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Managing manufacturer encroachment and product conflicts in a closed-loop supply chain: The case of information asymmetry☆

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ABSTRACT

The implementation of direct channels allows manufacturers to distribute new and remanufactured products through separate channels. This prompts manufacturers to carefully consider which products to channel directly. In the remanufacturing process, manufacturers often delegate the collection process to retailers. However, only retailers know their own collection efficiency information, whereas manufacturers can only know its probability distribution. To explore the choice of encroachment channel strategy under information asymmetry, we constructed a dual-channel closed-loop supply chain model, in which the manufacturer can design non-linear contracts to incentivize the retailer to choose contracts that align with its capabilities, ultimately maximizing its profit. We discuss the case of manufacturer dual product encroachment and the impact of consumer channel preferences in the extended model. The findings reveal that, contrary to previous studies, the profits of low-type manufacturers are not always reduced, and the effect of information asymmetry may be opposite. Moreover, information asymmetry can be detrimental to high-type retailers. The optimal channel choice is affected by factors such as remanufacturing cost, consumer channel preference, information asymmetry, and reserved profit differences. Manufacturers and retailers can achieve a win-win situation through new product encroachment, which can also counteract the negative effects of information asymmetry and enhance consumer surplus.

1. Introduction

As e-commerce has advanced recently, a growing number of manufacturers have embraced multi-channel strategies for product distribution. This trend involves manufacturers venturing into direct sales channels, entering wholesale markets, and competing with retailers—a phenomenon commonly known as manufacturer encroachment[1]. Examples of manufacturer encroachment abound. For instance, HP sells computers both through its official website and the eBay platform, while Apple and Microsoft sell their products through third-party retail stores as well as their own stores or websites [1]. The introduction of direct channels has proven beneficial for manufacturers simultaneously offering distinct products. Historically, before the advent of direct channels, several manufacturers engaged in remanufacturing and retailing remanufactured products, with notable examples including companies like Kodak and Dell ([2,3]). The disparity in consumer preference between remanufactured and new products stems from perceived quality differences. Yet, remanufactured products offer cost advantages and greater price competitiveness compared to new ones [1]. Consequently, manufacturers offering both types of products face the challenge of mitigating competition between the two.

The growth of direct channels offers manufacturers a powerful way to seperate the sales markets for new and remanufactured products, mitigating competition between them [4]. For example, Apple

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[1] The growing influence of the internet on consumer and business purchasing behaviors has created unprecedented opportunities for manufacturers to easily and broadly access to customers. Encroachment occurs when upstream manufacturers in the supply chain establish direct-to-consumer online sales channels, such as online stores, catalogs, or factory outlets, in addition to selling their products through traditional offline channels [4,55]. For example, electronics manufacturerslike Apple, Sony, and Microsoft sell their products both through third-party e-tailers as well as through their own stores or websites. Similarly, apparel and fashion accessory brands may sell through independent retailers as well as their own factory outlets.

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strategically sells remanufactured products through its official websites and third-party platforms to minimize competition with new products sold by downstream retailers [5]. In scholarly literature, Gan et al. [6] delved into the pricing dilemma faced by manufacturers separating sales of differentiated products through retail channels and direct channels. Their findings demonstrate that the adoption of separate channels is beneficial to the supply chain. Furthermore, Yan et al. [7] explored manufacturers' strategies for selling remanufactured products separately from new products through direct channels or third-party channels. Similarly, Zhang et al. [1] investigated manufacturers' choices in opening direct channels and how they sell green and ordinary products through these channels alongside retail channels. While direct channels can alleviate competition between products, manufacturers still need to consider how they distribute their products, whether through encroaching with new or remanufactured products.

Beyond product encroachment, manufacturers must also manage the production of remanufactured products, as profits in different channel structures derive from both new and remanufactured goods. Given the cannibalization effect between these products across dual channels, manufacturers need to regulate remanufactured production under different encroachment strategies to minimize its impact on new product sale. Remanufacturing processes typically commence with the retrieval of used products from consumers. Guo et al. [8] argued that the effectiveness of collection efforts increases when the collection distance from consumers is minimized. For reasons of cost and economies of scale, manufacturers commonly delegate this process to retailers in practice. This choice is justified by the proximity of retailers to the demand side of the market, enabling them to conveniently collect old products from consumers. Savaskan et al. [9] found that among the three product recycling methods, manufacturers prefer to recycle second-hand products through retailers. Hong et al. [10] demonstrated that this conclusion remains valid even when accounting for advertising competition between retailers and manufacturers. In reality, numerous manufacturers opt for product collection through retailers. A notable example is Kodak, where the raw materials for the production of new cameras are partly derived from the retailer's disposable cameras [11]. Apple also collaborates with retailers to provide old phone collection services, allowing consumers to return old phones to retailers in exchange for discounts or rewards.

The involvement of the retailer in remanufacturing complicates the manufacturer's encroachment strategy because the manufacturer needs to pay a transfer fee tied to the retailer's collection efficiency. However, retailers may conceal their true efficiency to maximize profits, as higher collection efficiency translates to lowers costs [12,13]. On the one hand, manufacturers offer retailers a wholesale price for remanufactured products based on production and collection costs. In scenarios where production costs are fixed, as collection costs increase, Manufacturers may take measures to incentivize retailers to participate in collection process, such as lowering the wholesale price of the product, increasing transfer payments, etc. Consequently, when retailers have high collection efficiency or low collection costs, they may feign lower efficiency to secure a lower wholesale price. On the other hand, when manufacturers encroach through remanufactured products, retailers selling new products may reluctant to collect too many used items due to the cannibalizing effect between new and remanufactured products. For retailers with high collection efficiency, this creates an incentive to underreport efficiency and limit remanufactured production. Without knowing the retailer's actual collection efficiency, manufacturers struggle to set optimal wholesale prices and quantities for remanufactured products, which directly affects their encroachment strategy. In other words, the concealment of retailer collection efficiency poses a significant challenge for manufacturers in implementating effective encroachment strategies and maximizing profits: how manufacturers can acquire information on retailer collection efficiency through contract negotiations to make informed decisions.

To make better decisions, manufacturers have a reason to obtain information on retailer collection efficiency [14]. According to existing research, manufacturers can effectively distinguish private information by designing asymmetric pricing contracts [15,16,17]. Manufacturers can provide separate contracts to different types of retailers. When retailers select a contract from the non-linear pricing contract, manufacturers can infer their actual collection efficiency based on the selected contract. While existing dual-channel closed-loop supply chain models have examined the information asymmetry problem of contract design against the backdrop of manufacturer encroachment, most have primarily focused on uncertainty in market demand and assumed homogeneous product quality [18,19]. The impact of cost information asymmetry caused by differentiated product sales on manufacturer encroachment is not considered, nor are the different encroachment channels of manufacturers discussed. In addition, most scholars assumed that products are homogeneous or that products with different characteristics are sold by different channels when studying encroachment. Based on the observation that in real life, most manufacturers may simultaneously sell differentiated products in the direct channel, we explore this situation and analyze the profits in the extended model. To solve this problem, we propose a dual-channel closed-loop supply chain model. Faced with the introduction of direct channels, the manufacturer can decide not to encroach or encroach with remanufactured products or new products. The retailer undertakes the task of recycling old products from consumers, but the manufacturer does not have information about their actual collection efficiency. To address this informational asymmetry, non-linear contracts are employed as incentives for the retailer to disclose its collection efficiency. Specifically, the questions that our article aims to address are as follows:

(1) Should the manufacturer choose to encroach, and if so, what channel should it choose for encroachment?
(2) How does information asymmetry affect the strategic choice of the encroachment channel structure?
(3) How do encroachment strategies and information asymmetry impact the manufacturer's equilibrium decision and consumer surplus?

This study's contribution lies in the comprehensive consideration of factors such as information asymmetry, manufacturer encroachment, and outsourcing of collection in contract design. This paper delves into how encroachment strategy of the manufacturer is influenced by the asymmetric cost information, it also complements the study of simultaneous sales of differentiated products through the online channel. Furthermore, this paper also deeply analyzes the influence of information asymmetry and manufacturer encroachment on manufacturer equilibrium strategy. This expansion broadens the current research on the existing encroachment channels.

The rest of the article is shown below. Section 2 reviews the existing related literature and outlines our contributions to the existing body of work. In Section 3, we describe the model in detail. The equilibrium strategies of manufacturers under information symmetry and asymmetry are presented in Sections 4 and 5, respectively. Section 6 analyzes the comparison of equilibrium strategies in different situations, examines the effects of encroachment strategies and information asymmetry on consumer surplus, and studies the case of selling differentiated products simultaneously by an extended model. Section 7 summarizes the paper. The online supplement provides all the proofs.

2. Literature review

Our study is related to three mainstream literatures: (1) Manufacturer encroachment, (2) Product recovery in closed-loop supply chains, and (3) Information asymmetry in supply chains.

2.1. Manufacturer encroachment

In existing research on manufacturer encroachment, the impact of product differentiation and channel differentiation has been a prominent and extensively explored topic. In their study on product differentiation, Li et al. [20] investigated how substitutable green product differentiation affects manufacturers' channel selection, considering consumers' green consciousness. Similarly, Raza et al. [21] analyzed product greenness by exploring how manufacturers sell both green and convential products through retailers and online channels. They proposed a model that enables manufacturers determine optimal pricing strategies for different channels and green products under different situations. Their results show that differentiated pricing can lead to demand leakage between channels, ultimately increasing profits. Ha et al. [22] delved into how manufacturers choose encroachment strategies when product quality is differentiated, considering whether quality is endogenous or exogenous. Jabarzare et al. [23] built on this topic by examining channel strategies that account for demand influenced by price and quality, under the assumption that manufacturers sell both low- and high-quality products directly through independent retailers. In terms of channel differentiation, Du, Cui, and Su [24] presented a case study demonstrating how customer channel preferences influence manufacturers' decisions to adopt direct channels. Gan et al. [6] explored the scenario of manufacturers selling differentiated remanufactured and new products through separate channels, considering the product preferences of different types of consumers as well as the effect of channel preferences. Zhang et al. [4] considered a combination of product and channel differences, exploring how manufacturers should conduct product distribution and channel selection when selling differentiated products.

These studies collectively enhance our understanding of the complex dynamics surrounding manufacturer encroachment, product differentiation, and channel strategies, offering insights into the various factors influencing these decisions within closed-loop supply chains. However, while their models focus on manufacturers selling the same or homogeneous products through both direct and retail channels, we take into account the distribution of differentiated products for the manufacturer.

2.2. Product recovery in closed-loop supply chains

Currently, most scholars have extensively studied collection models in the remanufacturing field. Savaskan et al. [9] analyzed three methods for recycling available cores from the market and found that manufacturers prefer to collect old products through retailers. Subsequent research has built on this model with various innovations. For example, Yang et al. [11] combined carbon emission reduction into the model to study manufacturers' reverse channel choices. Their findings showed that, unlike existing studies, carbon emissions per unit during the collection process determine the optimal selection of the reverse channel. Wu et al. [25] expanded the model of Savaskan et al. [9] by considering the effects of member competition on the optimal strategy for the recycling channel. Additionally, Saha et al. [26] considerd the impact of recycling incentives on manufacturers' reverse channel choice from a subsidy perspective, concluding that when customers prioritize recycling incentives, manufacturers should recycle products directly from the market rather than through alternative channels. In recent years, research on recovery methods has evolved to allow manufacturers to choose multi-channel recovery strategies. Ranjbar et al. [27] studied situations where both retailers and third parties engage in collection simultaneously. Taleizadeh et al. [28] investigated a multi-channel framework with multiple forward and reverse channels, concluding that employing multiple forward channels along with dual reverse channels is the optimal choice for retailers and suppliers. In contrast, Suvadarshini et al. [29] integrated information asymmetry and individual rationality to analyze how manufacturers choose single-channel and multi-channel collection methods, enabling them to collaborate with either retailers or third parties for product collection. Our research extends the existing literature by examining asymmetric information related to collection efficiency, specifically with retailers responsible for implementing collection activities. Additionally, we consider the impact of the manufacturer's distribution of differentiated product on the retailer's strategies for collecting used products.

2.3. Information asymmetry in supply chains

In supply chains, downstream members (retailers) usually have more demand information than upstream members (manufacturers). This information asymmetry complicates demand forecasting and capacity planning for manufacturers. Therefore, most scholars have investigated the impacts of demand information asymmetry on manufacturer encroachment. For example, Sun et al. [15] studied how market demand uncertainty affects the manufacturers' cost reduction strategies, finding that encroachment can enable manufacturers to capture a larger share of profits. Xu et al. [30] explored the relationship between demand information asymmetry, manufacturer encroachment, and carbon emission reduction investments, showing that when encroachment costs are low, manufacturers may choose to encroach and increase their carbon emission reduction efforts. Zhang et al. [16] considered how channel structure and demand uncertainty influence product quality, suggesting that while encroachment can reduce product quality, demand information asymmetry can either improve or degrade it. In light of demand information asymmetry, Li et al. [20] extended the understanding of supplier encroachment to situations involving nonlinear pricing. Zhou et al. [17] studied how manufacturers implement single-price and dual-price contracts under market demand uncertainty, concluding that single-price contracts may not optimize manufacturers' profits. In addition to demand information asymmetry, Zhang et al. [4], Ha et al. [22] and Huang et al. [31] examined the impacts of quality uncertainty and direct channel costs on manufacturer encroachment. While existing studies on the impact of information asymmetry on manufacturer encroachment mostly focus on uncertainties related to demand information, our paper explores the impact of collection efficiency information asymmetry on manufacturer encroachment, specifically from the perspective of cost information asymmetry.

Our research encompasses the three categories of literature mentioned above, with the most relevant being He et al. [32], who also considered the choice of manufacturer encroachment but did not address collection information asymmetry and recovery channels. Moreover, they only analyzed that the manufacturer sells one type of product through its official website or third-party online platform, ignoring the situation in real life when the manufacturer sells two different products directly to the customers. We make up for this deficiency in the extended study. Additionally, Zhang et al. [33] examined the outsourcing of remanufactured product collection to retailers and how manufacturers should design contracts for this, but they did not consider manufacturer encroachment and product differentiation. In summary, our study investigates how manufacturer encroachment strategies and information asymmetry impact manufacturers' optimal decisions and consumer surplus.

3. The model

In the traditional situation, the manufacturer sells new and remanufactured products to the retailer at wholesale prices, and the retailer sells them through brick-and-mortar stores, the development of e-commerce has enabled the manufacturer to sell products directly to consumers through online channels. The encroachment strategies of the manufacturer, as illustrated in Fig. 1, involves deciding whether to encroach and, if so, through which product, i.e., new or remanufactured products. Driven by economic considerations, the retailer is responsible for collecting old products from consumers. However, owing to the actual collection efficiency of retailers is private, the manufacturer can

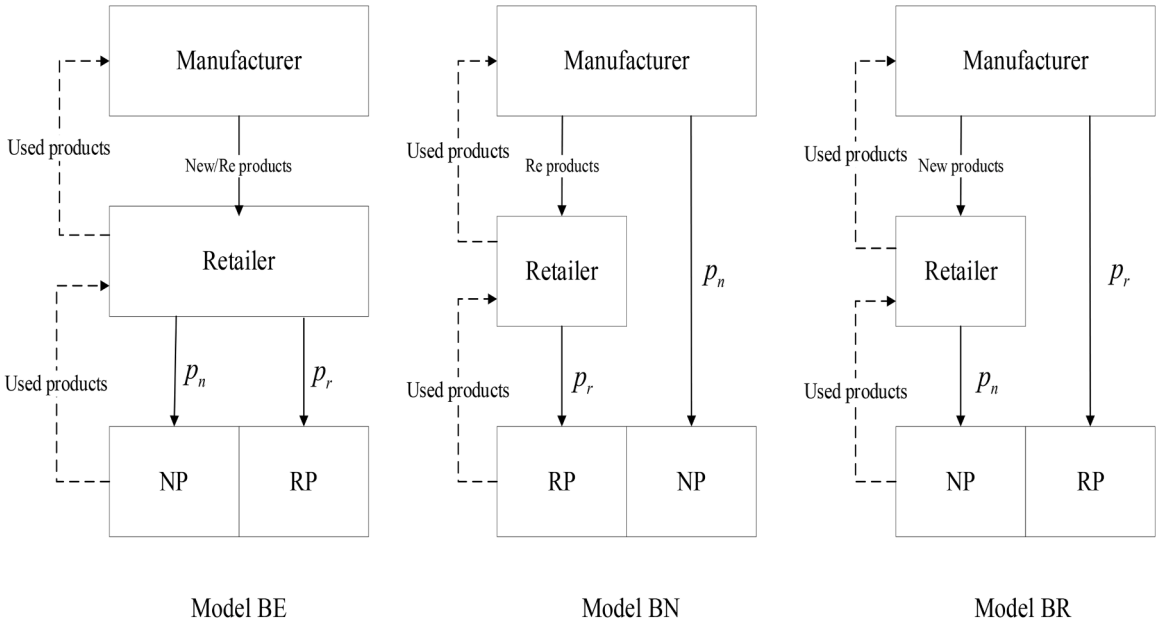


Fig. 1. Encroachment mode of manufacturer.

only ascertain the likely distribution of the retailer's collection efficiency based on available prior information. Based on the research of existing scholars, we assume that the retailer's collection probability η is either high-efficiency ($\eta = \eta_H$) with a probability of ρ or low-efficiency ($\eta = \eta_L$) with a probability of $1-\rho$, where $0 < \eta_L < \eta_H$ and $0 < \rho < 1$. These assumptions have been widely used by scholars ([19,34,35])

Due to asymmetric information regarding collection efficiency, the manufacturer encounters challenges in determining the optimal production and price. Consequently, the manufacturer is motivated to induce the accurate disclosure of the retailer's collection efficiency. The manufacturer can ensure that the retailer selects contracts matching its actual collection efficiency by designing contracts, thus revealing its real collection efficiency information. The manufacturer offers different types of contracts $\{\omega_r^i, q_r^i\}_{i\in\{H,L\}}$ or $\left\{b^i, q_r^i\right\}_{i\in\{H,L\}}$ to the retailer, where ω_r^i/b^i represents the wholesale/ transfer price of remanufactured products, and q_r^i represents the quantity of remanufactured products. The manufacturer aims to employ incentive constraints in the contracts to encourage the retailer to choose contracts corresponding to its expected type, thereby disclosing its collection efficiency information accurately [36]. This study assumes that contracts are third-party verifiable [31, 37] to ensure strict adherence to the contracts chosen by the retailer, whether to take it or leave it from them.

The decision-making sequence is shown below. First, the manufacturer chooses whether to open a direct channel. If not, the output of the new product q_n is determined by the retailer. If the manufacturer chooses to encroach through new or remanufactured products, the manufacturer or retailer determines the new product output. Second, the manufacturer offers contracts to the retailer with different collection efficiencies, i.e., $\{\omega_r^i, q_r^i\}_{i\in\{H,L\}}$, and/or $\left\{b^i, q_r^i\right\}_{i\in\{H,L\}}$. Third, the retailer chooses a contract that is consistent with its own collection efficiency η_i, where $i \in \{H, L\}$, and collects used products from the market and transfers them to the manufacturer for remanufacturing, receiving the stipulated transfer price, denoted as b. Subsequently, consumers make their purchase choice, culminating in the manufacturer obtaining the anticipated profit. This chronological sequence is visually depicted in Fig. 2.

The main assumptions are detailed below and all notations are summarized in Table 1.

Assumption 1. The utility consumers get from new products represented by v and uniformly distributed over a range [0, 1] [38–42]. Following the prior study on supply chain [42–47], we use α to indicate that consumers get lower utility from remanufactured products, i.e., $\alpha \in (0, 1)$. According to this, we can get the utility that consumers get from buying new and remanufacturing products ($U_n = v - p_n$, $U_r = \alpha v - p_r$), then consumers decide which product to buy based on utility maximization, we can infer that the demand functions are $p_n = 1 - q_n -$

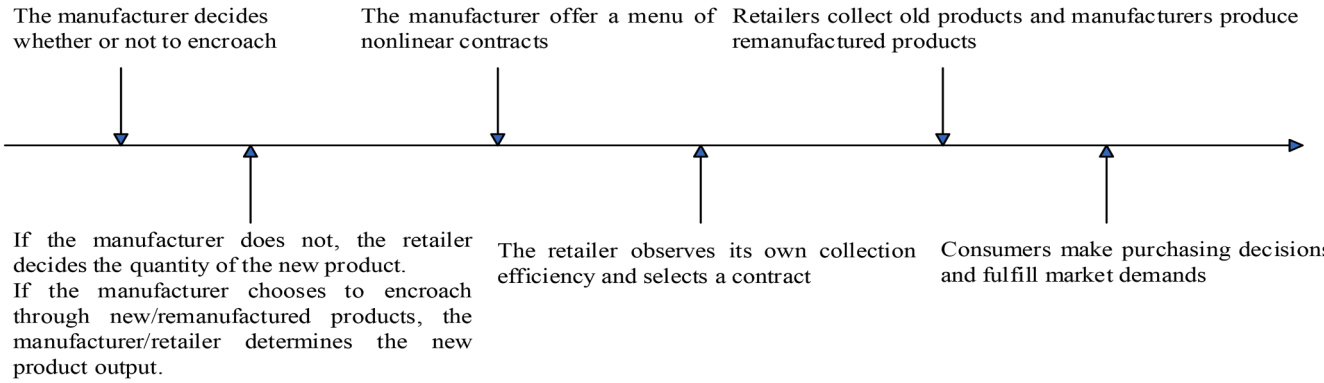


Fig. 2. The sequence of events.

Table 1
Notations.

Parameters	Definitions
c_n /c_r	Production cost per unit of new or remanufactured product
ω_n /ω_r	Wholesale price per unit of new or remanufactured product
q_n /q_r	Quantity of new or remanufactured products
p_n /p_r	Price of new or remanufactured products
α	Consumer's valuation discount for remanufactured product
ρ	The prior probability of the retailer with a high collection cost coefficient $\eta = \eta_H$
b	Transfer price per unit of the used product collected by the retailer
η	Retailer's collection cost coefficient
B,S,E	Superscript indicating the full information case or the benchmark case, the asymmetric information case, and no encroachment case, respectively
N,R	Superscript indicating the manufacturer opts to encroach through new products, remanufactured products, respectively
i	Type of retailer, $i = H$ for the retailer with a high collection cost coefficient, and $i = L$ for the retailer with a low collection cost coefficient
j	$j \in \{E, N, R\}$
π_0, π_1	Retailer's reservation profit in models BE and BN, BR, respectively
π_M, π_{Re}	The manufacturer and the retailer's total profit, respectively

αq_r and $p_r = \alpha(1 - q_n - q_r)$. The assumption of quantity competition rather than price competition between the two products is consistent with the practice that production decisions are made before the market clears ([44]).

Assumption 2. The retailer's total collection cost is related to the quantity collected q_r. Following the previous literatures, we assume a collection cost function of $\frac{\eta {q_r}^2}{2}$, where η is a nonnegative parameter and a larger value of η indicates lower recycling efficiency [1,48].

The collection cost accounts for reverse logistics, specifically the physical collection ([2]). Recycling efficiency is typically related to factors like the layout of collection centers, the deployment of collection staff, and the distance from consumers ([49]). As a result, retailers exert varying levels of effort in collection, leading to differences in collection costs. Atasu and Souza [2] used real data to simulate the collection cost function for two companies and demonstrated its applicability in our model. Based on Savaskan et al. [9] and Atasu et al. [2], Chuang et al. [50] considered the asymmetric collection efficiency of manufacturers, retailers and third parties, and found that the selection of reverse channels by manufacturers differs from previous research conclusions.

4. Equilibrium under full information

This section delves into the equilibrium outcomes when the retailer's collection efficiency is public information. The presentation of equilibrium results is outlined in Section 4.1, followed by an examination of comparative studies of different models in Section 4.2.

4.1. Equilibrium outcomes under full information

4.1.1. Full information and no encroachment

With complete information, the manufacturer knows the collection efficiency of retailers and chooses not to turn on direct channels. In this benchcase, the optimization problem for both parties can be expressed as:

$$\max_{\{\omega_n^{iBE},\omega_r^{iBE},q_r^{iBE}\}_{i\in\{H,L\}}} \pi_M^{iBE} = (\omega_n^{iBE} - c_n)q_n^{iBE} + \left(\omega_r^{iBE} - b^{iBE} - c_r\right)q_r^{iBE} \tag{1}$$

$$\max_{\{q_n^{iBE}\}_{i\in\{H,L\}}} \pi_{Re}^{iBE} = (p_n^{iBE} - \omega_n^{iBE})q_n^{iBE} + \left(p_r^{iBE} - \omega_r^{iBE} + b^{iBE}\right)q_r^{iBE} - \frac{1}{2}\eta_i\left(q_r^{iBE}\right)^2 \tag{2}$$

subject to:

$$q_n^{iBE} \geq q_r^{iBE} > 0, \ \vee_i \in \{H, L\} \tag{3}$$

$$\pi_{Re}^{iBE} \geq \left(p_n^{iBE} - \omega_n^{iBE}\right)q_n^{iBE} + \pi_0 \tag{4}$$

The two terms in the profit function (1) represent the manufacturer's profit from producing new and remanufactured products. The first and second terms in the profit function (2) are the profits that the retailer earns from product sales, and the third term is the retailer's collection cost. The constraints in (3) make sure that the amount of remanufactured products cannot exceed the output of new products and the manufacturer will participate in remanufacturing. Constraint (4) ensures that there is a minimum guarantee on the profit that the retailer receives from the contract. The retailer will choose to accept the contract only if the retailer's reserved profit is higher than the sales of the new product. Then through the formula calculation, we can get the optimal strategy for each member in this mode. To simplify the calculation, we observe that the transfer payment b is a constant, we can use $\omega_r^{iB*} = \omega_r^{iBE} - b$ to express the wholesale price minus transfer payments, and we directly use $\omega_r^{iBE}/\omega_r^{iBN}$ to denote the wholesale price after subtracting the transfer payment in the objective function.

Lemma 1. In this case, the manufacturer knows the retailer's collection efficiency, and to enable the retailer to accept the contract, the manufacturer's optimal wholesale price is $\omega_r^{iBE} = \alpha - \alpha q_n^{iBE} - \frac{\pi_0}{q_r^{iBE}} - \frac{1}{2}(2\alpha + \eta_i)q_r^{iBE}$.

Substituting ω_r^{iBE} into profit functions (1) and (2), and solving profit maximization problems, we can infer the best quantity decision under this benchcase, as shown in Proposition 1.

Proposition 1. In the scenario of full information without encroachment, the optimal quantity decisions are: (i) If $0 < c_r < c_r^{1i}$, then $q_r^{iBE} = q_n^{iBE} = \frac{1+\alpha-c_n-c_r}{4+6\alpha+\eta_i}$; (ii) If $c_r^{1i} < c_r < c_r^{9i}$, then $q_r^{iBE} = \frac{1}{3}\left(\frac{\alpha-c_r}{2\alpha+\eta_i} + \frac{5\alpha+3\alpha c_n-8c_r}{(8-3\alpha)\alpha+4\eta_i}\right)$ and $q_n^{iBE} = \frac{2\alpha(-1+\alpha+c_n-c_r)+(-1+c_n)\eta_i}{\alpha(-8+3\alpha)-4\eta_i}$.

Proposition 1 illustrates how the equilibrium outcomes are shaped by remanufacturing cost, as illustrated in Fig. 3. If the cost of remanufacturing is very low ($0 < c_r < c_r^{1i}$), producing remanufactured products becomes more cost-effective. As a result, the manufacturer actively pursues the collection of as many used products as possible for remanufacturing. However, within a range of remanufacturing costs that is neither excessively high nor extremely low, the manufacturer, considering the competition between products (the cannibalization effect), chooses to collect only a portion of the available old products for the remanufacturing process. This decision stems from the continuous decline in manufacturing cost advantages, and the advantages of new products are gradually reflected. Consequently, the manufacturer refrains from remanufacturing all used products to mitigate new product market share erosion. Ultimately, to ensure that the manufacturer participates in remanufacturing, we have a threshold for remanufacturing costs, i.e., $c_r < c_r^{9i}$.

4.1.2. Full information and encroachment with new products

In this section, the retailer's collection efficiency is public information. The manufacturer chooses to participate in encroachment through new products. The decision-making problems for the manufacturer and retailer are shown below:

$$\max_{\{q_n^{iBN},\omega_r^{iBN},q_r^{iBN}\}_{i\in\{H,L\}}} \pi_M^{iBN} = \left(p_n^{iBN} - c_n\right)q_n^{iBN} + \left(\omega_r^{iBN} - c_r\right)q_r^{iBN} \tag{5}$$

$$\pi_{Re}^{iBR} = \left(p_r^{iBN} - \omega_r^{iBN}\right)q_r^{iBN} - \frac{1}{2}\eta_i\left(q_r^{iBN}\right)^2 \tag{6}$$

subject to:

$$q_n^{iBN} \geq q_r^{iBN} > 0, \ \vee_i \in \{H, L\} \tag{7}$$

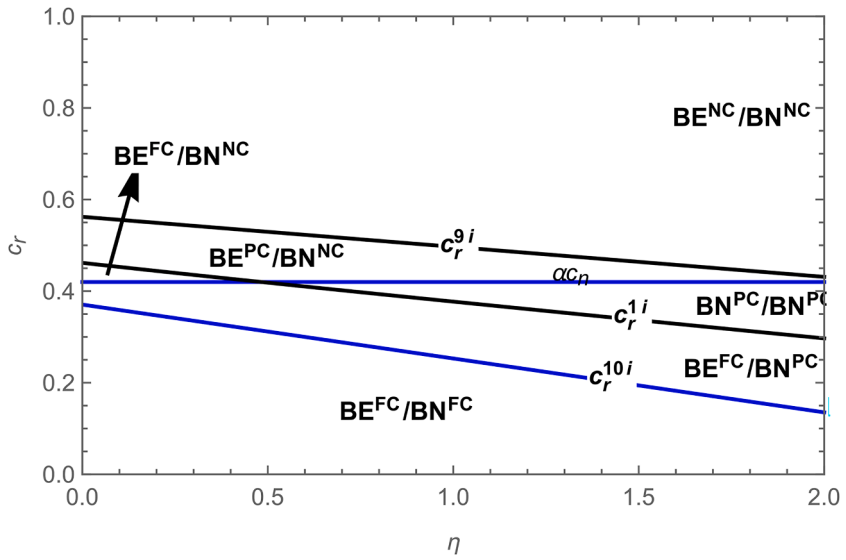


Fig. 3. Comparison of manufacturer's remanufacturing decisions under models BE and BN (NC, PC, FC denoting No, Partly, Full Collection, respectively).

$$\pi_{Re}^{iBN} \geq \pi_0 \tag{8}$$

With complete information, the manufacturer engages in direct channel encroachment through new products, the problem formulation process mirrors that of the situation without encroachment. Eqs. (5)–(6) imply that the manufacturer incurs no cost when opening a direct channel. In reality, suppliers typically have higher unit costs of goods sold compared to resellers due to less efficient retail operations. We assume indifference between channels in order to highlight our main result that an asymmetric product distribution policy arises without considering extraneous factors unrelated to the core result. This approach aligns with the assumptions made by other scholars ([4,51, 52]). Given that the manufacturer engages in encroachment through new products, direct benefits accrue to the manufacturer from the sale of these products. We refrain from delving into the intricate solving process. The outcomes are shown in Proposition 2.

Proposition 2. Under full information with encroachment through new products, the optimal quantity decisions are: (i) If $0 < c_r < c_r^{10i}$, then $q_r^{iBE} = q_n^{iBE} = \frac{1+\alpha-c_n-c_r}{2+6\alpha+\eta_i}$; (ii) If $c_r^{10i} < c_r < \alpha c_n$, then $q_r^{iBE} = \frac{\alpha c_n - c_r}{2(1-\alpha)\alpha+\eta_i}$ and $q_n^{iBE} = \frac{2\alpha(1-\alpha-c_n+c_r)+(1-c_n)\eta_i}{4(1-\alpha)\alpha+2\eta_i}$.

Proposition 2 indicates that in symmetric information, the yield of remanufactured products still has a huge amount of influence over the manufacturer's encroachment choice. This conclusion aligns closely with Proposition 1, except for a reduction in the threshold for remanufactured product entry ($\alpha c_n < \frac{\alpha(\alpha(6-\alpha+2c_n)+(3+c_n)\eta_i)}{(8-\alpha)\alpha+4\eta_i}$). In instances of high remanufacturing costs ($\alpha c_n < c_r < \frac{\alpha(\alpha(6-\alpha+2c_n)+(3+c_n)\eta_i)}{(8-\alpha)\alpha+4\eta_i}$), Under the case of no encroachment, the manufacturer can increase the competitive advantage of remanufactured products by raising the wholesale price of new products. Conversely, the manufacturer collects fewer used products to reduce the cannibalization effect, thereby ensuring sales of new products.

4.1.3. Full information and encroachment with remanufactured products

In this scenario, the collection efficiency of retailers is still disclosed, but the difference is that remanufactured products will be sold through direct channels rather than new products. Optimization problems for manufacturers and retailers are as follows:

$$\max_{\{b^{iBR}, q_r^{iBR}\}_{i\in\{H,L\}}} \pi_M^{iBR} = (\omega_n^{iBR} - c_n) q_n^{iBR} + \left(p_r^{iBR} - c_r - b^{iBR}\right) q_r^{iBR} \tag{9}$$

$$\max_{\{q_n^{iBR}\}_{i\in\{H,L\}}} \pi_{Re}^{iBR} = (p_n^{iBR} - \omega_n^{iBR}) q_n^{iBR} + b^{iBR} q_r^{iBR} - \frac{1}{2}\eta^{iBR} (q_r^{iBR})^2 \tag{10}$$

Subject to:

$$q_n^{iBR} \geq q_r^{iBR} > 0, \ \vee_i \in \{H, L\} \tag{11}$$

$$\pi_{Re}^{iBR} \geq \pi_1 \tag{12}$$

In the situation of encroaching through remanufactured products, the formulation process of the model closely resembles that of the case without encroachment or encroachment with new products. Therefore, we omit detailed explanations of these functions. It is noteworthy that the retailer only gets the transfer payment fee for the remanufactured products, so the reserved profit under this model should be lower than the reserved profit for the sale of the remanufactured product, *i.e.*, $\pi_1 < \pi_0$. Then, we employ the same methodology as previously to deduce the manufacturer's equilibrium outcomes, with the results outlined in Proposition 3.

Proposition 3. Under full information with encroachment through remanufactured products, the optimal quantity decisions mirror those in the scenario where an encroachment strategy is not implemented.

Proposition 3 reveals that the equilibrium decision under models BE and BR is identical. This convergence arises because, in the BE model, the manufacturer determines the collection efficiency of retailers by setting the recycling quantity of used products as well as transfer payments. Consequently, even though the manufacturer participates in encroachment through remanufactured products, it is still the manufacturer who makes the production decisions for two products. The decision order in both cases is nearly identical, with the only distinction being that the retailer obtains a lower reservation profit.

4.2. Comparative analysis of equilibrium results under full information

In this section, we analyze how a manufacturer's encroachment strategy is affected by different channel structures under full information. Since the optimal decisions under the models BE and BR are identical, our analysis focuses on comparing equilibrium decisions between models BE and BN. To start, we elucidate the comparable range for modes by comparing their feasible ranges.

Lemma 2. Encroachment strategy with new products lowers the threshold for the retailer to collect used products, i.e., $\alpha c_n < c_r^{9i}$ and $c_r^{10i} < c_r^{1i}$.

Lemma 2 implies that, in comparison to scenarios with no encroachment or encroachment with remanufactured products, the manufacturer will opt to produce more remanufactured products if remanufacturing cost is lower in model BN, as depicted in Fig. 3. This stems from the fact that in model BN, the manufacturer can derive greater profit from selling new products, while remanufactured products lack a production advantage. When $\alpha c_n < c_r < c_r^{9i}$, the cost advantage of remanufacturing is not very pronounced and hence, the manufacturer under model BE only collects part of the products used for remanufacturing. Moreover, in the BN case, the price advantage of new products is more apparent, making remanufacturing an impractical choice. When $c_r^{10i} < c_r < c_r^{1i}$, the cost advantage of remanufacturing prompts the manufacturer under model BE to choose to collect all products. In contrast, when the remanufacturing cost is low enough, the manufacturer in model BE may not even engage in remanufacturing. The substantial difference arises because the manufacturer prefers to enhance the output of new products in the BE case, reducing the cannibalization arisen by remanufactured products.

Proposition 4. In equilibrium under full information, (i) $q_n^{iBE} < q_n^{iBN}$ for all $0 < c_r < \alpha c_n$; (ii) $q_r^{iBE} < q_r^{iBN}$ if $0 < c_r < c_r^{12i}$, and $q_r^{iBE} \geq q_r^{iBN}$ otherwise.

Proposition 4 provides insights into how the manufacturer's channel structure choices affect the equilibrium quantity decisions. The conclusions indicate that the choice of encroachment strategy incentivizes the manufacturer to enhance the quantity of new products to occupy the new product market. The reason is that manufacturers can reduce product competition by coordinating the optimal production volumes of new and remanufactured products when choosing encroachment through the direct channel. This optimization enhances resource utilization. Additionally, it might be expected that manufacturers encroaching through new products would decrease the collection of used products to reduce cannibalization. However, when remanufacturing cost is low, the manufacturer participating in encroachment by remanufacturing products will collect more used products for remanufacturing. The main reason is that, in the BN mode, the manufacturer prefers to collect part of the product for remanufacturing, while in the BE mode, the manufacturer still collects all products for remanufacturing (refer to Lemma 2 for details).

Theorem 1. Under full information, the comparison of the channel members' profits is as follows: (i) $\pi_M^{iBE} < \pi_M^{iBR}$, $\pi_M^{iBE} < \pi_M^{iBN}$, and there exists a threshold x_{1i} such that when $0 < \pi_0 - \pi_1 < x_{1i}$, then $\pi_M^{iBN} > \pi_M^{iBR}$, and $\pi_M^{iBN} \leq \pi_M^{iBR}$ otherwise. (ii) $\pi_{Re}^{iBN} < \pi_{Re}^{iBE}$, $\pi_{Re}^{iBR} < \pi_{Re}^{iBE}$, and there exists a threshold x_{2i} such that when $x_{2i} < \pi_0 - \pi_1$, then $\pi_{Re}^{iBN} > \pi_{Re}^{iBR}$, and $\pi_{Re}^{iBN} \leq \pi_{Re}^{iBR}$ otherwise.

Fig. 4 illustrates the results of Theorem 1. Theorem 1 provides some insights into the comparison of the manufacturer' and retailer's profits when the manufacturer adopts different channel structures. First, engaging in encroachment is consistently profitable for the manufacturer, while the retailer's profits decline as a result of this encroachment. This conclusion aligns with existing literature [53]. However, previous studies have typically considered only a single encroachment channel structure. Our comparison of different encroachment channel structure reveals that the disparity in reversed profits significantly influences the manufacturer's decision of optimal encroachment channel structure, which in turn affects the retailer's channel choices. When the gap in reserved profit exceeds a certain threshold, retailers can obtain higher reserved profits by selling remanufactured products. In such cases, retailers prefer the manufacturer to engage in encroachment with new products, allowing them to maximize profits by focusing on remanufactured products. Conversely, if the gap falls below a certain threshold, the manufacturer tends to encroach with new products. This indicates that retailers selling remanufactured products can negotiate for higher reserved profits from the manufacturer, or that the manufacturer may lower the reserved profits available to retailers collecting remanufactured products to minmize cannibalization.

This dynamic creates mutually beneficial scenarios for both parties when the manufacturer chooses to encroach with new products. Specifically, win-win outcomes are attainable for both parties in various contexts. First, a win-win outcome appears in Region I when the expected profit margin is moderate, allowing any retailer and manufacturer to benefit. Second, if either the manufacturer or the retailer faces high collection costs, win-win scenarios unfold within both Region I and Region II ($x_{2H} < \pi_0 - \pi_1 < x_{1H}$). However, when the retailer's collection cost coefficient is relatively low, the win-win regions expand to encompass Regions I and III ($x_{2L} < \pi_0 - \pi_1 < x_{2H}$). The dymanic is observed when remanufacturing costs are low; the manufacturer provides higher reserved profits for product collection to retailer with low collection efficiency, thereby diminishing the gap in reserved profits. Conversely, retailers with high collection efficiency can secure greater reserve profits from the sales of remanufactured products, widening the difference in reserved profits. These insights offer valuable guidance for manufacturers in choosing encroachment strategies, particularly in balancing their profits with the interests of retailers.

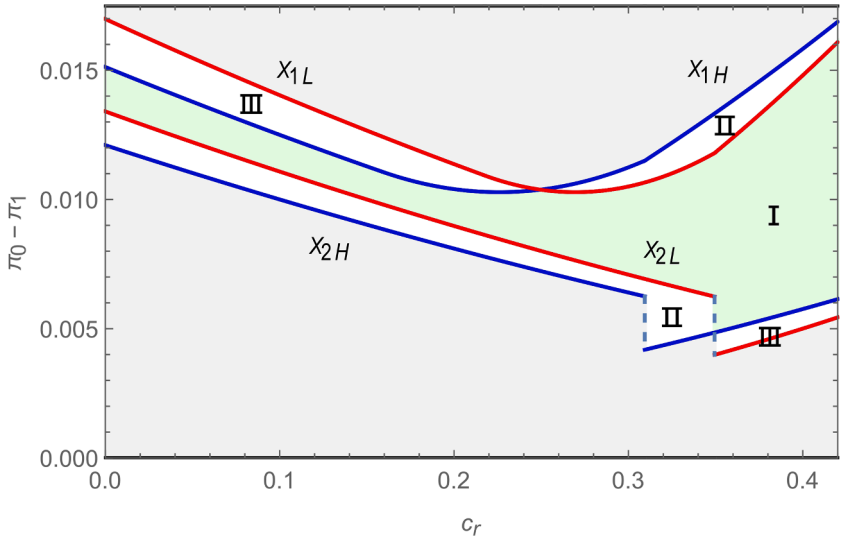


Fig. 4. Profits of the manufacturer and retailer under different encroachment channel structures.

5. Equilibrium under asymmetry information

This section investigates the equilibrium outcomes in scenarios where collection efficiency serves as private information of the retailer. Section 5.1 explores the equilibrium outcomes under various encroachment strategies, while Section 5.2 conducts comparative analyses of different models.

5.1. Equilibrium outcomes under asymmetry information

5.1.1. Asymmetry information with no encroachment

Under information asymmetry, the retailer maintains exclusive knowledge of its collection cost coefficient. The manufacturer faces two potential scenarios: the retailer's collection cost coefficient is either η_H with the probability of ρ or η_L with the probability of $(1-\rho)$. We proceed to examine the motivations behind the retailer's inclination to conceal its actual collection efficiency and explore how the manufacturer can employ contracts to encourage the retailer to disclose accurate information.

Lemma 3. In a scenario where the manufacturer lacks information about the retailer's collection efficiency, the retailer with low collection efficiency ($\eta = \eta_L$) will choose to conceal its collection efficiency and select contract $\left\{\omega_r^H/b^H, q_r^H\right\}$. Conversely, the retailer with high collection efficiency ($\eta = \eta_H$) will choose to reveal its collection efficiency to accept contract $\left\{\omega_r^H/b^H, q_r^H\right\}$.

Lemma 3 indicates that the manufacturer often lowers the wholesale price to incentivize retailers with a high collection cost coefficient to participate in the collection process. Consequently, the retailer with a low collection cost coefficient has an incentive to feign a higher collection cost coefficient, allowing it to secure lower wholesale prices and thereby maximize profits, i.e., $\pi_{Re}^{LBj}\left(\omega_r^{HBj}/b^{HBR}, q_r^{HBj}\right) > \pi_{Re}^{LBj}\left(\omega_r^{LBj}/b^{LBR}, q_r^{LBj}\right)$. In contrast, $\pi_{Re}^{HBj}\left(\omega_r^{HBj}/b^{LBR}, q_r^{HBj}\right) > \pi_{Re}^{HBj}\left(\omega_r^{LBj}/b^{LBR}, q_r^{LBj}\right)$, indicating that the retailer with a high collection cost coefficient cannot gain more profit by concealing information. Thus, the retailer with a high collection cost coefficient will only accept contracts corresponding to its type $\{\omega_r^{HBj}/b^{HBR}, q_r^{HBj}\}$. To mitigate the disadvantageous position caused by information asymmetry, the manufacturer has a reason to set the contract that makes the retailer accurately disclose its private information. With this in mind, the manufacturer needs to solve the corresponding problems as follows:

$$\max_{\left\{\omega_r^{iSE}, q_r^{iSE}\right\}_{i\in\{H,L\}}} \pi_M^{SE} = \rho\left(\left(\omega_n^{HSE}-c_n\right)q_n^{HSE} + \left(\omega_r^{HSE}-c_r\right)q_r^{HSE}\right) + (1-\rho)\left(\left(\omega_n^{LSE}-c_n\right)q_n^{LSE} + \left(\omega_r^{LSE}-c_r\right)q_r^{LSE}\right) \tag{13}$$

Subject to:

$$\pi_{Re}^{HSE}\left(\omega_r^{HSE}, q_r^{HSE}\right) > \pi_{Re}^{HSE}\left(\omega_r^{LSE}, q_r^{LSE}\right) \tag{14}$$

$$\pi_{Re}^{LSE}\left(\omega_r^{LSE}, q_r^{LSE}\right) > \pi_{Re}^{LSE}\left(\omega_r^{HSE}, q_r^{HSE}\right) \tag{15}$$

$$\pi_R^{iSE}\left(\omega_r^{iSE}, q_r^{iSE}\right) > \pi_0 \tag{16}$$

$$q_n^{iSE} \geq q_r^{iSE} > 0, \ \vee_i \in \{H,L\} \tag{17}$$

Then, the retailer's optimization problem can be formulated as:

$$\max_{\left\{q_n^{iSE}\right\}_{i\in\{H,L\}}} \pi_R^{iSE} = \left(p_n^{iSE}-\omega_n^{iSE}\right)q_r^{iSE} + \left(p_n^{iSE}-\omega_r^{iSE}\right)q_r^{iSE} - \frac{1}{2}\eta_i\left(q_r^{iSE}\right)^2 \tag{18}$$

Similar to information symmetry without encroachment, the manufacturer gains profits from producing the two products. However, under information asymmetry, the manufacturer lacks knowledge about actual collection cost coefficient of the retailer. Therefore, the two terms in Eq. (13) represent the expected profit obtained by the manufacturer when the retailer's collection cost coefficient is high or low. Constraints (14,15), and (16) ensure that the retailer does not misrepresent itself as another type and will accept the contract. The quantity constraints in (17) are similar to constraint (3). Nevertheless, the retailer still benefits from the sale of products, as indicated in Eq. (18). According to constraints (14)-(16), we infer the optimal wholesale price setting for different types of retailers under information asymmetry, and Lemma 4 shows the results.

Lemma 4. Under information asymmetry with no encroachment, the optimal wholesale price decision satisfies that $\omega_r^{HSE} = \frac{-2\pi_0+2\alpha q_r^{HSE}-2\alpha q_n^{HSE}q_r^{HSE}-2\alpha\left(q_r^{HSE}\right)^2-\left(q_r^{HSE}\right)^2\eta_H}{2q_r^{HSE}}$ and $\omega_r^{LSE} = -\frac{2\pi_0+\left(q_r^{HSE}\right)^2(\eta_H-\eta_L)+q_r^{LSE}\left(2\alpha\left(-1+q_n^{LSE}+q_r^{LSE}\right)+q_r^{LSE}\eta_L\right)}{2q_r^{LSE}}$.

Then, substituting ω_r^{HSE} and ω_r^{LSE} back, we derive the quantity policies under information asymmetry with encroachment, as shown in Proposition 5.

Proposition 5. With asymmetry information and no encroachment, the optimal quantity decisions are: (i) If $\eta = \eta_L$, then iif (ia) $0 < c_r < c_r^{1L}$, then $q_r^{LSE*} = q_n^{LSE*} = \frac{1+\alpha-c_n-c_r}{4+6\alpha+\eta_L}$; iif (ib) $c_r^{1L} < c_r < c_r^{9L}$, then $q_r^{LSE} = \frac{1}{3}\left(\frac{\alpha-c_r}{2\alpha+\eta_L} + \frac{5\alpha+3\alpha c_n-8c_r}{(8-3\alpha)\alpha+4\eta_L}\right)$ and $q_n^{LSE} = \frac{2\alpha(1-\alpha-c_n+c_r)+(1-c_n)\eta_L}{\alpha(8-3\alpha)+4\eta_L}$. (ii) If $\eta = \eta_H$, then iif (iia) $0 < c_r < c_r^2$, then $q_r^{HSE} = q_n^{HSE} = \frac{\rho(1+\alpha-c_n-c_r)}{4\rho+6\alpha\rho+\eta_H-(1-\rho)\eta_L}$; iif (iib) $c_r^2 < c_r < c_r^{11}$, then $q_r^{HSE} = \frac{1}{3}\rho\left(\frac{\alpha-c_r}{2\alpha\rho+\eta_H-(1-\rho)\eta_L} + \frac{5\alpha+3\alpha c_n-8c_r}{(8-3\alpha)\alpha\rho+4\eta_H-4(1-\rho)\eta_L}\right)$ and $q_n^{HSE} = \frac{1}{4}\left(1-c_n-\frac{\alpha\rho(5\alpha+3\alpha c_n-8c_r)}{\alpha(8-3\alpha)\rho+4\eta_H-4(1-\rho)\eta_L}\right)$.

Proposition 5 outlines the non-linear contracts offered to the retailer, when the manufacturer opts not to encroach under information asymmetry. A comparison with the benchmark case indicates that for the retailer with a high collection cost factor, the information asymmetry does not change the contract established by the manufacturer. This is because the retailer with a high collection cost coefficient gains no advantage from concealing information and will only choose contracts aligned with its actual circumstances. On the contrary, the high-efficiency retailer can maximize its profits by hiding its efficiency information and selecting the contract designed for high collection cost coefficients. This makes it challenging for the contracts under benchmark conditions to effectively screen out the true information about the retailer's collection efficiency. Hence, the manufacturer can adjust the prices and quantities specified in the contract to better align with their own objectives.

5.1.2. Asymmetry information and encroachment with new products

In the scenario where the retailer chooses not to disclose its true collection efficiency, and the manufacturer opts to engage in encroachment through new products, both parties' profit maximization problem is as follows:

$$\max_{\left\{q_n^{iSN}, \omega_r^{iSN}, q_r^{iSN}\right\}_{i\in\{H,L\}}} \pi_M^{SN} = \rho\left(\left(p_n^{HSN}-c_n\right)q_n^{HSN} + \left(\omega_r^{HSN}-c_r\right)q_r^{HSN}\right) + (1-\rho)\left(\left(p_n^{LSN}-c_n\right)q_n^{LSN} + \left(\omega_r^{LSN}-c_r\right)q_r^{LSN}\right) \tag{19}$$

Subject to:

$$\pi_{Re}^{HSN}\left(\omega_r^{HSN}, q_r^{HSN}\right) > \pi_{Re}^{HSN}\left(\omega_r^{LSN}, q_r^{LSN}\right) \tag{20}$$

$$\pi_{Re}^{LSN}\left(\omega_r^{LSN}, q_r^{LSN}\right) > \pi_{Re}^{LSN}\left(\omega_r^{HSN}, q_r^{HSN}\right) \tag{21}$$

$$\pi_{Re}^{iSN}\left(\omega_r^{iSN}, q_r^{iSN}\right) > \pi_0 \tag{22}$$

$$q_n^{iSN} \geq q_r^{iSN} > 0, \ \vee_i \in \{H,L\} \tag{23}$$

Similarly, the decision problem for the retailer can be expressed as:

$$\pi_{Re}^{iSN} = \left(p_r^{iSN} - \omega_r^{iSN}\right) q_r^{iSN} - \frac{1}{2}\eta_i \left(q_r^{iSN}\right)^2 \tag{24}$$

The problem formulation process is similar to that without encroachment. The distinction lies in the fact that, when encroaching with new products, the manufacturer directly gains from selling new products. Without further elaboration, the optimal results can be derived, as shown in Lemma 5.

Lemma 5. Under information asymmetry with encroachment involving new products, the optimal wholesale price decision for the manufacturer satisfies $\omega_r^{HSN} = \frac{-2\pi_0 + 2\alpha q_r^{HSN} - 2\alpha q_n^{HSN} q_r^{HSN} - 2\alpha\left(q_r^{HSN}\right)^2 - \left(q_r^{HSN}\right)^2 \eta_H}{2q_r^{HSN}}$ and $\omega_r^{LSN} = -\frac{2\pi_0 + \left(q_r^{HSN}\right)^2(\eta_H - \eta_L) + q_r^{LSN}\left(2\alpha\left(-1 + q_n^{LSN} + q_r^{LSN}\right) + q_r^{LSN}\eta_L\right)}{2q_r^{LSN}}$.

Then, by substituting ω_r^{HSN} and ω_r^{LSN} back into the equations, we can establish the quantity policies, as detailed in Proposition 6.

Proposition 6. Under information asymmetry and encroachment with new products, the optimal quantity decisions are: (i) If $\eta = \eta_L$, then iif (ia) $0 < c_r < c_r^{10L}$, then $q_r^{LSE} = q_n^{LSE} = \frac{1+\alpha-c_n-c_r}{2+6\alpha+\eta_L}$; iif (ib) $c_r^{10L} < c_r < \alpha c_n$, then $q_r^{LSE} = \frac{\alpha c_n - c_r}{2(1-\alpha)\alpha+\eta_L}$ and $q_n^{LSE} = \frac{2\alpha(1-\alpha-c_n+c_r)+(1\pm)\eta_L}{4(1-\alpha)\alpha+2\eta_L}$. (ii) If $\eta = \eta_H$, then iif (iia) $0 < c_r < c_r^3$, then $q_r^{HSE} = q_n^{HSE} = \frac{\rho(1+\alpha-c_n-c_r)}{2\rho+6\alpha\rho+\eta_H-(1-\rho)\eta_L}$; iif (iib) $c_r^3 < c_r < \alpha c_n$, then $q_r^{HSE} = \frac{\rho(\alpha c_n - c_r)}{2(1-\alpha)\alpha\rho+\eta_H-(1-\rho)\eta_L}$ and $q_n^{HSE} = \frac{1}{2}\left(1 - c_n - \frac{2\alpha\rho(\alpha c_n - c_r)}{2(1-\alpha)\alpha\rho+\eta_H-(1-\rho)\eta_L}\right)$.

Proposition 6 illustrates the nonlinear contract provided by the manufacturer to the retailer in the presence of asymmetric information and encroachment with new products. A comparison with Proposition 2 reveals a similar conclusion, indicating that information asymmetry exerts an impact on the manufacturer's optimal decisions. However, contrary to Proposition 2, it is observed that under encroachment with new products, information asymmetry does not affect the threshold for the manufacturer to enter remanufacturing. This is because the manufacturer decides the output of the two products simultaneously, and whether to remanufacture depends solely on the remanufacturing cost.

5.1.3. Asymmetry information and encroachment with remanufactured products

In this section, the manufacturer opts to encroach with remanufactured products without knowing the retailer's actual collection efficiency information. The optimization problem for the manufacturer is shown below:

$$\begin{aligned} \max_{\left\{b^{iSR}, q_r^{iSR}\right\}_{i\in\{H,L\}}} \quad & \pi_M^{SR} = \rho\left(\left(\omega_n^{HSR} - c_n\right) q_n^{HSR} + \left(p_r^{HSR} - c_r - b^{HSR}\right) q_r^{HSR}\right) + \\ & (1-\rho)\left(\left(\omega_n^{LSR} - c_n\right) q_n^{LSR} + \left(p_r^{LSR} - c_r - b^{LSR}\right) q_r^{LSR}\right) \end{aligned} \tag{25}$$

Subject to:

$$\pi_R^{HSR}\left(b^{HSR}, q_r^{HSR}\right) > \pi_R^{HSR}\left(b^{LSR}, q_r^{LSR}\right) \tag{26}$$

$$\pi_{Re}^{LSR}\left(b^{LSR}, q_r^{LSR}\right) > \pi_{Re}^{LSR}\left(b^{HSR}, q_r^{HSR}\right) \tag{27}$$

$$\pi_R^{iSR}\left(b^{LSR}, q_r^{iSR}\right) > \pi_1 \tag{28}$$

$$q_n^{iSR} \geq q_r^{iSR} > 0, \ \vee_i \in \{H, L\} \tag{29}$$

The retailer's profit can be expressed as:

$$\pi_R^{iSR} = \left(p_n^{iSR} - \omega_n^{iSR}\right) q_n^{iBR} + b^{iSR} q_r^{iSR} - \frac{1}{2}\eta_i \left(q_r^{iSR}\right)^2 \tag{30}$$

The problem formulation process is akin to that without encroachment and encroachment with new products. The distinction lies in the fact that the manufacturer engages in encroachment through remanufactured products instead of new products. Without further elaboration, we can get the optimal solution from the manufacturer, as shown in Proposition 7.

Proposition 7. Under information asymmetry and encroachment with remanufactured products, the optimal quantity decisions remain unchanged compared to the scenario where no encroachment strategy is implemented.

Proposition 7 demonstrates that the manufacturer's equilibrium decision does not change when selling remanufactured products directly. Moreover, Propositions 7 and 3 suggest that this observation remains valid in the presence of information asymmetry. This is because asymmetry information does not disrupt the power dynamics under models SE and SR, and the manufacturer continues to control the collection and production of remanufactured products.

5.2. Comparative analysis of equilibrium results with asymmetry information

In this section, we explore how the encroachment strategies influence the optimal decision of two parties under the condition of asymmetric information. Similar to Section 4.2, we begin by analyzing the feasible ranges of different models and the results are shown in Lemma 6.

Lemma 6. Under asymmetric information, the manufacturer continues to lower the production threshold for remanufactured products when adopting an encroachment strategy with new products, i.e., $\alpha c_n < c_r^{11}, c_r^3 < c_r^2$.

Lemma 6 (Fig. 5) confirms that the findings from Lemma 2 remain applicable under conditions of information asymmetry. Specifically, when $\alpha c_n < c_r < c_r^{11}$, the manufacturer in the SE model will opt for full or partial collection, while in the SN model, the manufacturer will not engage in remanufacturing. This is because even without knowledge of the retailer's true collection efficiency, the manufacturer can still derive profits from new product encroachment through the direct channel. Consequently, under the same remanufacturing cost, the manufacturer under Model BN produces lower quantities of remanufactured products. On the other hand, when $c_r^3 < c_r < c_r^2$, in the SE model, the manufacturer opts for full collection, while in the SN model, the manufacturer may choose full or partial collection for different types of retailers. This is because the retailer with high collection efficiency incurs lower costs in collecting products, prompting the manufacturer to improve remanufactured product yields.

Proposition 8. In equilibrium under asymmetry information, (i) $q_n^{iSE} < q_n^{iSN}$ for all $0 < c_r < \alpha c_n$; (ii) $q_r^{HSE} < q_r^{HSN}$ if $c_r < c_r^4$, and $q_r^{HSE} \geq q_r^{HSN}$ otherwise.

Proposition 8 reaffirms that the conclusion that manufacturer expropriation can affect product output is still applicable under conditions of information asymmetry. It is evident that encroaching with new products will cause the manufacturer to increase the output of new products. This is because, unlike the retailer, the manufacturer encroaching with new products does not need to consider the wholesale price of products, which may cause the price of the new product to increase. Under the SN mode, when remanufacturing is not cost-effective, selling new products directly makes manufacturers produce fewer remanufactured products, reducing competition between products. This is rooted in the fact that, in the face of a high collection cost coefficient retailer, the remanufacturing strategy of the manufacturer under the SN model shifts from full to partial collection, which means lower remanufactured product output. In contrast, in the SE mode, the manufacturer prefers to increase sales of remanufactured products through the retailer collecting all the used products available in the market.

Theorem 2. Under information asymmetry, the comparison of the channel members' profits is as follows: (i) $\pi_M^{SE} < \pi_M^{SR}$, $\pi_M^{SE} < \pi_M^{SN}$, and there exists a threshold x_3 such that when $0 < \pi_0 - \pi_1 < x_3$, then $\pi_M^{SN} > \pi_M^{SR}$, and $\pi_M^{SN} \leq \pi_M^{SR}$ otherwise. (ii) $\pi_{Re}^{iSN} < \pi_{Re}^{iSE}$, $\pi_{Re}^{iSR} < \pi_{Re}^{iSE}$, and there exists a threshold x_{4i} such that when $x_{4i} < \pi_0 - \pi_1$, then $\pi_{Re}^{iSN} > \pi_{Re}^{iSR}$, and $\pi_{Re}^{iSN} \leq \pi_{Re}^{iSR}$ otherwise.

Theorem 2 analyzes how different channel structures affect the

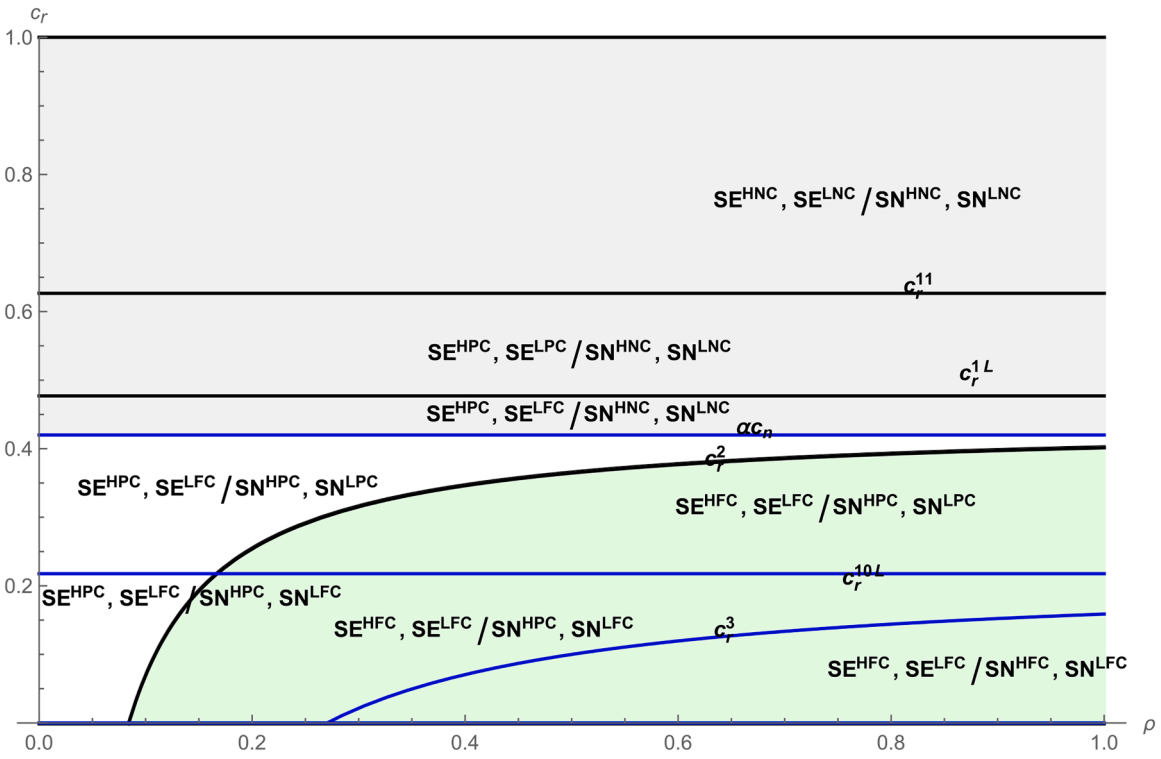


Fig. 5. Comparison of manufacturer's remanufacturing decision under model SE and SN.

profits of supply chain members under information asymmetry. Similar to the findings in Theorem 1, if the retailer keeps his or her private information, the manufacturer still demonstrates a preference for encroachment. Furthermore, a mutually beneficial situation can only be achieved if the manufacturer opts to encroach through new products. Specifically, whether the retailer's collection efficiency is high or low, a win-win situation can be achieved through encroachment with new products, as indicated in Region I in Fig. 6($\max\{x_{4H}, x_{4L}\} < c_r < x_3$). For the retailer, information asymmetry prevents him from benefiting significantly from manufacturer encroachment, and his choice of encroachment channel structure is determined by the reserved profit margin. When the retailer has a high collection cost coefficient, a win-win situation can be realized within Region I and Region II ($x_{4H} < \pi_0 - \pi_1 < x_3$). Conversely, for a manufacturer and a retailer with a low collection cost coefficient, the win-win regions are I and III ($x_{4L} < \pi_0 - \pi_1 < x_3$). The presence of Region II is due to information asymmetry allowing the low-type retailer to obtain information rent, thereby increasing product output and reserved profit. Therefore, Region II exists only when the margin of reserved profit is higher, prompting the retailer with a low collection cost coefficient to opt for the SN model. When remanufacturing is more profitable, the elevated production cost and collection cost encourage the high collection cost

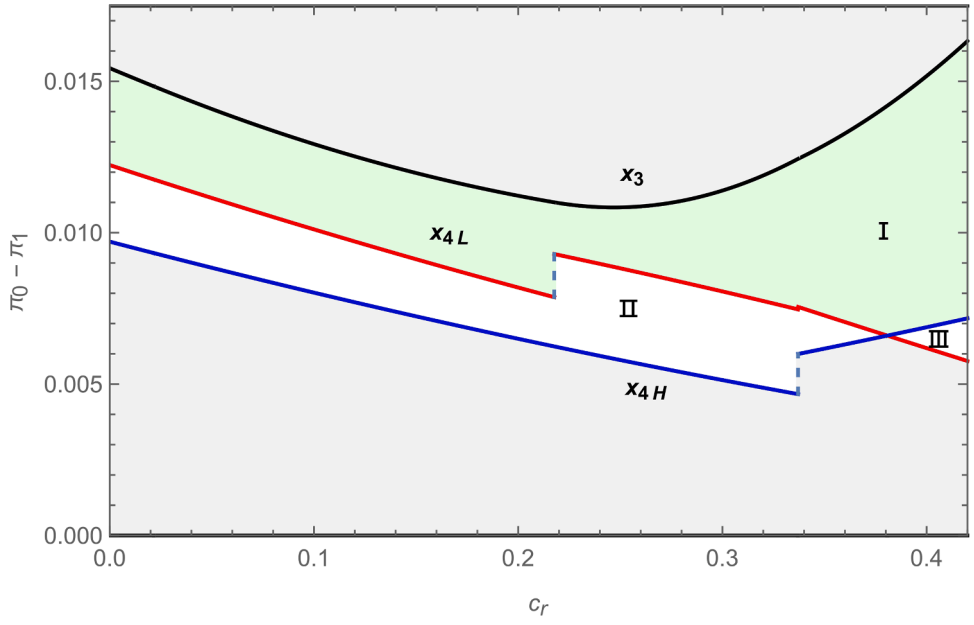


Fig. 6. Profits of the manufacturer and retailer under different encroachment channel structures.

coefficient retailer to seek a higher expected profit, represented by Region III.

Moreover, a comparison with Theorem 1 reveals that information asymmetry alters the range of win-win areas for both manufacturers and retailers. Specifically, when remanufacturing costs are low, information asymmetry narrows the win-win scope for manufacturers but expands it for retailers. This indicates that under information asymmetry, retailers' private information grants them greater bargaining power, allowing them to secure higher reserved profits from the manufacturer. Conversely, when the costs of remanufacturing are high, information asymmetry reduces the retailer's win-win area. The underlying reason is that the combined effect of low cost advantages for remanufactured products and information asymmetry makes manufacturers less inclined to produce these products, resulting in lower reserved profits for retailers from their collection and resale activities.

6. The role of private cost-efficiency information

6.1. How does cost efficiency asymmetry affect equilibrium outcomes

In this section, we juxtapose the equilibrium outcomes between symmetry and asymmetry information under various encroachment channels.

Proposition 9. When reaching an equilibrium state, we find: (i) $q_r^{LBj} = q_r^{LSj}$, $q_n^{LBj} = q_n^{LSj}$, $q_r^{HBj} > q_r^{HSj}$ for all $0 < c_r < c_r^{11}$. (ii) When $0 < c_r < c_r^{1H}$, $q_n^{HBE} > q_n^{HSE}$, and when $0 < c_r < c_r^{5}$, $q_n^{HBN} > q_n^{HSN}$.

Proposition 9 clarifies the influence of information asymmetry on optimal quantity choices, considering scenarios where the manufacturer engages or does not engage in the encroachment, as illustrated in Fig. 9. First, it is evident that no matter which encroachment channel structure the manufacturer chooses, information asymmetry has no impact on the manufacturer's contract design if the retailer's collection cost coefficient is high. This consistent observation aligns with our previous analysis, emphasizing that information asymmetry is not a significant factor in contract design under such circumstances. In contrast, when the retailer possesses a low collection cost coefficient, information asymmetry causes the manufacturer to be unwilling to participate too much in remanufacturing. This stems from the manufacturer's necessity to pay a specific information rent $(\frac{(\eta_H-\eta_L)(q_r^{HSj})^2}{2}+\pi_0)$ to the retailer for access to its collection efficiency information. Additionally, it's worth noting that increased production of remanufactured products will cause manufacturers to pay more information rents.

Proposition 9 further demonstrates that irrespective of the manufacturer's encroachment strategy, asymmetric information diminishes the contract-specified new product output intended for the retailer with low collection cost coefficients. This reduction is a result of information asymmetry prompting the manufacturer to decrease remanufactured product production. However, due to the continued profitability of remanufactured product production driven by low remanufacturing costs, increases in wholesale prices for new products can be used by manufacturers to lower their competitive position, considering that remanufactured products cannibalize sales of new products.

Proposition 10. When reaching an equilibrium state, we find: (i) $\omega_r^{LBj} > \omega_r^{LSj}$ and $\omega_r^{HBj} < \omega_r^{HSj}$ for all $0 < c_r < c_r^{11}$. (ii) $\omega_n^{LBE} = \omega_n^{LSE}$ for all $0 < c_r < c_r^{11}$; When $c_r^2 < c_r < c_r^{1H}$, $\omega_n^{HBE} > \omega_n^{HSE}$.

Proposition 10 provides insights into the interaction between information asymmetry and wholesale prices. In comparison to situations where information is transparent, for the retailer with a low collection cost coefficient, the manufacturer prefers to set a lower wholesale price for remanufactured products in a separating contract aiming to better discern the true efficiency information of the retailer. Conversely, when a retailer's collection cost coefficient is high, a higher wholesale price is preferred by manufacturers. This strategic pricing approach is designed to encourage the retailer with low collection cost coefficients to select contracts aligned with its efficiency levels $(q_n^L, \omega_r^L, q_r^L)$, dissuading the retailer from concealing information and opting for the contract $(q_n^H, \omega_r^H, q_r^H)$.

Moreover, we note that when the retailer demonstrates high collection efficiency, the wholesale price for new products set by the manufacturer has not changed. This is because the pricing of the new product is affected by the output of the remanufactured products and the production costs of both products. In this case, neither of them has changed, which means that the price for new products will remain unchanged. However, for the retailer with low collection efficiency, when remanufacturing costs fall into the range between neither high nor low ($c_r^2 < c_r < c_r^{1H}$), information asymmetry makes manufacturers unwilling to produce too much of either product. In order to reduce the impact of information asymmetry, the manufacturer will be more inclined to produce new products. A lower wholesale price is adopted by the manufacturer to encourage retailers to enhance the sales of new products and thus obtain more profits.

6.2. How does cost efficiency asymmetry affect the profits of supply chain members

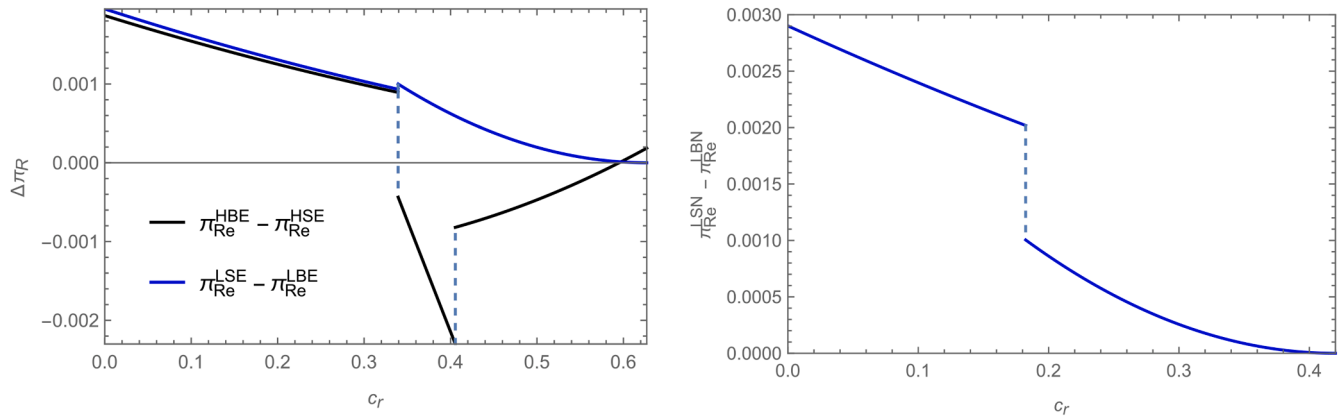
In order to analyze how information asymmetry affects the decision-making of supply chain members, the comparison of two parties' profits under perfect information and asymmetric information is studied, and the outcomes are summarized in Theorem 3.

Theorem 3. The comparison of the channel members' profits is as follows: (i) $\pi_M^{HBN} < \pi_M^{SN} < \pi_M^{LBN}$; When $c_r < c_r^6$, $\pi_M^{SE} < \pi_M^{LBE}$; When $c_r < c_r^7$, $\pi_M^{HBE} < \pi_M^{SE}$. (ii) $\pi_{Re}^{HSN} = \pi_{Re}^{HBN}$, $\pi_{Re}^{LSN} > \pi_{Re}^{LBN}$; $\pi_{Re}^{LSE} > \pi_{Re}^{LBE}$ when $c_r^2 < c_r < c_r^8$, $\pi_{Re}^{HBE} < \pi_{Re}^{HSE}$.

Theorem 3 indicates how the manufacturer' and retailer' profits are influenced by information asymmetry, depicted in Figs..7 and 8. First, the retailer with a low collection cost coefficient can consistently secure information fees through information asymmetry, augmenting its own profits. For the retailer with high collection cost coefficients, different encroachment modes of the manufacturer yield varying effects on its profits. When the manufacturer encroaches through new products, information asymmetry does not alter the retailer's profits, as its earnings primarily come from the reserved profits outlined in the contract. This conclusion is consistent with previous studies [54]. Conversely, when the manufacturer either refrains from encroachment or encroaches with remanufactured products, the impact of remanufacturing costs alters how information asymmetry influences retailer profits. When the remanufacturing costs are neither excessively high nor low, possessing private information increases the retailer's profit. However, when the remanufacturing costs are either very low or very high, the presence of information asymmetry actually diminishes the retailer's profit. This indicates that for retailers with low collection efficiency, holding private information does not consistently yield higher profits. In such cases, the manufacturer can reduce the impact of information asymmetry by allowing the retailer in the sales of new product, capitalizing on the cannibalization between product lines.

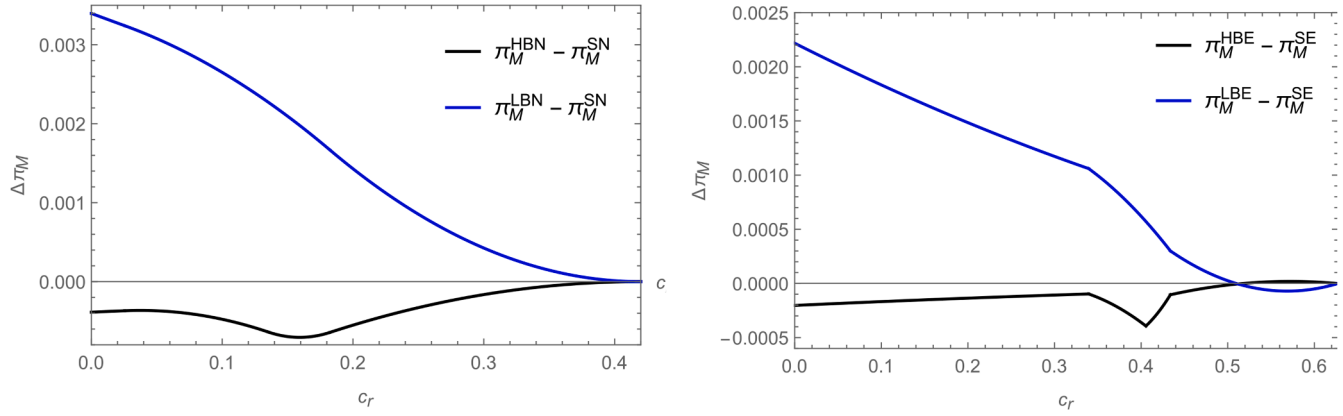
From the manufacturer's perspective, information asymmetry is a double-edged sword. When encroaching through new products, it can benefit the manufacturer when dealing with a retailer with low collection efficiency, but it can hurt profits when the retailer's collection efficiency is high. In such cases, retailers with low collection efficiency do not benefit from information asymmetry and may benefit more by disclosing their private information for the overall benefit of the supply chain. When the manufacturer does not open a direct channel or encroaches with remanufactured products, the effect of information asymmetry on the manufacturer's profits is influenced by remanufacturing costs.

When remanufacturing costs are low, the impact remains consistent, but when these costs are high, the affect reverses: information asymmetry benefits the manufacturer working with a high collection effi-



(a). Comparison of π_{Re}^{iBE} and π_{Re}^{iSE} **(b).** Comparison of π_{Re}^{LBN} and π_{Re}^{LSN}

Fig. 7. Comparison of retailer's profit under information symmetry and asymmetry.



(a). Comparison of π_M^{iBN} and π_M^{SN} **(b).** Comparison of π_M^{iBE} and π_M^{SE}

Fig. 8. Comparison of manufacturer's profit under information symmetry and asymmetry.

ciency retailer and harms profits when dealing with a low-efficiency retailer. This is because, for the retailer with low collection cost coefficients, the manufacturer tends to collect only a portion of used products for remanufacturing due to the extremely high cost of remanufacturing. This reduces the manufacturer's profit from remanufacturing but does not alter the strategy devised for the retailer with high collection cost coefficients. Consequently, under information asymmetry, the manufacturer's profit comprises two components, causing a slower decline in the manufacturer's profit (π_M^{SE}) compared to the decline rate under complete information (π_M^{LBE}). Similarly, as the strategy for the retailer with high collection cost coefficients remains unchanged, it holds that $\pi_M^{HBE} > \pi_M^{SE}$. This suggests that under conditions of asymmetric collection efficiency information, manufacturers can adapt their strategies by either adjusting remanufactured products collection efforts or modifying associated costs to suit different types of retailers.

6.3. How does cost efficiency asymmetry affect consumer surplus

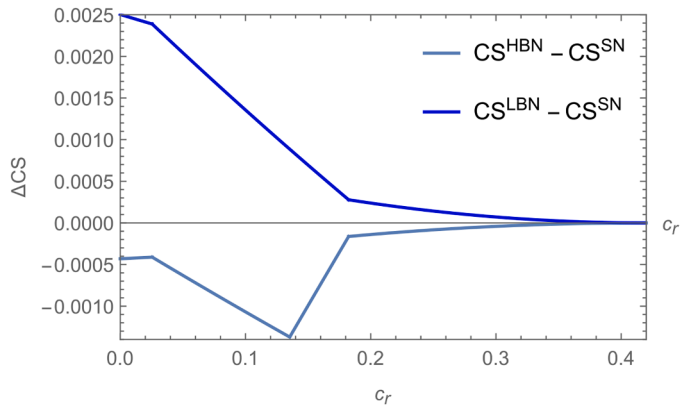
In this section, we explore how information asymmetry influences consumer surplus. As previous scholarly research suggests, consumer surplus can be defined as:

$$CS = \int_{\frac{p_n - p_r}{1-\alpha}}^{1} (v - p_n)\mathrm{d}v + \int_{\frac{p_r}{\alpha}}^{\frac{p_n - p_r}{1-\alpha}} (\alpha v - p_r)\mathrm{d}v$$

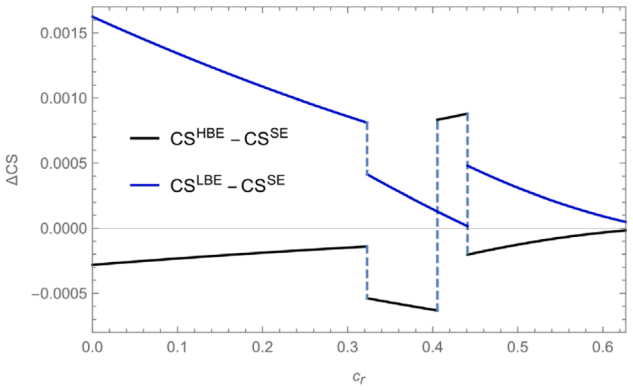
The first two terms represent the expected surplus that consumers obtain from the acquisition of new and remanufactured products. There is no difference in consumer surplus between the BE and BR models because the price and quantity of the product jointly determine consumer surplus. Consequently, we proceed to compare the consumer surplus in these two models: non-encroachment and encroachment with new products. Through this comparison, Observation 1 is derived.

Observation 1. By comparing the consumer surplus in different situations, we find that (i) $CS^{HBN} < CS^{SN} < CS^{LBN}$, $CS^{LBE} > CS^{SE}$, and when $c_r^{1H} < c_r < c_r^{1L}$, $CS^{HBE} > CS^{SE}$. (ii) $CS^{iBE} < CS^{iBN}$; $CS^{SE} < CS^{SN}$; $CS^{iBE} < CS^{SN}$;

Observation 1 outlines the impact of information asymmetry and manufacturer encroachment strategies on consumer surplus, as depicted in Figs 9-11. The analysis of consumer surplus shows that when the retailer's collection cost coefficient is low, regardless of how the manufacturer chooses the channel structure, information asymmetry always decreases the consumers' expected surplus. In such a scenario, a lower remanufactured product price can be adopted to discern the



(a). Comparison of CS^{iBN} and CS^{SN}



(b). Comparison of CS^{iBE} and CS^{SE}

Fig. 9. Comparison of consumer surplus under information symmetry and asymmetry.

retailer's true efficiency information. To counterbalance this loss, the manufacturer can use wholesale prices to force retailers to raise the retail prices of new products, leaving consumers to bear this burden. Consequently, it is consumers who ultimately bear the consequences of this adjustment. Additionally, when the retailer exhibits low collection efficiency, the manufacturer prioritizes production of new products. Information asymmetry results in an increased production of new products, resulting in reduced prices as well as an uptick in consumer surplus.

Fig. 10 affirms that irrespective of whether the retailer discloses its collection cost coefficient information, manufacturer encroachment enhances consumer surplus. This enhancement arises from the increased production of new products facilitated by encroachment. In cases where remanufacturing is profitable, the manufacturer can counteract the distortion deprived of information asymmetry in the decline of remanufactured product output. As a result, the prices of both products continued to fall. Therefore, consumers experience an expansion of their surplus. In situations where remanufactured products have cost advantages, the implementation of encroachment caused both parties to lower the prices for new products, which increases consumer surplus compared to scenarios without encroachment.

In our thorough examination of the joint influence of manufacturer encroachment and information asymmetry on consumer surplus, Fig. 11 illustrates that irrespective of whether the retailer has a high or low collection cost coefficient, the combined effect of information asymmetry and encroachment enhances consumer surplus, which is primarily ascribed to the increased production of both products by the

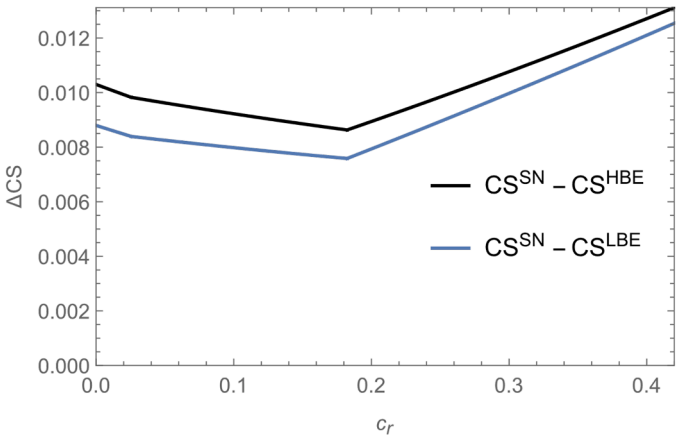
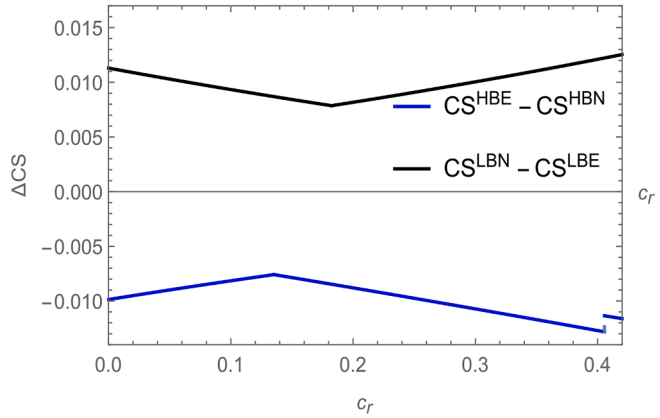
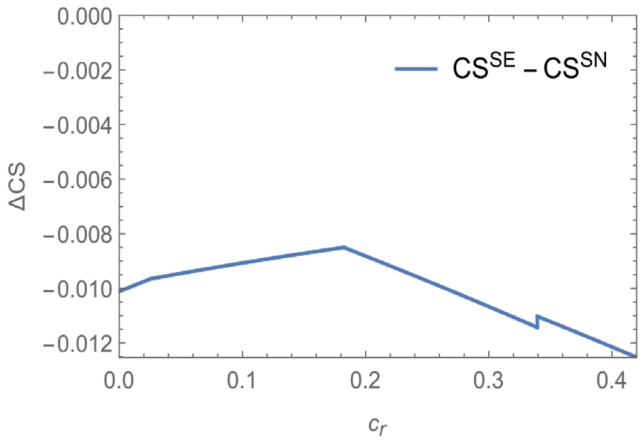


Fig. 11. Consumer surplus in modes SN and BE.



(a). Comparison of CS^{iBE} and CS^{iBN}



(b). Comparison of CS^{SN} and CS^{SE}

Fig. 10. Comparison of consumer surplus under different encroachment channel structures.

manufacturer under the encroachment strategy. Despite a potential rise in information costs due to heightened production of remanufactured products, the amplified profits from increased production of new products effectively offset these expenses. This results in the positive impact of encroachment on consumer surplus counteracting the negative effects caused by information asymmetry, ultimately leading to an augmentation in consumers' anticipated surplus.

6.4. Extension

In previous models, we assumed that manufacturers could only encroach on one type of product. However based on Zhang et al., [4] and real-world observations of network channels, we find that manufacturers may also sell both products directly to the customers. Therefore, we consider this case in this section and analyze it using numerical experiments. In addition, to better highlight the competition between channels and products, we consider how consumer channel preferences influence manufacturers' optimal decisions. In this case, the consumer demand function is: $p_{nI} = 1 - q_{nI} - \beta(q_{nD} + \alpha q_{rD})$, $p_{nD} = -\beta(-1 + q_{nD} + q_{nI} + \alpha q_{rD})$, $p_{rD} = -\alpha\beta(-1 + q_{nD} + q_{nI} + q_{rD})$, where I indicates indirect channel and D indicates direct channel. The profit of manufacturers and retailers can be expressed as:

$$\pi_M^{NR} = (p_{nD} - c_n)q_{nD} + (p_{rD} - c_r)q_{rD} + (\omega_n - c_n)q_{nI}$$

$$\pi_{Re}^{NR} = (p_{nI} - \omega_n)q_{nI} + bq_{rD} - \frac{\eta {q_{rD}}^2}{2}$$

Through using KKT and backward derivation, we can derive the equilibrium strategies of manufacturers and retailers under information symmetry and asymmetry. Given the calculation formula is too complicated, we use numerical analysis to examine how the consumers' channel preferences influence equilibrium decisions and compare the resulting profits with those of other models.

Fig. 12 illustrates that as consumer channel preferences increase, manufacturers' profits consistently rise, regardless of whether there is information symmetry or asymmetry. Second, the manufacturer's encroachment strategy choices are influenced by consumer channel preferences. Low consumer channel preference makes it impossible for the manufacturer to benefit from any form of encroachment. Conversely, when channel preference is high, all three encroachment channels will enhance profits. However, the optimal channel choice is influenced not only by remanufacturing costs but also by information asymmetry and differences in reserved profits.

When the remanufacturing cost is low, manufacturers opt to sell either new or remanufactured products through direct channels, with the choice depending on the reserved profit margin, consistent with our previous conclusions. When remanufacturing costs are high, manufacturers will choose to sell both products through direct channels. Comparing thresholds reveals that information asymmetry lowers this cost threshold, indicating that information asymmetry expands the viability of selling both products simultaneously to be the optimal strategy. Additionally, as consumer channel preferences increase, this threshold approaches a critical value, suggesting that with sufficiently high consumer channel preferences, manufacturers will ultimately avoid selling two products through direct channels.

7. Conclusion

7.1. Concluding remarks

The surge in e-commerce recently has led many manufacturers to venture into direct sales channels, intensifying competition with retailers. The manufacturers selling new and remanufactured products are considering how to mitigate direct competition between products. To navigate this challenge, some manufacturers opt for differentiated products through separate channels. Remanufactured product production involves collecting used products, often outsourced to retailers by manufacturers driven by profit considerations. Retailers' collection efficiency is treated as private information, known to manufacturers only within a specific probability distribution. This prompts an exploration of how information asymmetry in retailers' collection efficiency might influence manufacturers' decisions regarding encroachment strategies. To address this context, we establish a dual-channel closed-loop supply chain model to analyze how a manufacturer and a retailer make decisions based on profit maximization. We also delve into how manufacturer encroachment strategies affect the design of nonlinear contracts. Furthermore, we investigate how consumer surplus is influenced by both the strategies manufacturers employ in encroachment and information asymmetry.

The findings indicate that when remanufacturing has cost advantages, information asymmetry reduces the manufacturer's incentives to increase the quantity of two products. However, implementing an encroachment strategy can boost these production levels, mitigating the negative impacts of information asymmetry and increasing overall output. Furthermore, there is a cost threshold for the manufacturer to participate in remanufacturing, and information asymmetry lowers this threshold, suggesting that they will only opt for remanufacturing when costs are sufficiently low.

Information asymmetry affects manufacturers differently depending on the type of retailer involved. Specifically, when a retailer's collection efficiency is high, information asymmetry tends to diminish the manufacturer's profit. Conversely, if the retailer exhibits low collection efficiency, the manufacturer can benefit from the information asymmetry, aligning with previous findings. However, this dynamic changes when

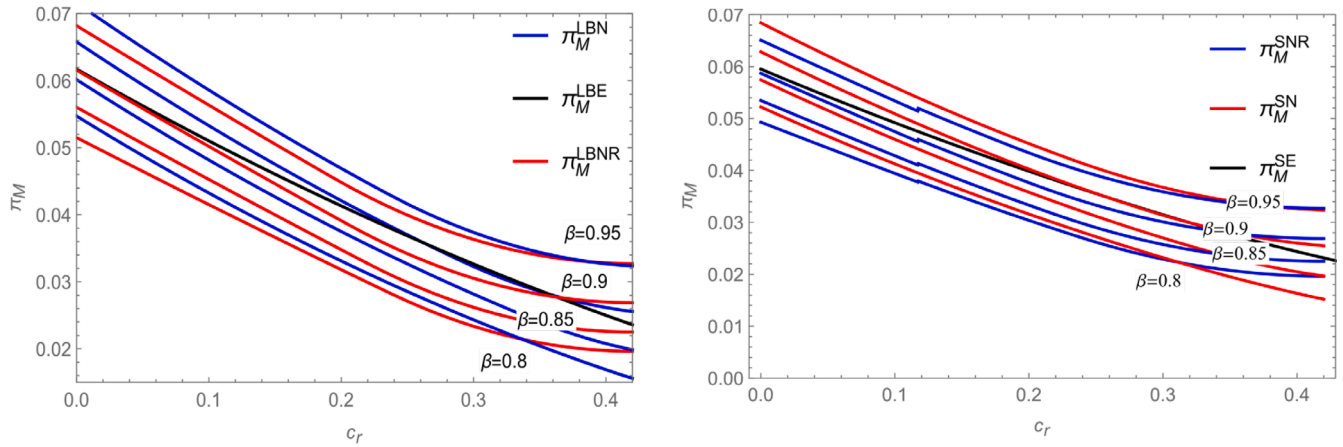


Fig. 12. Comparison of manufacturers' profits under information symmetry and asymmetry and different channel structures.

the manufacturer encroaches with remanufactured products, particularly when remanufacturing costs are sufficiently high. In these cases, information asymmetry may actually increase profits for the manufacturer working with a retailer that has high collection efficiency. Additionally, profit analysis reveals that retailers with high collection efficiency consistently benefit from information asymmetry. Nevertheless, if the manufacturer encroaches with remanufactured products and the remanufacturing costs fall within a specific range, retailers with low collection efficiency may see their profits deminish due to holding private information.

Moreover, we observe that the manufacturer encroachment strategies are influenced by consumer channel preference. Specifically, encroachment reduces manufacturer profits when consumer preference is low. The optimal channel choice is affected not only by remanufacturing cost but also by information asymmetry and reserved profit margins. When consumer channel preference is moderate and remanufacturing costs are low, manufacturers will prefer to sell either remanufactured products directly or both new and remanufactured products through direct channels, depending on the reserved profit margins. Conversely, if remanufacturing costs or consumer channel preferences are high, the manufacturer's choice is to encroach with new products or remanufactured products through direct channels. Information asymmetry enhances the feasibility of selling two products as optimal channels.

When the manufacturer chooses to encroach, both parties can achieve a win-win situation. Specifically, the best option for the manufacturer and retailer is to encroach with new products if the difference in the retailer's reserved profit is neither high nor low. Information asymmetry narrows the win-win scope for manufacturers but expands it for retailers.

In the final phase of our study, we evaluated how information asymmetry and encroachment strategies mutually affect consumer surplus. The results highlight that, from a consumer perspective, manufacturer encroachment consistently leads to positive outcomes. Additionally, under certain conditions, considering the cannibalization effect between products, information asymmetry can contribute to an improvement in consumers' expected surplus. Through a thorough comparison of these two factors, we conclude that manufacturers can increase consumer surplus through encroachment strategies and offset the negative impact of information asymmetry.

7.2. Managerial implications

The study conclusion found in this paper can offer both practical and theoretical insights into the management decisions of manufacturers and retailers. For manufacturers selling both new and remanufactured products, segmentating the market for these products (based on the manufacturer's encroachment choice) could be a more advantageous strategy, regardless of whether the retailer's collection efficiency is symmetric or not. The segmentation strategy depends on the profits the retailer earns from selling remanufactured products. When these profits are high, it indicates a stronger cannibalization effect of remanufactured products on new products, leading the manufacturer to sell remanufactured products through direct channels, and vice versa. As consumer awareness of environmental sustainability and carbon reduction continues to grow, the demand for remanufactured products is expanding rapidly. Therefore, distributing remanufactured products through direct channel may align better with market trends. In fact, brands like Apple and Samsung typically sell their remanufactured products only through official websites or third-party e-retailers. Second, manufacturers can reduce or even alter the impact of information asymmetry on their profits through encroachment. They can reduce the output of remanufactured products to minimize the impact of information rent or adjust the wholesale prices of new products, depending on the retailer's type and recycling strategies (full or partial collection, to control the production volume of both new and remanufactured products.

For retailers, irrespective of their type, manufacturer encroachment tends to reduce their profits. To counter this, retailers need to enhance the competitiveness of their retail channels by improving service quality and increasing advertising and marketing efforts. The managerial implications for the retailers depend on their collection efficiency and the structure of the manufacturer's channels. Specifically, when manufacturers sell new products through direct channels, retailers with high collection efficiency may withhold private information to gain information rents. They might also disseminate misleading information to shew the manufacturer's assessment of their collection efficiency. For retailers with low collection efficiency, concealing information does not directly alter their profits but increases the manufacturer's profits. Interestingly, from the perspective of overall supply chain, the private information of low-efficiency retailers can actually increase the overall profits of the supply chain.

Additionally, this model allows for potential win-win situations between manufacturers and retailers, as information asymmetry grants retailers greater bargaining power. Consequently, retailers with private information can negotiate for higher reservation profits from manufacturers. When manufacturers sell remanufactured products through direct channels, retailers with high collection efficiency can still earn information rents. For low-efficiency retailers, the benefit of processing private information is contingent on remanufacturing costs. Therefore, these retailers should accurately assess the manufacturer's strategy for selling remanufactured products. When remanufacturing costs are either low or high, low-efficiency retailers should conceal their private information to increase profits. However, when remanufacturing costs are neither high nor low, disclosing information and collaborating with manufacturers may be the better strategy for maximizing their gains.

7.3. Limitations and future research directions

The following directions warrant additional investigation in future research. First and foremost, we did not consider the costs associated with manufacturers establishing direct channels. Secondly, manufacturers might explore multi-channel strategies for collecting used products, including partnerships with third-party collection platforms or involving retailers in the collection process. Lastly, we consider remanufacturing costs to be fixed for all used products. In reality, since the integrity and quality of each product are different, the corresponding production cost should also be different. Therefore, future studies could benefit from examining how manufacturers make decisions in the face of quality uncertainty in used products.

CRediT authorship contribution statement

Senlin Zhao: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Mengxiang Wang:** Writing – original draft, Software, Formal analysis. **Qin Zhou:** Writing – review & editing, Supervision. **Xiqiang Xia:** Funding acquisition.

Declaration of competing interest

The authors report there are no competing interests to declare.

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Supplementary materials

Supplementary material associated with this article can be found, in

the online version, at doi:10.1016/j.omega.2024.103236.

Data availability

The authors confirm that data sharing is not applicable to this article as no new data were created or analyzed in this study.

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