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Dual-channel retail and multichannel recycling strategies considering electronic waste remanufacturing

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Abstract

The recycling channels and price competition of waste products will prompt the upstream and downstream enterprises of the supply chain to take more measures to obtain resource advantages. It is necessary to design a scientific and reasonable recycling and remanufacturing scheme, which is helpful for enterprises to save social resources and improve the recycling efficiency of waste electronic products. This paper constructs a recycling decision model that considers the remanufacturing of waste electronic products and designs a decision plan to promote the recycling of waste electronic products and the retail of remanufactured products. To explore some management implications for firms making those decisions, we develop three analytical game-theoretical models: manufacturer recycling (model M), retailer recycling (model R) and recycling by third-party recyclers (model 3P). Through comparison of the equilibrium results from the three models, we find that the optimal operating decision of manufacturers mainly depends on the recycling rate of waste products, remanufacturing revenue and market demand. Based on numerical examples and sensitivity analysis, we further studied the key factors that affect the selection of the manufacturer's optimal decision-making scheme. Comparing the three models, we find that when the investment recovery coefficient is high, and the cost savings of remanufacturing are low, the manufacturer will adopt model R; otherwise, the manufacturer will adopt model M. When model 3P is adopted, the impact on the environment is the lowest; and if there is a change in recycling channels, the impact of models M and R on the environment will also change.

Keywords E-waste · Remanufacturing · Recovery rate · Game model

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1 Introduction

Electronic products have always been closely related to our life and cover a wide range of fields, such as electronic products in construction, packaging and automotive applications (Kibria et al., 2023). E-waste is recognized as one of the fastest growing and most dangerous solid waste products in the world (Awasthi et al., 2019). In the 2020 Global E-Waste Monitoring Report released by the relevant departments of the United Nations, it is mentioned that by the end of 2019, the total amount of electronic waste products in the world has reached 53.6 million tons, an increase of 21% compared with 2014, and it is expected that by 2030, the amount of waste products will reach 74 million tons (Qiao and Su, 2021). In China, the situation in China is not good either. According to China's statistics in 2019, the waste volume of TV sets, refrigerators and other products increased by 10.4% annually, and it is estimated that the waste volume of these products will reach 27.22 million tons by 2030 (Wang et al., 2020). Due to the heavy metal elements such as mercury, lead and cadmium in these products, improper disposal will seriously affect people's health (Althaf et al, 2019). As a circular economy model, remanufacturing can not only prolong the life cycle of electronic products, but also restore the use value of products in a certain period of time, so as to achieve the purpose of energy saving and environmental protection (Aydin & Mansour, 2023). In addition, the recycling of used electronic products can also relieve the shortage of raw materials to some extent, so as to avoid sudden price increases or supply chain disruptions. Successful cases in the current market show that remanufacturing is profitable, and there is evidence that recycling waste products as raw materials can save about 40% of production costs (Li et al., 2023). As a result, well-known companies such as Apple, Bo and HP have adopted ways to reduce production costs (Ma et al., 2017). Remanufacturing also creates jobs (Qian, 2013). As one of the most advanced countries in the world in remanufacturing technology, the USA has maintained a great advantage in the consumption and export of its remanufactured products. According to the 2012 annual report of the U.S. International Trade Commission, the total value of industrial goods recycled in the USA reached 43 billion dollars last year, which supported about 180,000 jobs in the USA (U.S. International Trade Commission, 2012). In China, in order to effectively promote the recycling and remanufacturing of waste electronic products, the China Household Electrical Appliances Research Institute and other institutions have issued the White Paper of China's Waste Electrical and Electronic Products Recycling and Comprehensive Utilization Industry for 10 consecutive years.

Therefore, remanufacturing has not only become a way for enterprises to enhance their competitiveness, but also become an effective way for enterprises to take the initiative to undertake social responsibilities and improve their corporate image (Chen, 2021; Ferrer & Swaminathan, 2006). Although the recycling and remanufacturing of waste electronic products has economic, environmental and social benefits (Yenipazarli, 2016), the effective recycling and reuse of e-waste remains a major challenge for countries. It is necessary to design a new recycling and remanufacturing mechanism that can improve the efficiency of remanufacturing and ensure the upstream and downstream members of the supply chain all obtain optimal profits. Most of the existing literature is limited to vertical games between members of the same closed-loop supply chain (CLSC) or competition between members of the same kind (such as competition between two retailers or two recyclers), rarely involving competition between two or more CLSCs. With the evolution of economic globalization, competition in the same industry is no longer limited to competition among enterprises but gradually includes competition among CLSCs. Therefore, in addition to considering the manufacturer's recycling, we also consider the situations in which retailers and third-party recyclers also participate in recycling at the same time. We have designed three CLSCs (see Fig. 1). In fact, consumers will exhibit differences in willingness to pay for new products and remanufactured products (Moshtagh & Taleizadeh, 2017). Only when remanufactured products have a certain price advantage can consumers have the same willingness to buy. However, from the literature review, few researchers have considered the remanufacturing strategies of dual-channel sales and multichannel recycling in the context of the price segmentation of new products and remanufactured products. Therefore, this paper constructs two sales models for new and remanufactured products and for direct online sales and traditional retail to achieve price competition between channels (Alizadeh-Basban & Taleizadeh, 2020; Zhang et al., 2020a, 2020b).

The main research questions in this paper can be summarized as:

How do we choose recycling channels in the context of differentiated pricing of new products and remanufactured products?

When the investment recovery coefficient, remanufacturing cost savings and recycling channels all change, what impact will it have on the recovery rate of used home appliances, remanufacturing revenue, corporate profits and the environment?

Which recycling method is the best when recycling channels compete?

The contribution of this paper to research can be divided into three aspects. Firstly, we combined the recycling channels of used home appliances with the marketing channels of remanufactured products and analyzed the two-stage CLSC under different consumer preferences. Secondly, in the process of recycling, manufacturers will face multiple choices. What is the best way to recover economic benefits? At present, there is no clear solution to this problem, and our research can solve this problem. Thirdly, we also considered the impact of the investment recovery coefficient and cost savings on remanufacturing revenue,

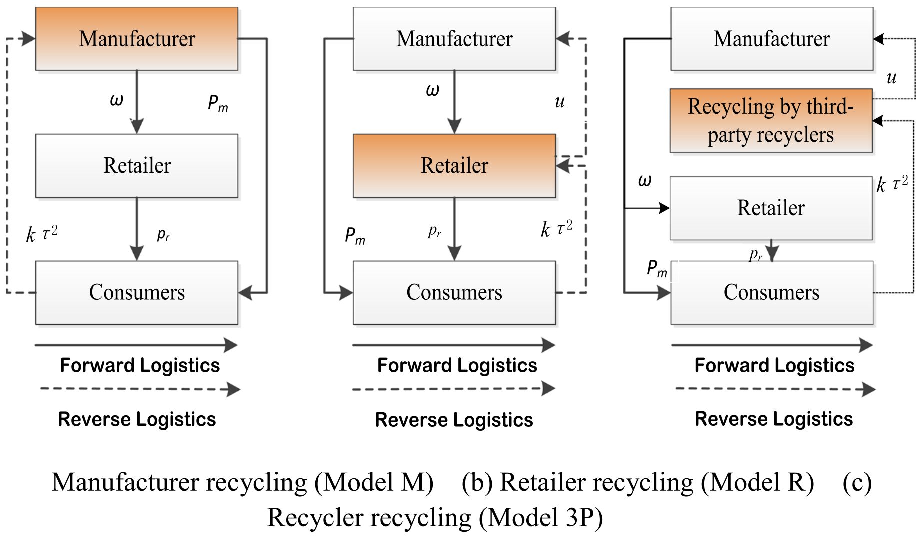

Fig. 1 Recycling modes under difference channels

which provides a theoretical reference for the selection of recycling programs for waste electronic products.

The rest of this paper is organized as follows. Section 2 presents the literature review. In Sect. 3, we describe the problem issue and explain the symbol of models. In Sect. 4, the solution methodologies using game-theoretical approaches are presented, and models are solved. In Sect. 5, the effects of recycling and remanufacturing are studied via a numerical analysis of a real case in the home appliances industry. In Sect. 6, we expand the model and analyzed the environmental impacts of remanufacturing. Finally, we summarize the research in Sect. 7.

2 Literature review

Remanufacturing mainly refers to the dismantling of WEEE in the recycling process, which is mainly used in the fields of used auto parts, construction machinery, machine tools, and so on (Ferrer & Swaminathan, 2006). The main purpose of industrial symbiosis is to promote the sustainability of production in a clean way, such as energy conservation, emission reduction and waste reuse (Oni et al., 2022). At present, there are many articles on recycling and remanufacturing research (Govindan et al., 2019; Long et al., 2019; Ngu et al., 2020). By pricing remanufactured products, the demand for new and remanufactured products can be adjusted, which is a way of remanufacturing management (Liu et al., 2018). There are also studies from recycling channels or product pricing. For example, Ferrer and Swaminathan (2010) analyzed the monopolistic environment in the two periods and described the optimal remanufacturing and pricing strategies of firms. They found that recycling and remanufacturing is not a single strategy. Zhao et al. (2013) studied pricing and remanufacturing decisions of two competitive supply chains. It is found that the optimal retail price increases with the increase of potential market demand. Like other businesses, cost savings are a priority before remanufacturing, because the profitability of a remanufactured system depends largely on the cost savings of the remanufactured product (Atasu et al., 2008). He et al. (2019) analyzed the situation in the case of government subsidies and found that both manufacturers' and governments' channel preferences were positively correlated with remanufacturing costs. In fact, their preferences are similar, and they all seek modest cost savings. In order to find the optimal combination of strategies for manufacturers' product selection, Han and Chen (2021) studied the supply chain consisting of manufacturers and retailers. The results show that the optimal product mix strategy of the manufacturer depends on the remanufacturing cost saving in all cases. Unlike the above research, we propose a two-period model to explore the optimal pricing and production strategies for new products and remanufactured products. We also considered the competition among WEEE recycling parties. Therefore, the optimal strategy and problem setting in this study are different from those in the above-mentioned literature.

Some studies also focus on recycling channel management. However, most studies in this field focus on the single-channel recycling strategy, focusing on the optimal economic performance of CLCS under different remanufacturing environments (Cao et al., 2020; Miao et al., 2017a, 2017b). From this perspective, Taleizadeh and Sadeghi (2019) and He et al. (2019) both proposed single-channel CLSCs and discussed the impact of cost recovery structure on the economic performance of remanufacturers. In subsequent studies, scholars extended this problem to dual channels, focusing on analyzing the strategic decisions of remanufacturers and recyclers. Savaskan et al. (2004) analyzed the profit problem of CLSCS under the interaction between retailer competition and recycling channels, and the results showed that under the manufacturer recycling model, the company's profit depends on the recycling scale. However, if the retailer is responsible for recycling, the company's profit depends on the scale of recycling and the degree of competition among retailers. By analyzing CLSC recycling channels, He (2015) found that when the risk of waste product recycling is low, the possibility of channel conflict between the product supply chain and the manufacturer is high; on the contrary, the possibility of channel conflict is low. Ren et al. (2014), Taleizadeh et al., (2019a, 2019b) and Taleizadeh et al., (2018a, 2018b) used dual-channel coordination strategies to help manufacturers and retailers achieve mutual benefits. In the above studies, the issue of the selection of recycling channels under different circumstances is discussed, but the influence of the difference of WEEE recycling entities on the selection of sales channels is ignored. According to the research of Saha et al. (2016), when the retailer is responsible for recycling, the bargaining power of the retailer's channel under the distribution channel model is stronger, while the influence of the retailer's channel under the direct sales channel model is reduced. Therefore, it is necessary to combine product recycling channels with sales channels and consider the impact of channel competition on the recycling of waste electronic products. Motivated by the above studies (Xiong et al., 2016; Teng & Feng, 2021; Zhang et al., 2021), this paper explores the remanufacturing closed-loop supply chain strategy under two sales models and three recycling channels. Table 1 summarizes some noteworthy recent studies in the literature and their contrast to this research.

3 Problem description and symbol explanation

3.1 Problem description

This paper constructs a dual-channel closed-loop supply chain composed of a single manufacturer, a single third-party recycler and a single retailer. The manufacturer is the channel leader and remanufactures e-waste. Considering the problem of pricing decision and recycling channel selection when there are three different power structures in the system, we design the schemes of two-channel retailing and multichannel recycling. In addition to retail channels, manufacturers also maintain direct sales channels. When the manufacturer does not directly recover e-waste from the customer, the manufacturer will recover e-waste from a third party or retailer at the price of u; that is, three recycling channels are considered: manufacturer recycling (model M), retailer recycling (model R) and recycling by third-party recyclers (model 3P). Diagrams of the three recycling modes are shown in Fig. 1.

3.2 Model assumptions

H1: Assuming that the demand function for new product sales in the retail channel is $D_r = h_1\alpha - \beta_1 p_r + \delta(p_m - p_r)$, the demand function for remanufactured products in direct sales channels is $D_m = h_2\alpha - \beta_2 p_m + \delta(p_m - p_r)$(Dabaghian et al., 2021). See Table 2 for the meaning of each parameter.

Table 1 Related research review

Literature	Channel structure			CLSC	Retail price of re-manufactured and new products	
	Recovery channel structure	Market channel structure	M + R channel structure		The same price	The different price
Zhao et al. (2020)	Parallel multi	Vertical dual		√	√	
Ma et al. (2016)	Parallel multi	Single		√	√	
Su et al. (2019)	Single	Single		√	√	
Wei et al. (2021)	Parallel multi	Single		√	√	
Zhou et al. (2022)	Single	Vertical dual				√
Tian et al. (2018)	Single	Single		√	√	
Taleizadeh et al., (2019a, 2019b)	Single	Single		√		√
Alaei er al.(2020)	Parallel dual	Vertical dual	√			√
Zeranget al. (2018)	Single	Single		√	√	
Taleizadeh and Sadeghi (2019)	Parallel dual	Vertical dual	√	√		√
Sadeghi et al.(2018)	Parallel dual	Vertical dual	√	√		√
Huang and Liang (2021)	Parallel multi	Single		√		√
Ma et al. (2013)	Parallel dual	Vertical dual	√	√		√
He et al. (2019)	Parallel multi	Parallel dual	√	√		√
Xu (2020)	Parallel dual	Single		√	√	
Miao et al., (2017a, 2017b)	Single	Single		√	√	
Sadeghi et al. (2018)	Vertical dual	Single		√	√	

Table 2 Symbol definition table

Parameters			
c_n	Unit production cost of the new product	D_m	Market demand for direct sales channels
c_r	Unit production cost of remanufactured products $c_r < c_n$	D_r	Market demand for retail channels
Δ	Cost savings from remanufacturing	δ	Cross-price elasticity coefficient
α	Market capacity	β_1	Retail channel preference coefficient
h_1	Number of customers buying new products $0 < h_1 < 1$	β_2	Preference coefficient of direct sales channels
h_2	Number of customers buying remanufactured products $0 < h_2 < 1$	u	Transfer payment recovery price ($u < \Delta$)
I	Recovered activity investment cost	k	Investment recovery factor
RE	Remanufacturing profit	π_m^M	Manufacturer's profit
π_r^R	Retailer's profit	π_τ^{3p}	Profits of third-party recyclers
Decision variables			
ω	Wholesale prices	p_m	Sales price of direct channel products
p_r	Selling prices of retail channel products $p_r > p_m$	τ	Recovery rate ($0 < \tau < 1$)

H2: Assume that in the three recycling channels, the recycling party is responsible for recycling e-waste and selling the recycled products back to the manufacturer at transfer payment price u, and all of the waste products repurchased by the manufacturer are used for remanufacturing. Following Huang et al. (2013), the relationship between investment in recycling activities and the rate of return satisfies $\mathrm{I} = k\tau^2$. The meaning of k is shown in Table 2. Under normal circumstances, there are still differences in quality between remanufactured and new products, but because of their price advantages, consumers still show a certain willingness to buy them. Therefore, new and remanufactured products can be sold in dual channels at the same time, forming price competition between channels.

H3: It is assumed that the enterprises participating in each recycling channel are economically rational. To protect the interests of manufacturers, the cost of e-waste production for manufacturers should be lower than the cost of production with new materials, that is, $c_n > c_r$; let $\Delta = c_n - c_r$(Min, et al., 2013). The meaning of Δ is shown in Table 2. To protect the interests of retailers, the retail price of a unit product is greater than the wholesale price, that is, $p > \omega$. To protect the interests of third-party recyclers, the recovery rate should be greater than zero, and the profits of third-party recyclers should be greater than the investment in their recycling activities, that is $\tau > 0$ and $\pi_\tau^{3p} > \mathrm{I}^{3p}$. Similarly, the profit of the manufacturer and that of the retailer are greater than the investment in recycling activities. Thus, we have $\pi_m^M > \mathrm{I}^M$,$\pi_m^R > \mathrm{I}^R$.

H4: It is assumed that the manufacturer is the Stackelberg leader of the entire recycling channel (Liu et al., 2016).

3.3 Symbol definitions

All parameters of the article are shown in Table 2.

4 Model construction and solution

4.1 Manufacturer's recycling model (model M)

In the manufacturer's recycling model, the manufacturer will invest the recycling funds of I^M to recycle e-waste from consumers, and recycling rate τ^M is used to remanufacture e-waste. To promote the sales of new and remanufactured products, manufacturers choose to sell new and remanufactured products to retailers and consumers at wholesale prices ω^M and direct sales prices p_m^M, respectively. In this model, the profit functions of each party are as follows:

$$\begin{aligned}\pi_m^M\left(p_m,\tau,\omega\right) =& \left[h_1\alpha - \beta_1 p_r + \delta\left(p_m - p_r\right)\right]\omega + \left[h_2\alpha - \beta_2 p_m + \delta\left(p_m - p_r\right)\right]p_m \\ &+ \left(\Delta\tau - c_n\right)\left[\left(h_1 + h_2\right)\alpha - \beta_1 p_r - \beta_2 p_m\right] - \tau^2\end{aligned} \tag{1}$$

$$\pi_r^M\left(p_r\right) = \left(p_m - \omega\right)\left[h_1\alpha - \beta_1 p_r + \delta\left(p_m - p_r\right)\right] \tag{2}$$

To simplify the calculation, we refer to the work of Taleizadeh et al., (2018a, 2018b) and Hilge et al. (2016) and apply $h_1 = h_2 = h, \beta_1 = \beta_2 = \beta$. We solve by reverse induction as follows:

Proposition 1 *In the manufacturer's recycling model, when* $k > \frac{\beta\Delta^2(1+\beta+2\delta)}{8(\beta+\delta)}$, *there is unique optimal wholesale price* ω^{M*}, *optimal retail price* p_r^{M*}, *optimal direct selling price* p_m^{M*} *and optimal recovery rate* τ^{M*}. *For the proof of proposition 1, see Appendix 1.*

Under these conditions, the market demand values for product direct sales channels and retail channels are as follows:

$$D_r^{M*} = \frac{2ahk(\beta + \delta)}{-3\beta^2\Delta^2 - 4\delta\beta\Delta^2 + 8k\beta + 8k\delta} \tag{3}$$

$$D_m^{M*} = \frac{2ahk(2\beta + 3\delta)}{(-3\beta^2\Delta^2 - 4\delta\beta\Delta^2 + 8k\beta + 8k\delta)} \tag{4}$$

The optimal profits brought by manufacturers, retailers and remanufacturing are, respectively, as follows:

$$\pi_m^{M*} = \frac{a^2h^2k(3\beta + 4\delta)}{\beta(-3\beta^2\Delta^2 - 4\delta\beta\Delta^2 + 8k\beta + 8k\delta)} \tag{5}$$

$$\pi_r^{M*} = \frac{4a^2h^2k^2(\beta + \delta)}{(-3\beta^2\Delta^2 - 4\delta\beta\Delta^2 + 8k\beta + 8k\delta)^2} \tag{6}$$

$$RE^{M*} = \frac{[a^2h^2k\Delta^2(3\beta + 4\delta)^2]}{(-3\beta^2\Delta^2 - 4\delta\beta\Delta^2 + 8k\beta + 8k\delta)^2} \tag{7}$$

To ensure that the calculation is meaningful, the price, recovery rate and profit of the product must be greater than 0. Under these conditions, the parameters in the model must satisfy: $\Delta < \sqrt{\frac{4k(\delta+\beta)}{3\beta^2+4\delta\beta)}}$.

As a result, we have Corollary 1:

Corollary 1: (i) *When the manufacturer is responsible for recycling, the wholesale price* (ω^{M*}), *retail price* (P_r^{M*}) *and direct sales price* (P_m^{M*}) *of the product are inversely proportional to the cost savings of remanufacturing* (Δ) *and directly proportional to the coefficient* (k) *of investment recovery. (ii) The recovery rate* (τ^{M*}) *of e-waste is directly proportional to the cost savings (Δ) of remanufacturing and inversely proportional to the coefficient* (k) *of investment recovery. (iii) The market demand of retail channels* (D_r^{M*}) *and direct sales channels* (D_m^M) *is directly proportional to the cost savings* (Δ) *of remanufacturing and inversely proportional to the coefficient* (k) *of investment recovery. (IV) The profit of manufacturer* (π_m^{M*}), *the profit of retailer* (π_r^{M*}), *and the profit of remanufacturing* (RE^*) *are directly proportional to the cost savings of remanufacturing* (Δ) *and inversely proportional to the coefficient of the return on investment* (k).

For the proof of Corollary 1, see Appendix 2.

Corollary 1 shows that in the manufacturer's recycling model, the greater the cost savings of remanufacturing becomes, the greater the profit margin for the company's recycling and remanufacturing becomes. The manufacturer is profitable and will increase the recycling rate. As the number of remanufactured products on the market increases, market demand also increases. To promote the sale of remanufactured products, manufacturers will reduce wholesale prices, and retail and direct sales prices will also drop. These lowered prices will stimulate market demand and prompt manufacturers to increase investment recovery and the rate of return to produce more products, forming a positive cycle and ultimately increasing the profits of both manufacturers and retailers. However, the increase in the return on investment increases the cost of the manufacturer's return, resulting in a reduction in the return of the profit. To compensate for the losses caused by the recovery of investment, manufacturers will reduce the recovery of investment and increase the wholesale price, retail prices and direct sales prices. This increase in prices reduces market demand and ultimately leads to reduced profits for both manufacturers and retailers.

4.2 Retailer recycling model (model R)

In the retailer recycling model, the manufacturer entrusts the retailer to recover e-waste from consumers at a unit price of u and to remanufacture the e-waste. In this recycling channel, the retailer first determines the retail price (P_r^R) of the new product, the recycling rate (τ^R), and the investment (I^R) in recycling e-waste. Subsequently, the manufacturer sets the wholesale price (ω^R) of the new product and the direct selling price (P_m^R) of the remanufactured product. Under these conditions, the profit function of each party is expressed as follows:

$$\pi_r^R\left(p_r, \tau\right) = \left(p_r - \omega\right)\left[h_1 a - \beta_1 p_r + \delta\left(p_m - p_r\right) + u\tau[\left(h_1 + h_2\right)\alpha - \beta_1 p_r - \beta_2 p_m\right] - k \tag{8}$$

$$\pi_m^R\left(p_m, \omega\right) = [h_1 a - \beta_1 p_r + \delta\left(p_m - p_r\right)\omega + \left[h_2 a - \beta_2 p_m + \delta\left(p_m - p_r\right)\right]p_m + \left(\Delta - u - c_m\right)\left[\left(h_1 + h_2\right)\alpha - \beta_1 p_r - \beta_2 p_m\right] \tag{9}$$

Similarly, we let $h_1 = h_2 = h, \beta_1 = \beta_2 = \beta$ and by reverse induction as follows:

Proposition 2 *When the retailer is responsible for recycling, when* $k < \frac{4\beta^2\left[\Delta(2u+\Delta)-2u^2\right]+4\beta\delta u(5\Delta-4u)+u^2\delta^2}{16\beta+16\delta}$ *and when the manufacturer and retailer each have the largest profit, there is a unique optimal wholesale price* (ω^{R*}), *retail price* (P_r^{R*}), *direct selling price* (P_m^{R*}) *and recovery rate* (τ^{R*}), *which are, respectively, written as follows*:

$$\omega^{R*} = \frac{ah(-4\beta^3u^2 + 4\beta^3\Delta^2 - 20\beta^2\delta u^2 + 14\beta^2\delta u\Delta + 8\beta\delta\Delta^2 - 23\beta\delta^2u^2 + 28\beta\delta^2u\Delta - 8k\beta\delta + 2\delta^3u^2 - 12k\delta^2)}{\beta(\beta + 2\delta)(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)} \tag{10}$$

$$p_r^{R*} = \frac{ah[2\beta^3(3u\Delta - 2u^2 + 2\Delta^2) + \beta^2(26\delta u\Delta - 17\delta u^2 + 8\delta\Delta^2 - 8k) + \beta\delta^2(28u\Delta - 17u^2) - 24k\beta\delta + 2\delta^3u^2 - 12k\delta^2]}{\beta(\beta + 2\delta)(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)} \tag{11}$$

$$p_m^{R*} = \frac{ah[2\beta^3(2u\Delta - 3u^2 + 2\Delta^2) + \beta^2\delta(22u\Delta - 23u^2 + 8\Delta^2) - 8k\beta^2 - 21\beta\delta^2u^2 + 28\beta\delta^2u\Delta - 20k\beta\delta + 2\delta^3u^2 - 12k\delta^2]}{\beta(\beta + 2\delta)(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)} \tag{12}$$

$$\tau^{R*} = \frac{-2(5ah\delta u + 2\beta ahu + 2\beta ah\Delta)}{(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)} \tag{13}$$

For the proof of proposition 2, see Appendix 1.

Under these conditions, the market demand values for product direct sales channels and retail channels are, respectively, as follows:

$$D_m^{R*} = \frac{-ah(2\beta^2u^2 - 4\Delta\beta^2u + 3\beta\delta u^2 - 8\Delta\beta\delta u + 8k\beta - 2\delta^2u^2 + 12k\delta)}{(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)} \tag{14}$$

$$D_r^{R*} = \frac{-ah(4\beta^2u^2 - 2\Delta\beta^2u + 9\beta\delta u^2 - 4\Delta\beta\delta u + 8k\beta + 2\delta^2u^2 + 8k\delta)}{(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)} \tag{15}$$

The optimal profits brought by manufacturers, retailers and recycling and remanufacturing are, respectively, as follows:

$$\pi_m^{R*} = \frac{\begin{array}{l} a^2h^2[4u^2\beta^5(u^2 - 4u\Delta + 4\Delta^2) + 2\beta^4(16ku^2 - 32ku\Delta + 17\delta u^4 - 46\delta u^3\Delta + 44\delta u^2\Delta^2) + \beta^3(64k^2 + 176k\delta u^2 \\ -336k\delta u\Delta + 43\delta^2u^4 - 170\delta^2u^3\Delta + 160\delta^2u^2\Delta^2) + \beta^2(320k^2\delta + 296k\delta^2u^2 - 568k\delta^2u\Delta + 12\delta^3u^4 - 88\delta^3u^3\Delta \\ +96\delta^3u^2\Delta^2) + \beta(496k^2\delta^2 + 124k\delta^3u^2 - 304k\delta^3u\Delta - 20\delta^4u^4 + 24\delta^4u^3\Delta) + 240k^2\delta^3 - 40k\delta^4u^2] \end{array}}{\beta(\beta + 2\delta)(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)^2} \tag{16}$$

$$\pi_r^{R*} = \frac{-a^2h^2(4k + 3\beta u^2 + 6\delta u^2)}{(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)} \tag{17}$$

$$RE^{R*} = \frac{-4a^2h^2(u - \Delta)(2\beta u + 2\beta\Delta + 5\delta u)(3\beta^2u^2 - 3\Delta\beta^2u + 6\delta\beta u^2 - 6\delta\Delta\beta u + 8k\beta + 10k\delta)}{(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)^2} \tag{18}$$

To ensure that the calculation is meaningful, the product price, recovery rate and profit should be greater than 0, so the parameters of the model need to satisfy the following:$\Delta < \frac{16(\beta\delta u^2+k\beta+k\delta)+8\beta^2u^2-u^2\delta^2}{4(2\beta^2u+\beta^2\Delta+5\beta\delta u)}$.

From the above results, we have Corollary 2:

Corollary 2 (i) *In the case of retailer recycling, the wholesale price* (ω^{R*}), *retail price* (P_r^{R*}) *and direct selling price* (P_m^{R*}) *of the product are inversely proportional to the cost savings* (Δ) *of remanufacturing and directly proportional to the coefficient* (k) *of investment recovery. (ii) The recovery rate* (τ^{R*}) *of e-waste is inversely proportional to the cost savings* (Δ) *of remanufacturing and directly proportional to the coefficient* (k) *of investment recovery. (iii) The market demand for retail channels* (D_r^{R*}) *and direct sales channels* (D_m^{R*}) *is directly proportional to the cost savings* (Δ) *of remanufacturing and inversely proportional to the coefficient* (k) *of the recovery of investment. (IV) The manufacturer's profit* (π_m^{R*}), *retailer's profit* (π_r^{R*}) *and remanufacturing profit* (RE^{R*}) *are directly proportional to the coefficient* (k) *of investment recovery and manufacturing cost savings* (Δ).

For the proof of Corollary 2, see Appendix 2.

Corollary 2 shows that in the retailer's recovery model, as the recovery of investment increases, the recovery rate of the retailer's e-waste also increases. For manufacturers, the volume of raw materials that can be used for remanufacturing is also increasing, which promotes market demand for new and remanufactured products and increases remanufacturing profits. With the increase in cost savings of remanufacturing, taking into account the interests of consumers, manufacturers will reduce wholesale prices, retail prices will also decrease, and market demand for new and remanufactured products will also increase. Under these conditions, the retailer will further increase the return on investment to meet market demand, which will ultimately increase both the manufacturer's profit and the retailer's profit.

4.3 Recycling model of third-party recyclers (model 3P)

In the recycler recycling model, the manufacturer entrusts a third-party recycler to recycle e-waste from consumers at a unit price of u and remanufacture e-waste. Under this recycling channel, the recycler first determines the recovery rate (τ^{3P}) of e-waste and the investment funds (I^{3P}) for recycling e-waste. Second, the manufacturer sets the direct selling price (P_m^{3P*}) of remanufactured products and the wholesale price (ω^{3P}) of new products. Finally, the retailer determines the retail price (P_r^{3P*}) of the new product. Under these conditions, the profit function of each party is expressed as follows:

$$\pi_r^{3P}(p_r) = (p_r - \omega)\left[h_1 a - \beta_1 p_r + \delta(p_m - p_r)\right] \tag{19}$$

$$\pi_r^{3P}(\tau) = (b - \tau)[(h_1 + h_2)\alpha - \beta_1 p_r - \beta_2 p_m] - k\tau^2 \tag{20}$$

$$\begin{aligned} \pi_m^{3P}(p_m, \omega) =& [h_1 a - \beta_1 p_r + \delta(p_m - p_r)\omega + \left[h_2 a - \beta_2 p_m + \delta(p_m - p_r)\right] p_m \\ &+ (\Delta - u - c_m)\left[(h_1 + h_2)\alpha - \beta_1 p_r - \beta_2 p_m\right] \end{aligned} \tag{21}$$

Similarly, with $h_1 = h_2 = h, \beta_1 = \beta_2 = \beta$, we solve by reverse induction as follows:

Proposition 3 *For the case of recycling by recyclers, when* $k > \frac{\beta\Delta^2(1+\beta+2\delta)}{8(\beta+\delta)}$ *and the respective profits of the manufacturer, retailer and recycler are maximized, we, respectively, have the following unique optimal wholesale prices, retail prices, direct sales prices and recycling rates, which are*:

$$\omega^{3P*} = \frac{ah(3\beta^2u^2 - 3z\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 2k\beta + 2k\delta)}{3\beta^3u^2 - 3\Delta\beta^3u + 4\delta\beta^2u^2 - 4\delta\Delta\beta^2u + 4k\beta^2 + 4k\delta\beta} \tag{22}$$

$$p_r^{3P*} = \frac{ah(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 3k\beta + 2k\delta)}{\beta(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)} \tag{23}$$

$$p_m^{3P*} = \frac{ah(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 2k\beta + 2k\delta)}{B(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)} \tag{24}$$

$$\tau^{3P*} = \frac{ahu(3\beta + 4\delta)}{2(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)} \tag{25}$$

For the proof of proposition 3 see Appendix1.

Under these conditions, the market demand of the direct sales channel and retail channel of the product are, respectively, as follows:

$$D_m^{3P*} = \frac{ahk(2\beta + 3\delta)}{(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)} \tag{26}$$

$$D_r^{3P*} = \frac{ahk(\beta + \delta)}{(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)} \tag{27}$$

The optimal profits brought by the manufacturer's, retailer's and enterprise's recycling and remanufacturing are as follows:

$$\pi_m^{3P*} = \frac{a^2h^2k(3\beta + 4\delta)}{2\beta(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)} \tag{28}$$

$$\pi_r^{3P*} = \frac{a^2h^2k^2(\beta + \delta)}{(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)^2} \tag{29}$$

$$\pi_\tau^{3P*} = \frac{a^2h^2ku^2(3\beta + 4\delta)^2}{4(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)^2} \tag{30}$$

$$RE^{3P*} = \frac{-a^2h^2ku(u - \Delta)(3\beta + 4\delta)^2}{2(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)^2} \tag{31}$$

To ensure that the results are meaningful, the product price, recovery rate and profit should be greater than 0, so the parameters of the model must satisfy the following: $\Delta < \frac{3u^2\beta^2+4\delta\beta u^2+4k\beta+4k\delta}{\beta u(3\beta+4\delta)}$.

Corollary 3 *In the case of third-party recycler recycling, (i) wholesale prices* (ω^{3P*}), *direct sales prices* (p_m^{3P*}), *and retail prices* (p_r^{3P*}) *are directly proportional to the coefficient* (k) *of investment recovery and inversely proportional to the cost savings* (Δ) *of remanufacturing. (ii) The recovery rate* (τ^{3P*}) *of e-waste is directly proportional to the cost savings* (Δ) *of remanufacturing and inversely proportional to the coefficient k of investment recovery. (iii) The market demand of retail channels* (D_r^{3P*}) *and direct sales channels* (D_m^{3P*}) *is directly proportional to the cost savings* Δ *of remanufacturing and inversely proportional to the coefficient k of the return on investment. (IV) The retailer's profit* (π_r^{3P*}), *manufacturer's profit* (π_m^{3P*}), *recycler's profit* (π_τ^{3P*}) *and remanufacturing profit* (RE^{3P*}) *are inversely proportional to the coefficient* (k) *of investment recovery and directly proportional to the cost savings* (Δ) *of remanufacturing.*

For the proof of Corollary 3, see Appendix 2.

Corollary 3 shows that in the third-party recycler's recycling model, with an increase in the investment recovered, the recycling rate of the recycler's e-waste also increases. When the cost savings of remanufacturing decrease, the higher the recovery rate is, the greater the cost of remanufacturing becomes. To reduce costs, manufacturers will reduce investment recovery and increase wholesale prices, and retail prices will also increase, leading to a decrease in market demand and ultimately to a decrease in the retailer's, manufacturer's and recycler's profits. When remanufacturing cost savings increase, the higher the recovery rate is, the greater the remanufacturing profit becomes. Taking into account the interests of consumers, manufacturers will lower wholesale prices, and retail prices will also decrease.

Under these conditions, market demand for new products and remanufactured products will also increase. From the increase in market demand, the profits of retailers, manufacturers and recyclers will also increase.

5 Analysis of the effect of recycling-remanufacturing

To express the results of the following propositions more intuitively, we use Haier's 216-L BCD-216STPT direct cooling fixed-frequency three-door refrigerator as an example for a numerical simulation. We assume that Haier Company (i.e., 'the manufacturer') has produced a batch of 216 l BCD-216STPT direct cooling fixed-frequency three-door refrigerators and sold them through a dual-channel system (direct online sales or traditional retail). The company uses raw materials to produce new products or waste products to produce remanufactured products. Studies have indicated that for remanufacturing companies to make a profit, the recycling rate of waste products should be at least 75%, while the remanufacturing rate of using waste products should be at least 55% (Zhang, et al., 2020a, 2020b). These values increase the recovery rate and ensure that remanufacturing activities result in income. The company adopts three recycling strategies: recycling by itself, entrusting retailers to recycle, or entrusting third-party recyclers to recycle. Through the comparison of these three recycling strategies, the company chooses the most suitable combination to maximize corporate profits. The current retail price of the refrigerator listed on the company's official website is RMB 1299. Assuming that the market capacity of the refrigerator is $a = 1000$, the production cost of a single refrigerator produced by the manufacturer is $c_n = 1000$, and the sales cost of a single refrigerator produced by the retailer is $c_r = 50$, as shown in Table 3. The following section will analyze the effects of recycling and remanufacturing in each situation.

5.1 Comparison of recovery rates

By comparing the recovery rates of existing household appliances in each situation, Proposition 4 is obtained.

Proposition 4 *The optimal recovery rate satisfies* $\tau^{M*} > \tau^{R*} > \tau^{3P*}$.

For the proof of proposition 4, see Appendix 1.

According to the results of each parameter assignment, the data shown in Table 2 were substituted into equations τ^{M*}, τ^{R*} and τ^{3p*}, and MATLAB R2015a software was used to analyze the optimal recovery rate for each case with k and Δ. The simulation results are given in Fig. 2.

Figure 2 shows that the manufacturer achieves the highest recovery rate for recycling e-waste. Under the same conditions, the recycling rate achieved when the manufacturer entrusts the retailer to recycle is higher than that of the third-party recycler. The reasoning is as follows. (1) Manufacturers are responsible for all remanufacturing cost savings when they are responsible for recycling. As remanufacturing cost savings (Δ) increase, product production

Table 3 Assignment of each variable parameter

a	h	β	c_n	c_r	p_m	p_r	ω	δ	u	k	Δ
1000	0.6	1	400	50	1060	1299	980	0.03	30	950	47

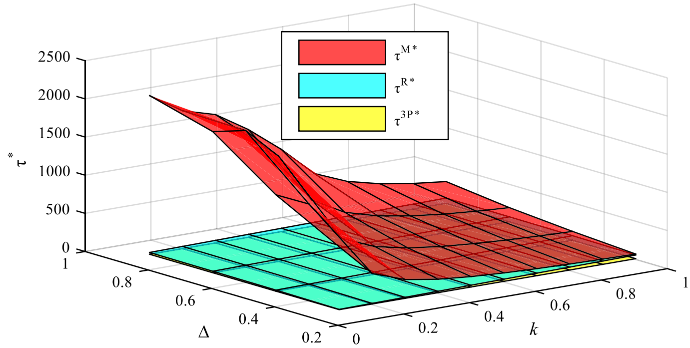

Fig. 2 Influence of changes in k and Δ on the optimal recovery rate

costs will decrease. Manufacturers will strive to increase recycling investment to obtain more production raw materials. Under these conditions, the recovery rate of e-waste is the highest, which is also consistent with current mainstream research conclusions (Teng & Feng, 2021; Zhang et al., 2021). (2) As the distance between retailers and consumers decreases, compared to third-party recyclers, retailers understand the needs of consumers better, so it is easier to recycle e-waste from consumers, resulting in a higher recycling rate for retailers.

5.2 Comparison of remanufacturing benefits

Proposition 5 Optimal remanufacturing profit satisfaction can be derived as follows:

When $k < \sqrt{\frac{-3u^2\beta^2+3\Delta\beta^2u-6\beta\delta u^2+6\Delta\delta u}{2(4\beta+5\delta)}}$, $\Delta > \sqrt{\frac{8\beta k^2+10k^2\delta+3\beta^2u^2+6\delta\beta u^2}{3\left(\beta^2u+2\beta\delta u\right)}}$, *we can conclude that* $\mathrm{RE}^{M*} > RE^{R*} > RE^{3P*}$; *when* $k > \sqrt{\frac{-3u^2\beta^2+3\Delta\beta^2u-6\beta\delta u^2+6\Delta\delta u}{2(4\beta+5\delta)}}$, $\Delta < \sqrt{\frac{8\beta k^2+10k^2\delta+3\beta^2u^2+6\delta\beta u^2}{3\left(\beta^2u+2\beta\delta u\right)}}$, *we can conclude that* $\mathrm{RE}^{R*} > RE^{M*} > RE^{3P*}$.

For the proof of proposition 5 see Appendix 1.

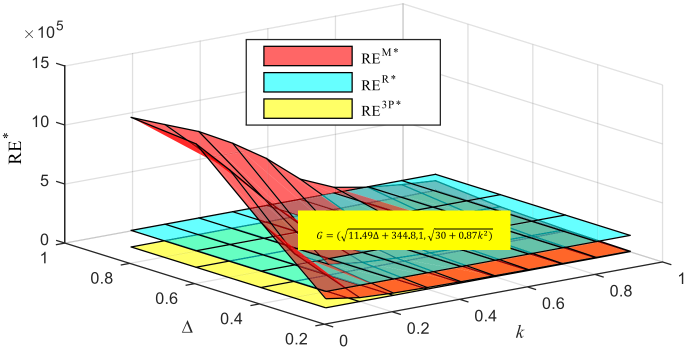

Fig. 3 Impact of changes in k and Δ on optimal remanufacturing revenue

By substituting the data shown in Table 2 into Eqs. (7), (18), and (31), the optimal remanufacturing revenue varies with k and Δ in each situation through numerical simulation, as shown in Fig. 3.

From Fig. 3, (1) when $k > \sqrt{11.49\Delta + 344.81}$ and $\Delta < \sqrt{30 + 0.87k^2}$, the manufacturer's remanufacturing revenue with recycling is lower than the retailer's remanufacturing revenue with recycling. In contrast, when $k < \sqrt{11.49\Delta + 344.81}$ and $\Delta > \sqrt{30 + 0.87k^2}$, the manufacturer's remanufacturing revenue with recycling is higher than the retailer's remanufacturing revenue. (2) Third-party recyclers have the lowest remanufacturing revenue from recycling. The reason is that when the cost saved (Δ) by remanufacturing is low, the revenue from remanufacturing decreases. As the retailer's investment parameter (k) increases investment recovery, the recovery cost paid by the manufacturer to the retailer will also increase, further reducing the remanufacturing gains. When the cost saved (Δ) by remanufacturing is higher, the profit that the manufacturer obtains from remanufacturing will increase. As the return on investment parameter(k) increases, the more raw materials a manufacturer can use for remanufacturing, and the higher the profit from remanufacturing becomes. (3) Combined with Proposition 4, it can be concluded that the third-party recycling rate is the lowest. Therefore, when the manufacturer's recycling investment remains unchanged, the decrease in the recycling rate will increase the unit product remanufacturing cost and ultimately reduce the remanufacturing revenue when the third party recycles.

Corollary 4 *Figure 4 shows that (1) the difference in recycling channels a has a small impact on the recycling rate and remanufacturing profits of third-party recyclers but has a greater impact on the recycling rate and remanufacturing profits of manufacturers and retailers. (2) Recycling channel δ is positively correlated with τ^{M*} and RE^{M*}When the difference in recycling channels is large, recycling channel δ is negatively correlated with τ^{R*} and RE^{R*}; when the difference in recycling channels is small, recycling channel δ is positively correlated with τ^{R*} and RE^{R*}. The manufacturer's recovery rate and remanufacturing benefits are the greatest when recycled, while the third-party recycler's recovery rate and remanufacturing benefits are the lowest.*

Corollary 4 shows that as the difference in the δ of the recycling channels increases, competition among the recycling channels increases as well. When there is a large

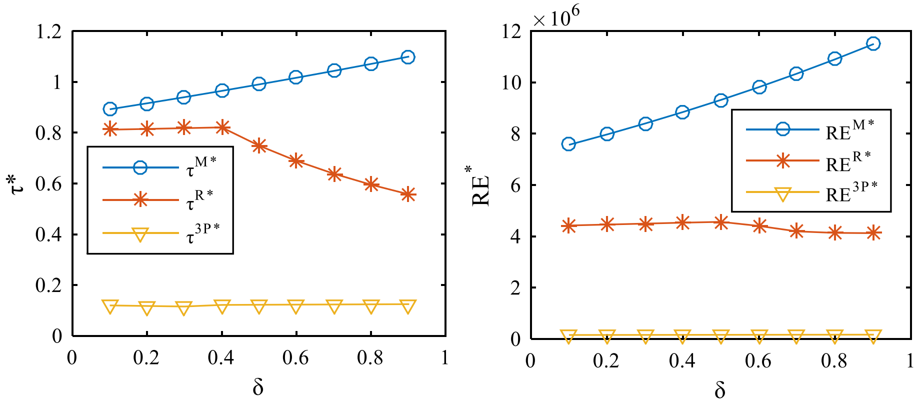

Fig. 4 Impact of changes in recycling channels δ on recycling rates and remanufacturing revenue

difference in recycling channel δ, the recycling rate of traditional retailers will decrease due to the influence of recycling channels, the raw materials provided by retailers for remanufacturing will decrease, and the remanufacturing revenue will also decrease. When the difference of recycling channel δ is small, the change in δ will have less of an impact on the retailer's recycling, so the retailer's recycling rate and remanufacturing profit will still increase. Combined with the analysis of Corollaries 1 and 2, it is found that the recovery rate of τ^{M*} is always greater than that of τ^{R*} and τ^{3P*}, which is consistent with the results of Corollary 4, indicating that each channel has practical significance for the recycling and remanufacturing of e-waste. The difference is that with the increase in investment recovery and cost savings from remanufacturing, the manufacturer's profits from recycling and remanufacturing may not be the highest, while changes in recycling channel δ can bring absolute benefits to the manufacturer's remanufacturing ($\mathrm{RE}^{M*} > \mathrm{RE}^{R*} > \mathrm{RE}^{3P*}$). This shows that the recycling channel has an important influence on the manufacturer's remanufacturing. It is thus inferred that in the future remanufacturing market, channel disputes will become key to enterprises' dominant positioning and benefits.

5.3 Comparison of corporate profits

Proposition 6 The optimal profit of manufacturers, retailers and third-party recyclers satisfies:

(i) $\pi_m^{M*} > \pi_m^{R*} > \pi_m^{3P*}$;

(ii) When $k > \sqrt{\frac{192\beta^3\delta^2u^2\Delta^4+126\delta u^2\Delta^4\beta^4+27\beta^5u^2\Delta^4}{176\beta^3-160\beta^3u^2-32\beta^3u\Delta}}$, we can conclude that $\pi_r^{R*} > \pi_r^{M*} > \pi_r^{3P*}$.

When $k < \sqrt{\frac{192\beta^3\delta^2u^2\Delta^4+126\delta u^2\Delta^4\beta^4+27\beta^5u^2\Delta^4}{176\beta^3-160\beta^3u^2-32\beta^3u\Delta}}$, we can conclude that $\pi_r^{M*} > \pi_r^{R*} > \pi_r^{3P*}$.

(iii) $\pi_\tau^{3P*}(\tau) = \frac{a^2h^2ku^2(3\beta+4\delta)^2}{4(3\beta^2u^2-3\Delta\beta^2u+4\delta\beta u^2-4\delta\Delta\beta u+4k\beta+4k\delta)^2}$.

For the proof of proposition 6 see Appendix 1.

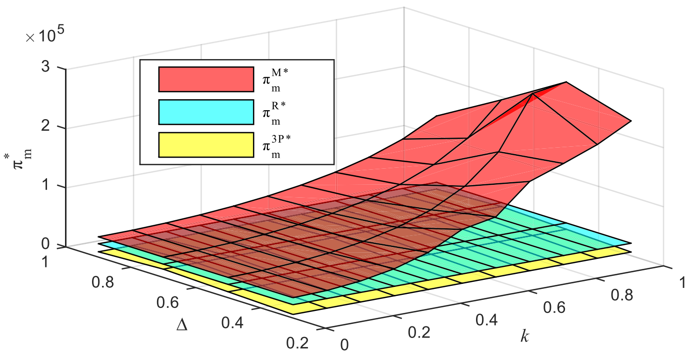

Fig. 5 Impact of changes in k and Δ on the profit of the best manufacturer

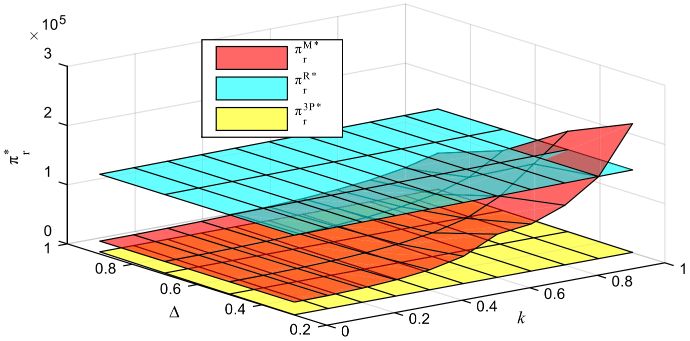

Fig. 6 Impact of changes in k and Δ on the profit of the optimal retailer

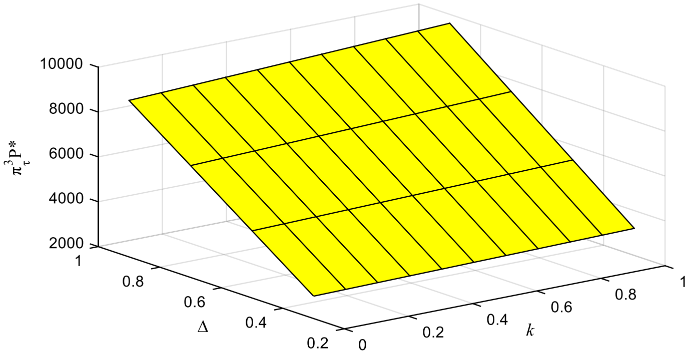

Fig. 7 Impact of changes in k and Δ on the profits of the best third-party recyclers

To further verify the results of Propositions 6, the data shown in Table 2 are substituted into Eqs. (5), (16) and (28); Eqs. (6), (17) and (29); and Eq. (30), respectively. MATLAB R2015a software was used to analyze the profit changes of the best manufacturers, retailers and third-party recyclers with k and Δ for the three situations as shown in Figs. 5, 6 and 7.

Figure 5 shows that with the increase of k and Δ, the profit of the best manufacturer in the three scenarios increases. The manufacturer generates the highest profit and achieves the greatest change in recycling and in the profits of third-party recyclers. The lowest change range verifies proposition 6 (i).

Figure 6 shows that with an increase of k and Δ, the profit of the best retailer in the three situations increases. In terms of the growth rate, manufacturers achieve the largest increase in profits when recycling, while retailers and third-party recyclers achieve the smallest increase in profits when recycling. Among them, third-party recyclers generate the lowest profits when recycling. When $k > \sqrt{\frac{192\beta^3\delta^2u^2\Delta^4+126\delta u^2\Delta^4\beta^4+27\beta^5u^2\Delta^4}{176\beta^3-160\beta^3u^2-32\beta^3u\Delta}}$, the retailer's profit is the highest; in contrast, the manufacturer's profit is the highest. However, from the perspective of the retailer's entire profit coverage, the profit coverage area of the retailer's recycling is much higher than that of the manufacturer's recycling. This result verifies proposition 6 (ii).

Figure 7 shows that with the increase of k and Δ, the profits of third-party recyclers also increase, and the increase in the third-party recycler's profits with Δ is greater than the increase in k, showing that the profits of third-party recyclers are greatly more affected by Δ. This result verifies proposition 6 (iii).

Combined with the analysis of Figs. 5 and 7, the optimal profit of the leader of the recycling channel is almost higher than the profits of the other participants. It can be concluded that the recycling channel has an important influence on the recycling participants, consistent with the result of Corollary 4.

Corollary 5 *Figure 8 shows that (i) when the manufacturer or retailer is selected for recycling, recycling channel δ has less of an impact on the profits of retailers and third-party recyclers, but it has a greater impact on the profits of manufacturers. When a third-party recycler recycles, recycling channel δ has a greater impact on the profit of the third-party recycler. (ii) Recycling channel δ is positively correlated with π_m^*,π_r^* and π_{3P}^*.*

Corollary 5 shows that as the difference in recycling channels increases, the manufacturer's profits do so as well. When the difference in recycling channels is large, the change in δ will have a greater impact on the manufacturer's profit. When the difference in recycling channels is small, the change in δ will have a small impact on the manufacturer's profit, so the manufacturer's profit will continue to increase.

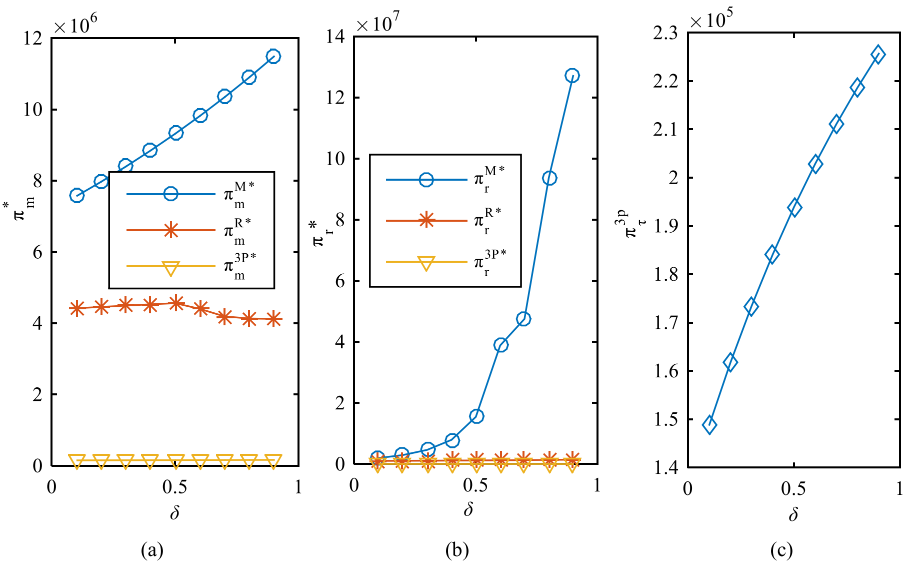

Fig. 8 Impact of changes in recycling channel δ on the profits of manufacturers and retailers

6 Model expansion

This section examines the environmental impact of different recycling channels in three situations. Referring to Visnjic and Looy (2012) and Atasu and Souza (2013), parameters θ and φ are, respectively, introduced to represent the environmental impact of direct and traditional retail channels (including the environmental impact of remanufacturing). F is the total impact of the two retail channels on the environment under different recycling scenarios, and the functional relationship expression is written as $F=\theta D_m^*+\varphi D_r^*$.

Proposition 7 (1) *When* $\theta > -\varphi x_1/j_1$, *we can conclude that* $F^{M*} > F^{R*}$; *in contrast,* $F^{M*} < F^{R*}$.(2) *When* $\theta < -\varphi x_2/j_2$, *we can conclude that* $F^{R*} > F^{3P*}$; *in contrast,* $F^{R*} < F^{3P*}$. (3)$F^{M*} > F^{3P*}$. *For the proof of proposition* 7 *see Appendix* 1.

Figure 9 shows that the recycling of e-waste by third-party recyclers has the least environmental impact. When environmental parameters θ and φ are, respectively, at points A(0.258,0.379) and B(0.416,0.905), that is $\theta < 0.25$,$\varphi > 0.379$ and $\theta > 0.905$, $\varphi < 0.416$, e-waste recycling by manufacturers has less of an environmental impact than e-waste recycling by retailers. In contrast, the impact of e-waste recycling by manufacturers on the environment is greater than the environmental impact of retailers recycling e-waste. This result shows that recycling by manufacturers and retailers has a greater impact on the environment, while recycling by third-party recyclers has less of an impact on the environment. This is the case because third-party recyclers have the lowest recycling and remanufacturing rates when recycling, so their impact on the environment is also the least significant. In addition, third-party recyclers may use their professionalism and selective recycling in the recycling process. Although the recycling rate is low, the recycling quality of e-waste is high, so the impact on the environment is minimal. Therefore, from a purely environmental point of view, it is optimal to have a third-party recycler responsible for recycling. This result verifies proposition 7.

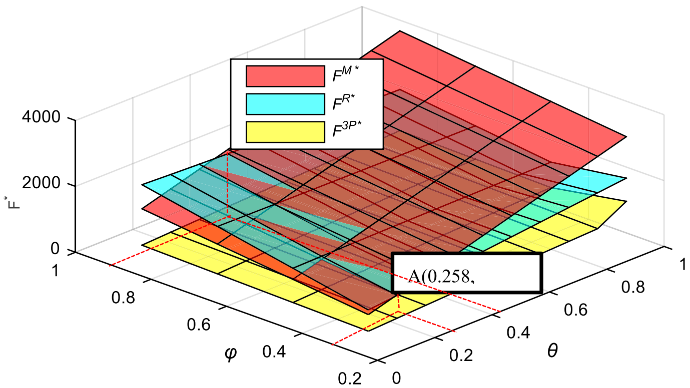

Fig. 9 Impact of changes in θ and φ on the environment

7 Research conclusions and future prospects

7.1 Research conclusions

According to the policy recommendations of the "Global Electronic Waste Monitoring Report 2020" and the "White Paper on China's Waste Electrical and Electronic Products Recycling and Comprehensive Utilization Industry," this paper studies a closed-loop supply chain game model based on online direct sales, traditional retail, and upstream and downstream stakeholders in the supply chain participating in recycling and remanufacturing. We consider possible recycling channels and analyze the optimal selection strategy for e-waste recycling by manufacturers, retailers, and third-party recycling companies. First, we compare recovery rates, remanufacturing revenues, corporate profits and environmental impacts under the recovery of various channels. Second, we use MATLAB simulation software to verify the impact of the return on investment coefficient (k), remanufacturing cost savings (Δ) and the change in the return channel (δ) on the return rate, remanufacturing revenue, corporate profits and the environment. Finally, we propose means to promote the implementation of guidelines outlined in the above white paper and monitoring report.

Our main conclusions are summarized as follows:

1. In terms of increasing the recovery rate, manufacturers prefer to recycle themselves. When choosing to entrust recycling to another entity, the manufacturer will give priority to the retailer for recycling.
2. In terms of increasing remanufacturing revenue, this mainly depends on the returnee's investment coefficient and remanufacturing cost savings. When the investment coefficient of the reclaimer is higher and the cost savings of remanufacturing are lower, the manufacturer will have the retailer reclaim it. In contrast, when the investment coefficient of the reclaimer is low and the cost savings of remanufacturing are high, the manufacturer will recycle by itself.
3. In terms of improving corporate profits, this mainly depends on the leader of the recycling channel. As far as the manufacturer is concerned, the manufacturer's profit is highest when it recycles by itself, and the profit is lowest when recycling is commissioned by a third-party recycler. For retailers, the retailer's corporate profits are highest when it performs recycling, but under certain conditions, the retailer's profit may be lower than the manufacturer's profit. For third-party recyclers, their profits are mainly affected by the cost savings of remanufacturing.
4. In terms of environmental impacts, third-party recyclers have the least environmental impact when recycling. However, as recycling channels change, the environmental impact of manufacturers' and retailers' recycling will also change.

Now let's briefly analyze the regulatory significance of the article from the perspective of manufacturer and government, respectively. First of all, for manufacturers, the choice of recycling mode determines the development strategy of enterprises to a certain extent. If the manufacturer is inclined to get a higher recovery rate of waste products and enterprise profits, then the manufacturer's direct recycling scheme is the best. Conversely, if a manufacturer simply wants to enhance its reputation and thereby expand its influence by taking responsibility for recycling, it is more cost effective to choose the retailer model. Secondly, for policy makers, they are more concerned about how to balance the relationship between economy, environment and social welfare. Electronic waste recycling as a new electronic industry, in order to achieve the purpose of sustainable development, the government needs to formulate scientific and effective policy measures to actively guide manufacturers to directly recycle waste electronic products, in order to improve the efficiency of resource recycling. For example, the Law on the Prevention and Control of Environmental Pollution by Solid Waste amended by the Chinese government in 2020 has clarified the recycling responsibility of manufacturers. For traditional commodities such as steel, where producers are far removed from consumer markets, government schemes to encourage retailers to take responsibility for recycling should be more effective.

8 Research outlook

From the above conclusions, recycling channels have a significant impact on the recycling and remanufacturing of e-waste. The implementation of reasonable recycling strategies can not only effectively increase the rate of e-waste recycling but also promote an increase in corporate profits and reduce the impact of e-waste on the environment to realize the sustainable development of the e-waste remanufacturing industry. In this article, we consider a situation where manufacturers, retailers and third-party recyclers are solely responsible for e-waste recycling, but we do not take into account cooperative recycling by various recycling parties. Cooperation through recycling channels can be better utilized. All involved parties can learn from each other's strengths to maximize the economic and environmental benefits of the e-waste recycling-remanufacturing process. In addition, while we assume demand to be determined, market demand is affected by a variety of factors, making it difficult to predict. Finally, we do not take into account the case where some entities act as both retailers and manufacturers. Therefore, future research can further consider the choice of e-waste recycling and remanufacturing strategy under uncertain demand and the closed-loop supply chain decision of a single actor acting as both manufacturer and retailer.

Appendix1: Proof of propositions 1–7

Proposition 1

Proof: Because $\partial^2\pi_r^M\left(p_r\right)/\partial^2 p_r = -2(\beta+\delta)$, $\pi_r^M\left(p_r\right)$ is a strictly concave function of p_r. Under these conditions, the retailer's profit function $\pi_r^M\left(p_r\right)$ has maximum value. We let $\partial\pi_r^M\left(p_r\right)/\partial p_r = 0$ and find the retail price of p_r with respect to $\pi_r^M\left(p_r\right)$ as follows:

$$p_r^M = \frac{ah + p_m\delta + \omega(\beta+\delta)}{2(\beta+\delta)} \tag{32}$$

By substituting Eq. (32) into equation π_m^M, the Hessian matrix of the manufacturer's profit function $\pi_m^M(p_m, \tau, \omega)$ with respect to p_m,τ and ω is as follows:

$$H_1 = \begin{pmatrix} \frac{\partial^2\pi_m^M}{\partial p_m^2} & \frac{\partial^2\pi_m^M}{\partial p_m\partial\tau} & \frac{\partial^2\pi_m^M}{\partial p_m\partial\omega} \\ \frac{\partial^2\pi_m^M}{\partial\tau\partial p_m} & \frac{\partial^2\pi_m^M}{\partial\tau^2} & \frac{\partial^2\pi_m^M}{\partial\tau\partial\omega} \\ \frac{\partial^2\pi_m^M}{\partial\omega\partial p_m} & \frac{\partial^2\pi_m^M}{\partial\omega\partial\tau} & \frac{\partial^2\pi_m^M}{\partial\omega^2} \end{pmatrix} = \begin{pmatrix} \frac{-(2\beta^2+4\beta\delta+\delta^2)}{\beta+\delta} & \frac{-\Delta\beta(1+\delta)}{2(\beta+\delta)} & \delta \\ -\Delta\left[\frac{2\beta^2+3\beta\delta}{2(\beta+\delta)}\right] & -2k & \frac{-\beta\Delta}{2} \\ \delta & \frac{-\beta\Delta}{2} & -(\beta+\delta) \end{pmatrix} \tag{33}$$

The third-order principal equation of the Hessian matrix is as follows:

$\beta(\beta+2\delta)\frac{\beta\Delta^2(1+\beta+2\delta)-8k(\beta+\delta)}{2(\beta+\delta)}<0$, namely, when $k>\frac{\beta\Delta^2(1+\beta+2\delta)}{8(\beta+\delta)}$, Hessian matrix H_1 is negative definite. Under these conditions, the manufacturer's profit function $\pi_m^M(p_m,\tau,\omega)$ is a joint concave function of p_m,τ and ω, and the manufacturer's profit function has maximum value. Therefore, we can derive the first-order partial derivative of $\pi_m^M(p_m,\tau,\omega)$ with respect to p_m, τ and ω, and the simultaneous equations can generate optimal wholesale price ω^{M*}, optimal retail price P_r^{M*} and optimal recovery rate τ^{M*}, respectively:

$$\omega^{M*}=\frac{ah(-3\beta^2\Delta^2-4\delta\beta\Delta^2+4k\beta+4k\delta)}{\beta(-3\beta^2\Delta^2-4\delta\beta\Delta^2+8k\beta+8k\delta)} \tag{34}$$

$$p_m^{M*}=\frac{ah(-3\beta^2\Delta^2-4\delta\beta\Delta^2+4k\beta+4k\delta)}{\beta(-3\beta^2\Delta^2-4\delta\beta\Delta^2+8k\beta+8k\delta)} \tag{35}$$

$$\tau^{M*}=\frac{ah\Delta(3\beta+4\delta)}{(-3\beta^2\Delta^2-4\delta\beta\Delta^2+8k\beta+8k\delta)} \tag{36}$$

When substituting Eqs. (34), (35), and (36) into Eq. (32), the optimal direct selling price P_r^{M*} is as follows:

$$p_r^{M*}=\frac{ah(-3\beta^2\Delta^2-4\delta\beta\Delta^2+6k\beta+4k\delta)}{\beta(-3\beta^2\Delta^2-4\delta\beta\Delta^2+8k\beta+8k\delta)} \tag{37}$$

Proposition 1
is proved.
Proposition 2
Proof: The Hessian matrix of $\pi_m^R\left(p_m,\omega\right)$ with respect to p_m and p_r is as follows:

$$H_2=\begin{pmatrix}\frac{\partial^2\pi_m^R(p_m,\omega)}{\partial p_m^2} & \frac{\partial^2\pi_m^R(p_m,\omega)}{\partial p_m\partial p_r}\\ \frac{\partial^2\pi_m^R(p_m,\omega)}{\partial p_r\partial p_m} & \frac{\partial^2\pi_m^R(p_m,\omega)}{\partial p_r^2}\end{pmatrix}=\begin{pmatrix}-2\beta-2\delta & \delta\\ \delta & 0\end{pmatrix} \tag{38}$$

The second-order principal equation of the Hessian matrix is $-\delta^2<0$, and we can conclude that Hessian matrix H_2 is negative definite. Therefore,$\pi_m^R\left(p_m,\omega\right)$ is a joint concave function of p_m and p_r, and there is a unique optimal solution for p_m and p_r.

From $\frac{\partial\pi_m^R(p_m,\omega)}{\partial p_m}=0$ and $\frac{\partial\pi_m^R(p_m,\omega)}{\partial p_r}=0$, we can derive direct selling price $P_m^R=\frac{\beta\omega+\delta\omega-\beta\tau\delta+\beta\tau\Delta}{\delta^2}$ and retail price $P_r^R=(2\beta^2\omega+\omega\delta^2+4\beta\delta\omega-ah\delta-2\beta^2\tau u$ $+2\beta^2\tau\Delta+3\beta\delta\tau\Delta-3\beta\delta\tau u)/\delta^2$. With substitution into equation $\pi_r^R\left(p_r,\tau\right)$, the Hessian matrix of $\pi_r^R\left(p_r,\tau\right)$ with respect to τ and ω is calculated as follows:

$$H_3=\begin{pmatrix}\frac{\partial^2\pi_r^R(p_r,\tau)}{\partial\tau^2} & \frac{\partial^2\pi_r^R(p_r,\tau)}{\partial\tau\partial\omega}\\ \frac{\partial^2\pi_r^R(p_r,\tau)}{\partial\omega\partial\tau} & \frac{\partial^2\pi_r^R(p_r,\tau)}{\partial\omega^2}\end{pmatrix}=\begin{pmatrix}\frac{\begin{matrix}2[(4\beta^5+16\delta\beta^4)(u-\Delta)^2+k\delta^4\\+\beta^3\delta^2\left(17u^2-36u\Delta+19\Delta^2\right)\\+2\delta^3\beta^2\left(u^2-4u\Delta+3\Delta^2\right)]\end{matrix}}{\delta^4} & \frac{\begin{matrix}-\beta(\beta+2\delta)[4\left(2\beta^3+5\beta^2\delta\right)\\(\Delta-u)+\delta^3u+2\beta\delta^2(5\Delta-4u)\end{matrix}}{\delta^4}\\ \frac{\begin{matrix}-\beta(\beta+2\delta)[4\left(2\beta^3+5\beta^2\delta\right)\\(\Delta-u)+\delta^3u+2\beta\delta^2(5\Delta-4u)\end{matrix}}{\delta^4} & \frac{-\beta^2(\beta+\delta)(\beta+2\delta)^2}{\delta^4}\end{pmatrix} \tag{39}$$

Therefore, when$k<\frac{4\beta^2(\Delta-u)^2-16\beta u^2+20\beta u\Delta+u^2\delta^2}{16\beta+16\delta}$, the determinant of the Hessian matrix is negative definite. Under these conditions, $\pi_r^R\left(p_r,\tau\right)$ is the joint concave function of ω

andτ, and there is a unique optimal solution for ω andτ. From$\frac{\partial \pi_r^R(p_r,\tau)}{\partial \omega} = 0$,$\frac{\partial \pi_r^R(p_r,\tau)}{\partial \tau} = 0$, optimal wholesale price (ω^{R*}) and optimal recovery rate (τ^{R*}) can be obtained. We substitute ω^{R*} and τ^{R*} into retail price P_r^R and direct sales price P_m^R, respectively, to obtain best retail price (P_r^{R*}) and best direct sales price(P_m^{R*}). Proposition 2 is proved.

Proposition 3

Because $\frac{\partial^2 \pi_r^{3P}(p_r)}{\partial^2 p_r} = -2(\beta + \delta)$, it is concluded that $\pi_r^{3P}\left(p_r\right)$ is a strictly concave function of p_r, and the retailer's profit function $\pi_r^{3P}\left(p_r\right)$ has a maximum value. Under these conditions, the retail price of $\pi_r^{3P}\left(p_r\right)$ with respect to p_r is as follows:

$$p_r^{3P} = \frac{ah + p_m\delta + \omega(\beta + \delta)}{2(\beta + \delta)} \tag{40}$$

By substituting Eq. (9) into equation $\pi_r^{3P}(\tau)$ and finding the first derivative $\frac{\pi_\tau^{3P}(\tau)}{\partial \tau}$ with respect to τ and setting $\frac{\partial \pi_\tau^{3P}(\tau)}{\partial \tau} = 0$, we can derive the following: that:

$$\tau^{3P} = \frac{-4u(2\beta^2 p_m + \beta^2\omega - 3\beta ah + 3\beta p_m\delta + \beta\delta\omega - 4ah\delta)}{(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta + \delta^2u^2)} \tag{41}$$

By substituting Eq. (10) into equation $\pi_m^{3P}\left(p_m, \omega\right)$, we obtain the Hessian matrix of $\pi_m^{3P}\left(p_m, \omega\right)$ with respect to p_m and ω as follows:

$$H_4 = \begin{pmatrix} \frac{\partial^2 \pi_m^{3P}(p_m,\omega)}{\partial p_m^2} & \frac{\partial^2 \pi_m^{3P}(p_m,\omega)}{\partial p_m \partial \omega} \\ \frac{\partial^2 \pi_m^{3P}(p_m,\omega)}{\partial \omega \partial p_m} & \frac{\partial^2 \pi_m^{3P}(p_m,\omega)}{\partial \omega^2} \end{pmatrix} = \begin{pmatrix} \frac{-2\beta-\delta(2\beta+\delta)}{\beta+\delta} - \frac{u\beta^2(u-\Delta)(2\beta+3\delta)^2}{4k(\beta+\delta)^2} & \frac{\left(2u\beta^3+3\beta^2\delta u\right)(\Delta-u)+4k\delta(\beta+\delta)}{4k(\beta+\delta)} \\ \frac{\left(2u\beta^3+3\beta^2\delta u\right)(\Delta-u)+4k\delta(\beta+\delta)}{4k(\beta+\delta)} & \frac{-(\beta^2u-\Delta\beta^2u+4k\beta+4k\delta)}{4k} \end{pmatrix} \tag{42}$$

Therefore, when $k < \frac{3\Delta\beta^2u-3\beta^2u^2-4\delta\beta u^2+4\delta\Delta\beta u}{4(\beta+\delta)}$, the determinant of the Hessian matrix is negative definite. Under these conditions, π_m^{3P} is a joint concave function of p_m and ω, and there is a unique optimal solution for p_m and ω. By combining $\frac{\partial \pi_m^{3P}}{\partial \omega} = 0$ and $\frac{\partial \pi_m^{3P}}{\partial p_m} = 0$, the best wholesale price (ω^{3P*}) and best direct selling price (p_m^{3P*}) can be obtained. Substituting ω^{3P*} and p_m^{3P*} into recovery rate τ^{3P} and retail price p_r^{3P}, respectively, generates optimal recovery rate (τ^{3P*}) and optimal retail price (p_r^{3P*}). Proposition 3 is proved.

Proposition 4:

Proof:

$$\tau^{M*} - \tau^{R*}$$

$$= \frac{-4ah\Delta(3\beta + 4\delta)[\beta^2\Delta^2+2\beta^2u(\Delta - u)+16(\beta\delta u^2 + k\beta + k\delta)] - 8ah\Delta(3\beta + 4\delta)(5ah\delta u + 2\beta ahu + 2\beta ah\Delta)[3\beta^2\Delta^2 + 4\delta\beta\Delta^2 - 8k(\beta - \delta)]}{(-3\beta^2\Delta^2 - 4\delta\beta\Delta^2 + 8k\beta + 8k\delta)(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)} > 0$$

$$\tau^{R*} - \tau^{3P*} = \frac{\begin{array}{c}-ah(24\beta^3u^3 - 24\beta^3u^2\Delta + 12\beta^3\Delta^3 + 92\beta^2\delta u^3 - 140\beta^2\delta u^2\Delta + 60\beta^2\delta u\Delta^2 + 16\beta^2\delta\Delta^3 + 32k\beta^2u - 16k\beta^2\Delta \\ -141\beta\delta^2u^2\Delta + 80\beta\delta^2u\Delta^2 + 112k\beta\delta u - 80k\beta\delta\Delta + 4\delta^3u^2\Delta + 80k\delta^2u - 64k\delta^2\Delta)\end{array}}{2(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta +}$$

$$0$$

$$\tau^{M*} - \tau^{3P*} = \frac{\beta ah\Delta(3\beta + 4\delta)^2[u^2 + (u - \Delta)^2]}{-2(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)(-3\beta^2\Delta^2 - 4\delta\beta\Delta^2 + 8k\beta + 8k\delta)} > 0$$

It can be concluded that $\tau^{M*} > \tau^{R*} > \tau^{3P*}$, and thus Proposition 4 is proved.

Proposition 5:

Proof: $RE^{M*}-RE^{R*}=\frac{4a^2h^2(u-\Delta)(2\beta u+2\beta\Delta+5\delta u)(3\beta^2u^2-3\Delta\beta^2u+6\delta\beta u^2-6\delta\Delta\beta u+8k^2\beta+10k^2\delta)}{(-3\beta^2\Delta^2-4\delta\beta\Delta^2+8k\beta+8k\delta)^2(-8\beta^2u^2+8\beta^2u\Delta+4\beta^2\Delta^2-16\beta\delta u^2+20\beta\delta u\Delta-16k\beta+\delta^2u^2-16k\delta)^2}$.

Due to $\Delta>u$, when $k>\sqrt{\frac{-3u^2\beta^2+3\Delta\beta^2u-6\beta\delta u^2+6\Delta\delta u}{2(4\beta+5\delta)}}$, $\Delta<\sqrt{\frac{8\beta k^2+10k^2\delta+3\beta^2u^2+6\delta\beta u^2}{3(\beta^2u+2\beta\delta u)}}$, we can conclude that $\mathrm{RE}^{R*}>RE^{M*}$; in contrast, $\mathrm{RE}^{M*}>RE^{R*}$. In the same way, we calculate $\mathrm{RE}^{M*}>RE^{3P*}$,$\mathrm{RE}^{R*}>RE^{3P*}$. Proposition 5 is proved.

Proposition 6 (i):

Proof:

$$\pi_m^{M*}-\pi_m^{R*}=\frac{a^2h^2k(3\beta+4\delta)+160\beta^3\delta^2u^2\Delta^2+320\beta^2k^2\delta+296\beta^2k\delta^2u^2+32\beta^4ku^2-64\beta^4ku\Delta+24\beta^4\delta u^4}{\beta(\beta+2\delta)(-3\beta^2\Delta^2-4\delta\beta\Delta^2+8k\beta+8k\delta)(-8\beta^2u^2+8\beta^2u\Delta+4\beta^2\Delta^2-16\beta\delta u^2+20\beta\delta u\Delta-16k\beta+\delta^2u^2-16k\delta)^2}>0$$

$$\pi_m^{R*}-\pi_m^{3P*}=\frac{a^2h^2(4\beta^5u^4+160\beta^3\delta^2u^2\Delta^2+12\beta^2\delta^3u^4-88\beta^2\delta^3u^3\Delta+96\beta^2\delta^3u^2\Delta^2-20\beta\delta^4u^4+24\beta\delta^4u^3\Delta)}{2\beta(\beta+2\delta)(3\beta^2u^2-3\Delta\beta^2u+4\delta\beta u^2-4\delta\Delta\beta u+4k\beta+4k\delta)(-8\beta^2u^2+8\beta^2u\Delta+4\beta^2\Delta^2-16\beta\delta u^2+20\beta\delta u\Delta-16k\beta+\delta^2u^2-16k\delta)^2}>0$$

$\pi_m^{M*}-\pi_m^{3P*}=\frac{2\beta(3\beta^2u^2-3\Delta\beta^2u+4\delta\beta u^2-4\delta\Delta\beta u+4k\beta+4k\delta)a^2h^2k(3\beta+4\delta)-\beta a^2h^2k(3\beta+4\delta)(-3\beta^2\Delta^2-4\delta\beta\Delta^2+8k\beta+8k\delta)}{2\beta^2(-3\beta^2\Delta^2-4\delta\beta\Delta^2+8k\beta+8k\delta)(3\beta^2u^2-3\Delta\beta^2u+4\delta\beta u^2-4\delta\Delta\beta u+4k\beta+4k\delta)}>0$ Due to $\Delta<\frac{16(\beta\delta u^2+k\beta+k\delta)+8u^2\beta^2-\delta^2}{4(2\beta^2u+\beta^2\Delta+5\beta\delta u)}$ and$k>\frac{\beta\Delta^2(1+\beta+2\delta)}{8(\beta+\delta)}$,$\pi_m^{M*}>\pi_m^{R*}>\pi_m^{3P*}$. Proposition 6 **(i)** is proved.

Proposition 6 (ii):

Proof: $\begin{cases}-3\Delta^2\beta^2-4\delta\beta\Delta^2+8k\beta>0\\-8\beta^2u^2+8\beta^2u\Delta+4\beta^2\Delta^2-16\beta\delta u^2+20\beta\delta u\Delta-16k\ \beta+\delta^2u^2-16\ k\delta<0.\\3\beta^2u^2-3\Delta\beta^2u^2+4\delta\beta u^2-4\Delta\delta\beta u+4k\beta+4k\delta>0\end{cases}$

Therefore, when $k>\sqrt{\frac{192\beta^3\delta^2u^2\Delta^4+126\delta u^2\Delta^4\beta^4+27\beta^5u^2\Delta^4}{176\beta^3-160\beta^3u^2-32\beta^3u\Delta}}$ and $\pi_r^{M*}-\pi_r^{R*}<0$, we can conclude that $\pi_r^{M*}<\pi_r^{R*}$; otherwise, $\pi_r^{M*}>\pi_r^{R*}$.

$-a^2h^2(4k+3\beta u^2+6\delta u^2)(3\beta^2u^2-3\Delta\beta^2u+4\delta\beta u^2-4\delta\Delta\beta u+4k\beta+4k\delta)^2$

$$\pi_r^{R*}-\pi_r^{3P*}=\frac{-a^2h^2k^2(\beta+\delta)(-8\beta^2u^2+8\beta^2u\Delta+4\beta^2\Delta^2-16\beta\delta u^2+20\beta\delta u\Delta-16k\beta+\delta^2u^2-16k\delta)}{(-8\beta^2u^2+8\beta^2u\Delta+4\beta^2\Delta^2-16\beta\delta u^2+20\beta\delta u\Delta-16k\beta+\delta^2u^2-16k\delta)(3\beta^2u^2-3\Delta\beta^2u+4\delta\beta u^2-4\delta\Delta\beta u+4k\beta+4k\delta)^2}>0$$

$\pi_r^{M*}-\pi_r^{3P*}=\frac{4a^2h^2k^2(\beta+\delta)(3\beta^2u^2-3\Delta\beta^2u+4\delta\beta u^2-4\delta\Delta\beta u+4k\beta+4k\delta)^2-a^2h^2k^2(\beta+\delta)(-3\beta^2\Delta^2-4\delta\beta\Delta^2+8k\beta+8k\delta)^2}{(-3\beta^2\Delta^2-4\delta\beta\Delta^2+8k\beta+8k\delta)^2(3\beta^2u^2-3\Delta\beta^2u+4\delta\beta u^2-4\delta\Delta\beta u+4k\beta+4k\delta)^2}>0$ Proposition 6 (ii) is proved.

Proposition 6 (iii):

Proof: Substitutingω^{3P*},p_r^{3P*},p_m^{3P*} and τ^{3P*} into equation $\pi_r^{3P}(\tau)$ yields $\pi_\tau^{3P*}(\tau)=\frac{a^2h^2ku^2(3\beta+4\delta)^2}{4(3\beta^2u^2-3\Delta\beta^2u+4\delta\beta u^2-4\delta\Delta\beta u+4k\beta+4k\delta)^2}>0$. Proposition 6 (iii) is proved.

Proposition 7:

Proof:

$$F^{M*}-F^{R*}=\frac{-\varphi x_1-\theta j_1}{(-3\beta^2\Delta^2-4\delta\beta\Delta^2+8k\beta+8k\delta)(-8\beta^2u^2+8\beta^2u\Delta+4\beta^2\Delta^2-16\beta\delta u^2+20\beta\delta u\Delta-16k\beta+\delta^2u^2-16k\delta)}$$

$$F^{R*}-F^{TP*}=\frac{ah\theta j_2+ah\varphi x_2}{(-8\beta^2u^2+8\beta^2u\Delta+4\beta^2\Delta^2-16\beta\delta u^2+20\beta\delta u\Delta-16k\beta+\delta^2u^2-16k\delta)(3\beta^2u^2-3\Delta\beta^2u+4\delta\beta u^2-4\delta\Delta\beta u+4k\beta+4k\delta)}$$

$$F^{M*}-F^{TP*}=\frac{\beta ahk(3\beta+4\delta)(2u^2-2u\Delta+\Delta^2)(2\beta\varphi+\beta\theta+3\varphi\delta+\delta\theta)}{(-3\beta^2\Delta^2-4\delta\beta\Delta^2+8k\beta+8k\delta)(3\beta^2u^2-3\Delta\beta^2u+4\delta\beta u^2-4\delta\Delta\beta u+4k\beta+4k\delta)}$$

Because of $-3\beta^2\Delta^2-\ 4\ \delta\beta\Delta^2+8k\beta+8k\delta>0$,$4\ \beta^2[\Delta^2+2u(\Delta-u)]-16[\beta\delta u^2+k(\beta+\delta)]+20\ \beta\delta u\Delta+\delta^2u^2<0$, and so when $\theta>-\varphi x_1/j_1$, we can conclude that $F^{M*}<F^{R*}$; by contrast, $F^{M*}>F^{R*}$. Additionally, because $3\beta^2u^2-3\Delta\beta^2\ u+4\ \delta\beta u^2-4\delta\beta\Delta u+4k\beta+4k\delta>0$, when $\theta<-\varphi x_2/j_2$, we can conclude that $F^{R*}>F^{3P*}$; by contrast, $F^{R*}<F^{3P*}$. This result verifies Proposition 7.

Appendix2: proof of corollary 1–5.

Proof of corollary 1: In the manufacturer's recovery model, the first-order partial derivatives of remanufacturing cost savings Δ and recovery investment coefficient k are obtained for the wholesale price, direct sales price, and retail price of new products as follows:

$$\frac{\partial \omega^{M*}}{\partial \Delta} = \frac{-8ahk\Delta(3\beta^2 + 7\beta\delta + 4\delta^2)}{(-3\beta^2\Delta^2 - 4\delta\beta\Delta^2 + 8k\beta + 8k\delta)^2} < 0 \tag{43}$$

$$\frac{\partial \omega^{M*}}{\partial k} = \frac{4ah\Delta^2(3\beta^2 + 7\beta\delta + 4\delta^2)}{(-3\beta^2\Delta^2 - 4\delta\beta\Delta^2 + 8k\beta + 8k\delta)^2} > 0 \tag{44}$$

$$\frac{\partial p_m^{M*}}{\partial \Delta} = \frac{-8ahk\Delta(3\beta^2 + 7\beta\delta + 4\delta^2)}{(-3\beta^2\Delta^2 - 4\delta\beta\Delta^2 + 8k\beta + 8k\delta)^2} < 0 \tag{45}$$

$$\frac{\partial p_m^{M*}}{\partial k} = \frac{4ah\Delta^2(3\beta^2 + 7\beta\delta + 4\delta^2)}{(-3\beta^2\Delta^2 - 4\delta\beta\Delta^2 + 8k\beta + 8k\delta)^2} > 0 \tag{46}$$

$$\frac{\partial p_r^{*}}{\partial \Delta} = \frac{-4ahk\Delta(3\beta^2 + 10\beta\delta + 8\delta^2)}{(-3\beta^2\Delta^2 - 4\delta\beta\Delta^2 + 8k\beta + 8k\delta)^2} < 0 \tag{47}$$

$$\frac{\partial p_r^{*}}{\partial k} = \frac{2ah\Delta^2(3\beta^2 + 10\beta\delta + 8\delta^2)}{(-3\beta^2\Delta^2 - 4\delta\beta\Delta^2 + 8k\beta + 8k\delta)^2} > 0 \tag{48}$$

From Eqs. (12–17), the optimal wholesale price of remanufactured products, direct selling prices, and the retail price of new products are negatively related to the cost saved by remanufacturing Δ. In contrast, the optimal wholesale price of remanufactured products, direct sales prices and retail prices of new products are positively correlated with the coefficient of the return on investment k. In the same way, the calculation can be obtained as follows: $\frac{\partial \tau^{M*}}{\partial \Delta} > 0$, $\frac{\partial \tau^{M*}}{\partial k} < 0$; $\frac{\partial D_m^{M*}}{\partial \Delta} > 0$,$\frac{D_m^{M*}}{\partial k} < 0$;$\frac{\partial D_r^{M*}}{\partial \Delta} > 0$,$\frac{D_r^{M*}}{\partial k} < 0$;$\frac{\partial \pi_m^{M*}}{\partial \Delta} > 0$,$\frac{\partial \pi_m^{M*}}{\partial k} < 0$;$\frac{\partial \pi_r^{M*}}{\partial \Delta} > 0$,$\frac{\partial \pi_r^{M*}}{\partial k} < 0$;$\frac{\partial \mathrm{RE}^{M*}}{\partial \Delta} > 0$,$\frac{\partial \mathrm{RE}^{M*}}{\partial k} < 0$. corollary 1 is proved.

Proof of corollary 2: In the retailer recovery model, the first-order partial derivatives of remanufacturing cost savings Δ and recovery investment coefficient k are obtained for the wholesale price of remanufactured products, direct selling price, and retail price of new products as follows:

$$\frac{\partial \omega^{R*}}{\partial \Delta} = \frac{-2ah(-16\beta^4u^3 + 16\beta^4u^2\Delta - 16\beta^4u\Delta^2 + 48\beta^3\delta u^2\Delta + 32\beta^2\delta^2u^2\Delta + 80k\beta\delta^2\Delta + 6\delta^4u^3 + 104k\delta^3u)}{(\beta + 2\delta)(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)^2} < 0 \tag{49}$$

$$\frac{\partial \omega^{R*}}{\partial k} = \frac{4ah(-16\beta^4u^2 + 16\beta^4\Delta^2 - 80\beta^3\delta u^2 + 40\beta^3\delta u\Delta + 40\beta^3\delta\Delta^2 + 104\beta^2\delta^2u\Delta + 52\beta\delta^3u\Delta + 5\delta^4u^2)}{\beta(\beta + 2\delta)(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)^2} > 0 \tag{50}$$

$$\frac{\partial p_m^{R*}}{\partial \Delta} = \frac{-2ah(40\beta^2\delta^2u^2\Delta - 24\beta^2\delta^2u\Delta^2 + 48k\beta^2\delta u + 11\beta\delta^3u^3 + 80k\beta\delta^2\Delta + 6\delta^4u^3 + 104k\delta^3u)}{\beta(\beta+2\delta)(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)^2} < 0 \tag{51}$$

$$\frac{\partial p_m^{R*}}{\partial k} = \frac{4ah(\beta+\delta)(-8\beta^3u^2 + 8\beta^3\Delta^2 - 36\beta^2\delta u^2 + 24\beta^2\delta u\Delta + 20\beta^2\delta\Delta^2 - 38\beta\delta^2u^2 + 52\beta\delta^2u\Delta + 5\delta^3u^2)}{\beta(\beta+2\delta)(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)^2} > 0 \tag{52}$$

$$\frac{\partial p_r^{R*}}{\partial \Delta} = \frac{-2ah(8\beta^4u^3 32k\beta^3\Delta + 79\beta^2\delta^2u^3 + 56\beta^2\delta^2u^2\Delta + 144k\beta\delta^2u + 80k\beta\delta^2\Delta + 6q^4u^3 + 104k\delta^3u)}{(\beta+2\delta)(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)^2} < 0 \tag{53}$$

$$\frac{\partial p_r^{R*}}{\partial k} = \frac{4ah(8\beta^4u\Delta + 8\beta^4\Delta^2 - 4\beta^3\delta u^2 + 40\beta^3\delta u\Delta + 24\beta^3\delta\Delta^2 + 72\beta^2\delta^2u\Delta + 20\beta^2\delta^2\Delta^2 + 52\beta\delta^3u\Delta + 5\delta u^2)}{\beta(\beta+2\delta)(-8\beta^2u^2 + 8\beta^2u\Delta + 4\beta^2\Delta^2 - 16\beta\delta u^2 + 20\beta\delta u\Delta - 16k\beta + \delta^2u^2 - 16k\delta)^2} > 0 \tag{54}$$

From Eqs. (18–23), in the retailer recycling model, the optimal wholesale price ω^{R*} of remanufactured products, direct selling prices p_m^{R*} and retail prices p_r^{R*} of new products are negatively correlated with remanufacturing cost savings Δ, and by contrast, optimal wholesale prices ω^{R*}, direct sales prices p_m^{R*}, and retail prices p_r^{R*} of new products are positively correlated with coefficient k of the return on investment. In the same way, the calculation can be obtained as follows: $\frac{\partial \tau^{R*}}{\partial \Delta} > 0, \frac{\partial \tau^{R*}}{\partial k} < 0; \frac{\partial D_m^{R*}}{\partial \Delta} > 0, \frac{D_m^{R*}}{\partial k} < 0; \frac{\partial D_r^{R*}}{\partial \Delta} > 0, \frac{D_r^{R*}}{\partial k} < 0;$ $\frac{\partial \pi_m^{R*}}{\partial \Delta} > 0, \frac{\partial \pi_m^{R*}}{\partial k} > 0; \frac{\partial \pi_r^{R*}}{\partial \Delta} >; \frac{\partial \pi_r^{R*}}{\partial k} > 0; \frac{\partial \mathrm{RE}^{R*}}{\partial \Delta} > 0; \frac{\partial \mathrm{RE}^{R*}}{\partial k} > 0$. corollary 2 is proven.

Proof of corollary 3: In the third-party recycler recycling model, the first-order partial derivatives of remanufacturing cost savings Δ and recovery investment coefficient k are obtained for the wholesale price, direct sales price, and retail price of new products as follows:

$$\frac{\partial \omega^{3P*}}{\partial \Delta} = \frac{-2ahku(3\beta^2 + 7\beta\delta + 4\delta^2)}{(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)^2} < 0 \tag{55}$$

$$\frac{\partial \omega}{\partial k} = \frac{2ahu(\Delta - u)(3\beta^2 + 7\beta\delta + 4\delta^2)}{(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)^2} > 0 \tag{56}$$

$$\frac{\partial p_m^{3P*}}{\partial \Delta} = \frac{-2ahku(3\beta^2 + 7\beta\delta + 4\delta^2)}{(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)^2} < 0 \tag{57}$$

$$\frac{\partial p_m^{3P*}}{\partial k} = \frac{2ahu(\Delta - u)(3\beta^2 + 7\beta\delta + 4\delta^2)}{(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)^2} > 0 \tag{58}$$

$$\frac{\partial p_r^{3P*}}{\partial \Delta} = \frac{-ahku(3\beta^2 + 10\beta\delta + 8\delta^2)}{(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)^2} < 0 \tag{59}$$

$$\frac{\partial p_r^{3P*}}{\partial k} = \frac{ahu(\Delta - u)(3\beta^2 + 10\beta\delta + 8\delta^2)}{(3\beta^2u^2 - 3\Delta\beta^2u + 4\delta\beta u^2 - 4\delta\Delta\beta u + 4k\beta + 4k\delta)^2} > 0 \tag{60}$$

From Eqs. (55–60), in the third-party recycler recycling model, the optimal wholesale price, direct sales price, and retail price of new products are negatively related to the cost savings Δ of remanufacturing, and the opposite produces the most negative result. Excellent wholesale prices, direct sales prices, and retail prices of new products are positively correlated with the coefficient of the return on investment k. In the same way, the calculation can be obtained as follows:
$\frac{\partial \tau^{3P*}}{\partial \Delta} > 0, \frac{\partial \tau^{3P*}}{\partial k} < 0;$ $\frac{\partial D_m^{3P*}}{\partial \Delta} > 0, \frac{D_m^{3P*}}{\partial k} < 0;$ $\frac{\partial D_r^{3P*}}{\partial \Delta} > 0,$ $\frac{D_r^{3P*}}{\partial k} < 0;$ $\frac{\partial \pi_m^{3P*}}{\partial \Delta} > 0,$ $\frac{\partial \pi_m^{3P*}}{\partial k} < 0;$ $\frac{\partial \pi_r^{3P*}}{\partial \Delta} > 0, \frac{\partial \pi_r^{3P*}}{\partial k} < 0;$ $\frac{\partial RE^{3P*}}{\partial \Delta} > 0, \frac{\partial RE^{3P*}}{\partial k} < 0.$ Corollary 3 is proved.

The proof process of Corollary 4–5 is the same as Corollary 1–3.

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Declarations

Conflict of interest The first author declares that he has no conflict of interest. Corresponding author declares that he has no conflict of interest.

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