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Analysis of Factors Affecting the Profits of Closed-Loop Supply Chain Members Under Different Subsidy Objects

Jing-Hua Zhao[1]*, Da-Lin Zeng[2]†, Ting-Wei Zhou[1]‡, Yan Hui[3]§ and Na Sun[1]¶

[1] *University of Shanghai for Science and Technology, Shanghai, China, 200082*
[2] *School of Management Engineering, Shandong Jianzhu University, Jinan, China*
[3] *Shanghai Research Institute of Sports Science, Shanghai, China, 200020*

Based on the research hypothesis in a fully competitive closed-loop supply chain for mixed recycling channels, different closed-loop supply chain pricing models are established for the government's strategy of adopting different subsidies (consumers, retailers, manufacturers or third-party recyclers). In this work, we use game theory to establish a price formula, and identify the factors affecting the profit of five closed-loop supply chain members. Through solution verification, the sales channel pricing, the recycling channel pricing and the channel member profit change of the closed-loop supply chain under different subsidy objects are compared after changing only one influencing factor. By providing a reference and suggesting how the government can control these factors, this study can assist the government to put subsidies in place, and optimize the operations of the closed-loop supply chain.

Keywords: Subsidy object, Closed-loop supply chain, Influencing factors, Member pricing

INTRODUCTION

As a powerful tool for stimulating domestic demand and promoting certain green products and industries, government subsidies are indispensable. With the strengthening of government subsidies, their targets are gradually increasing. The difference between the design of a government subsidy model and the choice of subsidy objects for the operation efficiency of closed-loop supply chain is very significant. In response to this, based on the research hypothesis in the fully competitive closed-loop supply chain of mixed recycling channels, Zhao Jinghua [1] established a closed-loop supply chain pricing model for the government to adopt different subsidy target strategies (consumers, retailers, manufacturers or third-party recyclers). By comparing sales channel pricing indicators, recycling channel pricing indicators and channel members' profit distribution for different subsidy objects, the impact coefficient of different subsidy objects on channel member pricing decisions and profits is analyzed [1]. However, in the actual implementation process, when the subsidy target has been determined, what factors will affect the profits of the members in the supply chain, how to control these factors so that the government subsidies are put in place, and the optimal operation of the closed-loop supply chain, are also questions worth discussing. Hence, based on the aforementioned research, this paper introduces the consumer's sensitivity coefficient r_2 for recycling channels, r_0 for consumer environmental awareness, δl for government subsidy quota and

*zhaojinghua@usst.edu.cn
†Corresponding author: Da-Lin Zeng, zengdalin@sdjzu.edu.cn
‡1713490319@st.usst.edu.cn
§yanhui@shriss.cn
¶sunna@usst.edu.cn

other influencing factors, taking the dual-channel closed-loop supply chain as the research object, using the idea of game theory to construct the pricing model of four supply chain members of consumers, manufacturers, third-party recyclers and retailers, and determining the factors that can make the corresponding models work optimally under different government subsidies.

At present, the factors influencing the pricing decisions of a closed-loop supply chain under government control are based on environmental awareness and government subsidies. Zhu Xiaoxi [2] analyzed the impact of government subsidies on the efficiency of a closed-loop supply chain, and concluded that the government subsidies, intended to optimally maximize social welfare, increase the amount of recycling of discarded products, as well as the profits of retailers and manufacturers. Ge Jingyan et al. [3] used the theory of game theory in the closed-loop supply chain of a single manufacturer and retailer to explore the impact of social environmental awareness on pricing when there are vertical differences between new products and remanufactured products. In the secondary closed-loop supply chain of a single manufacturer and a single retailer, Shi Wei et al. [4] considered the environmental awareness of consumers. Consumers have different preferences for environmentally friendly products and common products, thus establishing a differential pricing model and the manufacturer will decide on both the production of ordinary products and the production of environmentally friendly products. Conrad K [5] established a duopoly model and found that balanced prices and market share are affected by the environmental awareness of consumers, not only by product production costs. For the first time, Xiong Zhongkai and Liang Xiaoping [6] considered the level of consumer awareness of environmental protection in different recycling modes: direct recycling by manufacturers, recycling by manufacturers, and recycling of third-party recyclers by manufacturers. They found that an increased awareness of environmental protection will help to increase the profitability of channel members, as well as the total profit, wholesale price and retail price. Zugang (Leo) Liu et al. [7] used the two-stage Starkberg game model to introduce consumers' environmental awareness into the supply chain network structure, and found that if consumers' environmental awareness is improved, those who manufacture and retail environmentally friendly products can make a profit. However, companies which produce and operate ordinary products will also benefit from low levels of product competition, but they will benefit less in a highly competitive environment. Focusing on the impact of consumer environmental awareness on recycling channels, Xu Qingchun and Chen Yihua [8] introduced the notion of consumers' environmental awareness and established a closed-loop network optimization model to reflect the different consumer demand functions of different products. The statistical findings indicated that the public's environmental awareness will affect the optimal recovery rate. Fang Qiaohong [9] regards the public's expectation of product recycling rate and product environmental protection sensitivity as public environmental awareness, and analyzed the impact of environmental awareness on product manufacturing, then concluded that public environmental protection will decrease. The product recycling rate is increased, and the increase in environmental sensitivity will increase the recycling rate of the product. Other relevant influencing factors are mentioned only in reference [1], but such problems exist in reality. These factors not only affect demand and pricing, but also affect the price and profit indicators of each member of the reverse supply chain. Therefore, in this paper, a closed-loop supply chain pricing model is constructed for the mixed competition recycling channel, which optimizes the overall target profit of the supply chain under the subsidy of consumers, manufacturers, retailers and third-party recyclers. Using the game theory method, the following three points are discussed:

(1) In the closed-loop supply chain with mixed competitive recycling channels, the government subsidies are studied in terms of consumers, manufacturers, retailers and third-party recyclers, and four pricing models are established.

(2) Based on the four pricing models in (1), the main factors affecting the closed-loop supply chain are proposed and discussed.

(3) Through numerical examples, the effects of different influence coefficients on the profit optimization of the overall supply chain after balancing the model operation are compared in the closed-loop supply chain of different subsidy objects.

In this paper, the mathematical modeling method is used to establish a closed-loop supply chain model, and the important influencing factors are analyzed. The game theory method is used to solve the problem. The solution is verified by the example, and the supply chain member's profit transfer process is calculated and analyzed under different parameters., which provides reference and advice for government evaluation, decision making, implementation and improvement.

1. RESEARCH ASSUMPTIONS AND PARAMETER SETTINGS

The paper is based on a closed-loop supply chain pricing model for hybrid competitive recycling channels (as shown in Figure 1, the specific parameters are given in the hypothesis), and the impact factors of member pricing strategies and profit in the closed-loop supply chain of subsidized objects for manufacturers, retailers, consumers and third-party recyclers, are studied separately.

In order to make the research more specific and scientific, the following assumptions are established in combination with specific situations:

Hypothesis 1: In a closed-loop supply chain with mixed competitive recycling channels, there are two recycling channels for consumers: the direct recycling channel that the manufacturer is responsible for, and the recycling channel that the third-party recycler is responsible for. Consumers base their choice entirely on price, so there is competition between recycling channels.

Hypothesis 2: When the government adopts the old-for-new subsidy policy to expand domestic demand, referring to Zhou Lu [10] for the definition of subsidy coefficient δ, where $0 \leqslant \varepsilon \leqslant 1$, the size of the subsidy factor is determined by factors such as the selling price of home appliances and the residual value of used home appliances. l is the maximum government subsidy for unit products t, and l is a constant less than zero, therefore, the unit subsidy for used household appliances is δl. In addition, due to

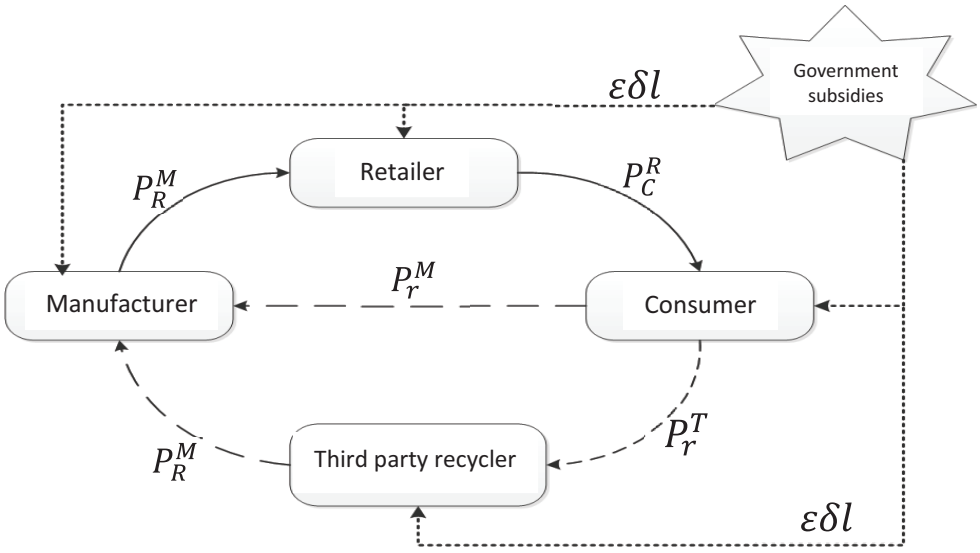

Figure 1 Closed-loop supply chain pricing model for hybrid competitive recycling channels

the difference in the degree of influence of government subsidies on different subsidy objects, we assume that ε_C, $\varepsilon_M, \varepsilon_R, \varepsilon_T$ are the influence coefficients of subsidies on consumer demand, retailer costs, manufacturer costs, and third-party recycler costs.

Hypothesis 3: The mathematical model established in this paper discusses only the single-cycle situation; that is, there are waste product in the market before the manufacturer remanufactures, and the products sold in the previous cycle can be recycled and reused, and the manufacturer's production process is a continuous one. The unit cost of the manufacturer's new product is C_n^M, and the unit cost of the recycled product is C_r^M, assuming $C_r^M < C_n^M$, thus ensuring that the manufacturing firm is profitable and the manufacturer actively participates in the remanufacturing operations. Let $\Delta = C_n^M - C_r^M \geqslant 0$, then Δ is the unit production cost saved by the manufacturer as a result of remanufacturing.

Hypothesis 4: Referring to the function of Yi Yuyin et al. [11] in the recycling of waste products through mixed channels, the recycling price in the direct recycling channel of the manufacturer is P_r^M, and the recycling price in the recycling channel of the third-party recycler is P_r^T, the recycling functions of the waste product coexisting in the two channels are as follows:

(1) The function of recycling the amount of waste products in the recycling channel of the third-party recycler is:

$$D_T = r_0 + r_1 P_r^T + r_2 \left(P_r^T - P_r^M\right) \tag{1}$$

(2) The direct recycling function of the manufacturer's waste products' amount is:

$$D_M = \begin{cases} r_2 \left(P_r^M - P_r^T\right), P_r^M > P_r^T \\ 0, P_r^M \leqslant P_r^T \end{cases} \tag{2}$$

Here, r_0 represents the consumer's environmental awareness, that is, whether the consumer is willing to selflessly return the discarded product to the recycler; r_1 indicates the consumer's sensitivity coefficient to the third-party recycler's recycling price; r_2 represents the consumer's sensitivity to the price difference between the manufacturer and the third-party recycler, the larger the r_2 is, the greater the competition between the two recycling channels will be. Therefore, we can use r_2 as the competition coefficient of the recycling channel to measure the degree of competition in the recycling channel.

Hypothesis 5: Assume that the performance, quality and other indicators of the remanufactured product are completely consistent with the new product. The market sales price is P_C^R, then the market demand for the product is $Q_R = D - kP_C^R$, where D is the maximum demand in the market. $k \geq 0$ is the market sales price sensitivity coefficient.

Hypothesis 6: Assume that home appliance manufacturers are the price leaders in the entire closed-loop supply chain and have absolute control, while retailers and third-party recyclers are followers.

Hypothesis 7: Assuming that the closed-loop supply chain under study is a fully competitive system, government subsidies can be transferred among members of the supply chain.

In this paper, π_i^j is used to represent the benefit of the member i of the closed-loop supply chain in the model j, where $i = \{M, R, T\}$, M represents the market leader manufacturer, R represents the retailer, and T represents the third-party recycler; $j = \{C, M, R, T\}$, C indicates that the subsidy object is the consumer's Model C, M indicates that the subsidy object is the manufacturer's Model M, and R indicates that the subsidy object is the retailer's Model R. T indicates that the subsidy object is the third-party recycler's Model T; P_R^M indicates the wholesale price of the manufacturer's product, C_R indicates the retailer's operating cost, and C_T indicates the third-party recycler's recovery activity's operating cost.

2. MODEL BUILDING

2.1 Using Consumers as Subsidies - Model C

In order to stimulate the market demand of an industry, government agencies often adopt policies that directly subsidize product consumers. Take the domestic subsidies policy for home

appliances to the rural areas as an example, when consumers purchase electrical products that meet the requirements of home appliances to the countryside, the government directly subsidizes 13% of the product sales price. In order to reduce the complexity of the study, this section assumes that the amount of subsidy has a linear effect on the sales of the product, and the demand function of the product in the traditional distribution channel that the retailer is responsible for becomes:

$$Q_R = D - kP_C^R + \varepsilon_C \delta l \tag{3}$$

The manufacturer's revenue is mainly considered in two parts: wholesale price of products for retailers, and cost savings from remanufacturing activities; and the manufacturer's expenditure is mainly considered in three parts: raw material procurement and production costs, manufacturer's direct recycling channel costs, and manufacturer's cost of recycling used products from third-party recyclers. Therefore, the manufacturer's net profit is expressed as:

$$\pi_M^C = \left(P_R^M - C_n^M\right) Q_R + \Delta\left(D_M + D_T\right) - P_r^M D_M - P_T^M D_T \tag{4}$$

The retailer's income mainly includes revenue from product sales, and its main expenditure is the wholesale purchase cost of the product. Therefore, the retailer's final profit is expressed as:

$$\pi_R^C = \left(P_c^R - P_R^M - C_R\right) Q_R \tag{5}$$

The revenue of third-party recyclers is mainly obtained from the compensation given in return for the recovery of products, and the expenditure is mainly the cost of recovery. Therefore, the final profit of the third-party recycler is expressed as:

$$\pi_T^C = \left(P_T^M - P_r^T - C_T\right) D_T \tag{6}$$

Since the game is a complete information dynamic game, it can be solved by inverse induction. Thus, we can establish a pricing decision under Model C:

$$\max_{P_R^M, P_r^M, P_T^M} \pi_M^C$$

$$\text{s.t.} \begin{cases} P_C^R \in \max \pi_R^C \\ P_r^T \in \max \pi_T^C \end{cases}$$

$$P_R^M = \frac{D - kC_R + kC_n^M + \varepsilon_C \delta l}{2k} \tag{7}$$

$$P_T^M = \frac{\Delta r_1 - r_0 + r_1 C_T}{2r_1} \tag{8}$$

$$P_r^M = \frac{\Delta r_1 - r_0}{2r_1} \tag{9}$$

$$P_c^R = \frac{3D + kC_R + 3\varepsilon_C \delta l + kC_n^M}{4k} \tag{10}$$

$$P_r^T = \frac{\Delta r_1^2 - 3r_0 r_1 + 2\Delta r_1 r_2 - 2r_0 r_2 - r_1\left(r_1 + r_2\right) C_T}{4r_1\left(r_1 + r_2\right)} \tag{11}$$

The above is the optimal pricing strategy for manufacturers, retailers and third-party recyclers in Model C. All of these are based on the maximization of their own interests, and through this pricing strategy, they can maximize these interests.

Substituting the pricing strategy in the profit function can obtain the maximum profits for the manufacturer, retailer and third-party recycler $\pi_M^C, \pi_R^C, \pi_T^C$ and the total profit π_C of the closed-loop supply chain based on Model C, which is as follows:

$$\begin{aligned} \pi_M^C = & \frac{\left(D - kC_R - kC_n^M + \varepsilon_c \delta l\right)^2}{8k} \\ & + \frac{r_0 r_1 + 2r_0 r_2 + \Delta r_1^2 + 2\Delta r_1 r_2 - r_1\left(r_1 + r_2\right) C_T}{4\left(r_1 + r_2\right)} \\ & - \frac{\left(\Delta r_1 - r_0\right)\left(\Delta r_1 r_2 + r_0 r_2 + r_2\left(r_1 + r_2\right) C_T\right)}{8r_1\left(r_1 + r_2\right)} \\ & - \frac{\left(\Delta r_1 - r_0 + r_1 C_T\right)\left(r_0 + \Delta r_1 - \left(r_1 + r_2\right) C_T\right.}{8r_1} \end{aligned} \tag{12}$$

$$\pi_R^C = \frac{\left(D - kC_R + \varepsilon_c \delta l - kC_n^M\right)^2}{16k} \tag{13}$$

$$\pi_T^C = \frac{\left(\Delta r_1 + r_0 - \left(r_1 + r_2\right) C_T\right)^2}{16\left(r_1 + r_2\right)} \tag{14}$$

$$\pi_C = \pi_M^C + \pi_R^C + \pi_T^C \tag{15}$$

2.2 Using Retailers as Subsidies - Model R

Retailers, responsible for the sale of end products, are of great importance to the smooth operation of the closed-loop supply chain of an entire product. In order to expand the product sales market and stimulate sales channels, government agencies have adopted retailer subsidies (such as tax relief and fund subsidies) to encourage retailers to put more effort into exploring product sales channels. In order to simplify the model, this section assumes that the government encourages retailers to investigate product sales channels by reducing retailers' corresponding operating costs (such as electricity bills, venue rental fees, etc.). $\varepsilon_R \delta l$ indicates the cost reduction that subsidies bring to retailers.

Then the retailer's final profit becomes:

$$\pi_R^R = \left(P_C^R - P_R^M - C_R + \varepsilon_R \delta l\right) Q_R \tag{16}$$

The final profit of the manufacturer is expressed as:

$$\pi_M^R = \left(P_R^M - C_n^M\right) Q_R + \Delta\left(D_M + D_T\right) - P_r^M D_M - P_T^M D_T \tag{17}$$

The final profit of the third-party recycler is expressed as:

$$\pi_T^R = \left(P_T^M - P_r^T - C_T\right) D_T \tag{18}$$

Establishing a pricing decision model under Model R:

$$\max_{P_R^M, P_r^M, P_T^M} \pi_M^R$$

$$\text{S.t.} \begin{cases} P_C^R \in \max \pi_R^R \\ P_r^T \in \max \pi_T^R \end{cases}$$

$$P_r^M = \frac{\Delta r_1 - r_0}{2r_1} \tag{19}$$

$$P_T^M = \frac{\Delta r_1 - r_0 + r_1 C_T}{2r_1} \tag{20}$$

$$P_c^R = \frac{3D + kC_R - k\varepsilon_R \delta l + kC_n^M}{4k} \tag{21}$$

$$P_R^M = \frac{D - kC_R + k\varepsilon_R\delta l + kC_n^M}{2k} \tag{22}$$

$$P_r^T = \frac{\Delta r_1^2 - 3r_0r_1 + 2\Delta r_1r_2 - 2r_0r_2 - r_1(r_1+r_2)C_T}{4r_1(r_1+r_2)} \tag{23}$$

The above is the optimal pricing strategy for manufacturers, retailers and third-party recyclers in Model R. All of these are based on the maximization of their own interests, and through this pricing strategy, they can maximize their profits. Substituting the pricing strategy in the profit function can obtain optimal profits for the manufacturer, retailer and third-party recycler $\pi_M^R, \pi_R^R, \pi_T^R$ and the total profit π^R of the closed-loop supply chain based on Model R, which is as follows:

$$\begin{aligned}\pi_M^R = {} & \frac{\left(D - kC_R + k\varepsilon_R\delta l - kC_n^M\right)^2}{8k} \\ & + \frac{r_0r_1 + 2r_0r_2 + \Delta r_1^2 + 2\Delta r_1r_2 - r_1(r_1+r_2)C_T}{4(r_1+r_2)}\Delta \\ & - \frac{(\Delta r_1 - r_0)(\Delta r_1r_2 + r_0r_2 + r_2(r_1+r_2)C_T)}{8r_1(r_1+r_2)} \\ & - \frac{(\Delta r_1 - r_0 + r_1C_T)(r_0 + \Delta r_1 - (r_1+r_2)C_T}{8r_1}\end{aligned} \tag{24}$$

$$\pi_R^R = \frac{\left(D - kC_R + k\varepsilon_R\delta l - kC_n^M\right)^2}{16k} \tag{25}$$

$$\pi_T^R = \frac{(\Delta r_1 + r_0 - (r_1+r_2)C_T)^2}{16(r_1+r_2)} \tag{26}$$

$$\pi_R = \pi_M^R + \pi_R^R + \pi_T^R \tag{27}$$

2.3 Using Manufacturer as Subsidies - Model M

The manufacturer is the core of the closed-loop supply chain of products, being responsible for the production of products and the remanufacturing of used products. Therefore, the government can expand the market demand for a product by motivating manufacturers to participate in manufacturing and remanufacturing activities. For example, in October 2008, the US government adopted a tax credit for subsidies to polysilicon manufacturing companies to support the polysilicon industry and achieve better implementation results. This section assumes that the government has encouraged manufacturers to continually invest in the manufacturing and remanufacturing of products by reducing manufacturers' taxes, which indirectly reduces the manufacturing and remanufacturing costs, thereby increasing the manufacturers' profits. To reduce the complexity of the study, this section assumes that government subsidies have the same impact on both the manufacturing costs and remanufacturing costs, which are all $\varepsilon_M\delta l$.

Then the retailer's final profit becomes:

$$\begin{aligned}\pi_M^M = {} & (P_R^M - C_n^M + \varepsilon_M\delta l)Q_R + (\Delta + \varepsilon\delta l)(D_M + D_R) \\ & - P_r^M D_M - P_T^M D_T\end{aligned} \tag{28}$$

The final profit of the manufacturer is expressed as:

$$\pi_R^M = (P_C^R - P_R^M - C_R)Q_R \tag{29}$$

The final profit of the third-party recycler is expressed as:

$$\pi_T^M = (P_T^M - P_r^T - C_T)D_T \tag{30}$$

Establishing a pricing decision model under Model M:

$$\max_{P_R^M, P_r^M, P_T^M} \pi_M^M$$

$$\text{s.t.} \begin{cases} P_C^R \in \max \pi_R^C \\ P_r^T \in \max \pi_T^C \end{cases}$$

$$P_R^M = \frac{D - kC_R + kC_n^M - \varepsilon_M\delta l}{2k} \tag{31}$$

$$P_T^M = \frac{(\Delta + \varepsilon_M\delta l)r_1 - r_0 + r_1C_T}{2r_1} \tag{32}$$

$$P_r^M = \frac{(\Delta + \varepsilon_M\delta l)r_1 - r_0}{2r_1} \tag{33}$$

$$P_c^R = \frac{3D + kC_R - \varepsilon_M\delta l + kC_n^M}{4k} \tag{34}$$

$$P_r^T = \frac{(\Delta + \varepsilon_M\delta l)r_1(r_1+2r_2) - r_1(r_1+r_2)C_T - 3r_0r_1 - 2r_0r_2}{4r_1(r_1+r_2)} \tag{35}$$

The above is the optimal pricing strategy for manufacturers, retailers and third-party recyclers in Model M. All of these are based on the maximization of their own interests, and through this pricing strategy, they can maximize their own interests. Substituting the pricing strategy in the profit function can obtain optimal profits for the manufacturer, retailer and third-party recycler π_M^M, π_R^M, π_T^M and the total profit π^M of the closed-loop supply chain based on Model M, which is as follows:

$$\begin{aligned}\pi_M^M = {} & \frac{\left(D - kC_R + \varepsilon_M\delta l - kC_n^M\right)\left(D - kC_R - kC_n^M + (2k-1)\varepsilon_M\delta l\right)}{8k} \\ & + \frac{(\Delta + \varepsilon_M\delta l)(r_1+2r_2)(\Delta r_1 + \varepsilon_M\delta lr_1 + r_0) - r_1(r_1+r_2)C_T}{4(r_1+r_2)} \\ & - \frac{((\Delta + \varepsilon_M\delta l)r_1 - r_0)((\Delta + \varepsilon_M\delta l)r_1r_2 + r_0r_2 + r_2(r_1+r_2)C_T)}{8r_1(r_1+r_2)} \\ & - \frac{((\Delta + \varepsilon_M\delta l)r_1 - r_0 + r_1C_T)\left(D - kC_R + \varepsilon_M\delta l - kC_n^M\right)}{8r_1}\end{aligned} \tag{36}$$

$$\pi_R^M = \frac{\left(D - kC_R + \varepsilon_R\delta l - kC_n^M\right)^2}{16k} \tag{37}$$

$$\pi_T^M = \frac{((\Delta + \varepsilon_M\delta l)r_1 + r_0 - (r_1+r_2)C_T)^2}{16(r_1+r_2)} \tag{38}$$

$$\pi^M = \pi_M^M + \pi_R^T + \pi_T^M \tag{39}$$

2.4 Using Third-Party Recycler as Subsidies - Model T

In order to simplify the model, this section assumes that the government is motivated by third-party recyclers to reduce the operating costs of their recycling activities (such as electricity costs, site rental costs, etc.) to motivate third-party recyclers to participate in the recycling of used products $\varepsilon_T\delta l$ indicates the cost reduction of subsidies to third-party recyclers.

Then the retailer's final profit becomes:

$$\pi_M^T = (P_R^M - C_n^M)Q_R + \Delta(D_M + D_T) - P_r^M D_M D_T \tag{40}$$

The final profit of the manufacturer is expressed as:

$$\pi_T^R = (P_C^R - P_R^M - C_R)Q_R \tag{41}$$

The final profit of the third-party recycler is expressed as:

$$\pi_T^R = (P_T^M - P_r^T - C_T + \varepsilon_T \delta l)D_T \tag{42}$$

Establishing a pricing decision model under Model T:

$$\max_{P_R^M, P_r^M, P_T^M} \pi_M^M$$

$$\text{s.t.} \begin{cases} P_C^R \in \max \pi_R^C \\ P_r^T \in \max \pi_T^C \end{cases}$$

$$P_R^M = \frac{D - kC_R + kC_n^M}{2k} \tag{43}$$

$$P_T^M = \frac{\Delta r_1 - r_0 + r_1 (C_T - \varepsilon_T \delta l)}{2r_1} \tag{44}$$

$$P_r^M = \frac{\Delta r_1 - r_0}{2r_1} \tag{45}$$

$$P_c^R = \frac{3D + kC_R + kC_n^M}{4k} \tag{46}$$

$$P_r^T = \frac{\Delta r_1^2 + 2\Delta r_1 r_2 - 3r_0 r_1 - 2r_0 r_2 + r_1 (r_1 + r_2)(\varepsilon_T \delta l - C_T)}{4r_1 (r_1 + r_2)} \tag{47}$$

The above is the optimal pricing strategy for manufacturers, retailers and third-party recyclers in Model T. All of these are based on the maximization of their own interests, and through this pricing strategy, they can maximize their own interests. Substituting the pricing strategy in the profit function can obtain optimal profits for the manufacturer, retailer and third-party recycler π_M^T, π_R^T, π_T^T and the total profit π^T of the closed-loop supply chain based on Model T, which is as follows:

$$\begin{aligned} \pi_M^T = & \frac{\left(D - kC_R - kC_n^M\right)^2}{8k} \\ & + \frac{(r_1 + 2r_2)(r_0 + \Delta r_1) + r_1 (r_1 + r_2)(\varepsilon_T \delta l - C_T)}{4(r_1 + r_2)} \Delta \\ & - \frac{(r_0 r_2 + \Delta r_1 r_2 - r_2 (r_1 + r_2)(\varepsilon_T \delta l - C_T))(\Delta r_1 - r_0)}{8r_1 (r_1 + r_2)} \\ & - \frac{(\Delta r_1 - r_0 + r_1 (C_T - \varepsilon_T \delta l))(\Delta r_1 + r_0 + (r_1 + r_2)(\varepsilon_T \delta l - C_T))}{8r_1} \end{aligned} \tag{48}$$

$$\pi_R^T = \frac{\left(D - kC_R - kC_n^M\right)^2}{16k} \tag{49}$$

$$\pi_T^T = \frac{(\Delta r_1 + r_0 + (r_1 + r_2)(\varepsilon_T \delta l - C_T))^2}{16(r_1 + r_2)} \tag{50}$$

$$\pi^T = \pi_M^T + \pi_R^T + \pi_R^T \tag{51}$$

3. NUMERICAL CALCULATION EXAMPLE

Based on the pricing model under game theory, when only one factor changed, the corresponding pricing and profit will be affected. This section uses a numerical example to analyze the changes in the profit of each of the four subsidy models when changing an influencing factor. According to the definition of parameters in the model and some relationship assumptions between them, the following settings are given respectively.

D=500; r_1=3; r_0=30; k=3; C_n^M=60; C_r^M=25; Δ=35; r_2=5; ε_c=2; ε_R=2.2; ε_M=2.4; ε_T=0.4; δ=0.2; l=120; C_R=12; C_T=6

Substituting the above specific parameter values in the four models under different subsidy objects, the following five conclusions are drawn.

3.1 The Impact of r_2 on the Profit of Supply Chain Members in Each Model

Using the consumers' sensitivity coefficient r_2 as a research variable for recycling channel competition, compare the variation of member profit and total profit of each supply chain under the four models (as shown in Figure 2–5).

In Figure 1, when the value of r_2 increases, the recycling price of the old product in the third-party recycling channel will rise, and the consumer will be more willing to sell the used product, but the change of r_2 has almost no influence on the sales price of each model. Therefore, the profit of the manufacturer in the four models increases to a certain extent with the increase of r_2, and when the government provides a quantitative subsidy quota to the manufacturer, its profit will first show a pattern of accelerated growth, and then the trend will gradually flatten.

In Figure 2, as r_2 increases, the retailer's profit in each supply chain model is constant. Therefore, retailer profits are not affected by consumers' sensitivity to competition in recycling channels.

In Figure 3, with the increase of r_2, the third-party recycler's recycling price P_r^T to consumers is correspondingly increased, but is still lower than the manufacturer's recycling price P_r^M, the third-party recycler's operating cost C_T and P_T^M unchanged, even if the amount of recycling of old products by third-party recyclers is increasing, the profit of third-party recycler products in Model C, Model R and Model T decreased too fast. The profit trends of third-party recyclers in these three models shows a downward trend. Only in Model M does the degree of change in the profit per unit product of the third-party recycler is less than the degree of change in the amount of recycling, so it shows a profit growth model.

In Figure 4, the total profit of the four models increases with the increase of r_2, and compared with the growth trend of Model M, the growth trend of the total profit of the other three models is negligible. It can be seen that the sensitivity of consumers in the competition of recycling channels has a greater impact on the total profits of Model M.

3.2 The Impact of r_0 on the Profit of Supply Chain Members in Each Model

Taking the consumer's environmental awareness r_0 as a research variable, compare the changes in the member profit and total profit of each supply chain under the four models (as shown in Figure 6–9).

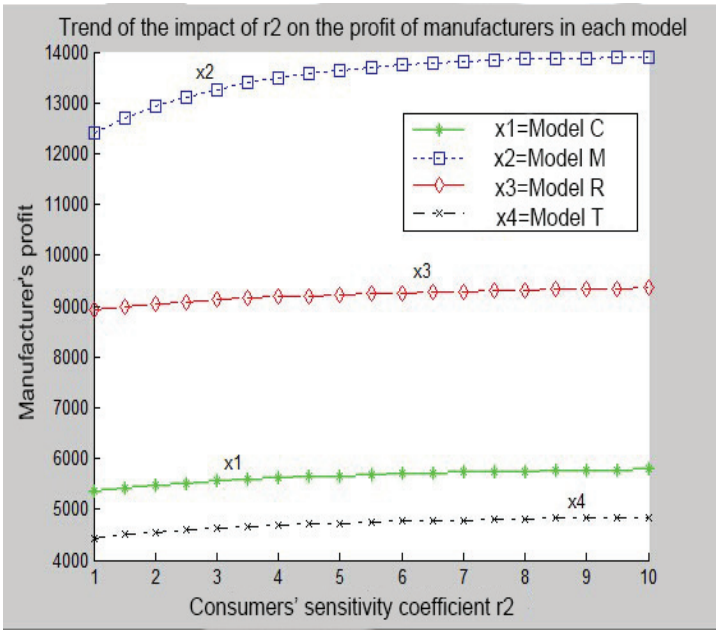

Figure 2 Trend of the impact of r_2 on the profit of manufacturers in each model

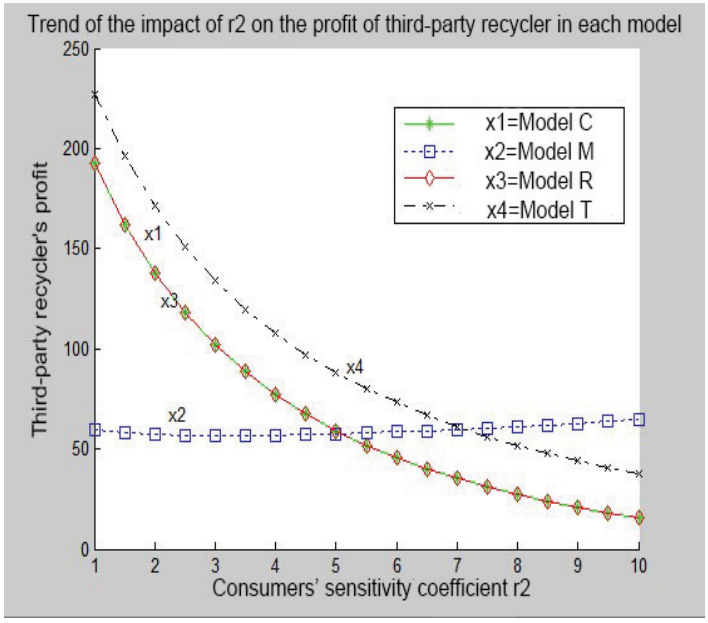

Figure 3 Trend of the impact of r_2 on the profit of third-party recycler in each model

(1) Under the condition that other parameters are kept constant, the profit of the manufacturers in each model increases as the environmental awareness r_0 of the consumer increases. Among them, the manufacturer-to-consumer recycling price P_r^M in Model M is far greater than the third-party recycler-to-consumer recycling price P_r^T, and the recycling of third-party recyclers has been greatly reduced, resulting in a significant increase in manufacturers' profits. It can be concluded that the change of r_0 improves the profits of the manufacturer in Model M more so than in other models.

(2) When the consumer's environmental awareness r_0 is larger, the retailers' profits in each supply chain model is constant because no other parameters are changed. It can be seen that retailers' profits may not be affected by consumers' environmental awareness.

(3) When consumers' awareness of environmental protection increases, people begin to abandon the concept of directly discarding used products, take the initiative to pay attention to the recycling channels of used goods, and will be willing to sell used products at low prices, so that three kinds of recycling prices emerge in the mixed competition recycling channels: P_r^T, P_r^M and P_T^M all showed different amounts of reductions, and the total amount of used, recycled products will increase.

In Model R, the third-party recycler's price reduction for consumers is much greater than the manufacturer's recycling price and the manufacturer's purchase price from third-party recyclers, causing consumers to sell large quantities of used products to manufacturers. Although the amount of recycling by third-party recyclers is reduced,

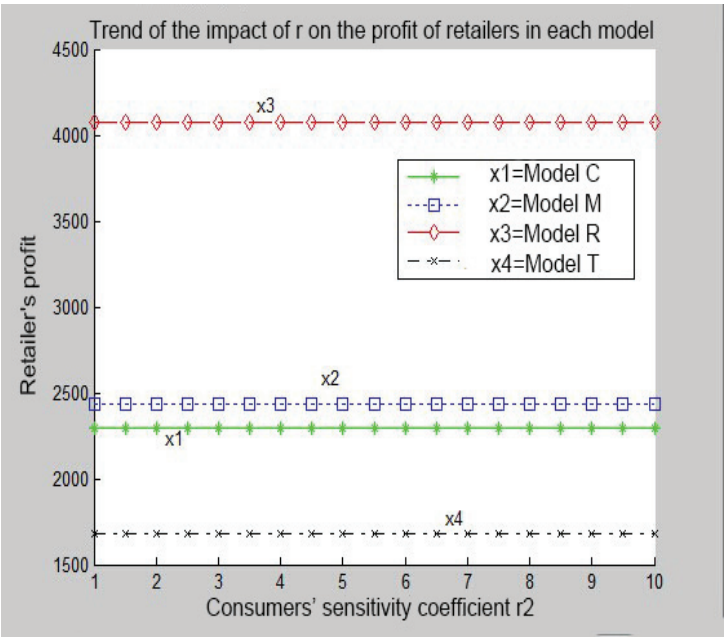

Figure 4 Trend of the impact of r_2 on the profit of retailers in each model

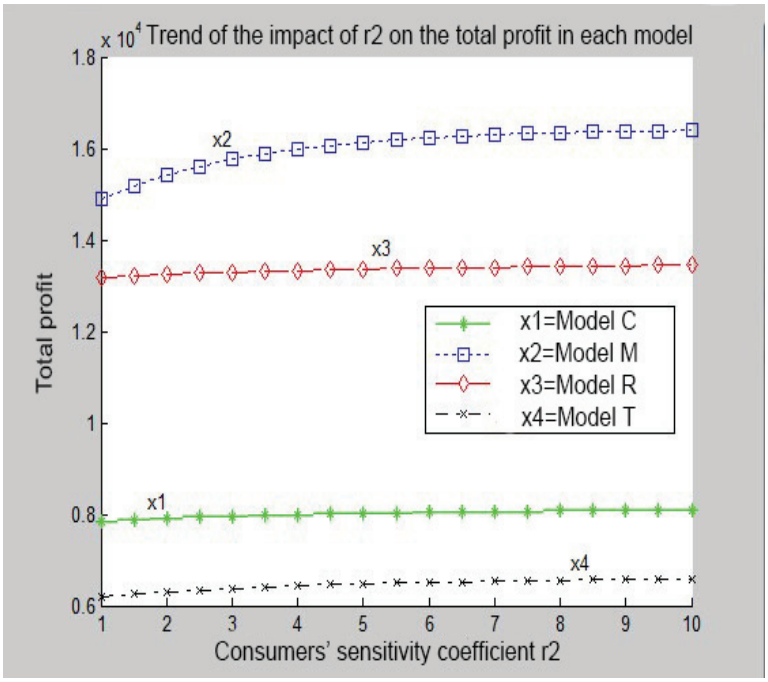

Figure 5 Trend of the impact of r_2 on the total profit in each model

the change is much smaller than the change in profit per unit of product, and the profit of third-party recyclers is still growing. In Model M, although the three prices of the mixed competition recovery channels are reduced respectively, the recycling price of the manufacturer to the consumer is far greater than the recycling price of the third-party recycler to the consumer. The recycling amount of the third-party recycler is rapidly reduced with the increase of r_0, which has a huge impact on the profit of the third-party recycler, and the profit value will be close to zero.

(4) The total profit of the four models is increased with the increase of consumers' environmental awareness, while the growth of Model M 's total profit is significant. The total profit in the other three models increases very little, suggesting that the consumer's environmental awareness still has the greatest impact on Model M.

3.3 The Impact of Government Subsidy Quota δl on Each Model

The government subsidy quota δl is taken as the research variable, and the variation of member's profit and total profit of each supply chain under the four models is compared (as shown in Figure 10–13).

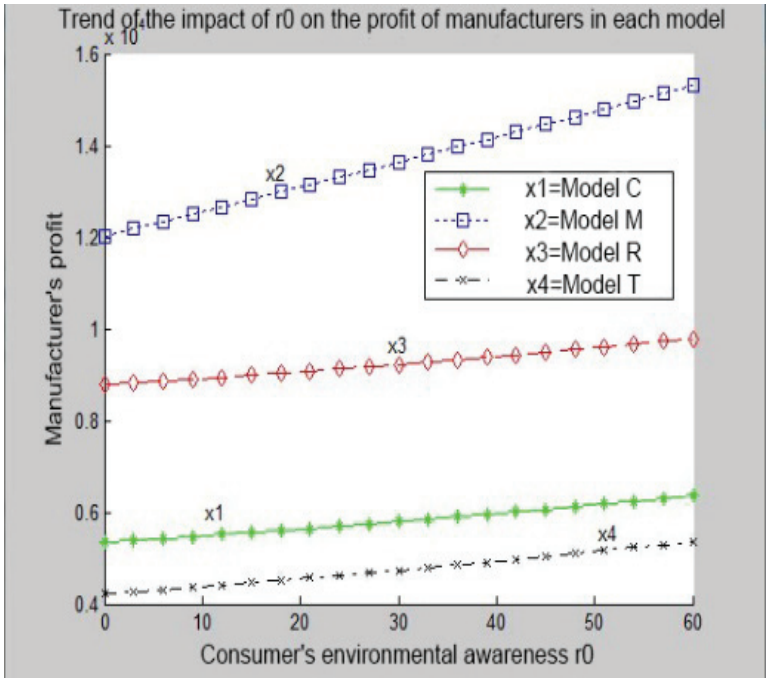

Figure 6 Trend of the impact of r_0 on the profit of manufacturers in each model

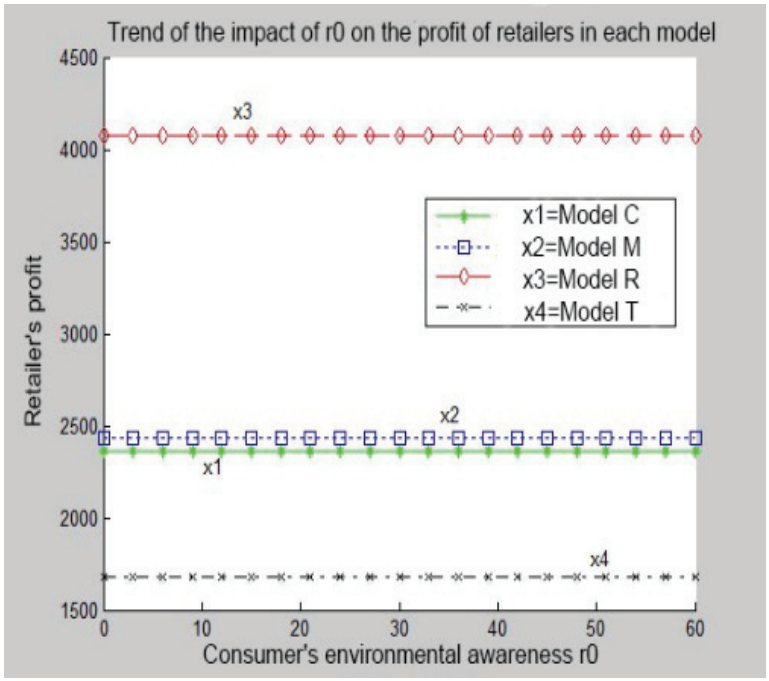

Figure 7 Trend of the impact of r_0 on the profit of retailers in each model

(1) In Model M, the increase in the amount of government subsidies has led to a decline in the market sales price and wholesale price of products, encouraging a large number of consumers to purchase, and the profits of manufacturers are greatly increased through the "small profits but quick turnover" model and government subsidies. In Model R, the increase in the subsidy amount has caused the wholesale price to increase too rapidly, and the profit of the manufacturer has only gradually increased.

(2) From the data in Figure 5.10 and the Appendix, in Model R, the market sales price and the wholesale price increase with the increase of the government subsidy amount. Even with a small decline in market demand, retailers' profits continue to rise rapidly as government subsidies and unit products continue to benefit.

In the T model, the product market selling price, wholesale price and market demand are hardly changed with the change of the subsidy amount, so the retailers' profit value does not produce any change in trend.

(3) Changes in government subsidies do not affect the profit of third-party recyclers in Model C and Model R. When the government directly subsidizes the manufacturer, it drives

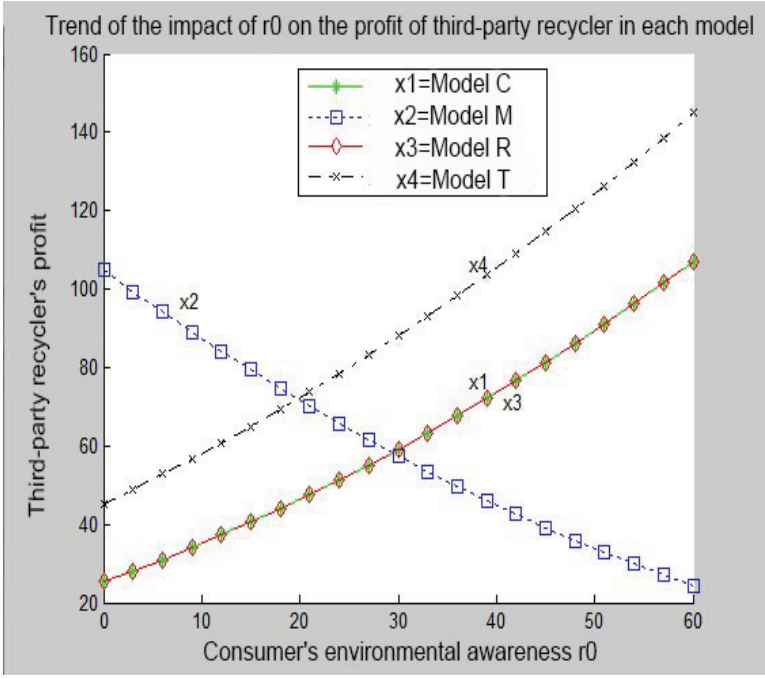

Figure 8 Trend of the impact of r_0 on the profit of third-party recycler in each model

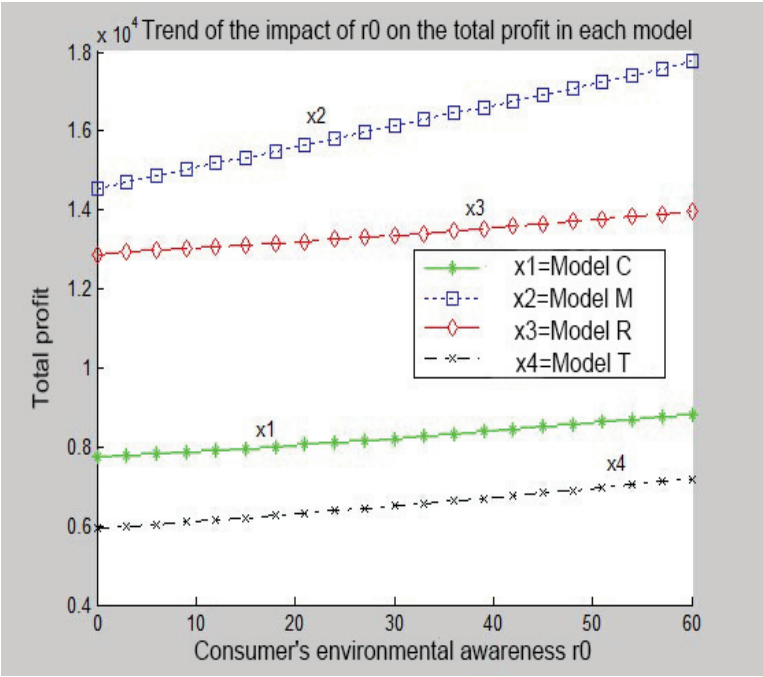

Figure 9 Trend of the impact of r_0 on the total profit in each model

the recycling price in the mixed competition recycling channel, which increases the recycling amount of the third-party recycler, and the profit of the third-party recycler increases significantly. When the government directly subsidizes the third-party manufacturers, the recovery price of manufacturers to consumers rises, while the price of products repurchased by manufacturers to the third-party recyclers gradually decreases. Even if the government subsidies are added, the profits of the third-party recyclers are still on a downward trend.

(4) The total profit of the four models increased with the increase of the subsidy amount. Among them, the growth of the total profit of Model M is significant, Model R is second, and the government subsidy quota is almost unchanged for Model T.

4. CONCLUSION

This paper uses game theory to construct a pricing model for the closed-loop supply chain under the dual-recovery channel structure for various subsidy items. Based on numerical examples, the influence of five influencing factors on the profit of supply chain members is discussed. The following conclusions are drawn:

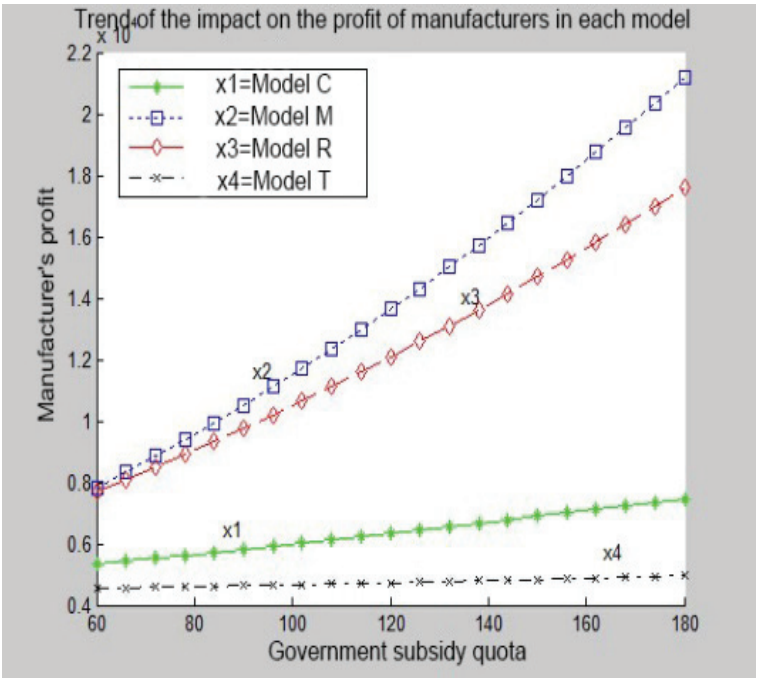

Figure 10 Trend of the impact of δl on the profit of manufacturers in each model

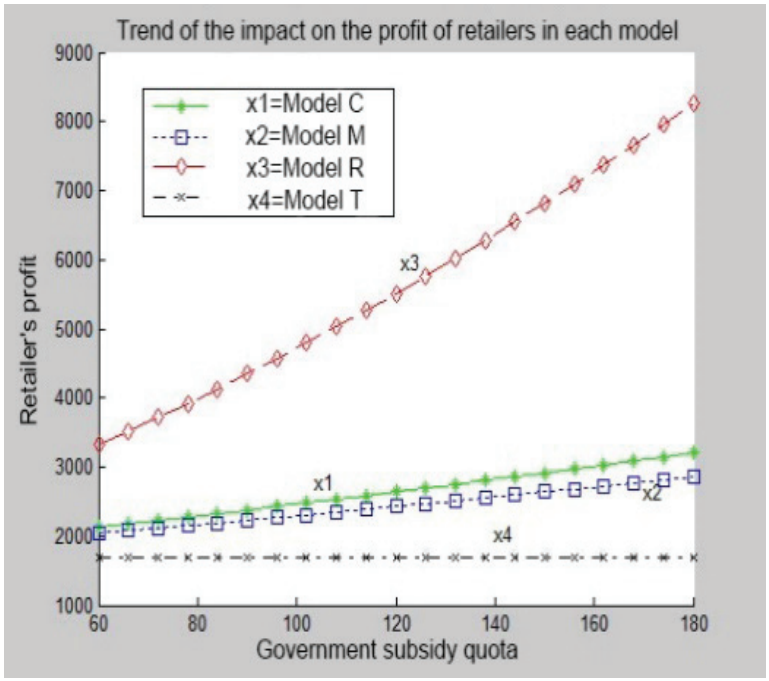

Figure 11 Trend of the impact of δl on the profit of retailers in each model

(1) The greater the value of the consumer's sensitivity coefficient (r_2) for recycling competition channels, the more will consumers pay attention to the recycling price in the recycling channel. In order to encourage more consumers to sell used products, third-party recyclers in each model have to increase the recycling price. Because of their ongoing operating costs, the profits of third-party recyclers are steadily decreasing. Therefore, in the case of a certain value of the sensitivity coefficient (r_2) of consumers to the recycling competition channel, the government should control the price range recovered in the mixed competition recycling channel at the initial stage of recycling, so as to avoid third-party recyclers having no profit;

(2) When the consumer's environmental awareness (r_0) increases, the prices P_r^M, P_r^T, P_T^M in the mixed competition recycling channel will decline, and the decline of P_r^M and P_r^T will directly affect the profit of third-party recyclers. In Model C, Model R and Model T, $P_r^M \ll P_r^T$, third-party recyclers have increased the amount of recycling, and their profit value has increased; and in Model M, $P_r^M \gg P_r^T$, the amount of recycling by third-party recyclers has dropped significantly, so profits have gradually diminished.

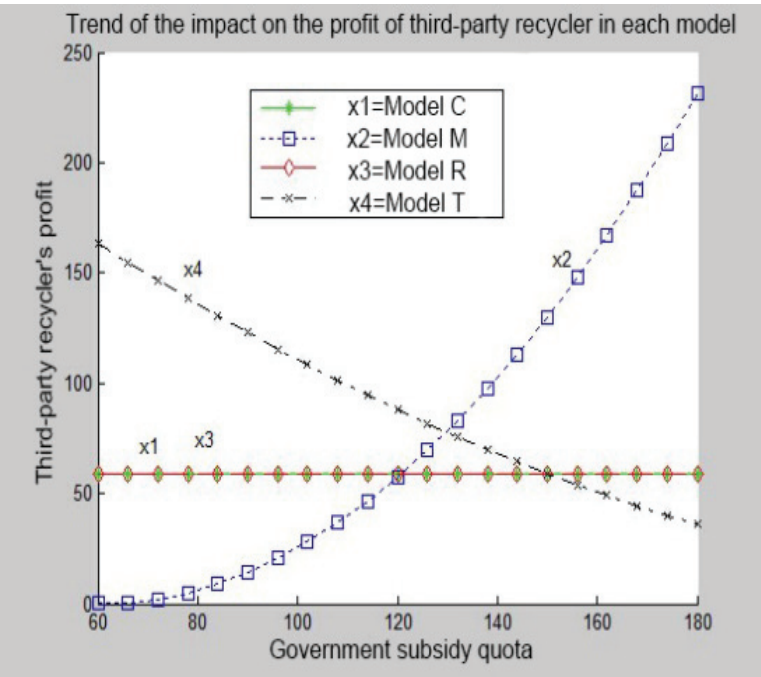

Figure 12 Trend of the impact of δl on the profit of third-party recycler in each model

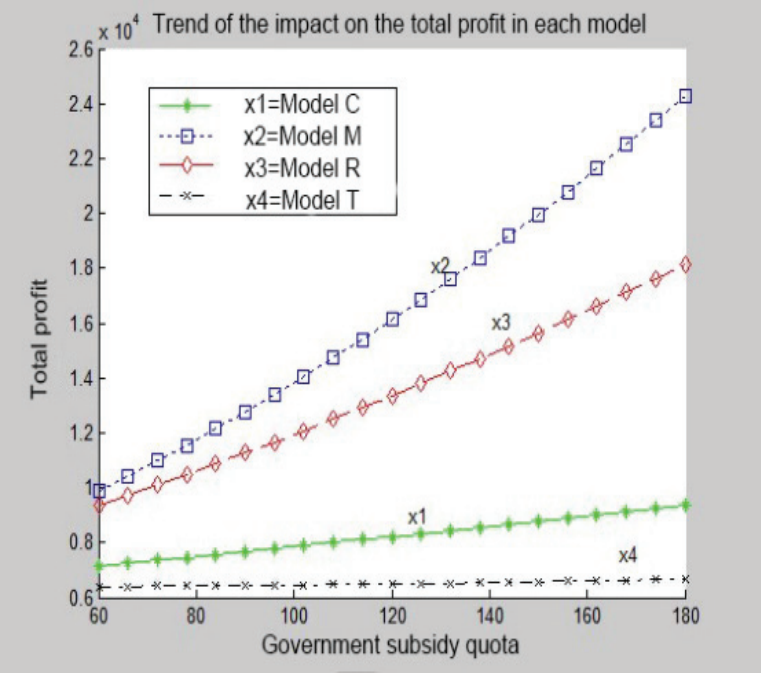

Figure 13 Trend of the impact of δl on the total profit in each model

Therefore, when taking consumers, retailers and third-party recyclers as subsidy objects, the government should vigorously publicize the importance of environmental protection, encourage consumers to actively respond to the call of "old-for-new", and contribute more to the improvement of the number of used household appliances, so as to increase the benefits of third-party recyclers.

(3) The government's change in the subsidy quota (δl) of the supply chain members will affect the market selling price of the product (P_C^R) and the wholesale price of the product to the retailer (P_R^M). The profitability of the firms in a supply chain depends largely on the attitude of the government. Especially in the early implementation stage of the home appliance trade-in policy, the government subsidies offered to a certain enterprise can protect it from losses. When the company is in poor financial condition, the government subsidies can reverse its losses.

ACKNOWLEDGEMENTS

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REFERENCES

1. Zhao Jinghua, Lin Jie. The closed-loop supply chain pricing model under different subsidy objects, Journal of Industrial Engineering and Engineering Management, 2017.1 v31(1): 85–92.
2. Zhu Xiaotong, Zhang Qian. Efficiency analysis of remanufacturing closed-loop supply chain considering government subsidies [J]. Logistics Technology, 2010(2).
3. Ge Jingyan, Huang Peiqing, Li Juan. Social Environmental Awareness and Closed-loop Supply Chain Pricing Strategy—— Based on Vertical Difference Model[J]. Industrial Engineering and Management, 2007, (04): 6–10+24.
4. Shi Wei, Zhang Xuemei. Supply Chain Decision and Coordination Considering Consumers' Environmental Awareness[J]. Journal of Fuyang Teachers College, 2017, 34(01): 85–90.
5. Conrad K. Price Competition and Product Differentiation When Consumers Care for the Environment [J]. Environmental and Resource Economics, 2005, 3: 11–19.
6. Xiong Zhongyu, Liang Xiaoping. Research on closed-loop supply chain recovery model considering consumer environmental awareness[J]. Soft Science, 2014, 28(11): 61–66.
7. Zugang (Leo) Liu, Trisha D. Anderson, Jose M. Cruz. Consumer environmental awareness and competition in two-stage supply chains [J]. European Journal of Operational Research. 2012, 218: 602–613.
8. Xu Qingchun, Chen Yihua. Research on Closed-loop Logistics Network Optimization Based on Consumer Environmental Awareness[J]. Journal of Logistics Technology, 2011, 30(13): 126–128.
9. Fang Qiaohong. Research on the Influence of Public Environmental Awareness on Remanufacturing Decisions[J]. Industrial Engineering, 2010, 13(01): 47–51.
10. Zhou Lu. Research on National Subsidy Methods and Subsidy Targets for Home Appliances to the Countryside [D]. Sichuan: University of Electronic Science and Technology, 2010
11. Yi Yuzhen, Yuan Jiang. Coordinated Pricing Model of Closed-Loop Supply Chain under Channel Conflict Environment[J]. Journal of Management Sciences, 2012, 15(1)