm{B}^2+4\mathrm{C}(\beta-1)(1+\rho)c_m}}{-2(\beta-1)(1+\rho)c_m}$ or $\lambda\beta\rho > \frac{-\mathrm{B}+\sqrt{\mathrm{B}^2+4\mathrm{C}(\beta-1)(1+\rho)c_m}}{-2(\beta-1)(1+\rho)c_m}$, $q_r^{ro*} < q_r^{rr*}$. When $\mathrm{B}^2 + 4\mathrm{C}(\beta-1)(1+\rho)c_m < 0$, $q_r^{ro*} < q_r^{rr*}$.

Proof of Corollary 1

Let $h = \rho - \beta + \beta^2(1+\rho)^2 + 4\beta c_m(1+\rho)(1-\beta(1+\rho)) - \beta\rho(3+2\rho)$,
$\kappa = \rho(1+\rho)(1-2\beta) - 2\left(2\rho + \beta(1+\rho)\left(c_m - 4\rho - 2c_r\right)\right)c_m - 2c_r^2$,
$\vartheta = 8\left((\beta(1+\rho)-1)\beta(1+\rho)\lambda^2 + \rho(1-2\beta(1+\rho))\lambda + \rho^2\right)$.
$\ell = \beta - \rho - \rho^2(1-\beta)^2 + 4c_m(\rho - \beta(1+\rho)) + \beta\rho(3-2\beta) + c_r^2 - \rho^2$,

$$\nu = 2\beta\rho - \rho^2(1-\beta)^2 + 2c_m\left(2\rho(1+\rho)\beta^2 + 2\rho^2(1-2\beta) + (\rho-\beta(1+\rho))c_r - 4\beta\rho\right) + 2c_m^2(\beta-\rho+\beta\rho) - (1+2\rho)\beta^2,$$

$\sigma = -8\lambda\left((\beta(1+\rho)-\rho)\lambda - \beta(1+\rho)(\beta(1+\rho)-2\rho) - \rho^2\right)$. From $\overline{M}^* = \pi_M^{RR*} - \pi_M^{RR*}$, the result is derived.

Proof of Proposition 5

The proof process is similar to Lemma 2 and will not be repeated. Where

$$\mu = \left(-4(1+\rho)^2\beta^2 + 4(\rho+1)\beta c_m + \left(-\rho^3 - 3\rho^2 - 3\rho - 1\right)\beta^3 + \left(\rho^3 + 4\rho^2 + 5\rho + 2\right)\beta^2 + \left(-3\rho^2 - 4\rho - 1\right)\beta + \rho\right)$$

$$\varphi = \left(((1+\rho)\beta - 2)(1+\rho)\beta c_m^2 + 2\left(-(1+\rho)\beta((1+\rho)\beta - 2)c_r + 2\left(\rho^3 + 3\rho^2 + 3\rho + 1\right)\beta^2(\beta-1) + 2\rho(3(1+\rho)\beta - 1)\right)c_m + \left((1+\rho)^2\beta^2 - 2\right)c_r^2 + \left(-\rho^3 - 3\rho^2 - 3\rho - 1\right)\beta^3 + \left(3\rho^3 + 7\rho^2 + 5\rho + 1\right)\beta^2 + \left(-2\rho^3 - 6\rho^2 - 4\rho\right)\beta + 2\rho^2 + \rho\right),$$

$$\begin{aligned}\varsigma = &\left(\left(\beta^2 - 3\beta\right)\rho^2 + \left(2\beta^2 - 3\beta + 2\right)\rho + \beta^2\right)c_m^2 \\ &+ \left(\left(-2\beta^2\rho^2 - 4\rho\beta^2 - 2\beta^2 + 6\beta\rho^2 + 6\beta\rho - 4\rho\right)c_r - 8\beta^2\rho \\ &(1+\rho)^2 + 4\beta\rho\left(2\rho^2 + 3\rho + 1\right) - 8\rho^2\right)c_m + \left(-\beta^2(1+\rho)^2 - \beta\rho^2 + \beta\rho + 2\beta - 2\rho\right)c_r^2 \\ &+ \left(2\beta^2 - 3\beta + 1\right)\rho^3 + 2\left(2\beta^2 - 2\beta + 1\right)\rho^2 + 2\beta(\beta - 1)\rho\end{aligned},$$

$$\begin{aligned}\varrho = &\left(2\rho^2 - \beta\rho^2 - \beta\rho\right)c_m^2 + 2\rho\left((\beta + \beta\rho - 2\rho)c_r + 2\beta\rho(1+\rho) - 2\rho^2\right)c_m \\ &+ \left(\beta\rho^2 + \beta\rho\right)c_r^2 + \rho^2(\rho - \beta\rho - \beta)\end{aligned},$$

Proof of Corollary 2

Combining Propositions 2, 3 and 5, Corollary 2 is proven.

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Declarations

Conflict of interest No potential of interest was reported by the authors.

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