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Pricing decision for recycling and remanufacturing supply chain considering consumer online consumption preferences and recycled products' quality

Yanhua Feng[a*]

[a]*School of Intelligent Manufacturing, Jianghan University, Wuhan,430056, PR China*

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A B S T R A C T

With the organic integration of the Internet and remanufacturing industry, traditional manufacturers can recycle used products and sell products (including new and remanufactured products) through e-commerce retail platforms. A recycling and remanufacturing supply chain with three members (manufacturer, e-commerce retail platform, third-party recycler) is constructed in this paper. Manufacturer has remanufacturing capabilities, and the e-commerce retail platform can provide logistics service. In response to the organic integration of the Internet and remanufacturing industry, we mainly consider the pricing decisions of consumer preferences for online sales models and recycled products' quality. Based on the impact of consumer used product recycling promotion activities on supply chain, a pricing game model was constructed for three recycling channels: manufacturer, e-commerce retail platform, and third-party recycler. Optimal pricing decision, logistics service level, used product recycling promotion intensity index, and recycling rate were obtained. Research has shown that consumer preferences can significantly improve supply chain logistics service level, pricing, market demand, and profits; Strengthening consumer awareness of remanufacturing used products and improving recycled products' quality can not only lower consumer purchase prices and expand consumer demand, but also increase profits of supply chain members.

1. Introduction

Nowadays, the swift advancement of Internet technology is progressively becoming an integral part of individuals' everyday existence. With the growth of online retail platforms and the growing trend of shopping on the internet, e-commerce retail platforms like Amazon have emerged as primary avenues for sales and reutilization. The continuous transformation from traditional remanufacturing supply chains to electronic remanufacturing supply chains has become an inevitable trend (Feng, Govindan, & Li, 2017). The speed of technological development in today's world is gradually accelerating, and residents' quality of life is constantly improving. The lifecycle of electronic devices such as refrigerators, personal computers, and televisions is gradually shortening, and the frequency of updates is constantly increasing (Islam, Abdullah, & Shahir, et al., 2016). Manufacturers of electronic devices like Huawei and Xiaomi have a technology product upgrade time frame set within a brief duration, for example, a couple of months (Yu, He, Li, Huang, & Zhu, 2014). Midea, Haier and other home appliance companies generally set the warranty period within 1-3 years to encourage users to exchange products for services. Enterprise like Hewlett-Packard and Intel have shortened their product development cycles from a few years to several months (Liu, Li, & Gu, 2021), and the replacement cycle for graphics cards is becoming shorter compared to the previous rate. The number of discarded electronic products is expected to increase further in the coming years (Tanskanen, 2013). Thus, remanufacturing of used products is a very effective approach to save the resources of earth and promote global economic circulation in today's era.

* Corresponding author
E-mail fengyh@jhun.edu.cn (Y. Feng)
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The integration of manufacturing, service, and resource recycling industries, as well as the development of residents' lives and information exchange, has accelerated swift advancement of the e-commerce retail platform, serving as the central electronic closed-loop supply chain. Swift advancement of information technology has significantly influenced the sales of products, the recycling of used products, and the efficiency of logistics. Consumers obtain the products produced by manufacturers through e-commerce retail platforms, and manufacturers recycle used products through various channels for remanufacturing (Gong, Chen, Wang, & Zhan, 2021). The management of recycling used products has made significant progress due to the emergence of online recycling channels. Because of spatial constraints and the distance involved, online recycling spans the distance between offline recycling, reducing the search costs required for recycling used products and other unnecessary costs incurred during the recycling process. Meanwhile, there is a significant improvement in the recycling efficiency through online recycling channels (Hong, Wang, & Zhang, 2013). Therefore, supported by an e-commerce retail platform, identification of better recycling channels has emerged as a primary focus within the realm of supply chain management.

Of course, due to varying levels of understanding among consumers about e-commerce retail platforms, especially among consumers of different age groups, the polarization situation is more prominent. Young people have a higher tendency towards online shopping and are more willing to accept new things, believing that it will bring them more convenience; Older people tend to have a lower acceptance of online shopping and a greater lack of understanding of the internet. Online shopping has brought countless conveniences to consumers and driven the development of more industries. The level of logistics service has gradually become an important indicator of consumer satisfaction with online shopping services. Similarly, in the increasingly developing recycling activities, the quality of logistics service will also provide users with unique and varied experiences. A more convenient and faster logistics service solution will increase the enthusiasm of users to recycle used products. Therefore, considering the influence of logistics service level on pricing of remanufacturing supply chain represents a crucially significant concern as well.

Supply chains with recycling and remanufacturing functions exhibit a considerable degree of uncertainty in contrast to traditional supply chains, particularly with regard to recycled products' quality. Recycled products' quality factors will have a direct impact on recycling and repurchase prices, remanufacturing costs, profits of nodes, and recycling rates. Recycling low-quality used products may bring significant costs to businesses. Given the circumstances, this paper will primarily concentrate on exploring three key issues:

I. How can one select more effective recycling channels with the guidance of e-commerce retail platform?

II. How do the differences in consumer preferences for sales channels and recycled products' quality affect the most efficacious pricing approach in the environment of e-commerce retail platform participation?

III. How do important parameters related to logistics service level and promotion of used product recycling affect optimal decision-making of participants?

The remainder of this paper is structured as follows. Section 2 encompasses a review of the existing literature. Based on problem description and modeling assumptions delineated in Section 3, numerous decision models are formulated in Section 4. In Section 5, numerical examples are employed to analyze and discuss the influence of parameter sensitivity. The final section presents conclusions and recommendations for future research undertakings.

2. Literature review

We organized and analyzed literature from the following five aspects.

2.1 Optimal pricing strategy for closed-loop supply chain (CLSC)

At present, some scholars have researched the optimal pricing strategy of CLSC and achieved some breakthroughs. Wang et al. (2018) discussed effect of bonus-penalty mechanisms on pricing strategy. Zhang, Wang and Liu (2015) conducted research on retail service and pricing choices. Huang et al. (2013) proposed a mathematical model that considered manufacturers optimizing enterprise profits under quantity and price constraints while producing new and remanufactured products. Companies frequently utilize remanufactured items and incorporate recycled materials into new products as a strategy to drive long-term revenue growth. Alqahtani et al. (2017) discovered that remanufacturing can leverage consumers' environmental preferences as a successful marketing tactic. Zhao et al. (2017) examined how manufacturers' remanufacturing strategies influence their choices of suppliers. In a study conducted by Wu (2012), the focus was on examining the competitive dynamics of pricing and service provision, comparing new products with remanufactured ones. Considering consumer preferences, Ferrer and Swaminathan (2010) researched the pricing approach of CLSC for electronic products with multiple cycles.

Currently, mainstream research on most supply chain related models assumes that manufacturers dominate. However, owing to the rapid progress of the retail industry, Wal-Mart, Gome, Suning and other powerful retailers have come to the forefront. In different supply chain channels, the corresponding positions of each member also vary significantly. Subramanian and Subramanyam (2012) pointed out through their research that an important shift in modern marketing channels was the shift of channel dominance from manufacturer to retailer. Eberhardt et al. (2020) studied the impact of power structure differences on pricing strategies in the context of duopoly. Huang and Wang (2018) researched influence of dominance on pricing tactics and recovery effectiveness in CLSC.

2.2 Selection of recycling channels

Savaskan et al. (2004) studied how manufacturers, as leaders, choose recycling channels based on the actual situation faced by enterprises. They set up some channels for recycling and determined that retailer recycling is most effective. In addition, several academics examined how the inclusion of competition among retailers affects choice of recycling channels, drawing from previous research (Savaskan & Van, 2006). In the process of choosing recycling avenues, Giovanni and Zaccour (2014) chose to discuss two circular environmental conditions. They found that only when a manufacturer has higher recycling costs, will the manufacturer will opt to delegate recycling business to other members of the supply chain. With Internet development in recent years, CLSC management is facing more opportunities and challenges. Against this backdrop, an increasing number of practitioners and researchers have noticed impact of the Internet on channels for recycling. However, most existing studies have been limited to offline recycling, and insufficient attention has been paid to the emerging online recycling. Several scholars have realized the potential of online recycling. They established models for online and offline recycling and compared them (Feng, Govindan, & Li, 2017, Li, Li, & Sun, 2019). Therefore, this paper considers the logistics service level offered by e-commerce retail platform, as well as consumer understanding and recognition of recycling throughout the entire used product recycling process, namely the effectiveness of used product recycling promotion, and the impact of these two situations on recycling channels.

2.3 Closed loop supply chain (CLSC) led by e-commerce retail platform

At present, many industries have started to carry out recycling business on e-commerce retail platforms. The academic community has also begun to pay attention to research on CLSC of e-commerce. Considering performance issues of CLSC in e-commerce, Tu and Yang (2013) constructed a performance evaluation index system for e-commerce platform; Afterwards, Zhou and Wan (2017) studied the impact of e-commerce on the supply chain performance of manufacturing enterprises. Considering decision-making and coordination of e-commerce supply chains, Yi (2009) researched three CLSC game models under supplier led, network platform led, and leaderless markets; Li et al. (2015) discovered manufacturer's repurchase strategy in e-commerce supply chain; Considering impact of traditional supply chains, Feng et al. (2017) found effects of two fee contracts and revenue sharing contracts on coordinated bidirectional recycling supply chain; Ji et al. (2017) studied the emission reduction behavior of members in both online and offline supply chains. Regarding recycling strategy for used products, especially the issue of recycling electrical and electronic products, Xu et al. (2017) analyzed impact of consumer willingness to purchase WEEE on the implementation of online recycling; Giri, Chakraborty, and Maiti (2017) constructed a dual channel CLSC model for e-commerce platform responsible for sales and recycling. They studied pricing strategy and recycling decisions. These studies involve issues related to the performance, operation, and coordination of e-commerce CLSC, enriching and improving the theoretical foundation of e-commerce CLSC. Some researchers have investigated structural assignment of online recycling, considering consumer understanding and recognition of recycling. However, based on real-life situations, the level of logistics service has an important influence on shopping and recycling both online for consumers. Few studies have considered this aspect.

2.4 Preferential behavior and market demand

At present, numerous researchers have examined the process of recycling and remanufacturing by focusing on consumer inclinations and market requirements (Feng, & Yu, 2023). Studies have indicated that individuals possess specific preferences and are open to paying extra charges for their preferred choices. Based on this premise, an analysis was conducted on the decision-making conduct of both producers and sellers (Xiong, Zhang, & Guo, 2014). However, previous research has indicated that due to differences in consumer behavior and cognitive abilities, there are varying levels of market demand for new and remanufactured products (He, Xu, Hu, & Yong, 2020). While new and remanufactured products' quality may be indistinguishable, consumers exhibit varying levels of awareness and willingness to invest in these two types of products. There is a common belief among consumers that the value of remanufactured products is not as high as that of new ones, leading to a lower willingness to pay for them (Feng, Xia, Yin, Wang, & Zhang, 2022). Ho and Zhang (2008) developed a just utility function to analyze secondary supply chains and highlighted that consumer preference for remanufactured products could significantly impact market demand for such items. Additionally, if remanufacturing process is highly transparent, consumers are more likely to buy remanufactured products at a premium price (Hazen, Overstreet, Jones-Farmer, & Field, 2012); Xiong et al. (2014) identified the most effective strategy mix for manufacturers and retailers in two different scenarios, while also examining how consumer environmental awareness influences retail prices. Yu et al. (2016) examined the impact of consumer environmental awareness on the effectiveness of optimal production green policies. Zhang, Wang, and You (2015) analyzed the optimal decisions for traditional and green products; Li et al. (2017) identified notable variations in the inclination to choose low-carbon goods based on values, age, income, and educational attainment levels. Considering low-carbon awareness of consumers, Xia et al. (2018) developed a manufacturer-led gaming model focused on low-carbon initiatives. Their findings indicate that the preference for low-carbon products among consumers can significantly boost the willingness of supply chain participants to invest in low-carbon industries and enhance their investment returns. During their investigation into the low-carbon supply chain, Wang et al. (2021) found that altruistic preference positively influences the enhancement of profitability and system efficiency for small and medium-sized manufacturers, while potentially having a detrimental impact on retailer profitability. Zhao and Xiao (2018) discussed the operational strategies of supply chain from the perspectives of channel preferences.

2.5 The recycled products' quality

The current research findings primarily center on the pricing aspect of reverse logistics, while ignoring the differences in recycled products' quality. Preliminary research suggests that all used products have the same quality status, and the cost and disposal methods for recycled products are also similar (Feng, Xia, Wang, & Zhang, 2022). However, consumers have significant differences in the length of time, frequency, environment, habits, and methods of using products. Recycled products' quality varies significantly. When it comes to remanufacturing or other disposal, different treatment methods should be established or chosen.

Wei et al. (2015) conducted research on pricing strategy under the circumstance that all recycled products can be remanufactured. Aydin et al. (2018) suggested that pricing of recycled materials and cost of remanufacturing are significantly influenced by the quality of the products being recycled. Taleizadeh et al. (2019) studied the influence of the uncertainty of recycled products' quality on repurchase price and cost of the remanufacturing process. They analyzed dynamic pricing and recycling strategies of remanufacturing enterprises using modal interval algorithms. The costs of recycling and remanufacturing in the supply chain depend on the quality or grade of the product recovered (Bhattacharya, Kaur, & Amit, 2018); Deng et al. (2017) observed that recovery rate and profits of manufacturers are influenced by recycled products' quality. Heydari et al. (2018) found that refurbishment capability and recycling quality will affect supply chain coordination; For the two-stage CLSC involving only one manufacturer and one retailer, Giri, Mondal, and Maiti (2017) discussed influence of recycled products' quality and pricing strategies on optimal decisions. Establishing theoretical models in the case of studying helps to be better applicable to the actual situation.

To address these issues, this paper explores pricing decisions in recycling and remanufacturing supply chain, taking into account consumers preferences for online sales mode and recycled products' quality. Organic combination of Internet and remanufacturing industry enables manufacturer to have remanufacturing capabilities, and e-commerce retail platform can provide logistics service. Four game models were established based on the influence of logistics service level, the quality of recycled products, and used product recycling promotion on various recycling channels. According to our research results, we have drawn the best price decisions, logistics service levels, promotion intensity of used recycling, and recycling rates. These aspects are of great significance for the entire supply chain decisions.

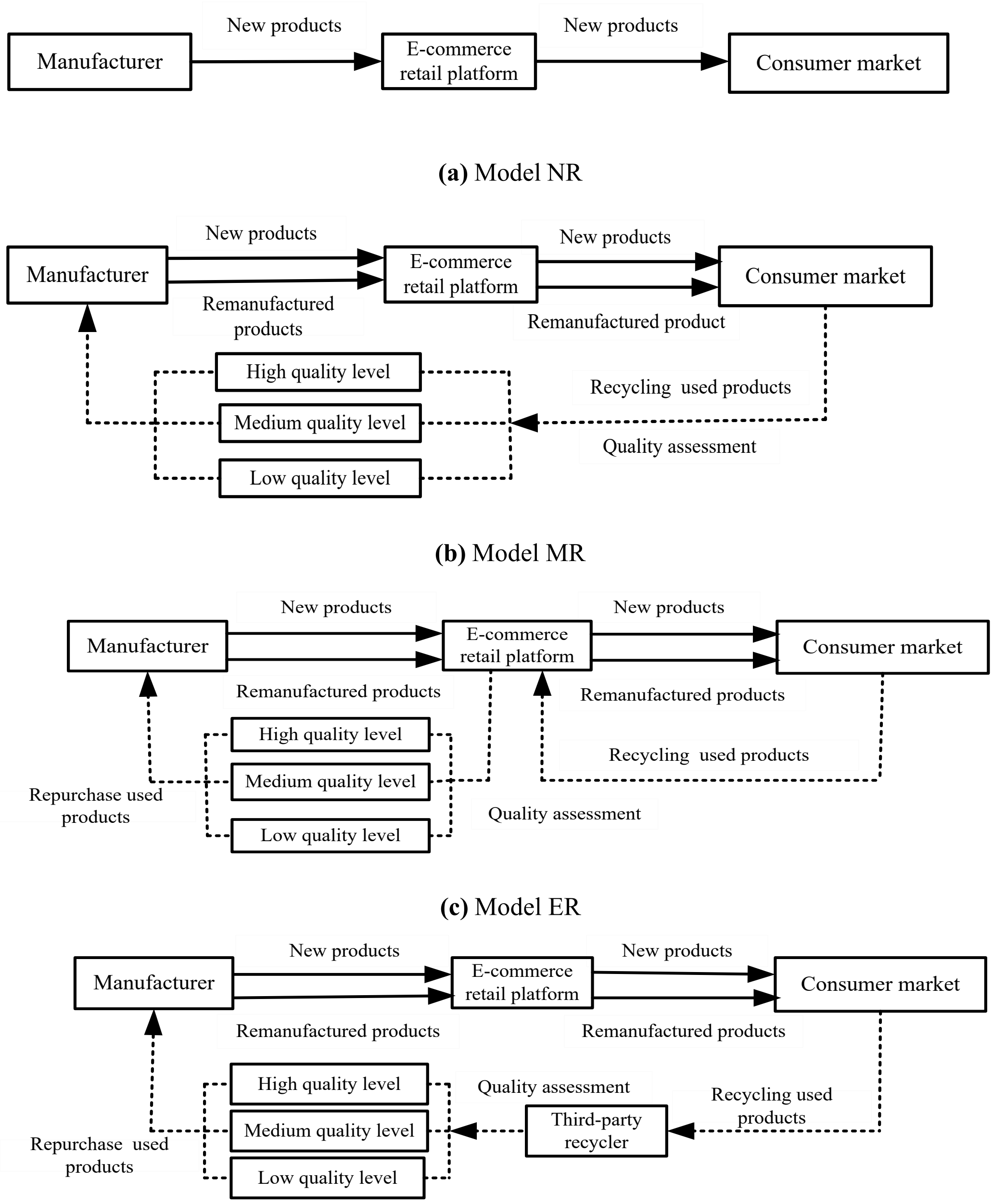
3. Model background description

3.1 Problem description

We have established a recycling and remanufacturing supply chain, which involves three members: third-party recycler, manufacturer and e-commerce retail platform. The manufacturer is responsible for manufacturing new products and remanufacturing used ones. Manufacturer offers both new and remanufactured products to e-commerce retail platform at an equal wholesale price. E-commerce retail platform promotes and sells products through online self-operated stores and provides product logistics service. Shoppers have developed a level of comprehension regarding the worth and capabilities of the merchandise through exploring the independently managed stores on the internet platform. Finally, they consider whether to purchase the product based on its selling price and logistics service level.

Manufacturer can recycle used products of varying quality levels from consumers through three channels: manufacturer recycling (model MR), e-commerce retail platform recycling (model ER), and third-party recycling (model RR). There is no recycling channel (model NR) as the control model, which does not have any recycling and remanufacturing capabilities. Other models have different recycling and remanufacturing options. The structure of the four models is shown in Fig. 1. We compared four models to find out the best pricing strategy and the method to maximize profits.

In model NR, due to the lack of any recycling channels in the supply chain, the manufacturer is unable to effectively obtain used products. Therefore, manufacturer cannot carry out remanufacturing activities. Manufacturer only produces new products. E-commerce retail platform acquires these products through wholesaling. Then, e-commerce retail platform sells these products online to consumers. In models MR, ER, and RR, the responsibility for production of both new and remanufactured products lies with the manufacturer. E-commerce retail platform can purchase two types of products from manufacturer. However, in model MR, manufacturer recycles used products of varying quality levels from consumers. The entire recycling channel and strategy are controlled and determined by the manufacturer; In model ER, e-commerce retail platform recycles used materials of various quality levels from consumers, and manufacturer repurchases used products from e-commerce retail platform for remanufacturing activities. The entire recycling channel and strategy are controlled and determined by e-commerce retail platform; In model RR, third-party recycler recycles used materials of various quality levels from consumers, and manufacturer repurchases used products from e-commerce retail platform for remanufacturing activities. The entire recycling channel and strategy are controlled and determined by third-party recycler. In models MR, ER, and RR, quality and selling price between two types of products are the same. Consumers cannot distinguish them on e-commerce retail platform and can be considered as the same type of product.



(a) Model NR

(b) Model MR

(c) Model ER

(d) Model RR

Fig. 1. Model structure diagram: (a) NR, (b) MR, (c) ER, (d) RR

3.2 Symbol description and model assumptions

The symbols and their explanations have been listed in Table 1-3 in detail.

Table 1
Indices

Index	Define
i	i=1, 2, 3, which represent used products with high, medium, and low-quality levels respectively;
j	j=NR, MR, ER, RR, which respectively represent no recycling channel, manufacturer recycling channel, e-commerce retail platform recycling channel, and third-party recycling channel.

Table 2
Parameters

Parameter	Define
c_n	The cost per unit for manufacturing new products;
γ	Elasticity coefficient of logistics service level;
η	Repurchase price at which the manufacturer buys back used products from e-commerce retail platform or third-party recycler;
b	Unit recycling price from consumer market through recycling party;
τ	Coefficient of consumer preference for e-commerce sales models;
c_z	The cost per unit for manufacturing remanufactured products;
c_i	The cost of remanufacturing pre-owned items with a certain level i of quality;
h	Consumer response coefficient to promotional activities for recycling used products;
q_i	The proportion of unit used products with a quality grade of i after disassembly;
c_o	The cost savings per unit for manufacturing remanufactured products compared to new ones, namely, $c_o = c_n - c_z$;
π	Cost elasticity coefficient of logistics service level.

Table 3
Variables

Variable	Define
N^j	The level of recycling promotion intensity index determined by the recycling party in model j;
w^j	Wholesale price in model j;
d^j	Demand for new and remanufactured products by consumers in model j;
p^j	Retail price in model j;
G^j	The recovery rate in model j;
f_m^j	Profit function of manufacturer in model j;
D^j	Logistics service level of e-commerce retail platform in model j;
f_B^j	Profit function of e-commerce retail platform in model j;
f_R^j	Profit function of third-party recycler in model j;
f^j	Total profit function of system in model j.

Based on modeling needs, we will proceed with seven logical assumptions.

Assumption 1 Cost of producing new products exceeds that of remanufactured ones.

Assumption 2 For convenience of calculation, total market size is set to ϕ and standardized, i.e. $\phi = 1$.

Assumption 3 In model j, the total logistics service cost of e-commerce retail platform is $\frac{1}{2}\pi(D^j)^2$ (Zhao, & Wei, 2014).

Assumption 4 The demand function serves as the manifestation of product demand within the consumer market: $d^j = 1 - \frac{p^j - \gamma D^j}{\tau}$

Assumption 5 In order to receive a more positive response from consumers and obtain more used products, recycling companies usually increase their promotion of used product recycling before recycling, such as advertising in prosperous areas, organizing recycling activities, and providing promotional training to employees. The response of consumers to the promotion of recycling these used products will significantly impact the recycling rate. Therefore, the recovery rate function is determined as follows, $G^j = hN^j$. Meanwhile, according to the research of Giovanni and Zaccour (2014), the cost of promotional activities is $\frac{1}{2}(N^j)^2$ in model j.

Assumption 6 Unit used products can be divided into three quality levels after disassembly, such as high, medium, and low, with ratios of q_1, q_2, and q_3. They are satisfied $\sum_{i=1}^{3} q_i = 1$(Liu, Qin, Shen, Zhang, & Chang, 2020). Recycled products' quality that are disassembled relies on that of the used products provided by consumers to recycling facility. The remanufacturing cost c_i corresponding to used products with a quality level of i satisfies the following relationship, $c_1 < c_2 < c_3$. The average production cost of remanufactured products per unit is $c_z = \sum_{i=1}^{3} q_i c_i$.

Assumption 7 The repurchase price η for manufacturer to repurchase used products from e-commerce retail platform or third-party recycler is related to c_o and b , which satisfies the following relationship $\eta = \frac{c_o+b}{2}$.

4. Model construction and solution

4.1 No recycling model (model NR)

In model NR, e-commerce retail platform first determines the $p^{NR}$and D^{NR}; Manufacturer determines the w^{NR}. Therefore, profit equations for them can be presented as Eq. (1) and Eq. (2).

$$f_m^{NR} = (w^{NR} - c_n)(1 - \frac{p^{NR} - \gamma D^{NR}}{\tau}) \tag{1}$$

$$f_B^{NR} = (p^{NR} - w^{NR})(1 - \frac{p^{NR} - \gamma D^{NR}}{\tau}) - \frac{1}{2}\pi(D^{NR})^2 \tag{2}$$

Proposition 1 In model NR, the equilibrium outcomes of e-commerce retail platform and manufacturer are outlined in Eqs. (3-6).

$$w^{NR*} = \frac{\pi\tau^2 + 3\pi\tau c_n - c_n\gamma^2}{4\pi\tau - \gamma^2} \tag{3}$$

$$s^{NR*} = \frac{\gamma(\tau - c_n)}{4\pi\tau - \gamma^2} \tag{4}$$

$$p^{NR*} = \frac{3\pi\tau^2 + \pi\tau c_n - c_n\gamma^2}{4\pi\tau - \gamma^2} \tag{5}$$

$$d^{NR*} = \frac{\pi(\tau - c_n)}{4\pi\tau - \gamma^2} \tag{6}$$

The profits are as Eqs. (7-9).

$$f_m^{NR*} = \frac{\tau\pi^2(\tau - c_n)^2}{(4\pi\tau - \gamma^2)^2} \tag{7}$$

$$f_B^{NR*} = \frac{\pi(\tau - c_n)^2}{2(4\pi\tau - \gamma^2)} \tag{8}$$

$$f^{NR*} = \frac{\pi(6\pi\tau - \gamma^2)(\tau - c_n)^2}{2(4\pi\tau - \gamma^2)^2} \tag{9}$$

The supporting evidence can be found in Appendix A.

4.2 Manufacturer recycling model (model MR)

In model MR, e-commerce retail platform first determines the $p^{MR}$and D^{MR}; Manufacturer determines the $w^{MR}$and N^{MR}. Consequently, profit equations for them can be denoted by Eq. (10) and Eq. (11).

$$f_m^{MR} = [w^{MR} - c_n + (c_o - b)hN^{MR}](1 - \frac{p^{MR} - \gamma D^{MR}}{\tau}) - \frac{1}{2}(N^{MR})^2 \tag{10}$$

$$f_B^{MR} = (p^{MR} - w^{MR})(1 - \frac{p^{MR} - \gamma D^{MR}}{\tau}) - \frac{1}{2}\pi(D^{MR})^2 \tag{11}$$

Proposition 2 In model MR, the equilibrium outcomes of e-commerce retail platform and manufacturer are outlined in (12) - (16), where, $A = \pi h^2(c_o - b)^2$.

$$N^{MR*} = \frac{h\pi(\tau - c_n)(c_o - b)}{4\pi\tau - \gamma^2 - 2A} \tag{12}$$

$$w^{MR*} = \frac{c_n(3\pi\tau - \gamma^2 - 2A) + \tau(\pi\tau - 2A)}{4\pi\tau - \gamma^2 - 2A} \tag{13}$$

$$p^{MR*} = \frac{c_n(\pi\tau - \gamma^2) + \tau(3\pi\tau - 2A)}{4\pi\tau - \gamma^2 - 2A} \tag{14}$$

$$D^{MR*} = \frac{\gamma(\tau - c_n)}{4\pi\tau - \gamma^2 - 2A} \tag{15}$$

$$d^{MR*} = \frac{\pi(\tau - c_n)}{4\pi\tau - \gamma^2 - 2A} \tag{16}$$

The profits are detailed in expressions (17) - (19).

$$f_m^{MR*} = \frac{\pi(2\pi\tau - A)(\tau - c_n)^2}{2(4\pi\tau - \gamma^2 - 2A)^2} \tag{17}$$

$$f_B^{MR*} = \frac{\pi(\tau - c_n)^2}{2(4\pi\tau - \gamma^2 - 2A)^2} \tag{18}$$

$$f^{MR*} = \frac{\pi(6\pi\tau - 3A - \gamma^2)(\tau - c_n)^2}{2(4\pi\tau - \gamma^2 - 2A)^2} \tag{19}$$

The supporting evidence can be found in Appendix **B**.

4.3 E-commerce retail platform recycling model (model ER)

In model ER, first, e-commerce retail platform determines p^{ER}, D^{ER}, and N^{ER}; Then, manufacturer determines the w^{ER}. Hence, profit equations for them can be expressed as Eq. (20) and Eq. (21).

$$f_m^{ER} = [w^{ER} - c_n + (c_o - \eta)hN^{ER}](1 - \frac{p^{ER} - \gamma D^{ER}}{\tau}) \tag{20}$$

$$f_B^{ER} = [p^{ER} - w^{ER} + (\eta - b)hN^{ER}](1 - \frac{p^{ER} - \gamma D^{ER}}{\tau}) - \frac{1}{2}(N^{ER})^2 - \frac{1}{2}\pi(D^{ER})^2 \tag{21}$$

Proposition 3 In model ER, the equilibrium outcomes of e-commerce retail platform and manufacturer are outlined in (22) - (26), where, $A = \pi h^2(c_o - b)^2$.

$$N^{ER*} = \frac{h\pi(\tau - c_n)(c_o - b)}{4\pi\tau - \gamma^2 - A} \tag{22}$$

$$w^{ER*} = \frac{c_n[3\pi\tau - \gamma^2 - \pi h^2(c_o - b)(c_o - \eta)] + \pi\tau[\tau - h^2(c_o - b)(c_o - \eta)]}{4\pi\tau - \gamma^2 - A} \tag{23}$$

$$p^{ER*} = \frac{c_n(\pi\tau - \gamma^2) + \pi\tau[3\tau - h^2(c_o - b)^2]}{4\pi\tau - \gamma^2 - A} \tag{24}$$

$$D^{ER*} = \frac{\gamma(\tau - c_n)}{4\pi\tau - \gamma^2 - A} \tag{25}$$

$$d^{ER*} = \frac{\pi(\tau - c_n)}{4\pi\tau - \gamma^2 - A} \tag{26}$$

The profits are detailed in expressions (27) - (29).

$$f_m^{ER*} = \frac{\pi^2\tau(\tau - c_n)^2}{(4\pi\tau - \gamma^2 - A)^2} \tag{27}$$

$$f_B^{ER*} = \frac{\pi(\tau - c_n)^2}{2(4\pi\tau - \gamma^2 - A)} \tag{28}$$

$$f^{ER*} = \frac{\pi(\tau - c_n)^2(6\pi\tau - A - \gamma^2)}{2(4\pi\tau - \gamma^2 - A)^2} \tag{29}$$

The supporting evidence can be found in Appendix **C**.

4.4 Third-party recycler recycling model (model RR)

In model RR, first, e-commerce retail platform decides the p^{RR} and D^{RR}; Then, manufacturer decides on the w^{RR}; Third-party recycler determines the N^{RR} in the end. Hence, profit equations for them can be expressed as Eq. (30), Eq. (31), and Eq. (32).

$$f_m^{RR} = [w^{RR} - c_n + (c_o - \eta)hN^{RR}](1 - \frac{p^{RR} - \gamma D^{RR}}{\tau}) \tag{30}$$

$$f_B^{RR} = (p^{RR} - w^{RR})(1 - \frac{p^{RR} - \gamma D^{RR}}{\tau}) - \frac{1}{2}\pi(D^{RR})^2 \tag{31}$$

$$f_R^{RR} = (\eta - b)hN^{RR}(1 - \frac{p^{RR} - \gamma D^{RR}}{\tau}) - \frac{1}{2}(N^{RR})^2 \tag{32}$$

Proposition 4 In model RR, equilibrium outcomes of supply chain members are outlined in Eqs. (33-37).

$$N^{RR*} = \frac{h\pi(\tau - c_n)(\eta - b)}{4\pi\tau - \gamma^2 - 4\pi h^2(c_o - \eta)(\eta - b)} \tag{33}$$

$$w^{RR*} = \frac{\pi\tau[\tau - 2h^2(c_o - \eta)(\eta - b)] + c_n[3\pi\tau - \gamma^2 - 2\pi h^2(c_o - \eta)(\eta - b)]}{4\pi\tau - \gamma^2 - 4\pi h^2(c_o - \eta)(\eta - b)} \tag{34}$$

$$p^{RR*} = \frac{\pi\tau[3\tau - 4h^2(c_o - \eta)(\eta - b)] + c_n(\pi\tau - \gamma^2)}{4\pi\tau - \gamma^2 - 4\pi h^2(c_o - \eta)(\eta - b)} \tag{35}$$

$$D^{RR*} = \frac{\gamma(\tau - c_n)}{4\pi\tau - \gamma^2 - 4\pi h^2(c_o - \eta)(\eta - b)} \tag{36}$$

$$d^{RR*} = \frac{\pi(\tau - c_n)}{4\pi\tau - \gamma^2 - 4\pi h^2(c_o - \eta)(\eta - b)} \tag{37}$$

The profits are detailed in expressions (38) - (41).

$$f_m^{RR*} = \frac{\pi^2(\tau - c_n)^2[\tau - h^2(c_o - \eta)(\eta - b)]}{[4\pi\tau - \gamma^2 - 4\pi h^2(c_o - \eta)(\eta - b)]^2} \tag{38}$$

$$f_B^{RR*} = \frac{\pi(\tau - c_n)^2}{2[4\pi\tau - \gamma^2 - 4\pi h^2(c_o - \eta)(\eta - b)]} \tag{39}$$

$$f_R^{RR*} = \frac{\pi^2h^2(\tau - c_n)^2(\eta - b)^2}{2[4\pi\tau - \gamma^2 - 4\pi h^2(c_o - \eta)(\eta - b)]^2} \tag{40}$$

$$f^{RR*} = \frac{\pi(\tau - c_n)^2[6\pi\tau - \gamma^2 - \pi h^2(6c_o - 7\eta + b)(\eta - b)]}{2[4\pi\tau - \gamma^2 - 4\pi h^2(c_o - \eta)(\eta - b)]^2} \tag{41}$$

The supporting evidence can be found in Appendix **D**.

Analyzing Propositions 1 to 4, we obtain Corollary 1 and Corollary 2.

Corollary 1 Among the three different recycling channels, consumers' understanding and recognition of used product recycling promotional activities have different impacts on logistics service level D^{j*}, product market demand d^{j*}, and retail prices p^{j*}. Specific results are as follows, where j=MR, ER, RR.

$$\frac{\partial D^{j*}}{\partial h} > 0, \qquad \frac{\partial d^{j*}}{\partial h} > 0, \frac{\partial p^{j*}}{\partial h} < 0$$

The supporting evidence can be found in Appendix **E**.

Corollary 1 indicates that among the three different recycling channels, as h increases, i.e. with the improvement of consumer understanding and recognition of used product recycling promotional activities, the logistics service level and demand for products by consumers increase, but retail price decreases. Market demand relies on retail price and logistics service level of the product, which is negatively correlated with retail price and positively correlated with logistics service level. Therefore, in supply chain system participated in by e-commerce retail platform, manufacturer, and third-party recycler in the recycling sector should increase their promotional activities for the recycling of used products. This not only allows consumers to enjoy better logistics service, but also allows them to purchase products at lower prices. It brings advantages to customers; Expanding market demand for products is beneficial for sustained development of e-commerce retail platform and manufacturer.

Corollary 2 Regardless of the recycling channel we use, the level of consumer understanding and recognition of used product recycling promotional activities will affect the profits. The specific results are as follows, where, j =MR, ER, RR.

$$\frac{\partial f_m^{j*}}{\partial h} > 0, \quad \frac{\partial f_B^{j*}}{\partial h} > 0, \quad \frac{\partial f^{j*}}{\partial h} > 0$$

The demonstration of Corollary 2 employs a comparable method to the one adopted in Corollary 1, and we will not elaborate on it here.

Corollary 2 states that regardless of the recycling channel we use, as h increases, that is, with the increase in consumer understanding and recognition of used product recycling promotional activities, manufacturer profit f_m^{j*}, e-commerce retail platform profit f_B^{j*}, and profit of supply chain system f^{j*} have seen an overall increase. In the supply chain system, before recycling used products, the recycling party should increase the promotion of used product recycling, such as placing public service advertisements for used products in prosperous areas, organizing recycling activities, and providing promotional training to employees.

Further analyzing Propositions 1 to 4, we obtain Corollary 3 and Corollary 4.

Corollary 3 （1）$D^{MR*} > D^{ER*} = D^{RR*} > D^{NR*}$;

（2）$d^{MR*} > d^{ER*} = d^{RR*} > d^{NR*}$;
（3）$p^{ER*} = p^{RR*} > p^{MR*}$;
（4）$N^{MR*} > N^{ER*} > N^{RR*}$;
（5）$w^{NR*} > w^{ER*} = w^{RR*} > w^{MR*}$.

The proof can be found in Appendix **F**.

Corollary 3 indicates that among the models established in the paper, the model MR exhibits the highest level of the D^{MR*} and d^{MR*}, followed by model ER and model RR. Model NR is ranked last in terms of D^{MR*} and d^{MR*}. The p^{MR*} and w^{MR*} in model MR are lowest, followed by model ER and model RR, and finally the model NR. When the responsibility for recycling falls on the manufacturer or an e-commerce retail platform, the advertising intensity index levels N^{MR*} and N^{ER*} are the same, and higher than the N^{RR*}. In the recycling process managed by the manufacturer, used products are directly obtained from consumers. Compared to new products, remanufacturing saves costs, greatly incentivizes manufacturer to participate in promotional activities for used products and is willing to lower wholesale prices. E-commerce retail platform purchases products at lower wholesale prices, prompting them to sell online to consumers at lower retail prices and is willing to improve logistics service level. Consumers purchase products at lower prices and enjoy higher logistics service, making them the ultimate beneficiaries. Therefore, the demand in the consumer market has further expanded.

Corollary 4 （1）$f_m^{MR^*} > f_m^{ER^*} > f_m^{RR^*} > f_m^{NR^*}$;

（2）$f_B^{MR^*} > f_B^{ER^*} = f_B^{RR^*} > f_B^{NR^*}$;

(3) $f^{MR^*} > f^{ER^*} > f^{RR^*} > f^{NR^*}$.

The demonstration of Corollary 4 employs a comparable method to the one adopted in Corollary 3, and we will not elaborate on it here.

Corollary 4 states that among the four models, comparing $f_m^{MR^*}$, $f_B^{MR^*}$, and f^{MR^*}, the profits from model MR are highest, followed by model ER, then model RR, and finally model NR. Compared to traditional forward supply chains, regardless of the type of used product recycling channel used, the profits of supply chain members have all experienced enhancement. Consequently, supply chain of recycling and remanufacturing assumes a vital role in facilitating sustainable development of manufacturing industry.

By combining Corollary 3 with Corollary 4, one can draw the conclusion that when using the manufacturer's recycling channel, consumers can enjoy the optimal level of logistics service and purchase products at the lowest price. This stimulated the enthusiasm of consumers to engage in recycling initiatives. When retail prices decrease, market demand increases. Meanwhile, profits of manufacturer and e-commerce retail platform are increased, thereby increasing profits of the supply chain system. Therefore, when e-commerce retail platform engages in online sales, it is of the greatest advantage for manufacturer to undertake the responsibility of recycling discarded products. If manufacturer cannot establish effective recycling channels, e-commerce retail platform taking on the responsibility of recycling used products is also a good choice.

5. Numerical analysis and discussion

Through the establishment of four supply chain decision frameworks, we can tackle the equilibrium selections of supply chain members under no recycling channels and different recycling channels. Due to the complexity of some solution results, it is not possible to visually observe the relationships between variables. This paper employs numerical analysis methodologies to undertake a more profound exploration of decision variables and fluctuations in supply chain profitability. In Table 4, we provide a series of reasonable parameter values based on the previous assumptions.

Table 4
The numerical example of parameters

c_n	b	γ	π	c_1	c_2	c_3	τ	h
0.45	0.02	0.6	1	0.18	0.2	0.22	0.5	0.6

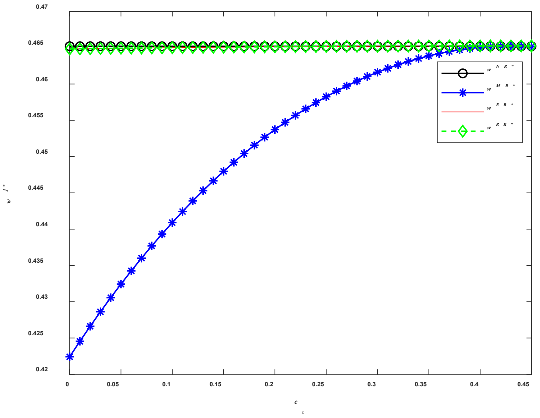
Assuming that when the quality of recycled products is all medium, that is, when $q_1 = 0, q_2 = 1, q_3 = 0,\ c_z = 0.2,\ c_0 = 0.25, \eta = 0.135$. The optimal solutions for variables are shown in Table 5.

Table 5
The most efficacious resolution for medium quality level

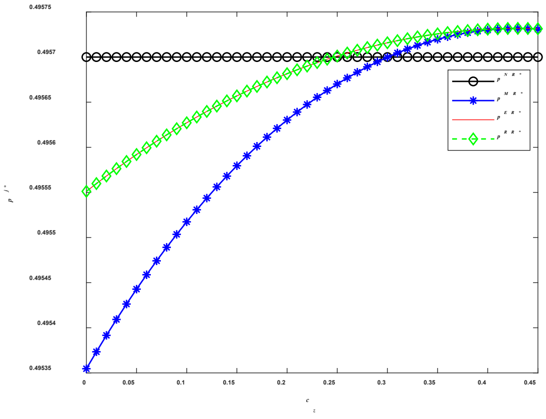
Model$j$	N^{j*}	D^{j*}	w^{j*}	p^{j*}	d^{j*}	G^{j*}	$f_m^{j*} \times 10^4$	$f_B^{j*} \times 10^4$	$f_R^{j*} \times 10^6$	$f^{j*} \times 10^4$
NR	-	0.0183	0.4652	0.4958	0.0305	-	4.6475	7.6220	-	12.2695
MR	0.0043	0.0187	0.4537	0.4956	0.0312	0.0026	4.7784	7.8032	-	12.5816
ER	0.0043	0.0185	0.4651	0.4957	0.0308	0.0026	4.7574	7.7115	-	12.4689
RR	0.0021	0.0185	0.4651	0.4957	0.0308	0.0013	4.7121	7.7115	2.2650	12.4462

5.1 The effects of quality differences in recycled product on the supply chain

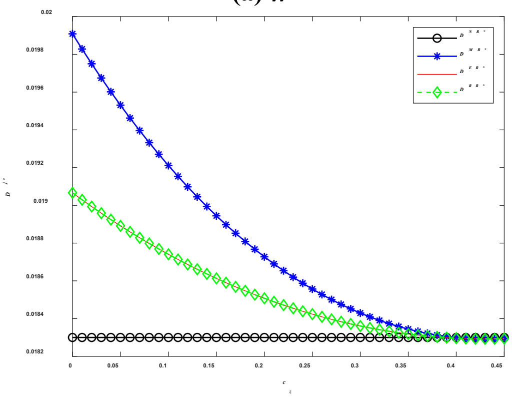
This section analyzes the effects of differences in recycled products' quality on optimal wholesale price, retail price, logistics service level, recycling promotion index level, demand, and profit. We compare the optimal results mentioned above. Fig. 2 shows effects of differences in recycled products' quality on wholesale prices, retail prices, logistics service level, and demand. When proportion of high-quality recycled products q_1 increases, unit cost c_z of manufacturer producing remanufactured products decreases. Regardless of the recycling channel, as c_z decreases, the wholesale and retail prices decrease. This indicates that the higher recycled products' quality, the lower remanufacturing cost for manufacturer, which motivates them to lower wholesale prices for products; Correspondingly, benefiting e-commerce retail platform also lower retail prices, making consumers ultimate beneficiaries. In the end, this has greatly increased market demand. At the same time, consumers can enjoy better logistics service by providing high-quality used products, stimulating their participation in recycling activities and providing high-quality recycling. High-quality recycling of used products can actively promote the development of the remanufacturing industry. For the same c_z, the $w^{MR*}$and $p^{MR*}$of the product are far lower than other values, while the D^{MR*} and $d^{MR*}$are far higher than other values. Therefore, when recycled products' quality is constant, the manufacturer's recycling approach is the most ideal. From perspective of change rate, with the change of c_z, w^{MR*}, p^{MR*}, D^{MR*}, and d^{MR*}have the fastest change rate. This implies that when the manufacturer assumes accountability for recycling used items, the variations in recycled products' quality exert the most significant influence on wholesale prices, retail prices, logistics service level, and demand sensitivity.



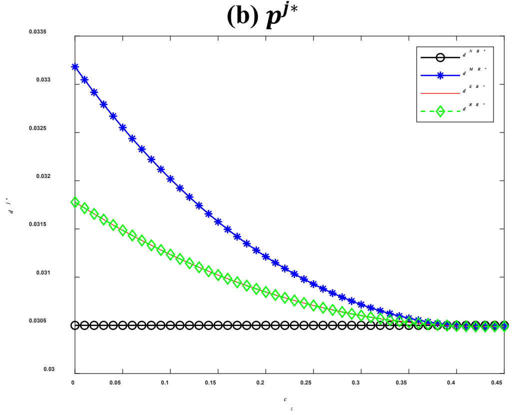
(a) w^{j*}



(b) p^{j*}



(c) D^{j*}

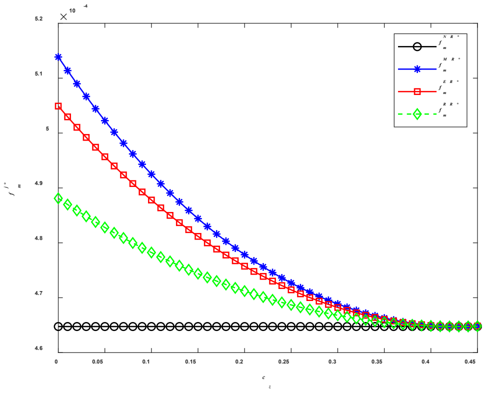


(d) d^{j*}

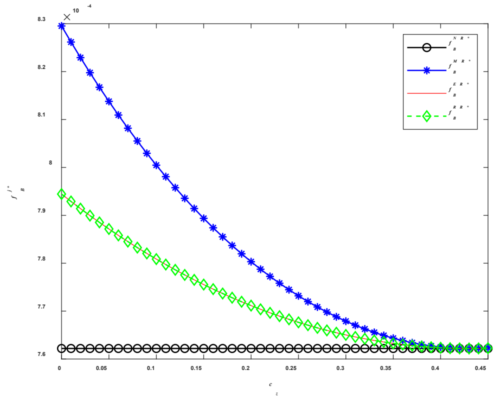
Fig. 2. The influence exerted by c_z on w^{j*}, p^{j*}, D^{j*} and d^{j*}, (a) w^{j*}, (b) p^{j*}, (c) D^{j*}, (d) d^{j*}

Fig. 3 shows the effects of differences in recycled products' quality on profits and promotional efforts of recycling parties. When the proportion of high-quality recycled product increases, unit cost of manufacturer producing remanufactured products decreases. Regardless of the recycling channel, as c_z decreases, profits of manufacturer, e-commerce retail platform, total supply chain system, and recycling promotion intensity index level determined by the recycling party all increase.

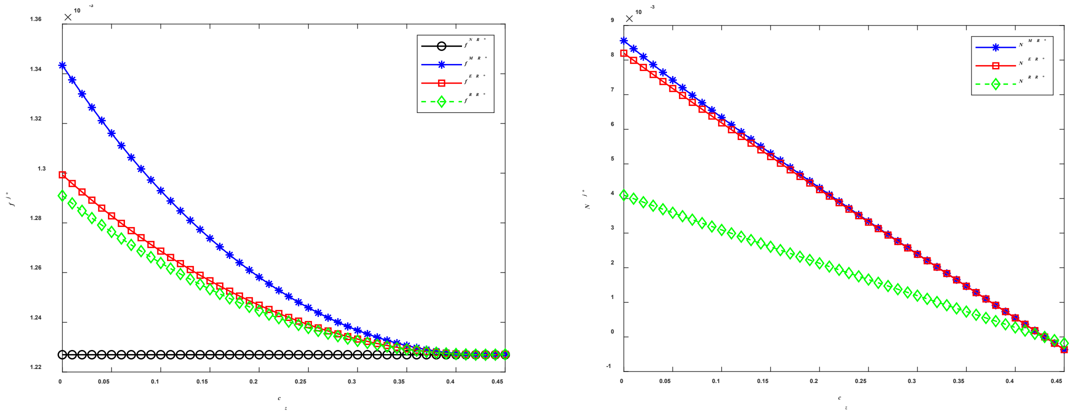
Combining Fig. 2 and Fig. 3, this indicates that the higher the standard of recycled products is, the more competitive wholesale and retail prices will be. Consumers have become the main beneficiaries of the supply chain. Meanwhile, in this case, market demand has also increased, thereby enhancing the revenues of manufacturer and e-commerce retail platform. On the one hand, profitable supply chain members are willing to take various measures to increase their recycling promotion efforts. On the other hand, consumers can enjoy better logistics service by providing high-quality used products. These two aspects stimulate consumers' enthusiasm for participating in recycling activities. Consequently, the remanufacturing industry's development is positively influenced by recycling of high-quality used products.



(a) f_m^{j*}



(b) f_B^{j*}

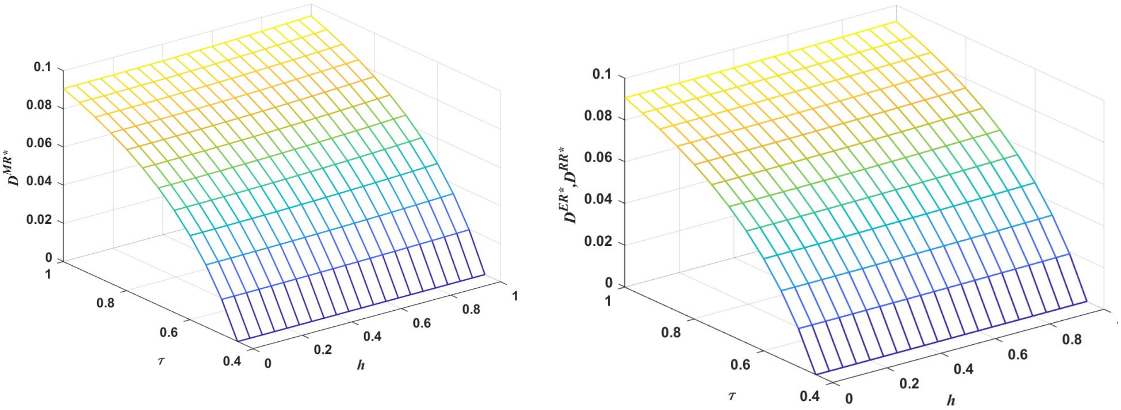


(c) $\boldsymbol{f^{j*}}$ **(d)** $\boldsymbol{N^{j*}}$

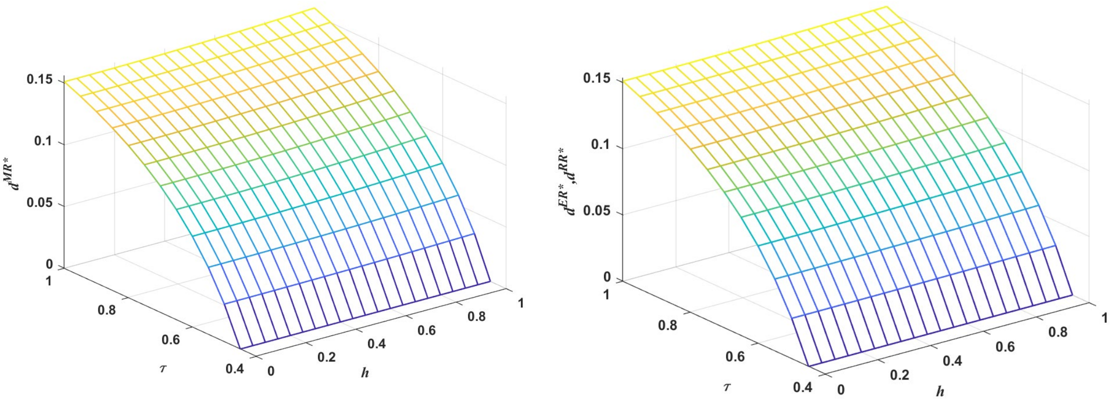
Fig. 3. The influence exerted by c_z on f_m^{j*}, f_B^{j*}, f^{j*} and N^{j*}, (a) f_m^{j*}, (b) f_B^{j*}, (c) f^{j*}, (d) N^{j*}

5.2 The effects of preferences and response to used product recycling promotion activities on supply chain

Fig. 4 displays effects of consumer preference coefficient τ in online sales mode and response h to used product recycling promotion activities on logistics service level $D^{j*}$and demand d^{j*}.



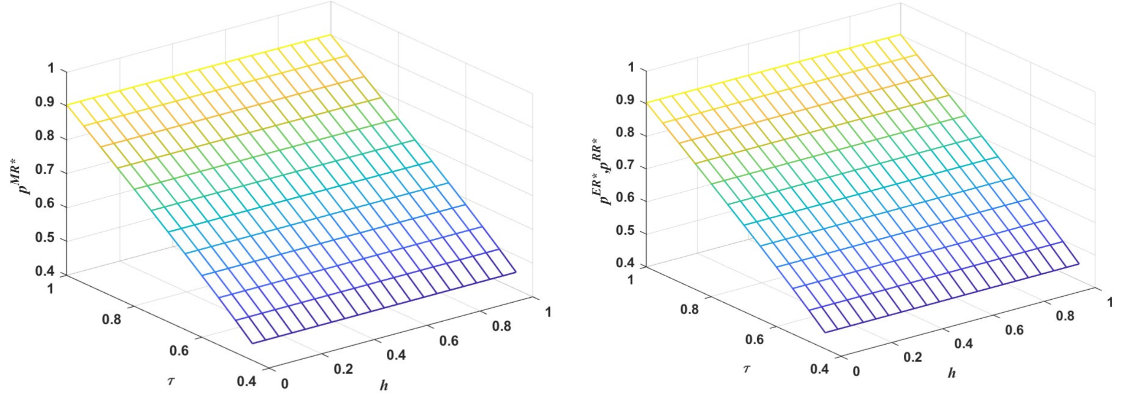
(a) $\boldsymbol{D^{j*}}$



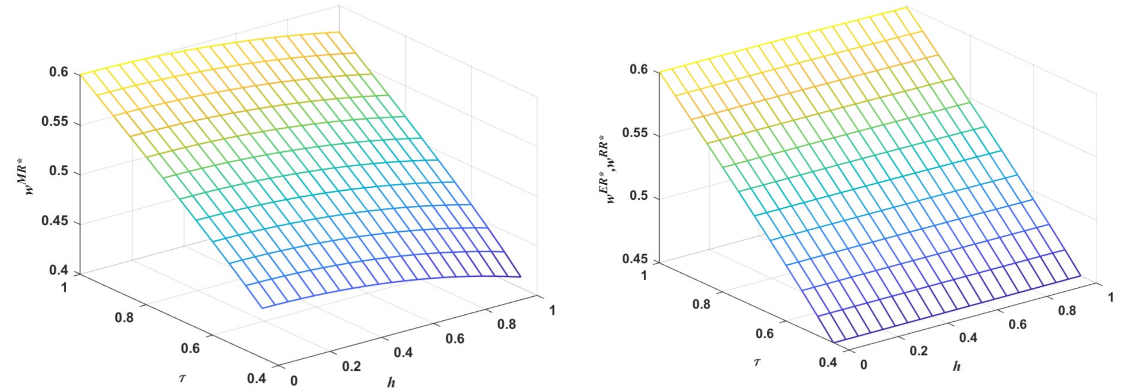
(b) $\boldsymbol{d^{j*}}$

Fig. 4. The influence exerted by τ and h on D^{j*} and d^{j*}, (a) D^{j*}, (b) d^{j*}

As τ increases, both $D^{j*}$and d^{j*}increase, and the growth rate changes from fast to slow. This indicates that the more consumers prefer online sales, the higher logistics service level, and larger consumer market for two types of products. Promotion of advertising on e-commerce retail platform has the potential to attract a larger number of online shoppers. As h increases, D^{j*} and d^{j*}increase, but the rate of increase is not significant. This indicates that if recycling companies increase their promotion of used product recycling and improve the response coefficient of consumers to used product recycling promotional activities, consumers can enjoy better logistics service level and expand market demand. From the perspective of increasing rate, τ has a more significant impact on $D^{j*}$and d^{j*}. Fig. 5 shows the effects of consumer preference coefficient τ for online sales mode and response h to used product recycling promotion activities on retail price $p^{j*}$and wholesale price w^{j*}. As τincreases, both $p^{j*}$and w^{j*}increase; The rate of increase in p^{j*} remains basically unchanged, and the rate of increase in w^{j*}also remains basically unchanged; However, the increase rate of p^{j*} is much higher than that of w^{j*}. This indicates that the more consumers who prefer online shopping, the greater the retail prices of e-commerce retail platform, and the higher wholesale prices of manufacturer. Due to the more significant changes in retail prices, stimulating more consumers to shop online is more beneficial for e-commerce retail platforms. As h increases, both p^{j*} and w^{j*}decrease, and the changes are not very significant, indicating that increasing the response coefficient of consumers to used product recycling promotional activities does not have important impact on positive supply chain.

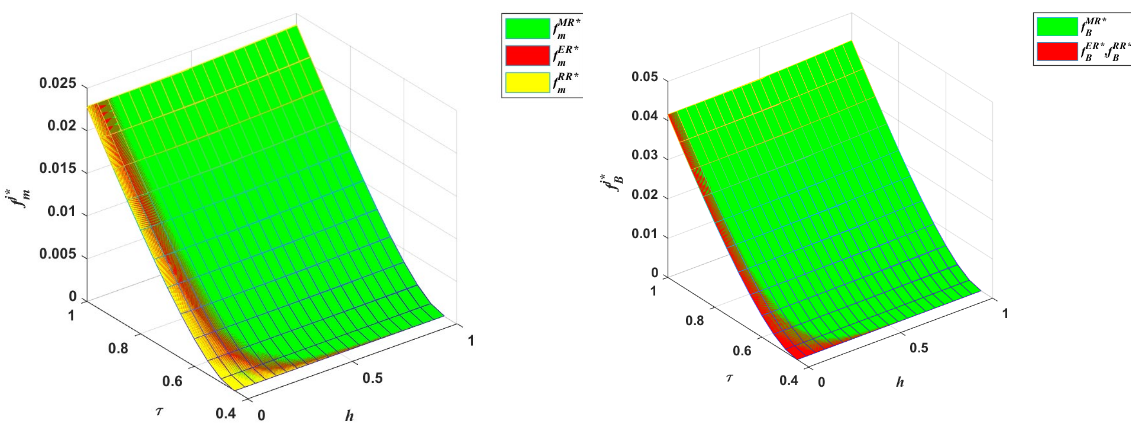


(a) p^{j*}



(b) w^{j*}

Fig. 5. The influence exerted by τ and h on $p^{j*}$and w^{j*}, (a) p^{j*}, (b) w^{j*}



(a) f_m^{j*} **(b) f_B^{j*}**

Fig. 6. The influence exerted by τ and h on f_m^{j*} and f_B^{j*}, (a) f_m^{j*}, (b) f_B^{j*}

Fig. 6 shows the effects of consumer preference coefficient $\boldsymbol{\tau}$ for online sales mode and response $\boldsymbol{h}$ to used product recycling promotion activities on profits of manufacturer $\boldsymbol{f_m^{j*}}$ and profits of e-commerce retail platform $\boldsymbol{f_B^{j*}}$. As $\boldsymbol{\tau}$ increases, both $\boldsymbol{f_m^{j*}}$ and $\boldsymbol{f_B^{j*}}$ increase at a faster rate, indicating that if more consumers prefer online shopping, $\boldsymbol{f_m^{j*}}$ and $\boldsymbol{f_B^{j*}}$ will be higher. For the same $\boldsymbol{\tau}$, in the manufacturer recycling model, $\boldsymbol{f_m^{j*}}$ and $\boldsymbol{f_B^{j*}}$ are higher than those of other models. As h increases, both $\boldsymbol{f_m^{j*}}$ and $\boldsymbol{f_B^{j*}}$ increase, and the changes are not very significant. The calculation results and research indicate that increasing the response coefficient of consumers to used product recycling promotional activities does not have significant influences on supply chain.

6. In conclusion and for future research

In an environment where the Internet and the remanufacturing sector are seamlessly integrated, the choices made by consumers in online sales and the quality standard of recycled products will not only mould market demand but also exert an influence on corporate management decisions.

(1) Improving recycled products' quality can effectively enhance the logistics service level of e-commerce retail platform, expand market demand, increase recycling rate , augment profits of manufacturer, e-commerce retail platform, and supply chain system.

(2) By implementing more expansive recycling and remanufacturing strategies, the increased adoption of recycled and remanufactured products can profoundly enhance supply chain efficiency. This, subsequently, influences profitability of e-commerce retail platform and manufacturer, resulting in an overall increase in profits for both parties.

(3) Encouraging a greater number of consumers to engage in online shopping can effectively enhance the level of service for logistics within an e-commerce retail platform. This, in turn, will expand market demand and increase recycling rate. Furthermore, it will lead to increased profits for manufacturer, e-commerce retail platform, and supply chain system.

(4) As a recycler, manufacturer can undoubtedly obtain higher profits. Only when consumers are not familiar with recycling and remanufacturing, and their enthusiasm is not high, will manufacturer choose to outsource the recycling process. Of course, if the effectiveness of used recycling promotion is equal across different recycling channels, manufacturer recycling is undoubtedly the optimal choice in any situation, and consumers' reactions to used product recycling promotion can greatly influence the selection of recycling avenues

Therefore, valuing the response of consumers to used product recycling activities, providing more convenient and high-quality services related to recycling, promoting a series of used product recycling publicity services, and improving the quality level of used product recycling will undoubtedly accelerate the development of social economy and resource conservation. Although this paper has drawn some conclusions through theoretical analysis and numerical simulation. These findings can provide highly valuable perspectives for making well-informed decisions in the long run within the supply chain and have substantial practical ramifications for improving effectiveness and efficiency of the supply chain. However, we did not consider situations in complex environments, such as multiple parties simultaneously recycling in the supply chain, the various differences between new manufacturing and remanufacturing. Recycled products' quality will also vary depending on actual situation; These will all affect the selection of recycling channels. We aim to conduct a comprehensive investigation into the research during the forthcoming period.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Appendix

A. The demonstration process of Proposition 1

Proof: In model NR, e-commerce retail platform's marginal profit from product is denoted as $F^{NR} = p^{NR} - w^{NR}$, the expression $p^{NR} = F^{NR} + w^{NR}$ can be obtained. Substitute it into function (1) to obtain the expression:

$$f_m^{NR} = (w^{NR} - c_n)(1 - \frac{F^{NR} + w^{NR} - \gamma D^{NR}}{\tau})$$

By taking the quadratic partial derivative of function f_m^{NR} over w^{NR}, we can obtain $\frac{\partial^2 f_m^{NR}}{\partial (w^{NR})^2} = -\frac{2}{\tau} < 0$. The function f_m^{NR} shows strict concavity in relation to w^{NR}. By computing initial partial derivative of f_m^{NR} in relation to w^{NR} and setting it to 0, we can infer:

$$w^{NR}(F^{NR},\ D^{NR}) = \frac{\tau - F^{NR} + \gamma D^{NR} + c_n}{2}$$

By substituting $p^{NR} = F^{NR} + w^{NR}$ into function (2), we obtain the expression:

$$f_B^{NR} = \frac{F^{NR}(\tau - c_n - F^{NR} + \gamma D^{NR})}{2\tau} - \frac{1}{2}\pi(D^{NR})^2$$

The Hessian matrix of function f_B^{NR} is:

$$H(F^{NR},\ D^{NR}) = \begin{bmatrix} -\frac{1}{\tau} & \frac{\gamma}{2\tau} \\ \frac{\gamma}{2\tau} & -\pi \end{bmatrix}$$

Therefore, it can be seen that the $H_1(F^{NR},\ D^{NR}) = -1/\tau < 0$. Due to $4\pi\tau - \gamma^2 > 0$, the $H_2(F^{NR},\ D^{NR}) = (4\pi\tau - \gamma^2)/4\tau^2 > 0$. Based on our meticulous analysis, we ascertain that the $H(F^{NR},\ D^{NR})$ exhibits the traits of a negative definite matrix, suggesting that the profit function f_B^{NR} shows strict concavity in relation to both F^{NR} and D^{NR}. Therefore, by computing initial partial derivative of f_B^{NR} in relation to F^{NR}, D^{NR} and setting them to 0, we obtain D^{NR*} and F^{NR*}. We substitute it into $w^{NR}(F^{NR}, D^{NR})$ to obtain w^{NR*}. We substitute F^{NR*} and w^{NR*} into the expression $p^{NR*} = F^{NR*} + w^{NR*}$ to obtain p^{NR*}. We substitute p^{NR*} and D^{NR*} into the expression $d^{NR} = 1 - (p^{NR} - \gamma D^{NR})/\tau$ to obtain d^{NR*}. Proposition 1 has been proven.

B. The demonstration process of Proposition 2

Proof: It is hypothesized that the e-commerce retail platform attains a marginal profit for its products, designated as $F^{MR} = p^{MR} - w^{MR}$. The expression $p^{MR} = F^{MR} + w^{MR}$can be obtained. By substituting it into function (10), we can obtain:

$$f_m^{MR} = [w^{MR} - c_n + (c_o - b)hN^{MR}](1 - \frac{F^{MR} + w^{MR} - \gamma D^{MR}}{\tau}) - \frac{1}{2}(N^{MR})^2$$

Hessian matrix of function f_m^{MR}:

$$H(w^{MR}, N^{MR}) = \begin{bmatrix} -\frac{2}{\tau} & -\frac{h(c_o - b)}{\tau} \\ -\frac{h(c_o - b)}{\tau} & -1 \end{bmatrix}$$

So, the primary equation of the first order and the subsidiary equation of the Hessian matrix satisfy condition $H_1(w^{MR}, N^{MR}) = -2/\tau < 0$. Because $0 < c_n < \tau$ and $c_n - h^2(c_o - b)^2 > 0$, the equation of the second-order principal subcomponent$H_2(w^{MR}, N^{MR}) = (2\tau - h^2(c_o - b)^2)/\tau^2 > 0$ can be obtained. Matrix$H(w^{MR}, N^{MR})$ is negative definite. To simplify the calculation, we let $A = \pi h^2(c_o - b)^2$. Take initial partial derivative of f_m^{MR} and equate them to 0, whence we obtain:

$$w^{MR}(F^{MR}, D^{MR}) = \frac{\tau c_n + (\tau - F^{MR} + \gamma D^{MR})[\tau - h^2(c_o - b)^2]}{2\tau - h^2(c_o - b)^2}$$

$$N^{MR}(F^{MR}, D^{MR}) = \frac{h(\tau - F^{MR} + \gamma D^{MR} - c_n)(c_o - b)}{2\tau - h^2(c_o - b)^2}$$

By substituting $p^{MR} = F^{MR} + w^{MR}$ into function (4), we can obtain:

$$f_B^{MR} = F^{MR}\{\frac{\tau - F^{MR} + \gamma D^{MR}}{\tau} - \frac{\tau c_n + (\tau - F^{MR} + \gamma D^{MR})[\tau - h^2(c_o - b)^2]}{\tau[2\tau - h^2(c_o - b)^2]}\} - \frac{1}{2}\pi(D^{MR})^2$$

Hessian matrix of function f_B^{MR}:

$$H(F^{MR}, D^{MR}) = \begin{bmatrix} -\frac{2}{2\tau - h^2(c_o - b)^2} & \frac{\gamma}{2\tau - h^2(c_o - b)^2} \\ \frac{\gamma}{2\tau - h^2(c_o - b)^2} & -\pi \end{bmatrix}$$

Because $H(F^{MR}, D^{MR})$ has a first-order principal sub formula $H_1(F^{MR}, D^{MR}) = -2/[2\tau - h^2(c_o - b)^2] < 0$ and a second-order principal sub formula $H_2(F^{MR}, D^{MR}) = \{2\pi[2\tau - h^2(c_o - b)^2] - \gamma^2\}/[2\tau - h^2(c_o - b)^2]^2 > 0$, matrix $H(F^{MR}, D^{MR})$ is negative definite . By taking initial partial derivative of f_B^{MR} and setting them to 0, we obtain that:

$$F^{MR*} = \frac{(2\pi\tau - A)(\tau - c_n)}{4\pi\tau - \gamma^2 - 2A}, \quad D^{MR*} = \frac{\gamma(\tau - c_n)}{4\pi\tau - \gamma^2 - 2A}$$

We substitute it into $w^{MR}(F^{MR}, D^{MR})$ and $N^{MR}(F^{MR}, D^{MR})$ to obtain $w^{MR*}$and N^{MR*}. Obtain p^{MR*}based on $p^{MR} = F^{MR} + w^{MR}$. Substitute p^{MR*} and D^{MR*} into $d^{MR} = 1 - (p^{MR} - \gamma D^{MR})/\tau$ to obtain d^{MR*}. The proof of Proposition 2 has been successfully established.

C. The demonstration process of Proposition 3

Proof: It is hypothesized that the e-commerce retail platform attains a marginal profit for its products, designated as $F^{ER} = p^{ER} - w^{ER}$. The expression $p^{ER} = F^{ER} + w^{ER}$ can be obtained. By substituting it into function (20), we can obtain the expression:

$$f_m^{ER} = [w^{ER} - c_n + (c_o - m)hN^{ER}](1 - \frac{F^{ER} + w^{ER} - \gamma D^{ER}}{\tau})$$

According to $\partial^2 f_m^{ER}/\partial(w^{ER})^2 = -2/\tau < 0$, function f_m^{ER} is strictly concave in w^{ER}. Compute initial partial derivative of f_m^{ER} and equate it to 0, thereby resulting in:

$$w^{ER}(F^{ER},\ D^{ER},\ N^{ER}) = \frac{\tau - F^{ER} + c_n + \gamma D^{ER} - hN^{ER}(c_o - \eta)}{2}$$

By substituting it into function (21), it can be obtained that:

$$f_B^{ER} = \frac{[F^{ER} + hN^{ER}(\eta - b)][\tau - c_n - F^{ER} + \gamma D^{ER} + hN^{ER}(c_o - \eta)]}{2\tau} - \frac{1}{2}(N^{ER})^2 - \frac{1}{2}\pi(D^{ER})^2$$

Hessian matrix of function f_B^{ER}:

$$H(F^{ER},\ D^{ER},\ N^{ER}) = \begin{bmatrix} -\frac{1}{\tau} & \frac{\gamma}{2\tau} & \frac{h(c_o + b - 2\eta)}{2\tau} \\ \frac{\gamma}{2\tau} & -\pi & \frac{\gamma h(\eta - b)}{2\tau} \\ \frac{h(c_o + b - 2\eta)}{2\tau} & \frac{\gamma h(\eta - b)}{2\tau} & -1 \end{bmatrix}$$

Because $0 < c_n < \tau$ and $c_n - h^2(c_o - b)^2 > 0$, we can know $\tau - h^2(c_o - b)^2 > 0$. The first-order principal and sub equations $H_1(F^{ER},\ D^{ER},\ N^{ER}) = -1/\tau < 0$, second-order principal and sub equations $H_2(F^{ER},\ D^{ER},\ N^{ER}) = (4\pi\tau - \gamma^2)/(4\tau^2) > 0$, and third-order principal and sub equations

$$H_3(F^{ER},\ D^{ER},\ N^{ER}) = -[\tau(4\pi\tau - \gamma^2) - \gamma^2 h(c_o - \eta)(\eta - b) - \pi\tau h^2(c_o + b - 2\eta)^2]/(4\tau^3) < 0$$

Matrix $H(F^{ER},\ D^{ER},\ N^{ER})$ is negative definite. Therefore, f_B^{ER} is strictly concave in F^{ER}, D^{ER}, and N^{ER}. Calculate initial partial derivatives of f_B^{ER} in relation to F^{ER}, D^{ER}, N^{ER}, and set them to 0. This brings about:

$$F^{ER*} = \frac{\pi(\tau - c_n)[2\tau - h^2(c_o - \eta)(\eta - b)]}{4\pi\tau - \gamma^2 - A}$$

$$N^{ER*} = \frac{h\pi(\tau - c_n)(c_o - b)}{4\pi\tau - \gamma^2 - A},\quad D^{ER*} = \frac{\gamma(\tau - c_n)}{4\pi\tau - \gamma^2 - A}$$

By substituting F^{ER*}, N^{ER*}, and D^{ER*} into $w^{ER}(F^{ER},\ D^{ER},\ k^{ER})$, we can obtain w^{ER*}. We find p^{ER*} and d^{ER*} from $p^{ER} = F^{ER} + w^{ER}$ and $d^{ER} = 1 - (p^{ER} - \gamma D^{ER})/\tau$. Proposition 3 has been successfully verified.

D. The demonstration process of Proposition 4

Proof: It can be readily demonstrated that f_R^{RR} shows strict concavity with regard to N^{RR}. The best decision for third-party recycler to determine the promotion of used product recycling efforts N^{RR} is:

$$N^{RR}(D^{RR},\ p^{RR}) = \frac{h(\eta - b)(\tau - p^{RR} + \gamma D^{RR})}{\tau}$$

It is believed that e-commerce retail platform has a marginal profit $F^{RR} = p^{RR} - w^{RR}$ for the product. The expression can be obtained: $p^{RR} = F^{RR} + w^{RR}$. By substituting it into function (30), we can obtain the expression:

$$f_m^{RR} = [w^{RR} - c_n + (c_o - \eta)hN^{RR}](1 - \frac{F^{RR} + w^{RR} - \gamma D^{RR}}{\tau})$$

Upon conducting the computation of second partial derivative of f_m^{RR} about w^{RR}, it is ascertained that:

$$\frac{\partial^2 f_m^{RR}}{\partial(w^{RR})^2} = -\frac{2[\tau - h^2(c_o - \eta)(\eta - b)]}{\tau^2}$$

Given $\tau - h^2(\eta - b)^2 > 0$ and $(\eta - b)^2 > (c_o - \eta)(\eta - b)$, the second partial derivative is less than 0. So f_m^{RR} is strictly concave in w^{RR}. We compute initial partial derivatives of f_m^{RR} and set it to 0. We determine optimal decision for manufacturer in setting w^{RR} and identify the most effective method for the third-party recycler to N^{RR} :

$$w^{RR}(D^{RR},\ F^{RR}) = \frac{\tau c_o + (\tau - F^{RR} + \gamma D^{RR})[\tau - 2h^2(c_o - \eta)(\eta - b)]}{2[\tau - h^2(c_o - \eta)(\eta - b)]}$$

$$N^{RR} = \frac{h(\eta - b)(\tau - p^{RR} + \gamma D^{RR})}{\tau}$$

By substituting it into function (31), we can obtain the expression:

$$f_B^{RR} = \frac{F^{RR}(\tau - F^{RR} - c_o + \gamma D^{RR})}{2[\tau - h^2(c_o - \eta)(\eta - b)]} - \frac{1}{2}\pi (D^{RR})^2$$

The Hessian matrix of the f_B^{RR} for e-commerce retail platform is:

$$H(F^{RR}, D^{RR}) = \begin{bmatrix} -\frac{1}{\tau - h^2(c_o - \eta)(\eta - b)} & \frac{\gamma}{2\tau - 2h^2(c_o - \eta)(\eta - b)} \\ \frac{\gamma}{2\tau - 2h^2(c_o - \eta)(\eta - b)} & -\pi \end{bmatrix}$$

The Hessian matrix has $H_1(F^{RR}, D^{RR}) = -1/[\tau - h^2(c_o - \eta)(\eta - b)] < 0$ and $H_2(F^{RR}, D^{RR}) = \{4\pi[\tau - h^2(c_o - \eta)(\eta - b)] - \gamma^2\}/4[\tau - h^2(c_o - \eta)(\eta - b)]^2 > 0$. Therefore, matrix $H(F^{RR}, D^{RR})$ is negative definite . Hence, through computing the initial partial derivative of f_B^{RR} in relation to both F^{RR} and D^{RR} and setting them to 0, we can deduce:

$$F^{RR*} = \frac{2\pi(\tau - c_n)[\tau - h^2(c_o - \eta)(\eta - b)]}{4\pi\tau - \gamma^2 - 4\pi h^2(c_o - \eta)(\eta - b)}$$

$$D^{RR*} = \frac{\gamma(\tau - c_n)}{4\pi\tau - \gamma^2 - 4\pi h^2(c_o - \eta)(\eta - b)}$$

By substituting $F^{RR*}$and D^{RR*} into $w^{RR}(D^{RR}, F^{RR})$, we can obtain w^{RR*} and N^{RR*}. Substitute F^{RR*} and w^{RR*} into $p^{RR} = F^{RR} + w^{RR}$ to obtain p^{RR*}. Substituting p^{RR*} and D^{RR*} into $d^{RR} = 1 - (p^{RR} - \gamma D^{RR})/\tau$ yields p^{RR*}. Proposition 4 has been demonstrated successfully.

E. The demonstration process of Corollary 1

Proof: Because $c_o > b$, $\tau > c_o, \tau > c_n, c_n - h^2(c_o - b)^2 > 0, \pi\tau - A > 0, A > 0$, through the analysis and calculation of Propositions 1 to Propositions 4, it can be concluded that:

$$\frac{\partial D^{MR*}}{\partial h} = \frac{4\gamma A(\tau - c_n)}{h(4\pi\tau - \gamma^2 - 2A)^2} > 0, \quad \frac{\partial D^{ER*}}{\partial h} = \frac{\partial D^{RR*}}{\partial h} = \frac{2\gamma A(\tau - c_n)}{h(4\pi\tau - \gamma^2 - A)^2} > 0$$

$$\frac{\partial d^{MR*}}{\partial h} = \frac{4\pi A(\tau - c_n)}{h(4\pi\tau - \gamma^2 - 2A)^2} > 0, \quad \frac{\partial d^{ER*}}{\partial h} = \frac{\partial d^{RR*}}{\partial h} = \frac{2\pi A(\tau - c_n)}{h(4\pi\tau - \gamma^2 - A)^2} > 0$$

$$\frac{\partial p^{MR*}}{\partial h} = -\frac{4A(\tau - c_n)(\pi\tau - \gamma^2)}{h(4\pi\tau - \gamma^2 - 2A)^2} < 0, \quad \frac{\partial p^{ER*}}{\partial h} = \frac{\partial p^{RR*}}{\partial h} = -\frac{2A(\tau - c_n)(\pi\tau - \gamma^2)}{h(4\pi\tau - \gamma^2 - A)^2} < 0$$

Corollary 1 has been proven.

F. The demonstration process of Corollary 3

Proof: Because $c_o > b$, $\tau > c_o$, $\pi\tau > \gamma^2$, $c_n - h^2(c_o - b)^2 > 0$, $\pi\tau - A > 0$, through analyzing and calculating Propositions 1 to Propositions 4, we can obtain:

(1)$D^{MR*} - D^{ER*} > 0$, $D^{ER*} - D^{RR*} = 0$, $D^{RR*} - D^{NR*} > 0$. So Corollary 3 (1) is supported.

The proof method for Corollary 3 (2) to Corollary 3 (5) is the same as Corollary 3 (1) and will not be repeated here.