Production and Pricing Strategy of Closed-loop Supply Chain Based on Customer Preference

Cheng-Tang Zhang [1*], Zong-Hong Cao [1], Jie Min [2], Miao-Miao Wang[3]

***Abstract*—In the closed-loop supply chain systems of recycling and remanufacturing, which are comprised of manufacturers, retailers, and the third-party recyclers, there are niche markets for the co-existence and mutual substitution of new and remanufactured products. The new product production mode, remanufacturing mode, and hybrid manufacturing mode without cooperation have been separately studied to obtain the equilibrium results under different production modes. The theoretical analysis shows that when customers have different preference coefficients for remanufactured products, different production costs will influence the manufacturer's choice of production mode and product pricing. The analysis also shows that the market demands for remanufactured and new products under the hybrid production mode have a "cannibalization effect" and the remanufactured products with cooperation will be completely bumped out of the market. Finally, an analysis of examples is carried out to further verify the related conclusions.**

***Index Terms*—closed-loop supply chain, game theory, production mode, pricing strategy**

I. INTRODUCTION

A. Motivation

WITH the continuous deepening of economic globalization and rapid development of science and technology, resource and environmental problems have become increasingly serious. Many countries have intensified environmental and resource protection legislation, and many industries have strengthened their efforts on the recycling and remanufacturing of used products. Many enterprises, such as HP, Ford, and Kodak, have found that the recycling of used products can greatly save manufacturing costs and improve the social reputation and economic benefit of the enterprise, creating the closed-loop feedback-enabled cycling supply chain of "resource-production-consumption-renewable resource" (Guide et al. 2003[1]). Due to uncertainties in the return channel and in the quantity and quality of used products in the reverse logistics of the closed-loop supply chain, as well as the increase in information flow, fund flow, and node enterprises, the management of the closed-loop supply chain becomes very complicated. As a result, the management research on the closed-loop supply chain has become one of the hot issues that attracts the attention of the academic community (Mitra and Webster 2008[2], Turan et al. 2011[3]).

This paper will discuss a three-echelon closed-loop supply chain system under different production modes. Based on customers' different preferences of new and remanufactured products and different market-resulted demands for the two kinds of products, we will investigate manufacturers' choice of production mode, retailers and the third-party recyclers' equilibrium options, and their corresponding pricing policies.

B. Literature Review

In recent years, the theory and practice of the closed-loop supply chain have been increasingly emphasized by scholars and market regulators.

Tsai (2011) [4] has specifically mentioned that if electronic waste is not recycled in a timely manner, it will heavily pollute the environment and damage the natural ecology. To increase the recycling of such products, the manufacturing and remanufacturing simulation model with supply chain members, including supplier, manufacturer, logistics center, and customer, has been established. Savaskan et al. (2004)[5] assume that if customers would not differentiate between new and remanufactured products, through a discussion of the closed-loop supply chain efficiency problem in the case of recycling by retailer and recycling by third party, they found that the supply chain efficiency of recycling by retailer is higher than that of recycling by third party . Shi et al.(2011) [6] examined the production quantity, selling price, and used products recycling price of new and the remanufactured products when the new and remanufactured products have the same selling price and the demand is related to the price. Hong et al. (2015) [7] proposed that advertisement plays an important role in consumers' acceptance of remanufactured products. They obtained the optimal option that manufacturers should entrust retailers to recycle products by analyzing the optimal strategy of local advertisement, used products recycling, and pricing through a comparison of the three recycling modes. Wei and Zhao (2011) [8] applied game theory and fuzzy theory to

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study the optimal wholesale price and retail price of the closed-loop supply chain under retailer competition. Jean-Pierre et al. (2012) [9] proposed that, when comparing a new product approaching the end of its shelf-life and a remanufactured product, customers prefer the latter. For the circumstance where manufacturing and remanufacturing efficiency is subject to the influence of machine equipment, they provided the production quantity plan and inventory decision model for the two kinds of products. Shi et al. (2010) [10] studied the manufacturing and remanufacturing supply chain system with limited production and recycling capacity and concluded that the uncertainties of market demands and recycling have an effect on the decision-making of production and recycling. Ferrer (2010) [11] further probed into two-period and multi-period pricing issues for two different products based on the above-mentioned study on the assumption that new products are not different from remanufactured items, and found that remanufacturing cost savings was no longer the only factor that affects multi-period optimal strategy at a limited level of production. Zhang and Ren (2016) [12], through establishing the mathematical model of pricing and patent license fee of recycled patented products, new products, and remanufactured products with patents, studied the pricing and coordination problem of the patented products remanufacturing supply chain consisting of the original manufacturer, remanufacturer, and retailer. Huang and Wang (2017) [13] established three hybrid remanufacturing models: manufacturer recycles and remanufactures by itself; manufacturer remanufactures a portion and entrusts another portion to the dealer for recycling and remanufacturing through patented technology licensing; and manufacturer remanufactures a portion and then authorizes a patent license to the third party for recycling and remanufacturing; based on the game theory, they have analyzed the equilibrium result of enterprises on the chain and the influence of saved cost by remanufacturing. Liu et al. (2017) [14] assumed that original manufacturers recycle used products through dual channels and the retailers sell new and remanufactured products. They also analyzed the pricing of closed-loop supply chain and reverse channel choice under the conditions where the dual-recycling channels and three recycling modes for original manufacturers are in competition. They proposed that dual-recycling channels of the original manufacturer and retailer are the optimal recycling mode. In fact, the actual market demands for these two kinds of products often depend on the utility of products bought by customers, and it also affects the manufacturer's choice of production mode. Additionally, to reduce the reverse logistics cost to achieve the benefit of economies of scale, the supply chain enterprises may entrust the recycling business to the third-party enterprises, which could also greatly reduce the uncertainty of recycling quantity and time. In particular, for electronic wastes, if they fail to be recycled in time, they will heavily pollute the environment and damage the natural ecology. Currently, most of the research on the closed-loop supply chain focus on recycling mode, recycling price, recycling rate and remanufacturing rate, as well as the pricing of new and remanufactured products, resulting in the lack of study on production mode choice by the manufacturer and corresponding pricing.

For the closed-loop supply chain system under new product production mode, remanufacturing production mode and hybrid production mode, the following specific issues will be studied in this paper: (1) the product pricing and sales volume under three production modes; (2) the influencing factors of choice of production mode by manufacturer and critical point of production mode choice; (3) the relationship between product price and sales volume under different production modes; and (4) the market "cannibalization effect" of new and remanufactured products under the hybrid production mode.

II. ASSUMPTIONS AND NOTATIONS

In this study, we consider a single-period closed-loop supply chain, which is comprised of a manufacturer, a third-party recycler, and a retailer. As for the potential demands and profit margin for remanufactured products on the current market, the manufacturers decide differential production. In addition to manufacturing new products, they also remanufacture through the third-party recycler, recycling used products. If it can be assumed that such products are mature on the market, there have been recyclable used products and the recycling quantity is enough to remanufacture product, then the third-party recycler only recycles the used products in quantities necessary for remanufacturing. Here, c_1 and c_2 separately represent the unit costs of producing new and remanufactured products. w_n and w_s separately denote the wholesale prices of new and remanufactured products provided by the manufacturer. p_n and p_s, respectively, refer to the selling prices of new and remanufactured products provided by the retailer. b and θb, respectively, mean the recycling price of waste by the third-party recycler and the manufacturer (see Fig. 1). $\theta\,(\theta > 1)$ refers to the fixed ratio of recycling subsidy paid by the manufacturer to the third-party recycler, $c_1 - c_2 = \Delta$ refers to the saved cost by remanufacturing, and $\Delta > \theta b > b > 0$, so that the manufacturer and the third-party recycler are incentivized in recycling. Additionally, $w_n > w_s > c_1 > c_2$, $p_n > p_s$.

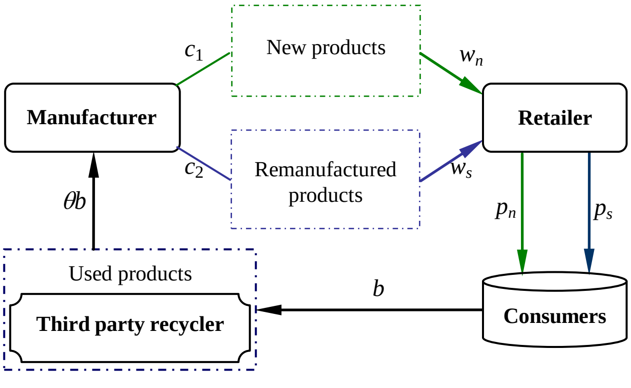

Fig. 1 Framework of three-echelon closed-loop supply chain

Hereinto, w_n and w_s are the decision variables of the manufacturer, p_n and p_s are the decision variables of the retailer, and b is the decision variable of the third-party recycler (the third-party recycler determines the collection price and collects used products directly from the customers). Moreover, the remanufacturing cost, c_2, does not include the cost for buying back used products from the third-party recycler, but includes the costs for quality assurance, components, dismantling, remanufacturing, and other management processes.

The remanufactured products and new products do not have significant differences in function, but only in price and extent of recognition. Such products have an end-consumer group with the largest market volume of 1 on the market. The consumers have a different valuation on the new and remanufactured products. Assuming that the valuation of new products is ξ, and by reference to Geraldo and Jayashankar (2006) [15], it can also be assumed that the valuation ξ by the consumer on new products is subject to the uniform distribution of $[0, A]$ and given $w_n + c_1 \le A$ to ensure that the sales of new products are normally profitable. Let $\lambda\xi$ denote the consumer valuation of remanufactured products, where λ is the preference coefficient of remanufactured products by consumer and $0 < \lambda < 1$. Then the effects of consumer's purchasing of new and remanufactured products are, respectively,

$$U_n = \xi - p_n \;. \tag{1}$$

$$U_s = \lambda\xi - p_s \;. \tag{2}$$

Obviously, only when utility $U_s > U_n$, will the consumer purchase remanufactured products, or choose to purchase new products. After the consumer determines the valuation ξ, the purchase choice of consumer will depend on the pricing p_s and p_n of both products, so as to influence the choice of manufacturers' production mode.

III. Non-cooperative decision-making situation

A. Hybrid production mode (marked as DH mode)

When the prices of new and remanufactured products satisfy $p_s \le \lambda p_n$, there are two possibilities for the utility comparison result of both products: (a) $U_n > U_s$ and (b) $U_n \le U_s$. Then, the manufacturer will choose hybrid production mode of new and remanufactured products.

If $U_n > U_s$, $\xi > \frac{p_n - p_s}{1-\lambda}$ may be determined from $\xi - p_n > \lambda\xi - p_s$. If valuation $\xi \sim U[0, A]$, the portion of consumer's choosing new products is:

$$Q_n = 1 \cdot \int_{\frac{p_n - p_s}{1-\lambda}}^{A} \frac{1}{A} d\xi = 1 - \frac{p_n - p_s}{(1-\lambda)A} \;. \tag{3}$$

If $U_n \le U_s$, those consumers sensitive to price will prefer purchasing remanufactured products. Then the purchase condition should satisfy: $U_n \le U_s$ and $U_s > 0$, that is, $\frac{p_s}{\lambda} < \xi \le \frac{p_n - p_s}{1-\lambda}$. Therefore for valuation $\xi \sim U[0, A]$, there will be another portion of demand for the remanufactured products.

$$Q_s = 1 \cdot \int_{\frac{p_s}{\lambda}}^{\frac{p_n - p_s}{1-\lambda}} \frac{1}{A} d\xi = \frac{\lambda p_n - p_s}{(1-\lambda)A\lambda} \tag{4}$$

Therefore, we can obtain the manufacturer's profit function as follows:

$$\Pi_m = (w_n - c_1)\left(1 - \frac{p_n - p_s}{(1-\lambda)A}\right) + (w_s - c_1 + \Delta - \theta b)\left(\frac{\lambda p_n - p_s}{(1-\lambda)A\lambda}\right). \tag{5}$$

The retailer's profit is:

$$\Pi_r = (p_n - w_n)\left(1 - \frac{p_n - p_s}{(1-\lambda)A}\right) + (p_s - w_s)\left(\frac{\lambda p_n - p_s}{(1-\lambda)A\lambda}\right). \tag{6}$$

And the third party recycler's profit is:

$$\Pi_t = (\theta b - b)\left(\frac{\lambda p_n - p_s}{(1-\lambda)A\lambda}\right). \tag{7}$$

Under non-cooperative decision-making, the game sequence of three parties is as follows. First, the third-party recycler determines its own recycling price b based on the market demand for remanufactured products and the recycling subsidy proportion. Second, the manufacturer will determine the wholesale prices w_n and w_s of the new and remanufactured products, respectively. Third, the retailer will determine its own selling prices p_n and p_s based on the wholesale price. The backward induction method is utilized to obtain such non-cooperative game equilibrium. First, the optimal price response function of the retailer is determined based on Equation (6):

$$\tilde{p}_n = \frac{A + w_n}{2}, \tilde{p}_s = \frac{\lambda A + w_s}{2}. \tag{8}$$

Substitute Equation (8) into Equation (5) and obtain the optimal wholesale price and selling price of new products based on first-order optimization condition and the price response function of the remanufactured products

$$w_n^{DH} = \frac{A + c_1}{2}, p_n^{DH} = \frac{3A + c_1}{4}. \tag{9}$$

$$\tilde{w}_s = \frac{A\lambda + \theta b + c_1 - \Delta}{2}. \tag{10}$$

Thereby, $\tilde{p}_s = \frac{3A\lambda + \theta b + c_1 - \Delta}{4}$. Substitute Equation (7) with Equation (9) to obtain the optimal recycling price:

$$b^{DH} = \frac{\Delta - (1-\lambda)c_1}{2\theta}. \tag{11}$$

Accordingly, the optimal price and the sales volume are given in Equations (12) and (13), respectively,

$$w_s^{DH} = \frac{2A\lambda + \lambda c_1 + c_1 - \Delta}{4},$$

$$p_s^{DH} = \frac{6A\lambda + \lambda c_1 + c_1 - \Delta}{8},$$

$$Q_n^{DH} = \frac{1}{4} - \frac{\Delta + (1-\lambda)c_1}{8A(1-\lambda)}. \quad (12)$$

$$Q_s^{DH} = \frac{\Delta - (1-\lambda)c_1}{8A\lambda(1-\lambda)}. \quad (13)$$

B. New product production mode (marked as DN mode)

When the prices of new and remanufactured products satisfy $\lambda p_n < p_s < p_n$, and then $\lambda\xi - p_s < \lambda\xi - \lambda p_n < \xi - p_n$ will be obtained, that is, $U_s < U_n$. Then, there are only consumption demands for new products on the market, and a rational manufacturer will choose a new product production mode. $\xi > p_n$ is obtained from $U_n = \xi - p_n > 0$, and for valuation $\xi \sim U[0, A]$, the market demands for new products are determined as:

$$Q_n = 1 \cdot \int_{p_n}^{A} \frac{1}{A} d\xi = \frac{A - p_n}{A}. \quad (14)$$

Then, the market demand of remanufactured products is $Q_s = 0$; based on the raw-material demands for remanufacturing, there is no recycling on the market, but only the decision-making model of new products:

$$\max_{w_n} \Pi_m = (w_n - c_1) \cdot \frac{A - p_n}{A}. \quad (15)$$

$$s.t. \begin{cases} \max\limits_{p_n} \Pi_r = (p_n - w_n) \cdot \dfrac{A - p_n}{A} \\ 0 < w_n < p_n < \xi \end{cases}. \quad (16)$$

It is a two-stage Stackelberg game process dominated by the manufacturer. According to the optimal price response function of the retailer,

$$\tilde{p}_n = \frac{A + w_n}{2}. \quad (17)$$

By combining Equations (14) to (16), solve and obtain the optimal wholesale price, selling price, and sales volume under new product production mode:

$$w_n^{DN} = \frac{A + c_1}{2}, \; p_n^{DN} = \frac{3A + c_1}{4},$$

$$Q_n^{DN} = \frac{A - c_1}{4A}. \quad (18)$$

Theorem 1. Under non-cooperative decision-making situation, the choice of production mode by the manufacturer is significantly correlated with the consumer's preference coefficient λ of remanufactured products. (1) When $1 - \Delta/c_1 \le \lambda < 1 - \Delta/(2A - c_1)$, the manufacturer will choose the hybrid production mode where new and remanufactured products will be put into production. (2) When $0 < \lambda < 1 - \Delta/c_1$, the manufacturer will only use the new product production mode. (3) When $1 - \Delta/(2A - c_1) \le \lambda < 1$, the manufacturer will choose remanufactured product production mode.

Theorem 1 shows that the consumer preference coefficients $\lambda = 1 - \Delta/c_1$ and $1 - \Delta/(2A - c_1)$ are the critical points of production mode chosen by the manufacturer.

According to the relationship between λ and qualitative behavior of sales function, the general delineation of λ is given as follows (see Fig. 2).

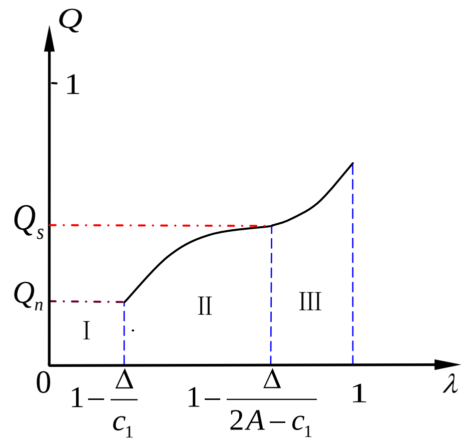

Fig. 2 Relationship between choice of production modes and λ

In Fig. 2, area I represents new product production mode, while areas II and III, respectively, represent hybrid production mode and remanufactured product production mode.

Theorem 2. Compare the new products equilibrium results under DH mode and DN mode, it's found: $w_n^{DH} = w_n^{DN}$, $p_n^{DH} = p_n^{DN}$ and $Q_n^{DH} \le Q_n^{DN}$.

C. Remanufacturing production mode (marked as DS mode)

According to Theorem 1, when $1 - \Delta/(2A - c_1) \le \lambda < 1$, the manufacturer will only use the remanufactured product production mode and obtain $p_s/\lambda < \xi$ from the utility of the remanufactured products $U_s > 0$, and for the valuation $\xi \sim U[0, A]$, the market demand for the remanufactured products is determined as:

$$Q_s = 1 \cdot \int_{\frac{p_s}{\lambda}}^{A} \frac{1}{A} d\xi = \frac{A\lambda - p_s}{A\lambda}. \quad (19)$$

Then, the market demand for new products is $Q_n = 0$ and there are only recycling and remanufacturing, and sales decision.

$$\Pi_m = (w_s - c_2 - \theta b) \cdot \frac{A\lambda - p_s}{A\lambda}. \quad (20)$$

$$\Pi_r = (p_s - w_s) \cdot \frac{A\lambda - p_s}{A\lambda} \quad (21)$$

$$\prod_t = (\theta b - b) \cdot \frac{A\lambda - p_s}{A\lambda}. \tag{22}$$

According to the analysis similar to DH mode, the equilibrium solution under DS mode can be obtained as follows:

$$b^{DS} = \frac{A\lambda - c_2}{2\theta}, \quad w_s^{DS} = \frac{3A\lambda + c_2}{4},$$

$$p_s^{DS} = \frac{7A\lambda + c_2}{8}, Q_s^{DS} = \frac{A\lambda - c_2}{8A\lambda}. \tag{23}$$

Theorem 3. When remanufactured products equilibrium results under DH mode and DS mode are compared, the following relation exists:

(1) $b^{DH} < b^{DS}$, and the recycling price b under both modes is negatively correlated with the recycling subsidy proportion θ of the manufacturer;

(2) $w_s^{DH} < w_s^{DS}$ and $p_s^{DH} < p_s^{DS}$;

(3) When $1 - \Delta/c_1 \le \lambda < \min\{2/3, 1 - \Delta/(2A - c_1)\}$, there must be $Q_s^{DH} < Q_s^{DS}$.

Theorems 2 and 3 show that, when the manufacturer and the retailer make non-cooperative decision, different production modes have no effect on the price of new products, but have an effect on the price of the remanufactured products; the recycling, wholesale and selling prices under DS mode are significantly higher than those under DH mode. If consumers' preference coefficient λ for the remanufactured products satisfies:

$$1 - \Delta/c_1 \le \lambda < \min\{2/3, 1 - \Delta/(2A - c_1)\}.$$

There must be market demand for the remanufactured products. Then, regardless of market demand for new products, the demands for remanufactured products under DS mode are far more than that under DH mode, which is beneficial to promote the recycling and remanufacturing by the supply chain members; the demands for new products under DH mode are lower than those under DN mode, due to "cannibalization effect" of demand for remanufactured products under hybrid production mode on the new products demand.

IV. Hybrid production mode WITH cooperation (marked as CH mode)

If the manufacturer, the retailer and the third-party recycler cooperate under hybrid production mode, then the decision-making model is:

$$\max_{p_n, p_s} \prod = (p_n - c_1) \cdot \left(1 - \frac{p_n - p_s}{(1-\lambda)A}\right) + (p_s - c_1 + \Delta - b)\left(\frac{\lambda p_n - p_s}{(1-\lambda)A\lambda}\right). \tag{24}$$

Solve the above optimization problem to obtain the optimal recycling price, selling price, sales volume and channel profit under the cooperation of the three members as follows:

$$b^{CH} = \Delta - (1-\lambda)c_1, \; p_n^{CH} = \frac{A + c_1}{2},$$

$$p_s^{CH} = \frac{\lambda(A + c_1)}{2}. \tag{25}$$

$$Q_n^{CH} = \frac{A - c_1}{2A}, \; Q_s^{CH} = 0,$$

$$\prod^{CH} = \frac{(A - c_1)^2}{4A}. \tag{26}$$

Theorem 4. When pricing strategy and demand for new and remanufactured products under CH mode and DH mode are compared, the following conclusion is tenable:

(1) $p_n^{CH} < p_n^{DH}, Q_n^{CH} > Q_n^{DH}$;

(2) $p_s^{CH} < p_s^{DH}, b^{CH} > b^{DH}, Q_s^{CH} < Q_s^{DH}$.

Theorem 4 shows that if three members of the supply chain jointly make a decision, it can be seen in combination with the equilibrium results of Equations (23) and (25) that the recycling price of used products is at its highest now, that is $b^{CH} > b^{DS} > b^{DH}$; the selling price of the remanufactured products is also greatly reduced, but the market demand for it is zero. On the one hand, it is because the prices of both products under CH mode just satisfy the critical state $p_s^{CH} = \lambda p_n^{CH}$, that is, the same utility of both products, while λ under hybrid production mode is between $1 - \Delta/c_1$ and $1 - \Delta/(2A - c_1)$; thus, it shows that consumers do not wholly prefer the remanufactured products, but naturally choose to purchase new products. On the other hand, the cooperative decision-making can integrate advantageous resources so as to make new products able to take more market shares with lower selling prices to sharply increase the market demands for new products, resulting in remanufactured products being totally bumped down the market.

V. Example Analysis

The above conclusions will be further verified and analyzed through the numerical examples as follows. It is assumed that if $c_1 = 20$, $c_2 = 10$, $A = 60$, and $\theta = 4$, then it can be derived that $\Delta = c_1 - c_2 = 10$, $1 - \Delta/c_1 = 0.5$, and $1 - \Delta/(2A - c_1) = 0.9$.

Therefore, when $0.5 \le \lambda < 0.9$, the manufacturer will choose hybrid production mode. Then, 0.1 is taken as a step-length to assign value to the preference coefficient λ and to obtain the performance of supply chain system and members under non-cooperative and cooperative situations. Some results will be free of the influence of the value of λ, including: $w_n^{DH} = 40.00$, $p_n^{DH} = 50.00$, $p_n^{CH} = 40.00$, $Q_n^{CH} = 0.33$, $Q_s^{CH} = 0$, and $\prod^{CH} = 6.67$.

As is shown in TABLE I, under hybrid production mode, on the comparison between the equilibrium results under cooperative and non-cooperative decisions, the product selling price under CH mode is effectively lowered, the product sales volumes are significantly raised and the supply chain channel benefits also increase; but the market demand for the remanufactured products will be reduced to zero, resulting from the cannibalization effect under the influence of consumer preference. Under DH mode, when $\lambda = 0.5$, the market demand for remanufactured products is zero, which is

TABLE I
SUPPLY CHAIN SYSTEM AND MEMBERS' PERFORMANCE UNDER HYBRID PRODUCTION MODE

λ	(b^{DH}, b^{CH})	w_s^{DH}	(p_s^{DH}, p_s^{CH})	Q_s^{DH}	Q_n^{DH}	$\prod^{DH}$
0.5	(0,0)	20.00	(25.00,20.00)	0	0.17	5.00
0.6	(0.25,2.00)	23.50	(29.75,24.00)	0.02	0.16	5.03
0.7	(0.50,4.00)	27.00	(34.50,28.00)	0.04	0.14	5.12
0.8	(0.75,6.00)	30.50	(39.25,32.00)	0.08	0.10	5.35
0.9	(1.00,8.00)	34.00	(44.00,36.00)	0.18	0	6.11

a critical value when the manufacturer chooses production mode. As parameter λ increases, the market demand for the remanufactured products will also increase and the market demand for the new products will be lowered. Accordingly, the cost and selling price of the remanufactured products gradually increase, but those of new products will be free of the influence of λ and, thus, will not change. In general, as λ increases, the overall profit of the supply chain will also increase. When λ increases to 0.9, the market demand for new products is reduced to zero, but there is only the market demand for the remanufactured products, then the manufacturer will enter the critical state of another production mode again. It also exactly exemplifies the conclusion in Theorem 1.

Thus, the consumers' preference coefficient (λ) directly impacts the manufacturer's choice of production modes. When $0 < \lambda < 0.5$, the manufacturer will choose new product production mode. When $0.5 \le \lambda < 0.9$, the manufacturer will choose hybrid production mode. When $0.9 \le \lambda < 1$, the manufacturer will choose remanufactured product production mode.

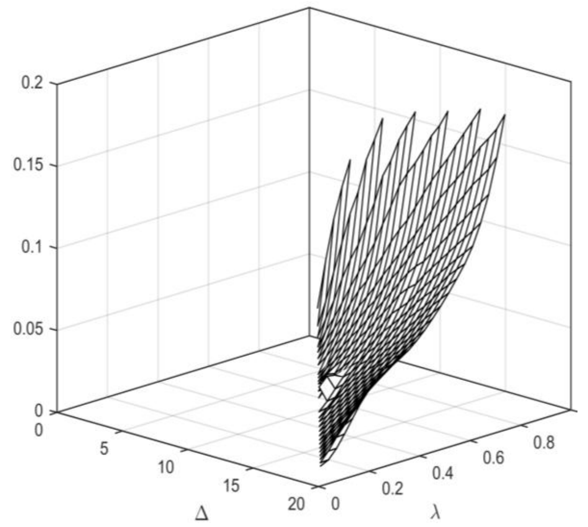

Fig.3 Q_s^{DH} vs. Δ & λ

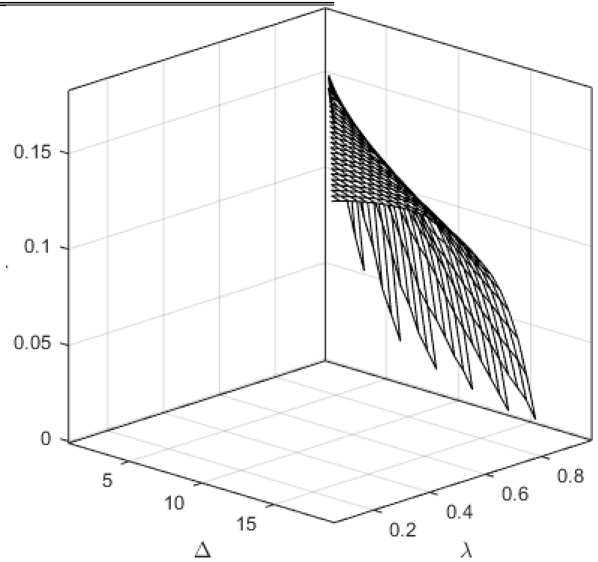

Fig. 4 Q_n^{DH} vs. Δ & λ

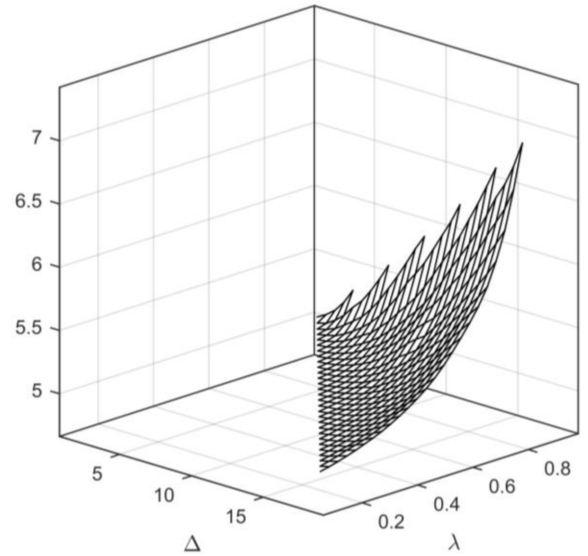

Fig. 5 Total profits ($\prod^{DH}$) vs. Δ & λ

For the product sales volume and the relation between parameters Δ and λ under DN mode and DS mode, it is easy to know according to the optimal results of DN mode and DS mode. Next, the sensitivity analysis of DH mode is mainly carried out, in which c_1 and A's value are kept constant, but only Δ is calculated based on the step-length 1 and λ is assigned value according to corresponding range $[1-\Delta/c_1, 1-\Delta/(2A-c_1))$. Then the sales volumes of remanufactured and new products, the system profit and relation between parameters Δ and λ under DH mode are obtained (see Figs.3- 5).

From Figs.3-5, it can be observed that, under non-cooperative hybrid production mode, the larger the saved cost by remanufacturing Δ and consumer preference coefficient λ, the more market demand for remanufactured products is and the more the system profit is. However, the market demand for the new products decreases to reach the critical state of the remanufactured product production mode in such cases. To improve the market competitiveness of the remanufactured products against the new products of the same type, the market demand for the remanufactured products needs to be stimulated. On the one hand, the production cost of remanufacturing needs to be reduced to improve the saved cost by remanufacturing, and thus the manufacturer is likely to produce remanufactured products. On the other hand, the market regulators can promote environmental protection, formulate a favorable policy to improve the social benefit and recognition of remanufactured products and increase the consumer preference coefficient for it. It will also facilitate the manufacturers to actively recycle and remanufacture, so as to promote a stable and sustainable development.

VI. CONCLUSION

For the consumer purchase preference, the production choice and pricing of recycling and remanufacturing supply chain under non-cooperative and cooperative decision making are studied in this paper. The game equilibrium results show that the product sales volume and pricing are significantly correlated with the product and production mode. Therefore, the supply chain members should pay attention to controlling the production cost and reasonably setting product selling price, so as to enlarge the market demands for the remanufactured products. Additionally, governments can improve the public's environmental protection awareness and establish related policies and regulations, such as a "trade-in" strategy and a government "recycling subsidy" policy to guide and control the closed-loop supply chain. Related conclusions provide certain reference and guidance for promoting the recycling and remanufacturing by enterprise and the management of the closed-loop supply chain. Further research could take the following problems into consideration: pricing, production and recycling mode of products of bilateral competition type, or multi-period closed-loop supply chain.

APPENDIX

Proof of Theorem 1. (1) Only when $p_s^{DH} \le \lambda p_n^{DH}$, will the manufacturer choose hybrid production mode, then:

$$\frac{6A\lambda + \lambda c_1 + c_1 - \Delta}{8} \le \lambda \cdot \frac{3A + c_1}{4}.$$

When $0 < \lambda < 1$, $Q_n^{DH} = \frac{1}{4} - \frac{\Delta + (1-\lambda)c_1}{8A(1-\lambda)} > 0$ and $Q_s^{DH} = \frac{\Delta - (1-\lambda)c_1}{8A\lambda(1-\lambda)} > 0$, the simultaneous solution is:

$$1-\Delta/c_1 \le \lambda < 1-\Delta/(2A-c_1);$$

(2) The condition $\lambda p_n < p_s$ is chosen based on the new product production, and in combination with $0 < \lambda < 1$, it can be known that when $0 < \lambda < 1-\Delta/c_1$, the manufacturer will choose new product production mode; certainly, when $1-\Delta/(2A-c_1) \le \lambda < 1$, the manufacturer will only use the remanufactured product production mode.

Proof of Theorem 2. According to the above game equilibrium results (9) and (18), we can easily see that conclusions of $w_n^{DH} = w_n^{DN}$ and $p_n^{DH} = p_n^{DN}$ are tenable

Because of:

$$\begin{aligned} Q_n^{DH} &= \frac{1}{4} - \frac{\Delta + (1-\lambda)c_1}{8A(1-\lambda)} \\ &= \frac{1}{4} - \frac{2(1-\lambda)c_1 + \Delta - (1-\lambda)c_1}{8A(1-\lambda)} \\ &= \frac{1}{4} - \frac{c_1}{4A} + \frac{-\Delta + (1-\lambda)c_1}{8A(1-\lambda)}, \end{aligned}$$

For DH mode, $\lambda \ge 1 - \frac{\Delta}{c_1}$ is obtained; therefore, $-\Delta + (1-\lambda)c_1 \le -\Delta + (1 + \frac{\Delta}{c_1} - 1)c_1 = 0$, and thus:

$$Q_n^{DH} = \frac{1}{4} - \frac{c_1}{4A} + \frac{-\Delta + (1-\lambda)c_1}{8A(1-\lambda)} \le Q_n^{DN} = \frac{1}{4} - \frac{c_1}{4A}$$

is tenable.

Proof of Theorem 3. (1) According to $w_n + c_1 \le A$ and $c_1 - c_2 = \Delta$, it is easy to know:

$$b^{DH} = \frac{\Delta - (1-\lambda)c_1}{2\theta} = \frac{\lambda c_1 - c_2}{2\theta} < \frac{A\lambda - c_2}{2\theta} = b^{DS}.$$

It can be seen that the recycling price b under DH mode and DS mode decreases with the increase in recycling subsidy proportion θ of the manufacturer;

(2) $$\begin{aligned} w_s^{DH} &= \frac{2A\lambda + \lambda c_1 + c_1 - \Delta}{4} \\ &< \frac{2A\lambda + A\lambda + c_1 - \Delta}{4} = \frac{3A\lambda + c_2}{4} = w_s^{DS}, \end{aligned}$$

$$\begin{aligned} p_s^{DH} &= \frac{6A\lambda + \lambda c_1 + c_1 - \Delta}{8} \\ &< \frac{6A\lambda + \lambda A + c_1 - \Delta}{8} = \frac{7A\lambda + c_2}{8} = p_s^{DS}; \end{aligned}$$

(3) Since $w_n^{DH} = \frac{A+c_1}{2}$,

$w_n^{DH} + c_1 = \frac{A+c_1}{2} + c_1 \le A$, that is $c_1 \le \frac{A}{3}$, then

$$\begin{aligned} Q_s^{DH} &= \frac{\Delta - (1-\lambda)c_1}{8A\lambda(1-\lambda)} \le \frac{\frac{A}{3}\lambda - c_2}{8A\lambda(1-\lambda)} \\ &= \frac{1}{3(1-\lambda)} \cdot \frac{A\lambda - c_2}{8A\lambda} - \frac{c_2}{12A\lambda(1-\lambda)} \\ &< \frac{1}{3(1-\lambda)} \cdot \frac{A\lambda - c_2}{8A\lambda} = \frac{1}{3(1-\lambda)} Q_s^{DS}. \end{aligned}$$

Thus, when $1 - \Delta/c_1 \le \lambda < \min\{2/3, 1-\Delta/(2A-c_1)\}$, there must be demands for remanufactured products and $Q_s^{DH} < Q_s^{DS}$.

Proof of Theorem 4. (1) According to $w_n + c_1 \le A$ and $c_1 < w_n$, $c_1 < \frac{A}{2}$ is obtained. Thus:

$$p_n^{CH} = \frac{A+c_1}{2} < \frac{3A+c_1}{4} = p_n^{DH} \quad \text{and}$$

$$Q_n^{CH} - Q_n^{DH} = \frac{2A-3c_1}{8A} + \frac{\Delta}{8A(1-\lambda)} > 0;$$

(2) According to $2c_1 < A$,

$$p_s^{CH} - p_s^{DH} = \frac{3\lambda c_1 - 2A\lambda - c_2}{8} < \frac{-\lambda c_1 - c_2}{8} < 0$$

is obtained, that is $p_s^{CH} < p_s^{DH}$.

For $\theta > 1$,

$$b^{CH} = \Delta - (1-\lambda)c_1 > \frac{\Delta - (1-\lambda)c_1}{2\theta} = b^{DH}$$ is

obvious; and $Q_s^{CH} = 0$, so $Q_s^{CH} < Q_s^{DH}$.

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