ICIC Express Letters
Part B: Applications
Volume **13**, Number **10**, October **2022**

ICIC International ©2022 ISSN 2185-2766
pp. 1077–1084

RESEARCH ON PRICING DECISION OF THIRD-PARTY RECYCLING CLOSED-LOOP SUPPLY CHAIN BASED ON RECYCLING QUALITY AND CSR

Wensheng Yang and Anxin Hu

School of Economics and Management
Dalian University
No. 10, Xuefu Street, Jinzhou New District, Dalian 116622, P. R. China
yangwensheng@dlu.edu.cn; 839354906@qq.com

Received February 2022; accepted April 2022

Abstract. *Based on the difference of recycling quality and retailers' CSR input, a closed-loop supply chain model of recycling by a third party was built. Stackelberg game theory and numerical simulation were used to analyze the influence of recycling quality level and retailers' CSR input on the optimal pricing decision of each participant under the mode of third-party recycling. The results show that CSR input by retailers can improve product pricing and increase the profits of retailers, manufacturers and the whole supply chain. As the quality threshold of remanufacturing input increases, the price of recycling decreases and the difficulty of recycling increases. It can be considered to lower the quality threshold of remanufacturing and increase the investment level in CSR, so as to enhance economic and environmental benefits.*

Keywords: Recycling quality, Closed-loop supply chain, Corporate social responsibility, Stackelberg game

1. **Introduction.** Nowadays, economic, green and low-carbon development has become the consensus of global development. The circular economy development plan for the 14th five year plan shows that vigorously developing circular economy and building a resource recycling industrial system and waste material recycling system are of great significance to promote the sustainable development of enterprises. As of August 31, 2021, ninety-two central enterprises have released the 2020 social responsibility report, accounting for 96% of the central enterprises qualified for release, which shows that more and more enterprises pay attention to the performance of corporate social responsibility.

Servaes and Tamayo found that enterprises undertaking CSR can improve their comprehensive benefits and help to establish corporate image and improve their reputation [1]. Panda et al. found that CSR can expand the market demand for new products and improve the recovery rate of used products [2]. In addition, Yao et al. studied the influence of leading manufacturers' undertaking of CSR on pricing of new products and recycling of waste products under three different recycling channels [3]. Liu et al. studied the optimal CSR allocation mechanism and pricing strategy of each member enterprise in a closed-loop supply chain with social responsibility under different power structures [4]. Dey and Giri found that remanufacturing is beneficial to the economic benefits and environmental sustainability of the supply chain when considering the influencing factors of social responsibility in the closed-loop supply chain model of duopoly retailers [5]. However, these are all studies in a certain environment.

Due to the different service life and wear degree of products, the recovery quality is uncertain. Zou and Ye studied the pricing and coordination when the proportion of reusable

DOI: 10.24507/icicelb.13.10.1077

parts and the quality of recycled products at the design stage resulted in random remanufacturing costs [6]. Huang et al. analyzed the dynamic pricing and recycling strategy of remanufacturers when the quality of waste products is uncertain through modal interval algorithm [7]. Jia found that the double participation of government subsidy and carbon tax guided the remanufacturing closed-loop supply chain more effectively when considering the uncertainty of recycling quality [8].

As for the selection of recycling mode, manufacturers will invest a large number of people and money into the research and development of new products, while retailers are responsible for product sales and publicity, so they usually entrust a third party to recycle waste products. Yao and Teng considered fairness concerns for third-party recycling [9]. Lu et al. considered the influence of third-party economies of scale on supply chain channel decision-making [10]. Tian and Li studied the influence of third-party recycling enterprises on the profits of the closed-loop supply chain [11].

To sum up, the proposed study differs from the prior works in the following aspects. Firstly, the Stackelberg game model comprehensively considers the uncertainty of recovery quality and the input of corporate social responsibility. Secondly, for the recycling quality of waste products, the impact of the quality threshold of remanufacturing on the closed-loop supply chain is considered, which has a certain reference significance for the formulation of policies. Finally, the CSR investment of enterprises is studied from the two aspects of consumer sensitivity and investment scale cost. Compared with the previous closed-loop supply chain considering corporate social responsibility, the research of this paper is more practical, and provides a certain theoretical reference for the research of corporate social responsibility behavior in closed-loop supply chain.

The outline of the study is as follows. Section 2 provides notations and assumptions. Section 3 establishes the centralized and decentralized CLSC models and finds the optimal solution. Section 4 compares the optimal solutions among different decision modes, combined with a realistic discussion. Section 5 provides a numerical simulation examining the impact of recovery quality and CSR investment. Finally, conclusions are outlined in Section 6.

2. **Symbol Definition and Hypotheses.** In the present study, we consider a CLSC is composed of manufacturers, retailers and third-party recyclers, as shown in Figure 1.

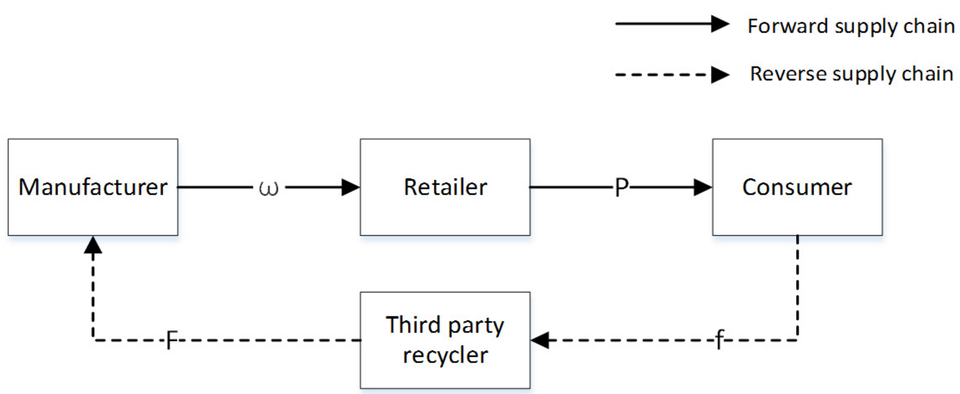


FIGURE 1. Recycling by third party recyclers

For the convenience of modeling, symbols are introduced here, and the relevant definitions can be seen in Table 1.

The following assumptions are made for building up the proposed models.

Hypothesis 1: The market information of the members of the closed-loop supply chain is completely symmetrical and all have risk-neutral preference.

Table 1. Symbol and definitions

Symbols	Definitions
c_n	Unit production cost of new products
c_r	Unit production cost of remanufactured products
ϖ	The wholesale price of products
p	The unit retail price of products
d	CSR investment of the retailer
q	The quality of recycled waste products, $q \in (0,1)$ is uniformly distributed and $f(q)$ is the mass density function
Q	The quantity of recycled waste products
Q_0	The quantity of recyclables available in manufacturing
F	The transfer price recovered by the manufacturer from a third party, $F = \delta q$, δ is the quality value coefficient, $\delta > 0$
f	The recycling price of waste products recycled by recyclers from consumers, $f = (1-r)F$, where $r \in (0,1)$ is the unit profit margin of products recycled by recyclers.
C	The fixed cost of waste that does not meet the minimum quality level of remanufacturing
D	The market demand for the new product, $D = \alpha - \beta p + \theta d$. α is the market capacity of the product, β is the sensitivity of the consumer to the selling price, θ is the sensitivity of the consumer to the level of CSR investment, $\theta > \beta > 0$, $\alpha > \beta p$
Π_i	The profit of member i in the centralized and decentralized decision model, $i = m, r, t$

Hypothesis 2: In order to be profitable, remanufacturing enterprises have $c_n > c_r(q) > 0$. With the improvement of the quality of recycled products, the unit cost of producing remanufactured products is lower. So $c_r(q) = c_n - c_s q$, c_s represents the maximum cost that remanufacturing can save.

Hypothesis 3: The quantity of recycled waste products is $Q(q) = h + kf$, where $h > 0$ represents the basic recyclable quantity in the market and $k > 0$ represents the sensitivity coefficient of the quantity of recycled products with respect to the recycling price [6]. Then the quantity that can be used for remanufacturing is $Q_0 = \int_{q_0}^{1} f(q)dqQ$.

Hypothesis 4: According to [12], it is assumed that the CSR investment behavior of retailers is to donate part of the profits from selling products to social welfare organizations.

Hypothesis 5: The cost of recovery quality efforts is $I(q) = \lambda q^2$, where $\lambda > 0$ is the effort cost parameter. The cost of CSR investment is $h(d) = gd^2$, where $g > 0$ is the scale parameter of CSR investment by retailers.

3. Model Formulation and Analysis.

3.1. **Centralized pricing decision model.** In the centralized case, there is only one centralized decision maker in the supply chain, who decides the recycling price of recycled products, the retail price of products and the investment level of retailers in CSR. Then the profit function of closed-loop supply chain under centralized decision-making is

$$\Pi^C = (p - c_n)D + (c_n - c_r)Q_0 - fQ - C - gd^2 - \lambda q^2 \tag{1}$$

Therefore, the inverse induction is used to solve the function, obtaining the decision variables and profit balance solutions (See Table 2).

TABLE 2. Optimal decision of each participating system in closed-loop supply chain

	Centralized decision-making (*)	**Decentralized decision-making (**)**
p	$\frac{2g(\alpha+\beta c_n)-\theta^2 c_n}{4\beta g-\theta^2}$	$\frac{2\beta g(3\alpha+\beta c_n)-\theta^2(\alpha+\beta c_n)}{2\beta(4\beta g-\theta^2)}$
ω	–	$\frac{\alpha+\beta c_n}{2\beta}$
f	$\frac{c_s\left(1-q_0^2\right)}{4}-\frac{h}{2k}$	$\frac{kc_s\left(1-q_0^2\right)-4h}{4k}$
F	–	$\frac{kc_s\left(1-q_0^2\right)-2h}{2k}$
d	$\frac{\theta(\alpha-\beta c_n)}{4\beta g-\theta^2}$	$\frac{\theta(\alpha-\beta c_n)}{2(4\beta g-\theta^2)}$
D_n	$\frac{2\beta g(\alpha-\beta c_n)}{4\beta g-\theta^2}-\frac{(1-q_0)\left(kc_s\left(1-q_0^2\right)+2h\right)}{4}$	$\frac{\beta g(\alpha-\beta c_n)}{4\beta g-\theta^2}-\frac{kc_s\left(1-q_0^2\right)(1-q_0)}{4}$
D_r	$\frac{(1-q_0)\left(kc_s\left(1-q_0^2\right)+2h\right)}{4}$	$\frac{kc_s\left(1-q_0^2\right)(1-q_0)}{4}$
Π_m	–	$\frac{g(\alpha-\beta c_n)^2}{2(4\beta g-\theta^2)}+\frac{hc_s\left(1-q_0^2\right)}{4}-C$
Π_r	–	$\frac{g(\alpha-\beta c_n)^2}{4(4\beta g-\theta^2)}$
Π_t	–	$\frac{kc_s^2\left(1-q_0^2\right)^2}{16}-\frac{\lambda(1+q_0)^2}{4}$
Π^C	$\frac{g(\alpha-\beta c_n)^2}{4\beta g-\theta^2}+\frac{\left[kc_s\left(1-q_0^2\right)+2h\right]^2}{4k}-\frac{\lambda(1+q_0)^2}{4}-C$	$\frac{3g(\alpha-\beta c_n)^2}{4(4\beta g-\theta^2)}+\frac{c_s\left(1-q_0^2\right)\left(kc_s\left(1-q_0^2\right)+4h\right)}{4k}-\frac{\lambda(1+q_0)^2}{4}-C$

3.2. **Decentralized pricing decision model.** Under the decentralized decision-making mode, the profits of all participants in the closed-loop supply chain are

$$\Pi_m = (\omega - c_n)(D - Q_0) + (\omega - c_r)Q_0 - FQ - C \tag{2}$$

$$\Pi_r = (p - \omega)D - gd^2 \tag{3}$$

$$\Pi_t = (F - f)Q - \lambda q^2 \tag{4}$$

The resulting equilibrium solution and optimal profit are shown in Table 2.

4. **Model Analysis.** By analyzing and comparing the optimal results of decentralized decision-making and centralized decision-making, the following conclusions can be obtained.

Conclusion 1: The retail price of retailers is independent of the remanufacturing quality threshold, but is directly proportional to the consumer's input sensitivity coefficient to CSR; The recycling price is independent of the manufacturing threshold, but inversely proportional to the remanufacturing threshold.

Proof:

$$\frac{\partial p^{**}}{\partial \theta} = \frac{2g\theta\left(\alpha-\beta c_n\right)}{\left(4\beta g-\theta^2\right)^2} > 0, \quad \frac{\partial f^*}{\partial q_0} = -\frac{c_s q_0}{2} < 0, \quad \frac{\partial F^*}{\partial q_0} = -c_s q_0 < 0$$

Conclusion 1 shows that the increase of consumers' sensitivity to corporate social responsibility will improve consumers' willingness to pay, so enterprises will increase prices to make up for CSR input costs; The increase of remanufacturing threshold means the reduction of remanufacturing output. In order to reduce losses, manufacturers will reduce the repurchase price of remanufactured products, and then reduce the recovery price.

Conclusion 2: The demand for new products is directly proportional to consumers' sensitivity to CSR investment and remanufacturing quality threshold. The demand for recycled products is independent of consumers' sensitivity to CSR investment, but inversely proportional to the quality threshold of recycled products.

Proof:

$$\frac{\partial D_n^{**}}{\partial\theta}=\frac{\beta g(\alpha-\beta c_n)}{(4\beta g-\theta)^2}>0,\quad \frac{\partial D_n^{**}}{\partial q_0}=\frac{kc_s\left[2q_0(1-q_0)+(1-q_0^2)\right]}{4}>0,$$

$$\frac{\partial D_r^{**}}{\partial q_0}=-\frac{kc_s\left[2q_0(1-q_0)+(1-q_0^2)\right]}{4}<0$$

Conclusion 2 shows that due to the improvement of consumers' sensitivity to CSR and consumers' willingness to buy, the demand for new products will increase; The improvement of remanufacturing quality threshold of reconstituted products will reduce the recycled products, so as to reduce the output of reconstituted products, and then lead to the reduction of demand for reconstituted products and the increase of demand for new products.

Conclusion 3: The manufacturer's income is directly proportional to the consumer's sensitivity to CSR, inversely proportional to the remanufacturing quality threshold, the retailer's income is directly proportional to the consumer's sensitivity to CSR, and the third-party recycling party's income is inversely proportional to the remanufacturing quality threshold.

Proof:

$$\frac{\partial\Pi_m^*}{\partial\theta}=\frac{4\theta g(\alpha-\beta c_n)^2}{4(4\beta g-\theta^2)^2}>0,\quad \frac{\partial\Pi_m^*}{\partial q_0}=-\frac{hc_sq_0}{2}<0,\quad \frac{\partial\Pi_r^*}{\partial\theta}=\frac{8\theta g(\alpha-\beta c_n)^2}{16(4\beta g-\theta^2)^2}>0,$$

$$\frac{\partial\Pi_t^*}{\partial q_0}=-\frac{kc_s^2q_0(1-q_0)+2\lambda(1+q_0)}{4}<0$$

Conclusion 3 shows that the increase of consumers' sensitivity to CSR will improve consumers' purchasing power, and then improve the profits of manufacturers and retailers; The increase of remanufacturing threshold makes consumers lose their recycling enthusiasm in the face of low return price, and the quality loss of products in recycling is serious, which leads to the increase of the total cost of dealing with these waste products that cannot be remanufactured, and finally leads to the reduction of the income of third parties and manufacturers.

Conclusion 4: The sales price of new products and products under manufacturing in centralized decision-making is lower than that in decentralized decision-making; The recycling price of waste products, the demand for new products and remanufactured products and the total profit in centralized decision-making are higher than those in decentralized decision-making.

Proof:

$$\begin{aligned}p^*-p^{**}&=\frac{2g(\beta c_n+\alpha)-\theta^2c_n}{4\beta g-\theta^2}-\frac{2\beta g(3\alpha+\beta c_n)-\theta^2(\alpha+\beta c_n)}{2\beta(4\beta g-\theta^2)}\\&=\frac{\alpha(\theta^2-4\beta g)-\theta^2\beta c_n}{2\beta(4\beta g-\theta^2)}<0\end{aligned}$$

$$f^*-f^{**}=\frac{c_s(1-q_0^2)}{4}-\frac{h}{2k}-\frac{kc_s(1-q_0^2)-4h}{4k}=\frac{h}{2k}>0$$

$$D_r^*-D_r^{**}=\frac{(1-q_0)(kc_s(1-q_0^2)+2h)}{4}-\frac{kc_s(1-q_0^2)(1-q_0)}{4}=\frac{(1-q_0)h}{2}>0$$

$$D_n^*-D_n^{**}=\frac{2\beta g(\alpha-\beta c_n)}{4\beta g-\theta^2}-\frac{(1-q_0)(kc_s(1-q_0^2)+2h)}{4}-\frac{\beta g(\alpha-\beta c_n)}{4\beta g-\theta^2}$$

$$+\frac{kc_s\left(1-q_0^2\right)\left(1-q_0\right)}{4}=\frac{\beta g\left(\alpha-\beta c_n\right)}{4\beta g-\theta^2}-\frac{h\left(1-q_0\right)}{2}>0$$

$$\Pi^{C*}-\Pi^{**}=\frac{\left(\alpha-\beta c_n\right)^2}{4\left(4\beta g-\theta^2\right)}+\frac{kc_s\left(1-q_0^2\right)\left(3kc_s\left(1-q_0^2\right)+12h\right)+16h^2}{16}>0$$

Conclusion 4 shows that centralized decision-making is more efficient than decentralized decision-making.

5. **Numerical Studies.** To verify the correctness of the above models and conclusions, a numerical example is used to simulate these conclusions, and further analysis is carried out. The parameters should be set to meet the assumptions, and the parameters should be assigned according to the relevant literature: $\alpha = 100$, $\beta = 1$, $\theta = 4$, $h = 4$, $k = 2.5$, $c_s = 40$, $c_n = 60$, $g = 100$, $C = 20$, $\lambda = 10$. The minimum threshold value of remanufacturing quality meets the requirement that the recycling and repurchase price of waste products, the demand for new products and remanufactured products, and the overall profit of the supply chain are positive, then assuming that the quality threshold for remanufacturing is $q_0 \in (0, 0.7)$. The numerical simulation is as follows.

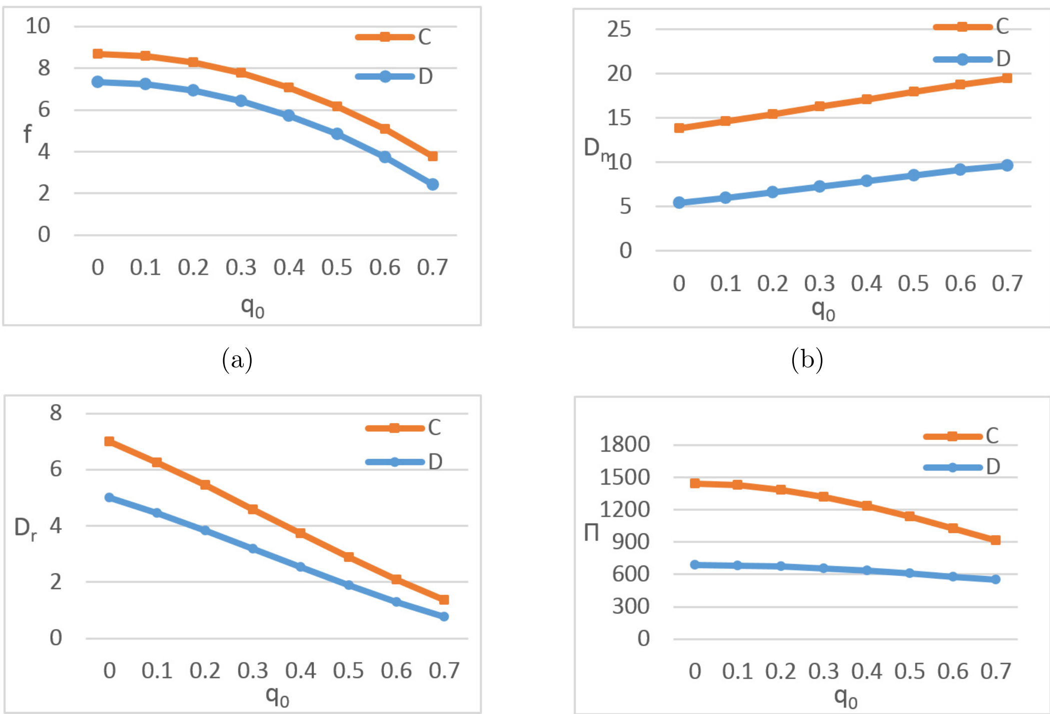
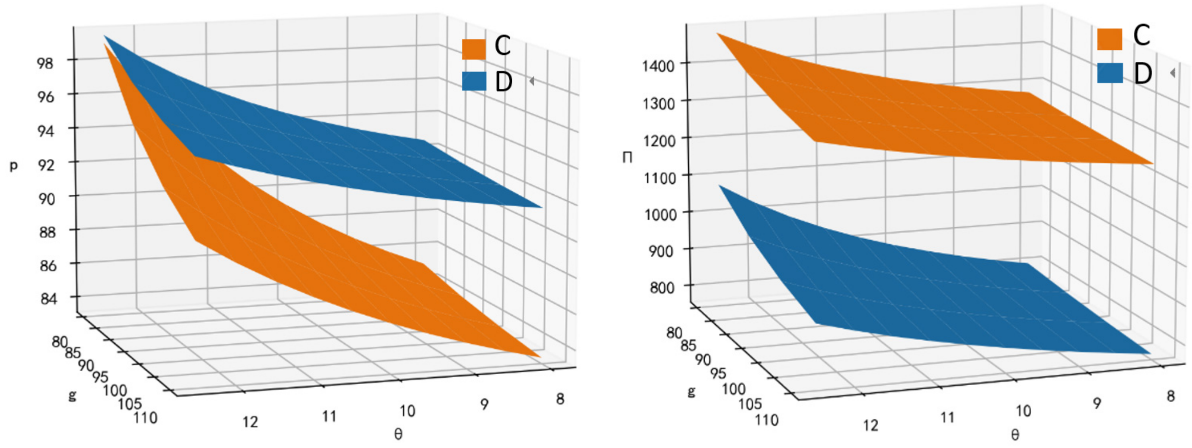


FIGURE 2. Remanufacturing quality threshold q_0 impact

Through the simulation results in Figure 2, it can be seen that when the remanufacturing quality threshold is increased, the recycling price of waste products will be reduced, and the overall profit of the closed-loop supply chain will also be reduced. At the same time, the demand for new products increases and the demand for remanufactured products decreases, which reduces the recycling of waste products, which is not conducive to the recycling of waste products in the whole closed loop.

The influence of consumers' sensitivity to CSR and the scale of CSR investment cost is shown in Figure 3.

From the simulation results in Figure 3, it can be seen that the product price and profit of closed-loop supply chain increase with the increase of consumers' sensitivity to corporate social responsibility investment, and decrease with the increase of CSR input



(a) (b)

Figure 3. Retailer CSR impact

cost coefficient. In fact, in order to meet the needs of consumers, the decision-makers of closed-loop supply chain will improve the level of corporate social responsibility investment, resulting in the increase of corporate social responsibility investment cost. However, since consumers are more willing to pay for enterprises that actively undertake corporate social responsibility, the price increase strategy will not reduce consumers' demand for products, but will obtain more profits, and finally increase the profits of members of the closed-loop supply chain and the whole system, so as to promote the stable operation of the closed-loop supply chain.

6. **Conclusion.** This paper considers the uncertainty of recycled product quality and retailer CSR input, and the Stackelberg model of closed-loop supply chain members was established under centralized and decentralized decision-making. Through analysis, we can get the following conclusions to provide decision-making reference for the government and enterprises.

First, enterprises should improve the sensitivity of consumers to the level of corporate social responsibility investment, pay attention to the innovation ability of member enterprises, and improve the efficiency of corporate social responsibility investment. Second, enterprises should reduce the cost of corporate social responsibility investment, increase the investment in manufacturing technology. Third, the government should reduce the quality threshold for recycled products to enter remanufacturing, and increase the social support for recycled products.

Compared with the previous closed-loop supply chain that considered CSR, this study considers the uncertain quality of recycled products, and provides a theoretical basis for the closed-loop supply chain to study CSR behavior. In the research process, it is found that compared with decentralized decision-making, centralized decision-making is still the optimal state, so future research can consider the study of the contract coordination in the supply chain, and can also be analyzed from different recycling channels.

REFERENCES

[1] H. Servaes and A. Tamayo, The impact of corporate social responsibility on firm value: The role of customer awareness, *Management Science*, vol.59, no.5, pp.1045-1061, 2013.

[2] S. Panda, N. M. Modak and L. E. Cárdenas-Barrón, Coordinating a socially responsible closed-loop supply chain with product recycling, *International Journal of Production Economics*, vol.188, pp.11-21, 2017.

[3] F. Yao, S. Liu, D. Chen and C. Teng, Closed-loop supply chain recycling and pricing decisions with corporate social responsibility, *Control and Decision Making*, vol.34, no.9, pp.1981-1990, 2019.

[4] S. Liu, F. Yao, D. Chen and C. Teng, CSR allocation mechanism and pricing strategy under different power structures in closed-loop supply chain, *Control and Decision*, vol.35, no.6, pp.1525-1536, 2020.

[5] S. K. Dey and B. C. Giri, Analyzing a closed-loop sustainable supply chain with duopolistic retailers under different game structures, *CIRP Journal of Manufacturing Science and Technology*, vol.33, pp.222-233, 2021.

[6] Q. Zou and G. Ye, Pricing-decision and coordination contract considering product design and quality of recovery product in a closed-loop supply chain, *Mathematical Problems in Engineering*, vol.2015, pp.1-14, 2015.

[7] M. Huang, P. Yi, T. Shi et al., A modal interval based method for dynamic decision model considering uncertain quality of used products in remanufacturing, *Journal of Intelligent Manufacturing*, vol.29, no.4, pp.925-935, 2018.

[8] X. Jia, Research on pricing strategy of remanufacturing closed-loop supply chain based on recycling quality uncertainty and government participation, *Application Research of Computers*, vol.37, no.9, pp.2718-2725, 2020.

[9] F. Yao and C. Teng, Decision model of third-party recycling closed-loop supply chain under equity concern, *Chinese Management Science*, vol.24, pp.577-583, 2016.

[10] Y. Lu, X. Xu and X. Ai, Third party closed-loop supply chain under the scale effect of the double channel recycling decision-making research, *Journal of Management Engineering*, vol.32, no.2, pp.207-217, 2018.

[11] L. Tian and W. Li, Research on recycling and pricing strategy of third-party recycling enterprises in closed-loop supply chain, *Systems Science and Mathematics*, vol.40, no.11, pp.2082-2092, 2020.

[12] N. M. Modak, N. Kazemi and L. E. Cárdenas-Barrónc, Investigating structure of a two-echelon closed-loop supply chain using social work donation as a corporate social responsibility practice, *International Journal of Production Economics*, vol.207, pp.19-33, 2019.