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Subsidy or not? Research on remanufacturing strategy under the influence of consumers' preferences

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Abstract
The number of electronic products has increased sharply with the development of hi-tech. The recycling of waste products is becoming an inevitable requirement for sustainable development. The government has also adopted a variety of subsidy strategies for the recycling and remanufacturing of electronic products. The improvement of people's living standards has also made consumer demand diverse, and promoting the development of the remanufactured electronic product market also needs to be analyzed from the demand side affected by consumer preferences. This paper takes the remanufacturing decision in the process of electronic product recycling and remanufacturing as the main focus, and analyzes the game relationship between manufacturers, remanufacturers and consumers under the two scenarios of whether the government subsidizes or not, mainly carry out numerical simulations to analyze two types of factors that affect supply chain members: consumers quality recognition and consumers environmental preferences, as well as remanufactured consumer subsidies and combined subsidies. Relevant conclusions are drawn: Consumers' environmental preference and the increase in the consumers' quality recognition of remanufactured products can increase the demand for remanufactured products and the profits of remanufacturers. Government subsidy will effectively increase the profits of remanufacturers, and the combined subsidy strategy can increase the influence of consumers quality recognition and consumers environmental preferences on remanufacturers, superior to single consumption subsidy strategy.

Keywords Government subsidy · Consumers' preference · Optimal decisions · Stackelberg game

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1 Introduction

With the rapid development of high-tech, the replacement of electronic products is accelerated, the product life cycle is getting shorter and shorter, and the waste electronic products are showing an explosive growth trend. "Report on the Development of Renewable Resources Recycling Industry in China" of 2016, 2018 and 2020 have all shown that recycling of waste products from major renewable resources in China has been on the rise over the past few years (shown in Table 1). It is estimated that the number of waste electronic products in China will surge at an annual rate of 25.7% from 2020 to 2030, while the output will reach 28.4 million tons in 2030 (Liu et al., 2020). Waste electronic products are not only a huge output, but also a combination of resources and the environment. On the one hand, it contains rich resources, including precious metals such as gold, silver, and copper, and is known as "urban mines". On the other hand, it contains toxic and harmful substances such as mercury and lead, which will not only seriously pollute the environment, but also pose a threat to the health of residents, if not properly disposed. Recycling and disposal of waste electronic products has become an urgent social problem (Feng et al., 2017). It is worthwhile to follow up on how to carry out harmless treatment after recycling in order to achieve the expected goal of alleviating environmental pressure.

In order to achieve the coordinated development of economy, society and human beings, all countries are vigorously developing circular economy and recycling and remanufacturing waste electronic products. As an effective form of recycling in the circular economy, remanufacturing can effectively produce the products required for economic development under the dual constraints of environment and resources, opening up a closed-loop supply chain of "resources-products-waste-remanufactured product".

Compared with developed countries, China's electronic product remanufacturing industry started relatively late, the technology for disposal and remanufacturing of waste electronic products is relatively backward, with low market recognition of remanufactured products. The government urgently needs to improve relevant laws and financial support to form a system of scale. Currently, the development of the remanufacturing industry has the following two main problems. 1) Market demand for remanufactured products is unstable. For consumers, environmental awareness of groups is uneven, and consumer preferences affect purchasing decisions. 2) For remanufacturing enterprises, government subsidies can alleviate the pressure of remanufacturing R&D costs and reduce the investment risk of

Table 1 Recycling situation of main varieties of renewable resources in China from 2014 to 2019

Entry	Unit	2014	2015	2016	2017	2018	2019
Waste electrical and electronic products							
Quantity	10,000 pieces	13,583	15,274	16,055	16,370	16,550	17,100
Weight	10,000 tons	313.5	348	366	373.5	380	390
Waste motor vehicle							
Quantity	10,000 vehicles	220	277.5	179.8	174.1	199.1	229.5
Weight	10,000 tons	426	682.79	491.6	453.6	478.79	564.8
Waste non-ferrous metals		798	876	937	1065	1110	1199
Waste plastic		2000	1800	1878	1693	1830	1890
Waste paper		4419	4832	4963	5285	4964	5244
Waste steel		15,230	14,380	15,130	17,391	21,277	24,097

enterprises to a certain extent, but the subsidy efficiency is relatively low. How to optimize the subsidy strategy and make it more conducive to promoting the development of remanufacturing enterprises deserves further exploration.

This study takes the government subsidy strategy for remanufactured electronic products under the influence of consumer preferences as the main research subject, constructs a product demand model under the influence of consumers' environmental preference and consumers' quality recognition of remanufactured products on the basis of consumer utility theory, and analyzes the impact of consumer preferences on decisions and profits of all parties in the absence of government subsidy. Then, this study discusses the influence of consumption subsidy and combined subsidy on remanufacturing parties with government subsidies, and explores the influence of relevant parameter changes on optimal decisions. Finally, the paper simulates the optimal results under two scenarios, graphically describes the effect of each parameter and present results from different scenarios.

This paper is organized as follows. In Sect. 2, a review and analysis of literature related to consumers' preferences and government subsidies is conducted. In Sect. 3, a remanufacturing game model under two scenarios with or without government subsidies considering consumers' preferences is constructed. In Sect. 4, we compared and numerically simulated the decision-making results in different scenarios. In Sect. 5, we provide managerial insights and concluding remarks.

2 Literature review

This paper is related to two research streams: one is the literature on the impact of consumer behavior on supply chain, and the other is the literature on government subsidies. We will review each of them below.

2.1 Impact of consumer behavior on supply chain

With the improvement of people's living standards, consumer demands are diversified, and consumer behavior has an inherent impact on the remanufacturing market (Zhang et al., 2022). In addition, the arrival of the era of big data provides manufacturers and retailers with new ways to cater to the needs of consumers. By collecting and analyzing information on consumer purchase behavior, merchants can accurately grasp the key factors affecting consumers' choices and provide products in a targeted manner. In this way, the original "push" development model of remanufacturing led by the recycling end has been turned into the "pull" development model of the consumer demand market. Therefore, it is of crucial importance to analyze the demand side of the remanufacturing process by focusing on consumer behavior and preferences. Considering the heterogeneity of consumers in the market, Debo, Toktay, and Van Wassenhove (2005) have studied the decision-making of product pricing and remanufacturing technology choices when consumers have different preferences for new products and remanufactured products, with different pay willingness. Atasu et al. (2008) have divided the consumers into ordinary consumers and green consumers, considering the impact of consumer behavior, and studied the influence of the proportion of green consumers on supply chain decision-making. The results show that when the proportion of remanufactured products is relatively small, the pricing difference between remanufactured products and new products is more obvious, if the proportion is higher, it is mainly by increasing the price of remanufactured products to get more profits. Chander

and Muthukrishnan (2015) have divided consumers into high environmental friendly and low environmental friendly consumers according to their environmental awareness, and studied the impact of preference differences on environmental pollution and social welfare. Research reveals that not only pollution is reduced, but prices, profits and social well-being are also increased as the proportion of consumers with a high preference for environmental friendliness increases. Taking into account the consumer preference for remanufactured products and the effect of government subsidies, Zhao et al. (2018) have built a decision model, and introduce the price elasticity of demand for remanufactured products to differentiate consumer environmental preferences. Two problems have been studied, one is the pricing of remanufactured products, and the other is the joint decision problem of subsidy shares between remanufacturers and consumers. Finally, it is found that the optimal price and subsidy sharing ratio are inversely proportional to the weighted sum of the price elasticity of demand. Rofin and Mahanty (2018), Zhang et al. (2020) have studied the optimal combination of traditional sales and online sales channels according to consumers' preferences for products and sales channels. These papers provide a solid foundation for our paper, but none of them consider government subsidies.

2.2 Government subsidies

Government subsidies will affect the development of the remanufacturing industry (Subramanian et al., 2013; Zhang et al., 2021). Wang et al. (2014) have studied how remanufacturing subsidies affect the choice of product sales channels and constructed two channels, direct sales by remanufacturers and sales by manufacturers. The results show that the government can stimulate remanufacturing activities under both channels, when the subsidy is "too high" or "too low", the competition between two manufacturers is better than cooperation, and vice versa, cooperation is the best. Zhu et al. (2017) have compared remanufactured sales subsidies with donation subsidies, found that donation subsidies can weaken the cannibalization of new products by remanufactured products, increase the number of new products, reduce the sales of remanufactured products, but increase the total amount of remanufactured products. Heydari et al. (2017) have taken environmental issues and product lifespan into consideration, and extended the model to a closed-loop supply chain, suggesting coordination through quantity discounts and increased fee contracts. The government provides two types of incentives for each member in the supply chain to have different tax exemptions or tax rebates. The study finds that, the government has better incentives for manufacturers. Yi et al. (2018) investigated the impact of incentives and penalties in a two-loop closed-loop supply chain and showed that government incentives and penalties reduce product pricing in both loops. Miao et al. (2018) have found that carbon regulations can promote the sales of remanufactured products, but reduce the demand for new products at the same time, reducing manufacturers' profits. At this time, government subsidies to manufacturers can meet the reduction of total emissions without sacrificing manufacturers' profits. Chen et al. (2019) have divided joint ventures into either retailer-initiated or manufacturer-initiated, and studied the impact of two types of subsidies on the supply chain of unit production subsidies and innovation effort subsidies. It is found that governments should not use both forms of subsidies to reduce costs and develop innovation at the same time. Wan and Hong (2019) have analyzed the impact of government subsidies on manufacturing companies and recyclers, and concluded that whether it is given to remanufacturers or recycling companies, the subsidy will stimulate consumption and increase market demand. Meng et al. (2020) have considered the government as one of

the decision makers to provide subsidies to improve social welfare, and have discussed the game between the government, new product manufacturers and remanufactured product manufacturers based on this.

The difference between this paper and the above research is the construction of a demand function under the influence of the consumer's environmental preference and the consumer's recognition of remanufactured electronic products based on the utility theory. First, this paper analyzes the influence of consumer preferences on the decision-making and profits of each member in the supply chain, with no government subsidies. Then, this paper compares the influence of consumption subsidy and combined subsidy on each member of the supply chain with government subsidies. This paper can not only provide decision-making basis for manufacturers and remanufacturers, but also provide certain scientific basis and reference for the government to improve the subsidy strategy.

3 Model development

Consumer utility theory is widely used in consumer behavior research. A product demand function under the influence of consumer preferences is constructed based on consumer utility function. This paper constructs a remanufacturing game model with or without government subsidies, based on this demand model. The single consumption subsidy strategy and the combined subsidy strategy are discussed separately under the government subsidies scenario. The establishment of decision model can provide theoretical basis for each member in supply chain to make optimal decision.

3.1 Model description

When building a remanufacturing game model under the influence of consumer preferences, the basic requirement is that is must meet the actual situation as much as possible. Thus, current analysis has only considered the sales of the remanufactured products and four types of participants (consumer, manufacturer, remanufacturer, government). Moreover, the following assumptions are made to ensure the simplicity of the model construction and solution.

Assumption 1. Consumers are rational people, and they will choose to buy products that maximize their own utility according to the consumer utility theory.

Assumption 2. The cost of producing new products by manufacturers is c_1, and the cost of producing remanufactured products by remanufacturers is c_2, and they need to satisfy the conditions $0 < c_1 < 1, 0 < c_2 < 1$. Considering the difference of production craft, the production process and the raw materials, it needs to satisfy the condition $c_1 > c_2$.

Assumption 3. The quality recognition level of consumers for remanufactured products is set to θ,$\theta \in (0, 1]$. ρ represents the consumer's environmental preference, and when it is higher, the willingness to pay for remanufactured products is stronger. Therefore, it can be expressed by consumers' willingness to pay for remanufactured products, $\rho \in (0, X)$, X is the highest willingness-to-pay intensity acceptable to consumers. The environmental improvement rate of a new product is a fixed value of g_1, and to simplify the calculation, $g_1 = 0$. The environmental improvement rate is g, remanufactured products are produced from recycled products, and the behavior has a beneficial effect on the environment, so $g > 0$.

Assumption 4. Remanufacturers need technology research when remanufacturing, and the research investment is c_0. The R&D cost is related to the environmental protection degree of the produced product, and is an increasing function of the environmental improvement rate of the remanufactured product. It has the property of a convex function, and is set as $c_0 = \frac{1}{2}\mu\left(g - g_1\right)^2 = \frac{1}{2}\mu g^2$, μ is the R&D cost factor.

Assumption 5. The relationship between manufacturers, remanufacturers, consumers and the government is a Stackelberg game, and the government has the priority decision-making power in the game, manufacturers, remanufacturers, consumers are followers. After the manufacturer and remanufacturers decides the selling price of the product, the consumers decide to choose the type of product to buy. At the same time, all participants in the supply chain are risk neutral and aim to maximize their own interests (Table 2).

3.2 Basic model without government subsidy

3.2.1 Demand function under the influence of consumers' preferences

The heterogeneity of consumers leads to different environmental awareness, which affects the demand for electronic products. Suppose that consumers have different valuations on new products and remanufactured products, the valuations are v and θv, and they all obey a uniform distribution on [0,1]. Consumers buy new products and remanufactured products to bring environmental utility to them, which are marked ρg_1 and ρg respectively.

Based on the utility theory, the market demand for new products and remanufactured products by consumers' environmental preference is investigated. It is assumed that when

Table 2 Notation

Symbol	Definition
c_1	Unit production cost of new products
c_2	Unit production cost of remanufactured products
c_0	R&D investment in remanufactured products
p_1	Unit sales price of new products
p_2	Unit sales price of remanufactured products
q_1	Market demand for new products
q_2	Market demand for remanufactured products
v	Consumer valuation of new product quality
θ	Consumers' quality recognition of remanufactured products
ρ	Consumers' environmental preference (Willingness to pay for environmentally friendly products)
U_1	The utility of consumers buying a new product
U_2	The utility of consumers buying a remanufactured product
μ	R&D cost factor
g_1	Environmental improvement rate of a new product
g	Environmental improvement rate of a remanufactured product
s	Total government subsidies for remanufactured products
$\pi_i(i = 1, 2, c, sw)$	Profit function without government subsidies
$\pi_i^j(i = 1, 2, c, sw)(j = SC, SG)$	Profit function with government subsidies,

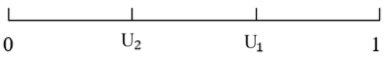

Fig. 1 Consumers' buying behavior decision diagram

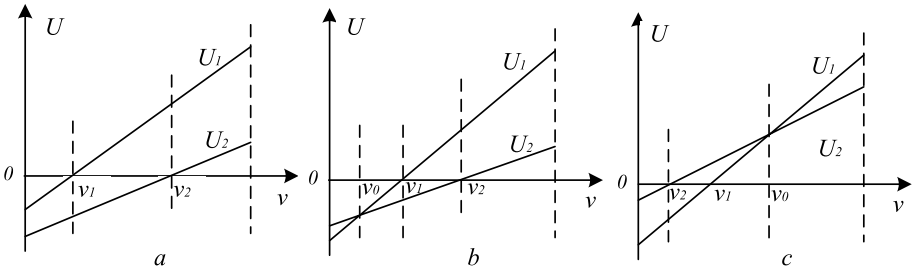

Fig. 2 Consumer utility function diagram

consumers buy 1 unit of new product, remanufactured product, and no product, their utilities are

$$U_1 = v + \rho g_1 - p_1 \tag{1}$$

$$U_2 = \theta v + \rho g - p_2 \tag{2}$$

$$U_3 = 0 \tag{3}$$

Consumers will compare the utility of the new product and remanufactured product, and choose to buy the one with greater utility. When the consumer's utility is positive and $U_1 > U_2$, consumers will buy the new product; if $U_2 > U_1$, consumers will buy the remanufactured product (Fig. 1).

To find the critical willingness-to-pay v_0 of consumers to differentiate between purchasing new products and remanufactured products, we let $U_1 = U_2$, and we obtain $v_0 = \frac{p_1 - p_2 + \rho(g - g_1)}{1-\theta}$.

To find the minimum willingness to pay for remanufactured and new products, we let $U_2 = U_3$, $U_1 = U_3$, and we obtain $v_2 = \frac{p_2 - \rho g}{\theta}$, $v_1 = p_1 - \rho g_1$. When $v > v_0$, consumers may choose to buy new products, when $v < v_0$, consumers may choose to buy remanufactured products.

Therefore, the necessary and sufficient conditions for consumers to buy new products can be expressed as: $v > \max(v_1, v_0)$, the necessary and sufficient conditions for consumers to buy remanufactured products can be expressed as: $v_2 < v < v_0$, and When $v < \min(v_1, v_0)$, the utility of consumers when purchasing is negative, so consumers choose not to buy, which is mainly divided into the following three situations.

As shown in Fig. 2a, the consumer utility function changes to a situation where there is no intersection. when $v = 0$, there is $U_1 > U_2$, at this time, $\rho(g - g_1) < p_2 - p_1$, consumers choose to buy the new product or not, there is no demand market for remanufactured products. This situation can be understood as, the additional utility when consumers choose to purchase remanufactured products, such as environmental improvement utility, government policy support and subsidies, etc., cannot make up for the negative utility brought to consumers by the price gap between new and remanufactured products. At this point, the consumer has only two choices: to buy or not to buy the new product.As shown in

Fig. 2b, when $v = 0$, there is $U_2 > U_1$, $\rho(g - g_1) > p_2 - p_1$, satisfying $v_0 < v_1$, which is $\frac{p_1 - p_2 + \rho(g - g_1)}{1 - \theta} < p_1 - \rho g_1$. At this point, it can be seen that when the utility is greater than 0, the utility of purchasing a remanufactured product is still smaller than purchasing a new product. This situation can be understood as: the additional utility brought by the purchase of remanufactured products to consumers, such as the utility of environmental utility, government policy support and subsidies, can make up for the negative utility brought by the price gap between new and remanufactured products, but can't make up for other negative effects such as functional quality attributes of remanufactured products. Thus, consumers only choose to buy the new product or not in this case.

As shown in Fig. 2c, when $v = 0$,$U_2 > U_1$, at this time $\rho(g - g_1) > p_2 - p_1$, satisfying $v_0 > v_1$, which is $\frac{p_1 - p_2 + \rho(g - g_1)}{1 - \theta} > p_1 - \rho g_1$. Consumers are faced with three choices in this case, not buying the product, buying remanufactured and new products. When consumer utility is negative, consumers choose not to buy, when $v \in (v_2, v_0)$, consumers choose to buy remanufactured products, and when $v > v_0$, consumers choose to buy new products.

To sum up, it can be concluded that the market demands for new products and remanufactured products are

$$q_1 = 1 - v_0 = 1 - \frac{p_1 - p_2 + \rho(g - g_1)}{1 - \theta} \tag{4}$$

$$q_2 = v_0 - v_2 = \frac{\theta p_1 - p_2 + \rho g - \rho\theta g_1}{\theta(1 - \theta)} \tag{5}$$

Since the assumption is proposed to simplify the calculation, let $g_1 = 0$. In this case, the market demands for new products and remanufactured products are

$$q_1 = 1 - \frac{p_1 - p_2 + \rho g}{1 - \theta} \tag{6}$$

$$q_2 = \frac{\theta p_1 - p_2 + \rho g}{\theta(1 - \theta)} \tag{7}$$

3.2.2 Supply chain member benefit model

The profit functions of the manufacturer and remanufacturer without government subsidy are

$$\pi_1 = (p_1 - c_1)q_1 = (p_1 - c_1)\left(1 - \frac{p_1 - p_2 + \rho g}{1 - \theta}\right) \tag{8}$$

$$\pi_2 = (p_2 - c_2)q_2 - c_0 = (p_2 - c_2)\frac{\theta p_1 - p_2 + \rho g}{\theta(1 - \theta)} - \frac{1}{2}\mu g^2 \tag{9}$$

The remanufacturer decides the optimal selling price p_2 and the optimal environmental improvement degree g of the remanufactured product to maximize its own interests. At the same time, the manufacturer decides the optimal selling price p_1 to maximize its own interests.

Hessian matrix of π_2 is

$$H = \begin{bmatrix} \frac{\partial^2 \pi_2}{\partial p_2^2} & \frac{\partial^2 \pi_2}{\partial p_2 \partial p_g} \\ \frac{\partial^2 \pi_2}{\partial g \partial p_2} & \frac{\partial^2 \pi_2}{\partial g^2} \end{bmatrix} = \begin{bmatrix} \frac{2}{\theta(\theta-1)} & \frac{-\rho}{\theta(\theta-1)} \\ \frac{-\rho}{\theta(\theta-1)} & -\mu \end{bmatrix} \tag{10}$$

$|H_1| = \frac{2}{\theta(\theta-1)} < 0$, $|H_2| = \frac{-2\mu\theta(\theta-1)-\rho^2}{\theta^2(\theta-1)^2}$. To make $|H_1||H_2| < 0$, $|H_2|$ needs to satisfy $|H_2| > 0$, $\theta \in [0,1]$, when $-2\mu\theta(\theta-1) > \rho^2$, that is, $|H_2| > 0$ is always established. Thus, π_2 is a strictly concave function with respect to g, p_2, there is a unique maximum.

For Eq. (8), find the first-order partial derivative with respect to p_1, and for Eq. (9), find the first-order partial derivative with respect to p_2, g. Moreover, set them to zero.

$$\begin{cases} \frac{\partial \pi_1}{\partial p_1} = \frac{c_1 - 2p_1 + p_2 - \theta - g\rho + 1}{1-\theta} = 0 \\ \frac{\partial \pi_2}{\partial p_2} = \frac{c_2 - 2p_2 + g\rho + p_1\theta}{\theta(1-\theta)} = 0 \\ \frac{\partial \pi_2}{\partial g} = \frac{(c_2 - p_2)\rho}{\theta(\theta-1)} - \mu g = 0 \end{cases} \tag{11}$$

The optimal selling price of the new product, the optimal selling price of the remanufactured product, and the degree of environmental improvement can be obtained as

$$p_1^* = \frac{2\theta\mu - c_1\rho^2 + \rho^2\theta - 4\mu\theta^2 + 2\mu\theta^3 - \rho^2 - 2c_1\theta^2\mu - c_2\theta^2\mu + 2c_1\theta\mu + c_2\mu\theta}{\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{12}$$

$$p_2^* = \frac{\mu\theta^2 - 2c_2\rho^2 - 2\mu\theta^3 + \mu\theta^4 + c_2\rho^2\theta + \mu\theta^2 c_1 - \mu\theta^3 c_1 - 2\mu\theta^2 c_2 + 2\mu\theta c_2}{\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{13}$$

$$g^* = \frac{\rho\left(\theta - 2c_2 + \theta c_1 + \theta c_2 - \theta^2\right)}{\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{14}$$

Substituting p_1^*,p_2^*, g^* into the demand function and profit function, the optimal demand and the optimal profit of the manufacturer and remanufacturer can be obtained as the following.

$$q_1^* = \frac{\mu\theta\left(2 - 2c_1 + c_2\right) + \rho^2\left(c_1 - 1\right) + \mu\theta^2(c_1 - 2)}{\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{15}$$

$$q_2^* = \frac{\mu\left(\theta - 2c_2 + \theta c_1 + \theta c_2 - \theta^2\right)}{\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{16}$$

$$\pi_1^* = \frac{-(\theta-1)(2\mu\theta + \rho^2 c_1 - 2\mu\theta^2 - \rho^2 + c_1\mu\theta^2 - 2c_1\mu\theta + c_2\mu\theta)^2}{(\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta)^2} \tag{17}$$

$$\pi_2^* = \frac{-\mu\left(\rho^2 + 2\mu\theta^2 - 2\mu\theta\right)(\theta - 2c_2 + c_1\theta + c_2\theta - \theta^2)^2}{2(\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta)^2} \tag{18}$$

At this time, the consumer surplus brought by consumers buying new and remanufactured products is π_c, with no government subsidy, so the government input $S_G^* = 0$.

$$\pi_c^* = \int_{v_0}^{1} \left(v + \rho g_1 - p_1\right) dv + \int_{v_2}^{v_0} \left(\theta v + \rho g - p_2\right) dv + \int_{0}^{v_2} 0 dv$$
$$= \frac{-\left[\rho^2 g^2 + \rho g\left(2\theta p_1 - 2p_2\right) + \theta^2\left(2p_1 - 1\right) + \theta(p_1^2 - 2p_1 p_2 - 2p_1 + 1) + p_2^2\right]}{2\theta(\theta - 1)} \tag{19}$$

At this time, the total social welfare is

$$\pi_{sw}^* = \pi_1^* + \pi_2^* + \pi_c^* - S_G^* \tag{20}$$

By substituting the optimal solutions p_1^*, p_2^*, g^* into the expressions of π_c^*, π_{sw}^*, the optimal values of consumer surplus and total social welfare can be obtained.

3.3 Model with government subsidy

3.3.1 Model with government consumption subsidy

(1) Demand Function under the Influence of Consumers' Preferences

When the government adopts a consumption subsidy strategy, a consumption subsidy ρp_2 (the amount of subsidy obtained per unit of remanufactured product purchased) is given to consumers for purchasing remanufactured products. At this time, the utility obtained by the consumer buying a unit of the new product is $U_1 = v + \rho g_1 - p_1$, and the utility obtained by the consumer buying a unit of the remanufactured product is $U_2 = \theta v + \rho g - p_2 + \rho p_2$.

To find consumers' critical willingness to pay to differentiate between new and remanufactured products, we let $U_1 = U_2$, and we can obtain $v_0 = \frac{p_1 - p_2 + \rho\left(g - g_1\right) + \rho p_2}{1-\theta}$. To find the minimum willingness to pay for a remanufactured product and the minimum willingness to pay for a new product, we let $U_2 = 0$, $U_1 = 0$, and we obtain $v_2 = \frac{p_2 - \rho g - \rho p_2}{\theta}$, $v_1 = p_1 - \rho g_1$. Similarly, the market demands for new products and remanufactured products can be obtained as

$$q_1^{SC} = 1 - \frac{p_1 - p_2 + \rho g + \rho p_2}{1 - \theta} \tag{21}$$

$$q_2^{SC} = \frac{\theta p_1 - p_2 + \rho g + \rho p_2}{\theta(1 - \theta)} \tag{22}$$

(2) Supply Chain Member Benefit Model

The profit functions of the manufacturer and remanufacturer with government consumption subsidy are

$$\pi_1^{SC} = \left(p_1 - c_1\right)\left(1 - \frac{p_1 - p_2 + \rho g + \rho p_2}{1 - \theta}\right) \tag{23}$$

$$\pi_2^{SC} = \left(p_2 - c_2\right)\frac{\theta p_1 - p_2 + \rho g + \rho p_2}{\theta(1 - \theta)} - \frac{1}{2}\mu g^2 \tag{24}$$

Government spending and total social welfare are

$$S_G = sq_2 \tag{25}$$

$$\pi_{sw}^{SC} = \pi_1^{SC} + \pi_2^{SC} + \pi_c^{SC} - S_G \tag{26}$$

When making decisions, the government is the leader of the Stackelberg game, and remanufacturers and manufacturers are followers. Thus, government firstly decides the subsidy intensity s. Then, the remanufacturer decides the optimal selling price p_2 and the optimal environmental improvement degree g of the remanufactured product, and the manufacturer decides the optimal selling price p_1 Finally, consumers choose to buy the type of product. The reverse solution method is used in the solution, which is the same as the solution process without subsidies. The optimal solutions can be obtained as

$$p_1^{SC*} = \frac{\left\{\begin{array}{c} c_1\rho^2 - 2\theta\mu - \rho^2\theta + 4\theta^2\mu - 2\theta^3\mu + \rho^2 + 2c_1\theta^2\mu + c_2\theta^2\mu \\ -4\rho\theta^2\mu + 2\rho\theta^3\mu - 2c_1\theta\mu - c_2\theta\mu + 2\rho\theta\mu + 2c_1\rho\theta\mu \\ +2c_2\rho\theta\mu - 2c_1\rho\theta^2\mu - 2c_2\rho\theta^2\mu - c_2\rho^2\theta\mu + c_2\rho^2\theta^2\mu \end{array}\right\}}{-\rho^2\theta + 2\rho^2 + \mu\rho\theta^3 - 5\mu\rho\theta^2 + 4\mu\rho\theta - \mu\theta^3 + 5\mu\theta^2 - 4\mu\theta} \tag{27}$$

$$p_2^{SC*} = \frac{\begin{array}{c} \theta^2\mu - 2c_2\rho^2 - 2\theta^3\mu + \theta^4\mu + c_2\rho^2\theta + c_1\theta^2\mu \\ -c_1\theta^3\mu - 2c_2\theta^2\mu + 2c_2\theta\mu - 2c_2\rho\theta\mu + 2c_2\rho\theta^2\mu \end{array}}{\rho^2\theta - 2\rho^2 - \mu\rho\theta^3 + 5\mu\rho\theta^2 - 4\mu\rho\theta + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{28}$$

$$g^{SC*} = \frac{\rho\left(\theta - 2c_2 + 2c_2\rho + c_1\theta + c_2\theta - \theta^2 - c_2\rho\theta\right)}{\rho^2\theta - 2\rho^2 - \mu\rho\theta^3 + 5\mu\rho\theta^2 - 4\mu\rho\theta + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{29}$$

$$q_1^{SC*} = \frac{\begin{array}{c} 2\theta\mu + c_1\rho^2 - 2\theta^2\mu - \rho^2 + c_1\theta^2\mu + 2\rho\theta^2\mu - 2c_1\theta\mu \\ +c_2\theta\mu - 2\rho\theta\mu + 2c_1\rho\theta\mu - 2c_2\rho\theta\mu - c_1\rho\theta^2\mu + c_2\rho^2\theta\mu \end{array}}{\rho^2\theta - 2\rho^2 - \mu\rho\theta^3 + 5\mu\rho\theta^2 - 4\mu\rho\theta + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{30}$$

$$q_2^{SC*} = \frac{-\mu(\rho - 1)\left(\theta - 2c_2 + 2c_2\rho + c_1\theta + c_2\theta - \theta^2 - c_2\rho\theta\right)}{\rho^2\theta - 2\rho^2 - \mu\rho\theta^3 + 5\mu\rho\theta^2 - 4\mu\rho\theta + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{31}$$

$$\pi_1^{SC*} = \frac{\begin{array}{c} (1-\theta)(2\theta\mu + c_1\rho^2 - 2\theta^2\mu - \rho^2 + c_1\theta^2\mu + 2\rho\theta^2\mu - 2c_1\theta\mu \\ +c_2\theta\mu - 2\rho\theta\mu + 2c_1\rho\theta\mu - 2c_2\rho\theta\mu - c_1\rho\theta^2\mu + c_2\rho^2\theta\mu)^2 \end{array}}{(\rho^2\theta - 2\rho^2 - \mu\rho\theta^3 + 5\mu\rho\theta^2 - 4\mu\rho\theta + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta)^2} \tag{32}$$

$$\pi_2^{SC*} = \frac{\begin{array}{c} -\mu\left(\rho^2 - 2\mu\rho\theta^2 + 2\mu\rho\theta + 2\mu\theta^2 - 2\mu\theta\right) \\ (\theta - 2c_2 + 2c_2\rho + c_1\theta + c_2\theta - \theta^2 - c_2\rho\theta)^2 \end{array}}{2(\rho^2\theta - 2\rho^2 - \mu\rho\theta^3 + 5\mu\rho\theta^2 - 4\mu\rho\theta + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta)^2} \tag{33}$$

$$S_G^{SC*} = \frac{\left\{\begin{array}{c} -\mu\rho(\rho-1)\left(\theta-2c_2+2c_2\rho+c_1\theta+c_2\theta-\theta^2-c_2\rho\theta\right) \\ (\theta^2\mu-2c_2\rho^2-2\theta^3\mu+\theta^4\mu+c_2\rho^2\theta+c_1\theta^2\mu \\ -c_1\theta^3\mu-2c_2\theta^2\mu+2c_2\theta\mu-2c_2\rho\theta\mu+2c_2\rho\theta^2\mu) \end{array}\right\}}{2(\rho^2\theta-2\rho^2-\mu\rho\theta^3+5\mu\rho\theta^2-4\mu\rho\theta+\mu\theta^3-5\mu\theta^2+4\mu\theta)^2} \tag{34}$$

$$\pi_c^{SC*} = \frac{\left\{\begin{array}{c} g^2\rho^2+2g\rho^2p_2+2g\rho p_1\theta-2g\rho p_2+\rho^2p_2^2+2\rho p_1p_2\theta \\ -2\rho p_2^2+p_1^2\theta-2p_1p_2\theta-2p_1\theta^2-2p_1\theta+p_2^2-\theta^2+\theta \end{array}\right\}}{2\theta(1-\theta)} \tag{35}$$

Total social welfare is

$$\pi_{sw}^{SC} = \pi_1^{SC} + \pi_2^{SC} + \pi_c^{SC} - S_G \tag{36}$$

To solve the derivative of the total subsidy intensity s for the total social welfare function, and set it to 0, the optimal government subsidy amount is obtained.

$$s^{SC*} = \frac{\left\{\begin{array}{c} \rho(\theta^2\mu-2c_2\rho^2-2\theta^3\mu+\theta^4\mu+c_2\rho^2\theta+c_1\theta^2\mu \\ -c_1\theta^3\mu-2c_2\theta^2\mu+2c_2\theta\mu-2c_2\rho\theta\mu+2c_2\rho\theta^2\mu) \end{array}\right\}}{\rho^2\theta-2\rho^2-\mu\rho\theta^3+5\mu\rho\theta^2-4\mu\rho\theta+\mu\theta^3-5\mu\theta^2+4\mu\theta} \tag{37}$$

3.3.2 Model with government combined subsidy

(1) Demand Function under the Influence of Consumers' Preferences

When the government adopts the combined subsidy strategy, the subsidy method is to subsidize the consumer unit as ρp_2, and the rest is subsidized to the remanufacturer, that is, $s-\rho p_2$. In this case, the market demands for new and remanufactured products are

$$q_1^{SG} = 1 - \frac{p_1 - p_2 + \rho g + \rho p_2}{1-\theta} \tag{38}$$

$$q_2^{SG} = \frac{\theta p_1 - p_2 + \rho g + \rho p_2}{\theta(1-\theta)} \tag{39}$$

(2) Supply Chain Member Benefit Model

The profit functions of the manufacturer and remanufacturer with government combined subsidy are

$$\pi_1^{SG} = (p_1 - c_1)\left(1 - \frac{p_1 - p_2 + \rho g + \rho p_2}{1-\theta}\right) \tag{40}$$

$$\pi_2^{SG} = (p_2 - c_2 + s - \rho p_2)\frac{\theta p_1 - p_2 + \rho g + \rho p_2}{\theta(1-\theta)} - \frac{1}{2}\mu g^2 \tag{41}$$

The consumer surplus arising from the purchase of the product by the consumer is

$$\pi_c^{SG} = \int_{v_0}^{1} \left(v + \rho g_1 - p_1\right) dv + \int_{v_2}^{v_0} \left(\theta v + \rho g - p_2 + \rho p_2\right) dv + \int_{0}^{v_2} 0 dv \tag{42}$$

Government spending and total social welfare are

$$S_G^{SG} = sq_2 \tag{43}$$

$$\pi_{sw}^{SG} = \pi_1^{SG} + \pi_2^{SG} + \pi_c^{SG} - S_G \tag{44}$$

Similar to 3.3.1, the optimal solutions can be obtained as

$$p_1^{SG*} = \frac{\begin{array}{c} 2\theta\mu - c_1\rho^2 + \rho^2\theta - 4\theta^2\mu + 2\theta^3\mu - \rho^2 - 2c_1\theta^2\mu \\ -c_2\theta^2\mu + s\theta^2\mu + 2c_1\theta\mu + c_2\theta\mu - s\theta\mu \end{array}}{\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{45}$$

$$p_2^{SG*} = \frac{\begin{array}{c} 2\rho^2 s - 2c_2\rho^2 + \theta^2\mu - 2\theta^3\mu + \theta^4\mu + c_2\rho^2\theta + c_1\theta^2\mu \\ -c_1\theta^3\mu - 2c_2\theta^2\mu - \rho^2 s\theta + 2s\theta^2\mu + 2c_2\theta\mu - 2s\theta\mu \end{array}}{(1-\rho)(\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta)} \tag{46}$$

$$g^{SG*} = \frac{\rho\left(2s - 2c_2 + \theta + c_1\theta + c_2\theta - s\theta - \theta^2\right)}{\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{47}$$

$$q_1^{SG*} = \frac{2\theta\mu + c_1\rho^2 - 2\theta^2\mu - \rho^2 + c_1\theta^2\mu - 2c_1\theta\mu + c_2\theta\mu - s\theta\mu}{\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{48}$$

$$q_2^{SG*} = \frac{\mu\left(2s - 2c_2 + \theta + c_1\theta + c_2\theta - s\theta - \theta^2\right)}{\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{49}$$

$$\pi_1^{SG*} = \frac{(1-\theta)(2\theta\mu + c_1\rho^2 - 2\theta^2\mu - \rho^2 + c_1\theta^2\mu - 2c_1\theta\mu + c_2\theta\mu - s\theta\mu)^2}{(\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta)^2} \tag{50}$$

$$\pi_2^{SG*} = \frac{\mu\left(\rho^2 - 2\mu\theta^2 + 2\mu\theta\right)(2s - 2c_2 + \theta + c_1\theta + c_2\theta - s\theta - \theta^2)^2}{2(\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta)^2} \tag{51}$$

$$S_G^* = \frac{s\mu\left(2s - 2c_2 + \theta + c_1\theta + c_2\theta - s\theta - \theta^2\right)}{\rho^2\theta - 2\rho^2 + \mu\theta^3 - 5\mu\theta^2 + 4\mu\theta} \tag{52}$$

At this time, the amount of government subsidy per unit product and the total social welfare are as follows. Due to the relatively complex structure, no specific details are given here.

$$\pi_c^{SG*} = \frac{\left\{\begin{array}{c} g^2\rho^2 + 2g\rho^2 p_2 + 2g\rho p_1\theta - 2g\rho p_2 + p_1^2 p_2^2 + 2\rho p_1 p_2\theta \\ -2\rho p_2^2 + p_1^2\theta - 2p_1 p_2\theta + 2p_1\theta^2 - 2p_1\theta + p_2^2 - \theta^2 + \theta \end{array}\right\}}{2\theta(1-\theta)} \tag{53}$$

$$\pi_{sw}^{SG*} = \pi_1^* + \pi_2^* + \pi_c^* - S_G^* \tag{54}$$

Solve the derivative of the total subsidy intensity s for the total social welfare function, and set it to 0, and simultaneously obtain the optimal government subsidy amount.

$$s^{SG*} = \frac{\left\{ \begin{array}{c} \rho^2\theta^2 - \rho^2\theta + \theta^3\mu - 2\theta^4\mu + \theta^5\mu + c_1\rho^2\theta - 4c_1\theta^2\mu + 6c_1\theta^3\mu \\ -7c_2\theta^2\mu - 2c_1\theta^4\mu + 4c_2\theta^3\mu - c_2\theta^4\mu - c_1\rho^2\theta^2 + 4c_2\theta\mu \end{array} \right\}}{\rho^2\theta^2 - 4\rho^2\theta + 4\rho^2 - 3\mu\theta^3 + 7\mu\theta^2 - 4\mu\theta} \tag{55}$$

4 Simulation and results discussion

The values of parameters and coefficients used in the numerical examples are assumed. The basic relationships between different parameters are considered when we give the specific values. In combination with the reality, in order to ensure that each decision variable has practical significance, it must meet the following requirements: $q_1 > 0$, $q_2 > 0$, $q_1 + q_2 < 1$. In addition, $\rho^2 < 2\mu\theta(1-\theta)$ shall be met. Due to the large number of model parameters, the structure of the results is relatively complex, so it refers to the existing research literatures (Wang et al., 2020; Zhang et al., 2023) for assignment. Let $c_1 = 0.4$, $c_2 = 0.2$, $\mu = 0.2$, $\theta = 0.6$, $\rho = 0.1$, this paper explains and analyzes the similarities and differences of the changing trends of each decision variable. In fact, the specific value may not coincide with reality, but the changes of the parameters have no impact on the conclusions and their analysis in our paper.

4.1 The effect of consumers' preferences on optimal decisions

The conclusions of the analysis based on the impact of consumer environmental preferences on optimal decision making are first given:

Under the situation of no government subsidy, the derivative of ρ with respect to the most efficient sales price, product demand, manufacturer's profit, consumer surplus is obtained, and total social welfare can obtain the change trend of each decision variable with ρ. Details as follows: $\frac{\partial p_1^*}{\partial \rho} < 0$, $\frac{\partial p_2^*}{\partial \rho} > 0$, $\frac{\partial q_1^*}{\partial \rho} < 0$, $\frac{\partial q_2^*}{\partial \rho} > 0$, $\frac{\partial g^*}{\partial \rho} > 0$, $\frac{\partial \pi_1^*}{\partial \rho} < 0$, $\frac{\partial \pi_2^*}{\partial \rho} > 0$, $\frac{\partial \pi_c^*}{\partial \rho} > 0$, $\frac{\partial \pi_{sw}^*}{\partial \rho} > 0$.

As consumers' environmental preference increases, the selling price of remanufactured products continues to increase and the selling price of new products continues to decrease.

The impact of consumers' environmental preference on the demand for new and remanufactured products follows the same trend as the impact on sales prices. This is due to the increased environmental preference of consumers, which makes consumers aware of the utility of the manufacturer's products on the environment, and they are more inclined to buy remanufactured products.

Consumers' environmental preference is proportional to the optimal environmental improvement of remanufactured products. This is also the adjustment that remanufacturers must make to meet market demand.

Manufacturers and remanufacturers are less profitable as consumers' environmental preference grow. As the sales price and demand for new products decrease, the

manufacturer's profit gradually decreases. The price of remanufactured products has also increased steadily after the sales market has been opened, bringing greater income to the remanufacturer.

As consumers' environmental preference grows, consumer surplus and total social welfare will grow. It can be seen that the environmental benefits and economic benefits brought by remanufactured products can offset the impact of lower revenue brought by new products.

Assigning relevant parameters, the above conclusions are verified through numerical simulations and the impact of consumer environmental preferences on decision variables and supply chain profit outcomes in different consumer groups is analyzed.

As can be seen from Fig. 3, as consumers' environmental preference increases, consumers' preference for remanufactured products continues to increase, and their sales prices and demand rise steadily, bringing increased revenue to remanufacturers at the same time. As can be seen from Fig. 3b, new products and remanufactured products coexist in the market initially, and the demand for new products dominates the market. Subsequently, with the increase of consumers' environmental preference, the degree of environmental improvement of remanufactured products gradually increases, the market for remanufactured products gradually opens up. When consumers' environmental preference reach a certain level, the demand curve overlap, that is, the demand for the two products is equal. Then, as consumers' environmental preference continues to increase, remanufactured products gradually occupy the main market, and new product demand is lower than remanufactured product demand.

The changing trend of the profit curve of the two manufacturers is consistent with the demand curve, but the profit of the manufacturer is much higher than that of the remanufacturer at the beginning, due to the higher selling price of the new product in the market. In the later period, with the increase of consumers' environmental preference, the contrast in profits between the two is mainly caused by the sudden changes in market demand. At this time, the sales price of new products has dropped, but their manufacturing uses new materials. The high cost makes it impossible to take price competition and thus lose the advantage.

Consumer surplus and total social welfare gradually increase with the rise of preference. Consumers' purchase of remanufactured products can bring them additional environmental utility, which can effectively prevent the utility loss caused by the reduction of new product purchases. However, social welfare does not change significantly at first, and then, with the rapid increase of consumer utility, it shows an overall upward trend. It can be seen that improving consumers' awareness of environmental protection and making them form environmental preferences is of great significance to improving social welfare. At the same time, the degree of environmental improvement of production products is gradually increasing, which is beneficial to preventing and reducing environmental pollution. The demand for remanufactured products increases, thus promoting the development of the remanufacturing industry, which is conducive to the recycling and reuse of resources.

Then, the analytical conclusions on the impact of consumer-based recognition of remanufactured product quality on optimal decision-making are given:

Under the situation of no government subsidy, finding the derivative of μ with respect to the most efficient sales price, product demand, manufacturer's profit, consumer surplus, and total social welfare, we can obtain the change trend of each decision variable

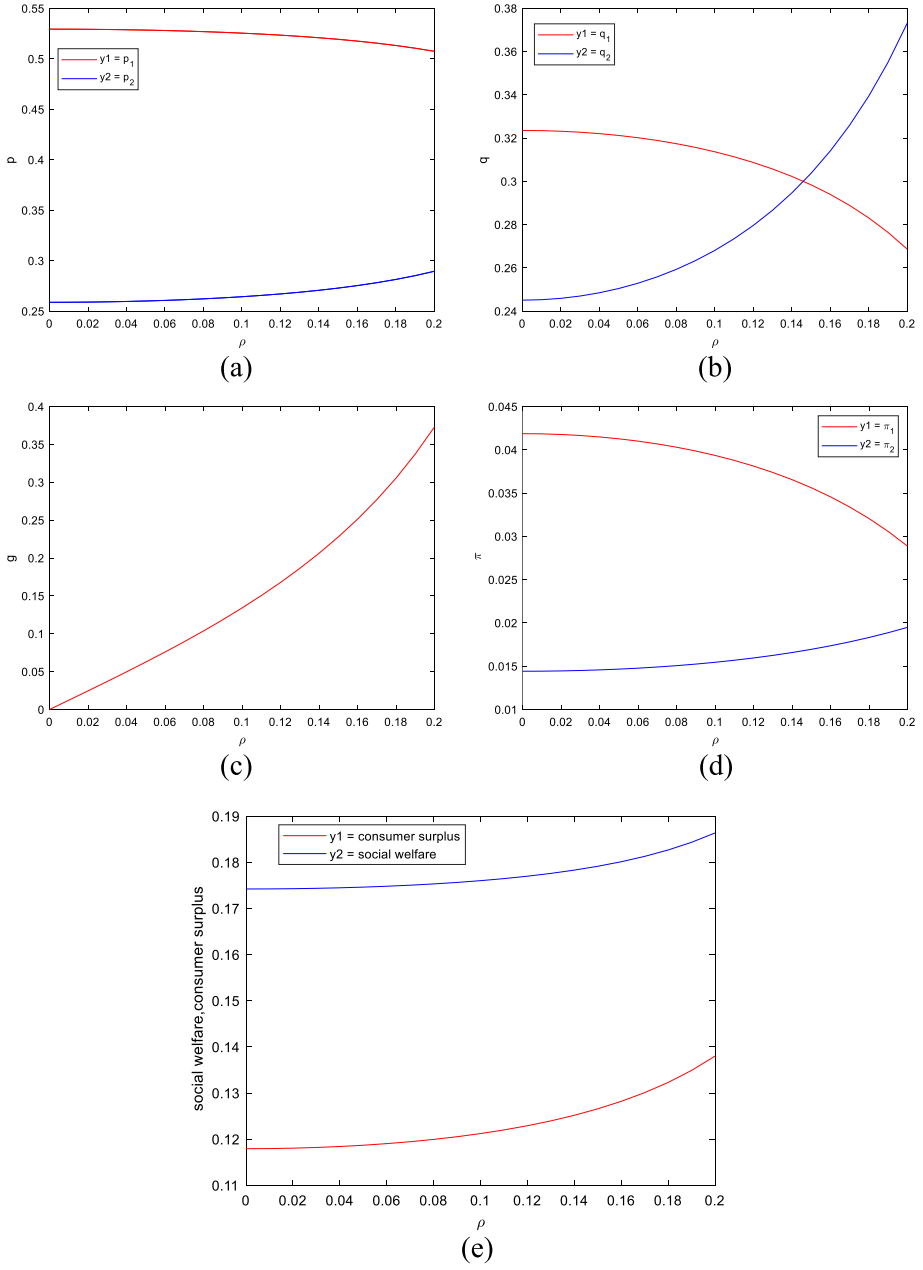

Fig. 3 The impact of consumers' environmental preference on optimal decisions

with μ. Details as follows: $\frac{\partial p_1^*}{\partial \theta} < 0$, $\frac{\partial p_2^*}{\partial \theta} > 0$, $\frac{\partial q_1^*}{\partial \theta} < 0$, $\frac{\partial q_2^*}{\partial \theta} > 0$, $\frac{\partial g^*}{\partial \theta} > 0$, $\frac{\partial \pi_1^*}{\partial \theta} < 0$, $\frac{\partial \pi_2^*}{\partial \theta} > 0$, $\frac{\partial \pi_c^*}{\partial \theta} > 0$, $\frac{\partial \pi_{sw}^*}{\partial \theta} > 0$.

As consumers' quality recognition of remanufactured products increases, the selling price of remanufactured products continues to increase and the selling price of new products continues to decrease.

Consumers' quality recognition of remanufactured products has the same effect on the demand for new and remanufactured products as its sales price. This is because remanufactured products are more and more recognized, it is believed that the difference between the two types of products is gradually narrowing, and the price advantage of remanufactured products makes them occupy the main market.

Consumers' quality recognition of remanufactured products is proportional to the optimal environmental improvement of remanufactured products.

Consumers' quality recognition of remanufactured products has an inhibitory effect on the manufacturer's profit, while it has a positive correlation with remanufacturer profits, consumer surplus and total social welfare. The dual effects of new product markets and prices lead to declined manufacturing profits. However, the double benefits brought by remanufactured products effectively enhance the remanufacturer, consumer surplus and total social welfare. It can be seen that in the process of remanufacturing development, we should pay attention to the improvement of product quality, and truly win the trust of consumers technically.

Assigning relevant parameters, the above conclusions are verified through numerical simulation, and the impact of the difference in product quality between remanufactured and new products on the decision variables and supply chain profit outcomes is analyzed.

As can be seen from Fig. 4, with the increasing consumers' quality recognition of remanufactured products, consumers' demand for remanufactured products continues to increase, and their sales prices also increase slowly. As can be seen from Fig. 4b, new products and remanufactured products coexist in the market initially, the demand for new products is significantly higher than that of remanufactured products. As the degree of recognition increases, the demand for remanufactured products continues to increase. When the degree of recognition reaches a certain level, the demand curves overlap, that is, the two products are in equal demand. Then, with increasing recognition, the remanufactured products gradually occupy the main market, and the new products only account for a very small part of the market. The change trend of the profit curves of the two manufacturers is consistent with the demand curve, and it can be seen that the main reason for the change of the profits of the two manufacturers is the change of market demand.

Consumer surplus and total social welfare gradually increase with the degree of remanufactured product recognition, in the same way as consumers' environmental preference. The environmental utility brought about by consumers buying remanufactured products can effectively offset the utility loss caused by the reduced demand for new products, thereby increasing consumer utility. The total social welfare shows an upward trend as consumer utility and remanufacturer profits increase. It can be seen that improving the recognition of remanufactured products and narrowing the difference in quality perception between new products and remanufactured products is beneficial to improving the total social welfare.

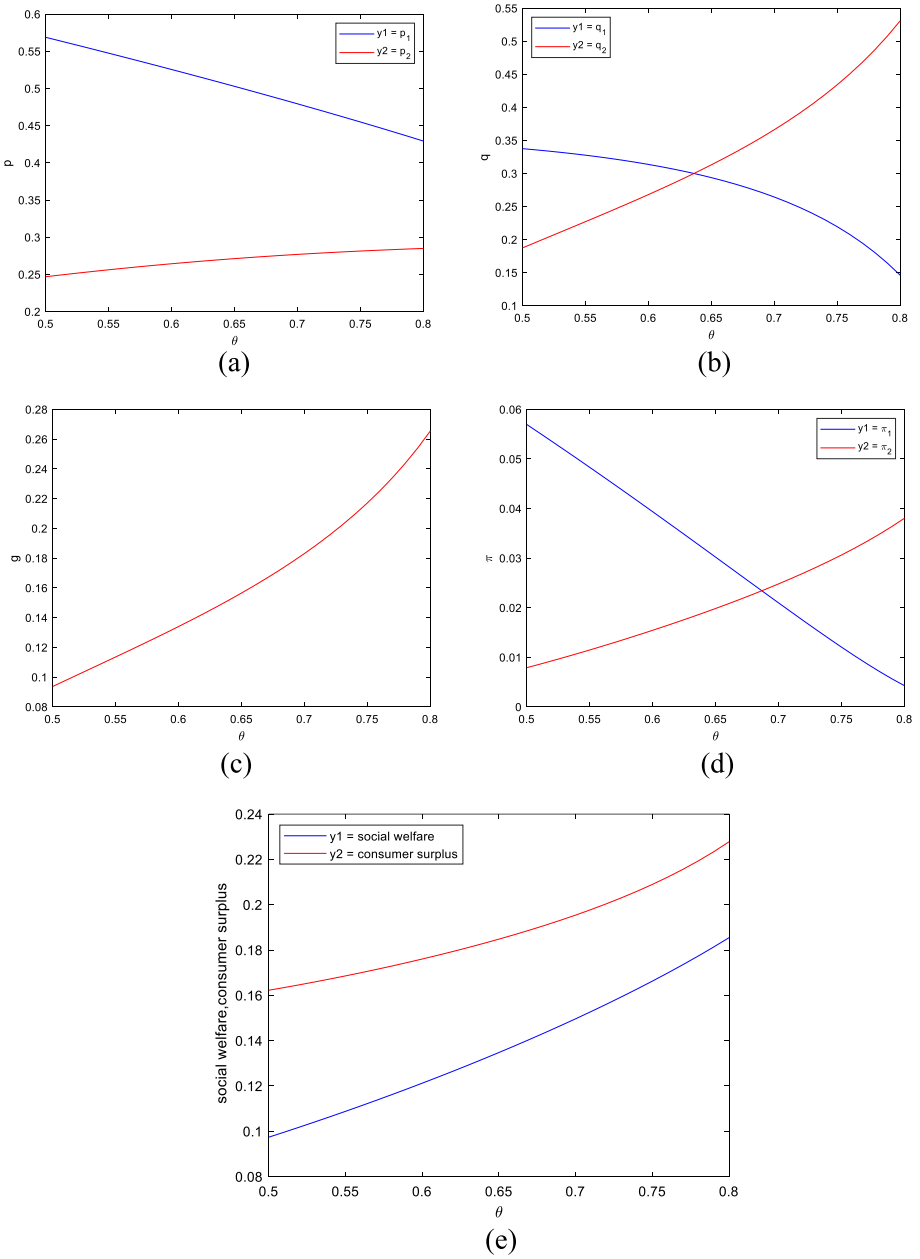

Fig. 4 The impact of consumers' quality recognition of remanufactured products on optimal decisions

4.2 The effect of government subsidy on optimal decisions

Based on the market demand under the influence of consumers' preferences, we firstly obtain the subsidy strategy and subsidy amount that the government should take to maximize social welfare, and obtain the optimal decision for enterprises to maximize their own profits under the situation of government subsidies. Secondly, we compare the two scenarios with or without government subsidies to derive the impacts of subsidies and subsidy strategies on the optimal decision-making of supply chain members. Due to the large number of model parameters, the structure of the results is relatively complex, so we mainly make analysis through numerical simulation.

4.2.1 Impact on the optimal environmental improvement of remanufactured products

It can be seen from Fig. 5a that the optimal environmental improvement degree of remanufactured products has the slowest growth rate when there is no subsidy, and when the combined subsidy strategy is adopted, it has the fastest growth rate. Therefore, subsidies can enhance the impact of consumers' quality recognition and consumers' environmental preference on the remanufactured products' optimal environmental improvement ability to a certain extent.

It can also be seen from Fig. 5a that when consumers' quality recognition of remanufactured products is at a medium level, the optimal environmental improvement rate of remanufacturers under consumer subsidies is the highest at this time. This is because in the context of consumer subsidy, when consumers' quality recognition of remanufactured products is not high, in order to attract consumers, remanufacturers will first improve the environmental improvement of products to make consumers see the environmental improvement brought by remanufactured products. In the combined subsidy scenario, after receiving subsidy, remanufacturers will first reduce product prices to attract consumers, so the initial degree of environmental improvement of remanufactured products is at a low level. Then, as consumers' quality recognition of remanufactured products increases, remanufacturers gradually increase the degree of environmental improvement of their products.

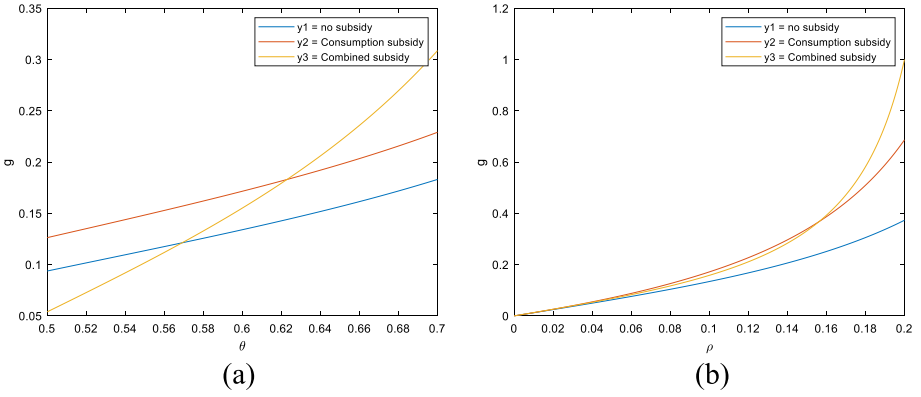

Fig. 5 The impact of consumers' quality recognition and consumers' environmental preference on the optimal environmental improvement of remanufactured products

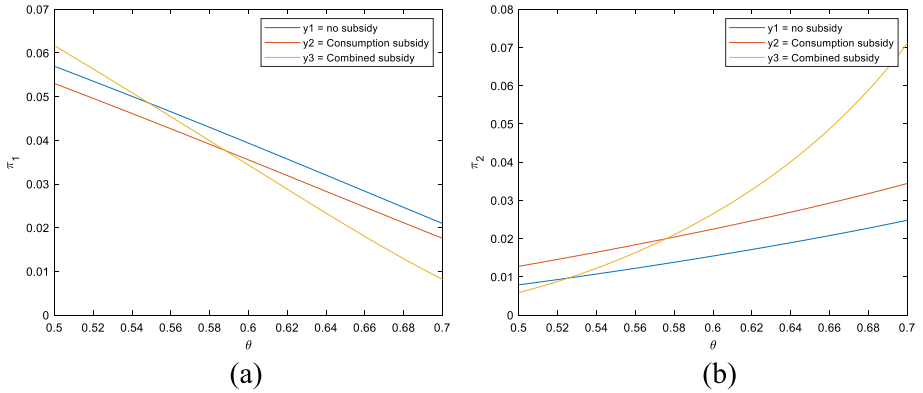

Fig. 6 The impact of consumers' quality recognition on optimal decisions

To a certain extent, government subsidies can enhance the influence of consumers' quality recognition of remanufactured products and consumers' environmental preference on the environmental improvement ability of remanufactured products, and the effect is most obvious when the combined subsidy strategy is adopted.

4.2.2 Impact on the profits of manufacturer and remanufacturer

It can be seen from Fig. 6 that whether the government adopts subsidy strategy or not, the influence trend of consumers' quality recognition of remanufactured products on the profits of the two manufacturers remains unchanged. Compared with no subsidy, the consumer subsidy strategy does not change the power of consumers' quality recognition of remanufactured products to affect the profits of manufacturers and remanufacturers. But it can increase remanufacturers' profits, because government subsidy make its profits increase. Compared with no subsidy, the combined subsidy strategy will increase the power of consumers' quality recognition of remanufactured products to affect the profits of manufacturers and remanufacturers. Moreover, as consumers' quality recognition of

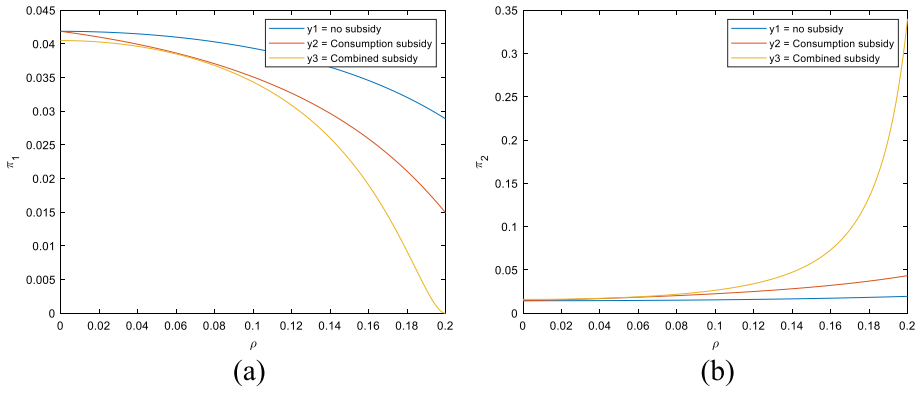

Fig. 7 The impact of consumers' environmental preference on optimal decisions

remanufactured products increases, the profit growth rate of remanufactured products will be faster and faster. This is because remanufacturers can not only transfer subsidies from consumers, but also obtain government subsidies. Once recognized by consumers, profits will grow more rapidly.

whether the government adopts subsidy or not, the impact of consumers' quality recognition of remanufactured products on the profits of the two manufacturers remains unchanged. The consumption subsidy strategy does not amplify its impact, while the combined subsidy strategy does.

It can also be seen from Fig. 7 that the influence of consumers' environmental preference on the two manufacturers is the same as the influence of consumers' quality recognition of remanufactured products. At this time, the advantage of combined subsidy is obviously greater than that of consumption subsidy, and both are higher than the profits without subsidy.

4.2.3 Analysis of the impact of government decisions

The government decides the optimal subsidy amount after the decision of the two manufacturers. Since there is no subsidy, the government expenditure is 0, and no decision-making

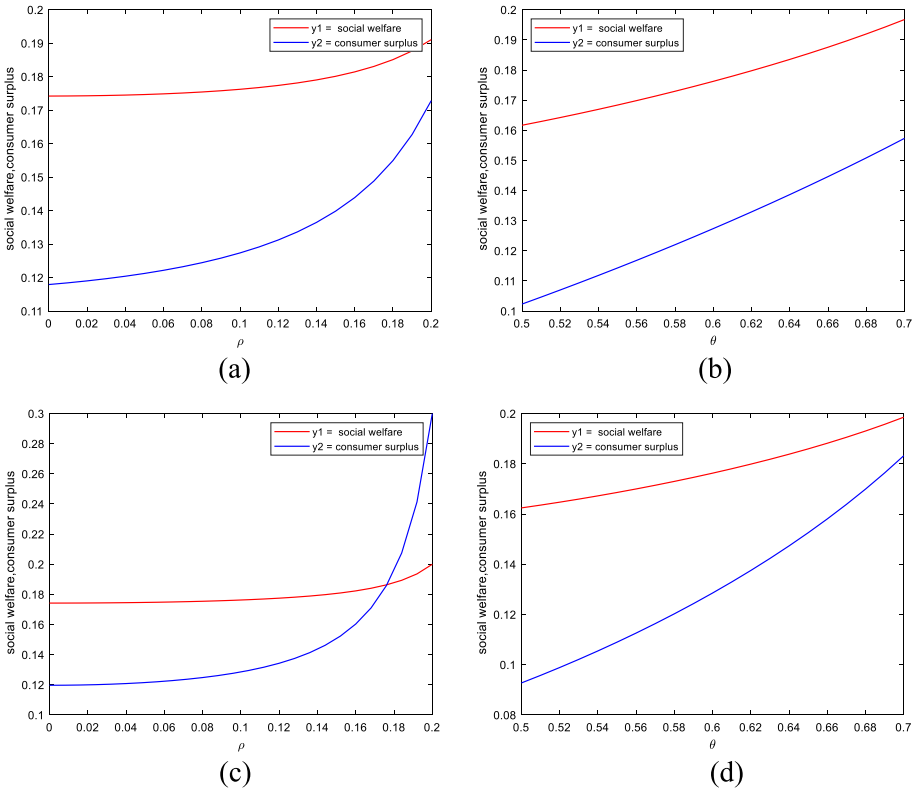

Fig. 8 The impact of consumers' environmental preference and quality recognition on consumer surplus and social welfare (**a** and **b** is under consumption subsidy strategy, **c** and **d** is under combined subsidy strategy)

is required. Therefore, the focus is on the comparative analysis of the impact of various parameters on decision-making in both the consumption subsidy and combined subsidy scenarios.

Combined with the comparative analysis in Fig. 8, it can be seen that in the context of implementing government subsidy, the two parameters of consumers environmental preference and the degree of recognition of remanufactured products have shown a positive role in promoting consumer surplus and the total social welfare, both in the context of the consumption subsidy strategy and in the context of the combined subsidy strategy..

Under the consumption subsidy strategy, social welfare is always higher than consumer surplus, and the difference between the two is the difference between the profit value of the two manufacturers and the government expenditure. As can be seen from Fig. 8-a and Fig. 8-b, the gap of consumer surplus and social welfare gradually narrows, possibly due to the increase in government subsidy. Under the combined subsidy strategy, when ρ and θ increase to more than a certain value, the consumer surplus is higher than the total social welfare. At this time, the increase in consumer utility is mainly caused by the increase in the subsidy amount of government units. In particular, with the change of the consumers' environmental preference, the consumer surplus has an almost exponential growth trend. It can be seen that with the increase of ρ at this time, the surge of consumer surplus mainly comes from government subsidies. With the increasing recognition of remanufactured products by consumers, the change of consumer surplus under combined subsidies is more obvious. At the beginning, the consumer surplus is smaller than that under the single consumption subsidy scenario, because the combined subsidies will cause some subsidies to flow into the hands of remanufacturers.

It can be seen from Fig. 9a and b that the impact of the two parameters on social welfare is the same as the impact on the profit of the remanufacturer. When the two parameters are larger, the remanufacturer's profit can be optimized while ensuring the maximization of social welfare. Consumers' quality recognition of remanufactured products has a strong impact on social welfare, and as recognition increases, consumers' environmental preferences are also affected.

When the two parameters are at a low level, it can be seen that the combined subsidy strategy is the most effective for improving social welfare. With the increase of the two parameters, when both are at a high level, although the profit growth rate under the

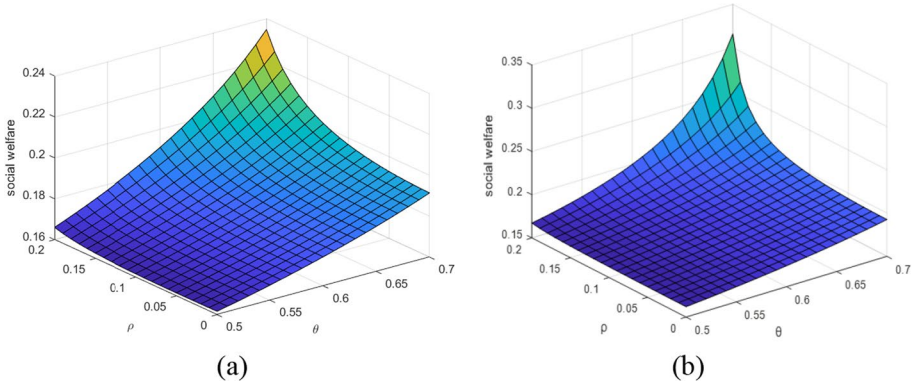

Fig. 9 The impact of consumers' environmental preference and quality recognition on social welfare under the consumption subsidy strategy and combined subsidy strategy

consumption subsidy becomes larger, it is still lower than the social welfare value under the combined subsidy.

In general, this is due to the fact that remanufacturing enterprises cannot win the trust of consumers in the early stage of development, while the overall consumers' environmental awareness is weak. At this time, the government subsidy policy is in favor of remanufacturers. Through subsidy, enterprises can pay more attention to R&D, and consumers can see the government's strong support for remanufacturing, thus eliminating consumers' doubts. In this way, the pressure of remanufacturing enterprises can also be effectively relieved, which is conducive to forming a price advantage and reducing sales prices to attract consumers to buy. So that consumers can truly feel that there is no difference between the quality of remanufactured products and new products, while buying remanufactured products can bring additional environmental benefits. Therefore, the combination subsidy strategy is better than the consumption subsidy strategy.

When remanufacturing enterprises are in the middle and late stage of development and occupy a stable position in the market, consumers have a high degree of recognition of remanufactured products and environmental preferences, and remanufactured products are recognized by the market. At this time, the focus of government subsidy should be shifted to consumers, and through the formation of a good group effect, it will drive the remaining few consumers with poor environmental awareness to participate in the purchase of remanufactured products. To a certain extent, it plays a positive role in advertising.

5 Concluding discussion and future research aspects

This paper studies the remanufacturing decision-making in the process of remanufacturing electronic products. There are manufacturers and remanufacturers in the market, which produce new products and remanufactured products respectively. Taking the remanufacturing process as the research object, this paper constructs a market demand model under the influence of consumers' environmental preference and consumers' quality recognition of remanufactured products based on the theory of consumer utility, and analyzes the game relationship among manufacturers, remanufacturers and consumers. Then, under the situation that the government subsidizes the supply chain, two subsidy strategies, consumption subsidy and combination subsidy, are designed. When two subsidy strategies are implemented, the optimal decision of supply chain members is solved. Compared with the unsubsidized scenario, the following conclusions can be drawn.

(1) Government subsidy will increase the run effect of remanufactured products on new products, and can effectively increase the market share of remanufactured products, improve their environmental improvement, corporate profits, consumer surplus and total social welfare, and the combined subsidy is obvious better than single consumption subsidy, which can realize the dynamic allocation of subsidies. In addition, it is found that the increase of consumers' quality recognition of remanufactured products and the implementation of subsidy strategy can expand the influence of consumers environmental preferences.
(2) Consumers' environmental preference and the degree of consumers' quality recognition of remanufactured products play a very important role in decision-making in the remanufacturing process. It is necessary to take consumers' preferences and key factors

that affect the formation of preferences into account. Whether subsidized or not, consumers' quality recognition of remanufactured products and consumers' environmental preference play a positive role in promoting the degree of environmental improvement of remanufactured products, remanufacturers' profits, and social welfare, and have a reverse effect on manufacturers' profits.

(3) To a certain extent, government subsidy can enhance the consumers' quality recognition of remanufactured products and consumers' environmental preference to influence remanufacturers' profits and degree of environmental improvement of remanufactured products. Moreover, the effect is most obvious when the combined subsidy strategy is implemented.

Future research can extend the line of inquiry of the present study in several directions. Firstly, it was assumed that all information is common knowledge among supply chain members. The following research can be carried out considering the situation of information asymmetry. In addition, our models consider a duopolistic setting in which the manufacturers only produce new products and the remanufacturers only produce remanufactured products. It is worth studying the duopolistic setting in which the manufactures also takes back used products to restrict the capacities of the remanufacturers.

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Data availability Data will be made available on request.

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