Production Mode and Pricing Strategy of a Two-period Closed-loop Supply Chain Considering Fairness Concerns

Cheng-Tang Zhang [1*], Yong Ye [2], and Miao-Miao Wang [3]

Abstract—**Under the assumption of two-period closed-loop supply chain and based on the degree of manufacturers and retailers' fairness concerns about the income in supply chain, this paper builds three models: without fairness concerns, only the retailer is concerned about fairness, and both channel members are concerned about fairness. Then it probes into the relationship between remanufacturing cost saving and the selection of different production modes, and presents the thresholds of remanufacturing cost saving for three models as well as the equilibrium pricing and optimum output of new products and remanufactured items in multi-period and different production modes. According to the result, all supply chain members' showing high tendency of fairness concerns is extremely disadvantageous for the channel performance of closed-loop supply chain system. Finally, through some numerical examples, this paper analyzes the impact of remanufacturing cost saving and degree of fairness concerns on product output, price and optimal supply chain performance etc.**

Index Terms—**closed-loop supply chain, fairness concerns, production mode, pricing strategy**

I. INTRODUCTION

A. Motivation

DUE to the dramatic development of global economy and the constant improvement in people's living standard, the upgrade rate of products becomes higher, and more and more used products are phased out - it should be noted that electronic wastes improperly disposed of are likely to cause pollution of heavy metals and polyvinyl chloride plastics etc. to soil. Statistical data show that approx. 46.1 million tons of electronic wastes were produced all over the world in 2016, namely around 6.3kg per capita. As a matter of fact, electronic wastes are highly valuable "urban minerals", of which the effective recycling & re-treatment or remanufacturing may help to improve resource utilization and protect the environment in a favorable manner. Take GEM China for example: in 2015, this company consumed over 200 million tons of waste resources, thereby saving 5.7 million barrels of oil and 1.17 million tons of standard coal, reducing polluted water by 82.1 billion tons, reducing polluted soil by 23,000 square kilometers (GEM, 2016[1]), and bringing about other unquantifiable environmental added values. Furthermore, the recycling & remanufacturing of used products by this company has effectively reduced manufacturing cost, indirectly created new profit growth points, and enhanced its competitive edge in market. From this point of view, recycling & remanufacturing concept-based closed-loop supply chain management offers a new way of effective resource utilization and environmental protection, and constitutes a "new engine" for sustainable development of modern enterprises.

Each member of a supply chain exhibits fairness concerns when his share of total profit is low, and they dislike unfair shares in a total pie. Therefore, this paper will, with a view to manufacturers and retailers' fairness concerns tendency, probe into the effect of the degree of fairness concerns and the threshold of remanufacturing cost saving on two-period closed-loop supply chain production mode and product pricing by building models without fairness concerns (UF), only the retailer is concerned about fairness (RF), and both channel members are concerned about fairness (MRF).

B. Literature Review

Study on closed-loop supply chain management has turned into one of the hot issues of general concern in the academic community; existing studies related to this paper principally involve pricing and coordination strategies regarding multi-period circumstances and fairness concerns tendency etc.

Multi-period closed-loop supply chain management: without direct recovery by manufacturer, it's normally difficult to recover, transport, remanufacture and sell used products within a sales cycle; hence, it's normally more practical to consider recycling & remanufacturing and the sale of remanufactured items from a multi-period perspective. Existing literatures mostly studied two-period circumstances in respect of remanufacturing strategy and product pricing etc.: Ferrer and Swaminathan (2006) [2] studied multi-period product pricing strategies in the event of oligopolistic

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competition and duopoly competition, analyzed the thresholds of multi-period product remanufacturing in the case of oligopolistic competition, conducted comparative review of duopoly competition between independent operator and raw material manufacturer, and presented the optimal product pricing where remanufacturing cost saving was below a certain threshold. Ferrer (2010)[3]further probed into two-period and multi-period pricing issues for two different products based on above-noted study on the assumption that new products were not different from remanufactured items, finding that remanufacturing cost saving was no longer the only factor that affected multi-period optimal strategy at a limited level of production. On the assumption that the quantity of remanufactured products in the current period is subject to the constraint of product sales realized in the previous period, Chen and Chang (2013) [4]built unrestricted static model and two constrained dynamic models using the Lagrangean relaxation and dynamic programming schemes, and studied the pricing strategies for multi-period dual-channel closed-loop supply chain. According to the result, the degree of effort for recovery is principally dependent on category of market (e.g. different phases of product lifecycle), remanufacturing cost saving, and demand substitution coefficient of new product and remanufactured product. Dutta et al. (2016) [5] performed product recovery at retailer's repurchase price, and analyzed the optimal repurchase price of multi-period closed-loop supply chain with uncertain demand and capability; the model offered three options, i.e. product remanufacturing, part remanufacturing, and recovery of raw material so as to determine the optimum decisions on manufacturing, remanufacturing and recovered quantity. Ramani et al. (2017) [6] found that cannibalization effect did not reduce manufacturer's two-period sales, it had a negative effect on manufacturer's profit that could not be counteracted even with price reduction of new product; then, they analyzed manufacturer's two-period product pricing and profit change by introducing advertising strategy. Wang et al. (2018) [7] examined the benefit of the reward-penalty mechanism in a two-period closed-loop supply chain. Some scholars studied multi-period closed-loop supply chain based on recovery business (Ketzenberg et al., 2010[8]; Giovanni Zaccour, 2014[9]) and optimized design of supply chain network (Dai & Zheng, 2015[10]) etc.

Supply chain management considering fairness concerns: It was found in previous behavioral economics studies that people often showed great concern for the fairness of income distribution, i.e. fairness concerns (Fehr Schmidt, 1999[11]) in real life. Ho and Zhang (2008) [12]demonstrated the existence of fairness concerns behavior disposition in a supply chain environment, and presented a descriptive fairness concerns utility function. All existing studies on multi-period circumstances are performed on assumption that participants in closed-loop supply chain are entirely rational, and that decisions are made for the maximization of their own profits or the minimization of total cost, having lost sight of the concern by participants for channel income distribution fairness. With this end in view, the introduction of theory of fairness to research on decision optimization of supply chain counts for much. Cui et al. (2007) [13]investigated how fairness may affect the interactions between the manufacturer and the retailer in a conventional dyadic channel, finding that the coordination in channel of fairness concerns requires no nonlinear pricing scheme since the manufacturer could coordinate this channel at a simple wholesale price. Based on Cui et al. (2007) [13], Caliskan-Demirag et al. (2010) [14] performed comparative analysis by extending its result to the exponential demand function, pointing out that a coordinating wholesale price contract is valid when only the retailer or both parties are concerned about fairness in the case of linear demand. By contrast, to realize coordination, the exponential demand function requires less stringent conditions when only the retailer is concerned about fairness. With a focus on potential fairness concerns, Hu et al. (2013) [15] probed into price-quoting strategies where all sellers get equal quotes, and argued that supplier's optimal mechanism is like a single quote auctioning among the sellers. This facilitates the pricing decision of upstream suppliers, and provides general insights into multitier supply chains' pricing dynamics. In view of the Newsvendor Problem where both supplier and retailer exhibit fairness concerns tendency, Du et al. (2014) [16]introduced Nash bargaining solution as the fairness reference point, construed the effect of the behavior of fairness concerns on the optimal decision on supply chain and the channel efficiency, and found that fairness concerns can't change the status of channel coordination in certain conditions. In view of closed loop supply chain pricing decision with retailer fairness concerns, the pricing decision mechanism of closed loop supply chain was studied by considering and neglecting retailer's concern about fairness manufacturers’ fairness (Ding et al., 2014[17]). According to the result, when the manufacturer takes into account retailer fairness concerns, the more retailer fairness concerns, the more retailer’s gains but the less manufacturer’s gains; when the manufacturer takes no account of retailer fairness concerns, the more retailer fairness concerns about, the less profits the member and the system gain. Han et al. (2015) [18]studied the pricing game of closed-loop supply chain from the perspective of decision maker's bounded rationality and fairness concerns, and probed into the effect of the social relations and optimum decisions of manufacturers and retailers on pricing and profit, reporting that the research findings obviously deviated from the optimal solutions of the traditional game models. Chen et al. (2017) [19] established retailer’s fairness-concerned utility function by taking Nash Bargaining Solution as the fairness reference point, and then built a two-echelon pricing/ordering game model for the analysis of aggregate effects of fairness concerns and buyback guarantee financing (BGF) on channel members’ equilibrium strategies. Ma et al. (2017) [20] incorporated retailer’s distributional fairness concerns into the manufacturer collection model, and investigated pricing decisions in closed-loop supply chains with marketing effort. Li et al. (2018) [21] analyzed the carbon emission reduction and price decisions in a two-echelon supply chain with a fairness-neutral manufacturer and a fairness-concerned retailer. In addition, some scholars probed into the performance of wholesale pricing under information asymmetry (Katok et al., 2014[22]), co-op advertising and emission reduction cost sharing contracts in low-carbon supply chain (Zhou et al., 2016[23]), a coordination mechanism that combines quantity discount contracts with fixed fees (Nie and Du, 2017[24]), and the impacts of private production-cost information and bounded rationality on supply-chain decision making (Fei et al., 2016[25]), etc. from the perspective of fairness concerns.

In view of the above, there are relatively few studies focusing on CLSC management considering fairness concerns, and the existing studies often neglect the discriminatory pricing and production mode selection of multi-period product. In point of fact, used products with high added value could normally be subjected to repeated recycling & remanufacturing, while economic benefit constitutes an extremely important factor for supply chain enterprises to participate in recycling & remanufacturing, because the cost of recycling & remanufacturing is remarkably lower than that of manufacturing from raw material; in such a manner, enterprises are in a position to guarantee environmental benefits while gain additional economic benefits.

II. Assumptions And Notations

It's assumed that a manufacturer manufactures brand-new products (new items) from raw materials in period 1, and chooses to manufacture new items, or manufactures remanufactured products (remanufactured items) from recovered used items, or manufactures both kinds of products in period 2. Retailers purchase products (new products and remanufactured items) of period 1 or 2 in bulk from manufacturers, and bring them to end consumer market. The following notations defined in Table 1 are used in the model.

Table 1
Notations

Parameter	Definition
c	Manufacturing cost of a new item
c_r	Manufacturing cost of a remanufactured item
$\delta = c - c_r$	Saving unit cost in the remanufacturing process
w_1, w_2	Wholesale price of the manufacturer in periods 1 and 2, respectively
η	Recovery rate of used items, $\eta \in [0,1]$
p_1, p_2	Retail price of the retailer in periods 1 and 2, respectively
τ	Discount factor of second-period profit, $\tau \in [0,1]$
λ_m, λ_r	Fairness concerns parameters of the manufacturer and the retailer, respectively
U_M, U_R	Utility functions of the manufacturer and the retailer, respectively

Hereinto, w_1 and w_2 are the decision variables of the manufacturer, p_1 and p_2 are the decision variables of the retailer. The following assumptions are made in the subsequent model.

Assumption 1. All used products purchased are supposed to be remanufactured, so the remanufacturing rate is set to 1, similar forms of this assumption have been used in the sample (e.g. Savaskan et al., 2004[26]), it does not actually affect the important results in subsequent models. There is substitution relationship between new manufactured and remanufactured items. Recovery cost is a linear function of recovered quantity, and is included in remanufacturing cost c_r, where $c_n > c_r$.

Assumption 2. The CLSC decisions are considered in a two-period setting. All of manufacturers' period 1 products are new products, and the recovered used products can be used for remanufacturing and selling in period 2 - all the products manufactured are sold to retailers. New products are identical with remanufactured items in terms of quality and performance, and they exhibit no difference in terms of marketing. Discriminatory pricing is performed for products from different periods in order to reflect the temporal value of profit.

Assumption 3. Assume the inverse demand is $p_1 = \phi - Q_{1n}$ in the first period, and $p_{2n} = \phi - Q_{2n} - kQ_{2r}$, $p_{2r} = k(\phi - Q_{2n} - kQ_{2r})$ are the inverse demand functions of the new and remanufactured items in period 2 respectively (reference to Yenipazarli, 2016[27]). ϕ is a strictly positive parameter representing the market potential, and k ($0 < k \le 1$) denotes the difference between new and remanufactured items in terms of price. When $k = 1$, namely, $p_{2n} = p_{2r} = p_2$, the price of new items is equal to remanufactured items. Thus, we can easily get the direct demand functions of different products in periods 1 and 2, which are expressed as follows respectively

$$Q_{1a} = Q_{1n},\ Q_{2a} = Q_{2n} + Q_{2r}.$$

Then, the manufacturing and pricing strategies for products in multi-period closed-loop supply chain are studied respectively for the following three models: (I) Model UF; (II) Model RF; (III)Model MRF. In addition, variables with superscripts "I, II and III" respectively represent the optimal product operation strategies in the three models.

III. Decision on Manufacturing and Pricing of Multi-period products

Manufacturer's profit π_M and retailer's profit π_R determined based on above-noted description

$$\begin{aligned}\pi_M(w_1, w_2) &= (w_1 - c)Q_{1n} + \tau[(w_2 - c)Q_{2n} + (w_2 - c + \delta)Q_{2r}] \\ &= (w_1 - c)(\phi - p_1) + \tau[(w_2 - c)(\phi - p_2) + \delta Q_{2r}]\end{aligned} \quad (1)$$

$$\begin{aligned}\pi_R(p_1, p_2) &= (p_1 - w_1)Q_{1n} + \tau[(p_2 - w_2)Q_{2n} + (p_2 - w_2)Q_{2r}) \\ &= (p_1 - w_1)(\phi - p_1) + \tau(p_2 - w_2)(\phi - p_2)\end{aligned}. \quad (2)$$

A. Model UF: Without fairness concerns

The case without fairness concerns (i.e. Model UF) is reviewed firstly to obtain a reference. If neither manufacturers nor retailers have fairness preference, which is to say, they are not concerned about the distribution of closed-loop supply chain system income, then the decision making of both sides will take the maximization of their own profits as the objective. As leaders, manufacturers will figure out the optimal wholesale price and output based on retailers' response function; the retail price of retailers acting as followers is dependent on manufacturers' wholesale price and output; accordingly, they constitute a Stackelberg game.

Manufacturer's decision-making process

$$\max_{w_1,w_2} \pi_M(w_1,w_2)$$

$$s.t.\begin{cases}\eta Q_{1n} \geq Q_{2r} \\ Q_{2a} \geq Q_{2r}\end{cases} . \tag{3}$$

Retailer's decision-making process

$$\max_{p_1,p_2} \pi_R(p_1,p_2) \tag{4}$$

As shown in Equation (4), retailer's profit function is a strictly concave function regarding retail price; hence, retailer's optimum response function can be obtained using first-order optimization condition

$$\tilde{p}_1 = \frac{\phi+w_1}{2}, \quad \tilde{p}_2 = \frac{\phi+w_2}{2} . \tag{5}$$

Manufacturer's optimum solution is sought through Karush-Kuhn-Tucker (KKT) optimization conditions below. The Lagrange function established after substituting Equation (5) into Equation (3) is as follows

$$\begin{aligned} &L_1(w_1,w_2,Q_{2r},u_1,u_2) \\ &= (w_1-c)(\phi-w_1)/2+\tau[(w_2-c)(\phi-w_2)/2+\delta Q_{2r}] \\ &\quad +u_1[\eta(\phi-w_1)/2-Q_{2r}]+u_2[(\phi-w_2)/2-Q_{2r}] \end{aligned}$$

KKT optimization condition

$$\partial L_1/\partial w_1 = \partial L_1/\partial w_2 = 0 \tag{6}$$

$$\partial L_1/\partial Q_{2r} = \tau\delta - u_1 - u_2 = 0 \tag{7}$$

$$u_1[\eta(\phi-w_1)/2-Q_{2r}] = 0 \tag{8}$$

$$u_2[(\phi-w_2)/2-Q_{2r}] = 0 \tag{9}$$

Based on Condition (6)

$$w_1 = (\phi+c-u_1\eta)/2, \quad w_2 = \tau(\phi+c)-u_2/2\tau . \tag{10}$$

According to Condition (7), $\tau\delta = u_1+u_2$, while Lagrange multiplier $u_1 \geq 0$, $u_2 \geq 0$; hence, the following three cases shall be discussed.

(i) UF-H mode: When $u_2 = 0$ and $u_1 = \tau\delta$, manufacturers produce new products and remanufactured items simultaneously in period 2. As shown in Equation (10) in this mode

$$w_1^I = (\phi+c-\tau\delta\eta)/2, \; w_2^I = (\phi+c)/2 . \tag{11}$$

Hence, $p_1^I = (3\phi+c-\tau\delta\eta)/4$, and $p_2^I = (3\phi+c)/4$.

Substitute Equation (11) into Equation (8) to obtain $Q_{2r}^I = \eta(\phi-c+\tau\delta\eta)/4$, thereby

$$Q_{2n}^I = Q_{2a}^I - Q_{2r}^I = [(1-\eta)(\phi-c)-\tau\delta\eta^2]/4 .$$

To ensure $Q_{2r}^I \geq 0$ and $Q_{2n}^I \geq 0$, the remanufacturing cost saving must meet the condition below

$$\delta \leq (1-\eta)(\phi-c)/\tau\eta^2 .$$

(ii) UF-R mode: When $u_1 > 0$ and $u_2 = \tau\delta - u_1 > 0$, manufacturers use all recovered used products for remanufacturing and only produce remanufactured items in period 2. Simultaneously, set up KKT optimization conditions (6)-(9)

$$u_1^I = \frac{\tau(1-\eta)(\phi-c)+\tau\delta}{1+\tau\eta^2},$$

$$u_2^I = \tau\delta - u_1^I = \frac{\tau^2\delta\eta^2-\tau(1-\eta)(\phi-c)}{1+\tau\eta^2} . \tag{12}$$

By all appearances, since $u_1^I > 0$ and $u_2^I > 0$, the remanufacturing cost saving must meet the condition below

$$\delta > (1-\eta)(\phi-c)/\tau\eta^2 . \tag{13}$$

Substitute result (12) into KKT optimization conditions (6)-(9) to get $\hat{w}_1^I$, $\hat{w}_2^I$, $\hat{p}_1^I$, $\hat{p}_2^I$, and $\hat{Q}_{2r}^I$ (see Proposition 1 below for details).

(iii) Additionally, it is obvious that $u_1 = 0$ and $u_2 = \tau\delta$ only when $\delta = 0$, that is, the remanufacturing cost saving is equal to zero; hence, manufacturers employ new product manufacturing mode instead of recycling & remanufacturing mode; this case is skipped over since it is degraded to an open-loop supply chain.

We summarize the previous analysis in the following proposition and corollary.

Proposition 1. In Model UF, there is a threshold $\delta^I = (1-\eta)(\phi-c)/\tau\eta^2$ of remanufacturing cost saving, as a result of which

(1.1) When $\delta \leq \delta^I$, manufacturers employ the new product-remanufactured item hybrid manufacturing mode (UF-H mode) in period 2, and the respective optimal decisions of manufacturers and retailers are:

$$w_1^I = (\phi+c-\tau\delta\eta)/2, \; w_2^I = (\phi+c)/2 .$$

$$p_1^I = (3\phi+c-\tau\delta\eta)/4, \; p_2^I = (3\phi+c)/4 .$$

$$Q_{2r}^I = \eta(\phi-c+\tau\delta\eta)/4,$$

$$Q_{2n}^I = [(1-\eta)(\phi-c)-\tau\delta\eta^2]/4 .$$

(1.2) When $\delta > \delta^I$, manufacturers only manufacture remanufactured items in period 2 (UF-R mode) in period 2, and the respective optimal decisions of manufacturers and retailers are:

$$\hat{w}_1^I = \frac{(2\tau\eta^2-\tau\eta+1)\phi+(\tau\eta+1)c-\tau\delta\eta}{2(1+\tau\eta^2)},$$

$$\hat{w}_2^I = \frac{(\tau\eta^2-\eta+2)\phi+(\tau\eta^2+\eta)c-\tau\delta\eta^2}{2(1+\tau\eta^2)} .$$

$$\hat{p}_1^I = \frac{(4\tau\eta^2-\tau\eta+3)\phi+(\tau\eta+1)c-\tau\delta\eta}{4(1+\tau\eta^2)},$$

$$\hat{p}_2^I = \frac{(3\tau\eta^2-\eta+4)\phi+(\tau\eta^2+\eta)c-\tau\delta\eta^2}{4(1+\tau\eta^2)} .$$

$$\hat{Q}_{2r}^I = \frac{(\tau\eta^2+\eta)(\phi-c)+\tau\delta\eta^2}{4(1+\tau\eta^2)} .$$

Corollary 1. (2.1) When the recovery rate η of used product reaches 100%, the threshold of remanufacturing cost saving is zero; hence, manufacturers only employ UF-R mode in period 2, and $\hat{p}_2^I = \hat{p}_1^I$.

(2.2) Comparison between different periods in respect of product pricing: $w_2^I \geq w_1^I$, $\hat{w}_2^I \geq \hat{w}_1^I$, $p_2^I \geq p_1^I$, $\hat{p}_2^I \geq \hat{p}_1^I$; comparison of product pricing within the same period: $\hat{w}_1^I > w_1^I$, $\hat{w}_2^I < w_2^I$, $\hat{p}_1^I > p_1^I$, $\hat{p}_2^I < p_2^I$.

Proof. See the appendix.

Corollary 1 indicates that manufacturers choose production mode and determine rational product pricing based on remanufacturing cost saving. When recovery rate climbs up to 100%, it's not necessary to set different product prices for different periods. Regardless of remanufacturing cost saving, manufacturers will sell more products based on a relatively low pricing strategy in period 1 so that they can recover more products for remanufacturing in period 2; furthermore, manufacturers may set a relatively low price for remanufactured items if they manufacture no new products in period 2, especially in the UF-R mode; since remanufacturing saves more cost, the wholesale price and retail price of remanufactured products are the lowest, which facilitates the virtuous cycle of recycling & remanufacturing to a certain extent.

B. Model RF: Only the retailer is concerned about fairness

It is assumed that retailers are concerned about fairness, which is to say, retailers pay close attention to their own profits and the fairness of channel income, and that manufacturers are completely self-interested and know retailers have fair behavior tendency (i.e. Model RF). With reference to the fairness concerns utility form reported by Du et al. (2014) [15], this paper describes profit variance-induced change in utility loss by taking the other party's profit as own party's profit reference point and introducing the degree of fairness concerns , that is to say, the utility function of retailers' fairness concerns can be described as

$$U_R = \pi_R - \lambda_r(\pi_M - \pi_R). \tag{14}$$

Establish the following optimization problem

$$\max_{w_1,w_2} \pi_M(w_1, w_2)$$

$$s.t. \begin{cases} \eta Q_{1n} \geq Q_{2r} \\ Q_{2a} \geq Q_{2r} \\ \max\limits_{p_1,p_2} U_R(p_1, p_2) \end{cases}. \tag{15}$$

Where, retailer's decision-making process

$$\begin{aligned} &\max_{p_1,p_2} U_R(p_1, p_2) \\ &= \max_{p_1,p_2}\{[(1+\lambda_r)p_1 - (1+2\lambda_r)w_1 + \lambda_r c](\phi - p_1) \\ &\quad + \tau[(1+\lambda_r)p_2 - (1+2\lambda_r)w_2 + \lambda_r c](\phi - p_2) - \tau\lambda_r\delta Q_{2r}\} \end{aligned} \tag{16}$$

Solving the optimization problem above leads to the following proposition.

Proposition 2. In Model RF there is a threshold of remanufacturing cost saving $\delta^{II} = \dfrac{(1-\eta)(1+\lambda_r)(\phi - c)}{(1+2\lambda_r)\tau\eta^2}$, as a result,

(3.1) When $\delta \leq \delta^{II}$, manufacturers employ the new product-remanufactured item hybrid manufacturing mode (RF-H mode) in period 2, and the respective optimal decisions of manufacturers and retailers are:

$$w_1^{II} = \frac{(1+\lambda_r)\phi + (1+3\lambda_r)c - (1+2\lambda_r)\tau\delta\eta}{2(1+2\lambda_r)},$$

$$w_2^{II} = \frac{(1+\lambda_r)\phi + (1+3\lambda_r)c}{2(1+2\lambda_r)}.$$

$$p_1^{II} = \frac{(1+\lambda_r)(3\phi + c) - (1+2\lambda_r)\tau\delta\eta}{4(1+\lambda_r)},$$

$$p_2^{II} = \frac{3\phi + c}{4}.$$

$$Q_{2r}^{II} = \frac{\eta(1+\lambda_r)(\phi - c) + (1+2\lambda_r)\tau\delta\eta^2}{4(1+\lambda_r)},$$

$$Q_{2n}^{II} = \frac{(1-\eta)(1+\lambda_r)(\phi - c) - (1+2\lambda_r)\tau\delta\eta^2}{4(1+\lambda_r)}.$$

(3.2) When $\delta > \delta^{II}$, manufacturers only manufacture remanufactured items in period 2 (RF-R mode), and the respective optimal decisions of manufacturers and retailers are:

$$\hat{w}_1^{II} = \frac{(1+\lambda_r)(2\tau\eta^2 - \tau\eta + 1)\phi - (1+2\lambda_r)\tau\delta\eta}{2(1+2\lambda_r)(1+\tau\eta^2)} + \frac{[(2\tau\eta^2 + \tau\eta + 3)\lambda_r + (\tau\eta + 1)]c}{2(1+2\lambda_r)(1+\tau\eta^2)},$$

$$\hat{w}_2^{II} = \frac{(1+\lambda_r)(\tau\eta^2 - \eta + 2)\phi - (1+2\lambda_r)\tau\delta\eta^2}{2(1+2\lambda_r)(1+\tau\eta^2)} + \frac{[(3\tau\eta^2 + \eta + 2)\lambda_r + (\tau\eta^2 + \eta)]c}{2(1+2\lambda_r)(1+\tau\eta^2)}.$$

$$\hat{p}_1^{II} = \frac{(1+\lambda_r)(4\tau\eta^2 - \tau\eta + 3)\phi - (1+2\lambda_r)\tau\delta\eta}{4(1+\lambda_r)(1+\tau\eta^2)} + \frac{(\tau\eta + 1)c}{4(1+\tau\eta^2)},$$

$$\hat{p}_2^{II} = \frac{(1+\lambda_r)(3\tau\eta^2 - \eta + 4)\phi - (1+2\lambda_r)\tau\delta\eta^2}{4(1+\lambda_r)(1+\tau\eta^2)} + \frac{(\tau\eta^2 + \eta)c}{4(1+\tau\eta^2)}.$$

$$\hat{Q}_{2r}^{II} = \frac{(1+\lambda_r)(\tau\eta^2 + \eta)(\phi - c) + (1+2\lambda_r)\tau\delta\eta^2}{4(1+\lambda_r)(1+\tau\eta^2)}.$$

Proof. See the appendix.

Proposition 2 shows that if the cost savings of remanufacturing are relatively large, the manufacturer will not produce new products in period 2, the production volume in period 2 will be η times the production volume in period 1, and the recovered used products in period 1 will be all used for remanufacturing; if the remanufacturing cost savings are small, the manufacturer produces both remanufactured and new products in period 2, and the recovered used products are all used for remanufacturing. The retail and wholesale prices of the products in period 1 are lower than that of the products (new products or remanufactured items) in period 2. The price of remanufactured product in period 2 in the RF-H mode is higher than that of the new product. It can be seen that manufacturers and retailers can increase the recovery of period 2 by setting a lower wholesale price and retail price in period 1, thereby achieving the goal of reducing costs and increasing profits. When remanufacturing does not result in cost savings ($\delta = 0$), the wholesale and retail prices of manufacturers and retailers in periods 1 and 2 are equal, and the production of remanufactured products is equal too.

Corollary 2. Where manufacturers take into account retailers' fairness concerns (i.e. Model RF), manufacturers' wholesale price and retailers' retail price in period 1 are the decreasing function of degree of concern by retailers about fairness λ_r in RF-H mode and RF-R mode. The retail price of retailers' product in period 2 is not affected by coefficient λ_r in RF-H mode, but it's still a decreasing function of the coefficient λ_r in RF-R mode.

Proof. See the appendix.

According to Corollary 2, retailers' fairness preference helps to enhance their capability of bargaining with manufacturer in the market; as a result, with the enhancement of tendency of retailers' concern about channel fairness, retailers may force manufacturers to reduce the wholesale price of product, while retail price may go down there-with; however, the retail price of product in period 2 will not be affected by retailers' fairness concerns behavior in the hybrid production mode of new products and remanufactured items. Since the level of retailers' fairness preference is dependent on their competitive position in the market, their channel fairness preference is directly proportional to their position in the actual market; moreover, retailers normally gain more channel profits through the bargain with manufacturer, which demonstrates fairness concerns behavior is an effective means of gaining supply chain profit allocation by retailers.

C. Model MRF: Both channel members are concerned about fairness

If manufacturers and retailers both are concerned about fairness, which is to say, they pay close attention to the fairness of channel income (i.e. Model MRF), then manufacturers' optimization problem should be

$$\max_{w_1,w_2} U_M(w_1, w_2)$$

$$s.t. \begin{cases} \eta Q_{1n} \geq Q_{2r} \\ Q_{2a} \geq Q_{2r} \\ \max\limits_{p_1,p_2} U_R(p_1, p_2) \end{cases} . \tag{17}$$

Where,

$$U_M(w_1, w_2) = \pi_M - \lambda_m(\pi_R - \pi_M)$$
$$= [(1+2\lambda_m)w_1 - \lambda_m p_1 - \lambda_m c - c](\phi - p_1) + (1+\lambda_m)\tau\delta Q_{2r}$$
$$+\tau[(1+2\lambda_m)w_2 - \lambda_m p_2 - \lambda_m c - c](\phi - p_2) \cdot$$

Retailer's decision-making process

$$\max_{p_1,p_2} U_R(p_1, p_2). \tag{18}$$

Seek first-order optimization condition for Equation (18), and obtain retailer's optimum response function

$$\tilde{p}_1 = \frac{\phi}{2} + \frac{(1+2\lambda_r)w_1 - \lambda_r c}{2(1+\lambda_r)},$$
$$\tilde{p}_2 = \frac{\phi}{2} + \frac{(1+2\lambda_r)w_2 - \lambda_r c}{2(1+\lambda_r)}. \tag{19}$$

The Lagrange function established after substituting Equation (19) is as follows

$$L(w_1, w_2, Q_{2r}, u_1, u_2)$$
$$= \left((1+2\lambda_m)w_1 - \lambda_m[\frac{\phi}{2} + H_1] - \lambda_m c - c\right)[\frac{\phi}{2} - H_1]$$
$$+\tau\left((1+2\lambda_m)w_2 - \lambda_m[\frac{\phi}{2} + H_2] - \lambda_m c - c\right)[\frac{\phi}{2} - H_2]$$
$$+(1+\lambda_m)\tau\delta Q_{2r} + u_1\left(\eta[\frac{\phi}{2} - H_1] - Q_{2r}\right)$$
$$+u_2\left([\frac{\phi}{2} - H_2] - Q_{2r}\right)$$

Where,

$H_1 = \dfrac{(1+2\lambda_r)w_1 - \lambda_r c}{2(1+\lambda_r)}$, and $H_2 = \dfrac{(1+2\lambda_r)w_2 - \lambda_r c}{2(1+\lambda_r)}$.

Similarly to above-noted discussion about models, Proposition 3 can be obtained by seeking the solution using KKT optimization condition (proving omitted).

Proposition 3. In Model MRF there is a threshold of remanufacturing cost saving

$$\delta^{III} = \frac{(1+\lambda_m+\lambda_r)(1-\eta)(\phi - c)}{(1+\lambda_m)(1+2\lambda_r)\tau\eta^2},$$

As a result,

(4.1) When $\delta \leq \delta^{III}$, manufacturers employ the new product-remanufactured item hybrid manufacturing mode (MRF-H mode) in period 2, and the respective optimal decisions of manufacturers and retailers are:

$$w_1^{III} = \frac{\phi + 3c + 2\lambda_m(\phi + c) - 2\tau\delta\eta(1+\lambda_m)}{4(1+\lambda_m)} + \frac{\phi - c}{4(1+2\lambda_r)}$$
$$+\frac{2\lambda_m\tau\delta\eta(1+\lambda_m) - \lambda_m^2(\phi - c)}{4(1+\lambda_m)(3\lambda_m + 2\lambda_r + 2\lambda_m\lambda_r + 2)},$$

$$w_2^{III} = \frac{\phi + 3c + 2\lambda_m(\phi + c)}{4(1+\lambda_m)} + \frac{\phi - c}{4(1+2\lambda_r)}$$
$$-\frac{\lambda_m^2(\phi - c)}{4(1+\lambda_m)(3\lambda_m + 2\lambda_r + 2\lambda_m\lambda_r + 2)}.$$

$$p_1^{III} = \frac{5\phi + c + 4\lambda_r\phi - \tau\delta\eta(1+2\lambda_r)}{2(3+2\lambda_r)}$$
$$-\frac{(1+2\lambda_r)[(1+\lambda_r)(\phi - c) + \tau\delta\eta]}{2(3+2\lambda_r)(3\lambda_m + 2\lambda_r + 2\lambda_m\lambda_r + 2)},$$

$$p_2^{III} = \frac{(1+\lambda_r)(4\lambda_m\phi + 3\phi + c) + \lambda_m(\phi + c)}{2(3\lambda_m + 2\lambda_r + 2\lambda_m\lambda_r + 2)}.$$

$$Q_{2r}^{III} = \frac{\eta(1+\lambda_m+\lambda_r)(\phi - c) + \tau\delta\eta^2(1+\lambda_m)(1+2\lambda_r)}{2(3\lambda_m + 2\lambda_r + 2\lambda_m\lambda_r + 2)},$$

$$Q_{2n}^{III}=\frac{(1+2\lambda_m)[2\tau\delta\eta^2(1+\lambda_m)+\lambda_m(1-\eta)(\phi-c)]}{4(1+\lambda_m)(3\lambda_m+2\lambda_r+2\lambda_m\lambda_r+2)}-\frac{2\tau\delta\eta^2(1+\lambda_m)-(1-\eta)(\phi-c)}{4(1+\lambda_m)}.$$

(4.2) When $\delta>\delta^{III}$, manufacturers only manufacture remanufactured items in period 2 (MRF-R mode), and the respective optimal decisions of manufacturers and retailers are:

$$\hat{w}_1^{III}=\frac{\phi+3c+2\lambda_m(\phi+c)-2u_1^{III}\eta}{4(1+\lambda_m)}+\frac{\phi-c}{4(1+2\lambda_r)}+\frac{2\lambda_m u_1^{III}\eta-\lambda_m^2(\phi-c)}{4(1+\lambda_m)(3\lambda_m+2\lambda_r+2\lambda_m\lambda_r+2)},$$

$$\hat{w}_2^{III}=\frac{\phi+3c+2\lambda_m(\phi+c)-2u_2^{III}/\tau}{4(1+\lambda_m)}+\frac{\phi-c}{4(1+2\lambda_r)}+\frac{2\lambda_m u_2^{III}/\tau-\lambda_m^2(\phi-c)}{4(1+\lambda_m)(3\lambda_m+2\lambda_r+2\lambda_m\lambda_r+2)}.$$

$$\hat{p}_1^{III}=\frac{(1+\lambda_m+\lambda_r)(3\phi+c)+(1+2\lambda_r)(2\lambda_m\phi-u_1^{III}\eta)}{2(3\lambda_m+2\lambda_r+2\lambda_m\lambda_r+2)},$$

$$\hat{p}_2^{III}=\frac{3\phi+c+4\lambda_m\phi-2u_2^{III}/\tau}{4(1+\lambda_m)}+\frac{(1+2\lambda_m)[2u_2^{III}/\tau-\lambda_m(\phi-c)]}{4(1+\lambda_m)(3\lambda_m+2\lambda_r+2\lambda_m\lambda_r+2)}.$$

$$\hat{Q}_{2r}^{III}=\frac{(1+\lambda_m+\lambda_r)(\phi-c)+(1+2\lambda_r)u_2^{III}/\tau}{2(3\lambda_m+2\lambda_r+2\lambda_m\lambda_r+2)}.$$

Where,

$$u_1^{III}=\frac{2\tau\delta(1+\lambda_m)+\tau(1-\eta)(\phi-c)}{2(1+\tau\eta^2)}+\frac{\tau(1+2\lambda_m)(1-\eta)(\phi-c)}{2(1+2\lambda_r)(1+\tau\eta^2)},$$

$$u_2^{III}=\frac{2\tau^2\delta\eta^2(1+\lambda_m)-\tau(1-\eta)(\phi-c)}{2(1+\tau\eta^2)}-\frac{\tau(1+2\lambda_m)(1-\eta)(\phi-c)}{2(1+2\lambda_r)(1+\tau\eta^2)}.$$

Corollary 3. (5.1) Models RF and MRF can be regarded as the extension of Model UF. Moreover, Model MRF could also be taken as the extension of Model RF.

(5.2) The following relation is true between thresholds of the remanufacturing cost saving in Models UF, RF and MRF: $\delta^{I}\geq\delta^{II}\geq\delta^{III}$.

Proof. See the appendix.

It is observed from Corollary 3 that Models RF and MRF degenerate to Model UF if manufacturers and retailers are fair and neutral - this special case is consistent with the research findings of Debo et al. (2005) [28]. Whether upstream and downstream enterprises are concerned about the fairness of channel income or not, remanufacturing cost saving can affect the selection of production mode by manufacturer. The highest threshold of remanufacturing cost saving is observed without fairness concerns, which means the quantity of recycling & remanufacturing by manufacturers decreases correspondingly when retailers pay no attention to the fairness of channel income. The lowest threshold of remanufacturing cost saving is observed when manufacturers and retailers tend to get concerned about fairness, in which case manufacturers relax the threshold conditions for recycling & remanufacturing to a certain extent, which helps to improve the output of remanufactured items. Hence, supply chain members' concern about the fairness of channel income can drive manufacturers to produce more remanufactured items so as to reduce production costs and guarantee the gain of their own profits.

IV. EXAMPLE ANALYSIS

The model results are further explained and analyzed below through numerical examples. Assume model parameters: $\phi=100$, $c=20$, $\tau=0.95$, $\eta=0.9$, $\lambda_r=0.2$, $\lambda_m=0.7$. The thresholds of remanufacturing cost saving in the three models: $\delta^{I}=10.3946$, $\delta^{II}=8.9112$, and $\delta^{III}=8.2996$. Figs. 1-6 show the change in wholesale price, retail price and output of products in the three models determined through sensitivity analysis of remanufacturing cost saving δ with a step size of 2.

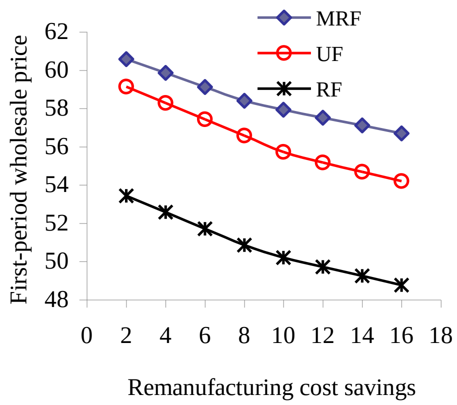

Fig. 1 First-period wholesale prices vs. δ

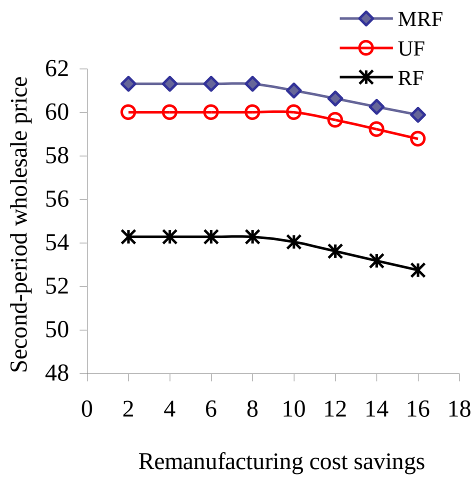

Fig. 2 Second-period wholesale prices vs. δ

As shown in Figs. 1-4, the prices of products in periods 1 and 2 decrease with the increase in remanufacturing cost saving δ , but why does the price of products in period 1 where only new products are manufactured decrease with δ ? It's easy to find based on the result of Corollary 1 (2.2) that manufacturers sell more products at low prices in period 1 so as to recover more products for remanufacturing, thereby making better use of cost saving to improve profits. Figs. 5-6 just corroborates this argument: The output of new product in period 2 is relatively low and decreases with the increase of δ , while the output of remanufactured item increases sharply there-with. Moreover, with the increase of δ value, the selling price of product in period 2 does not decrease unless a certain threshold is exceeded; when manufacturers and retailers tend to get concerned about fairness (Model MRF) simultaneously, the selling price of product is the highest while the output of corresponding remanufactured item is the lowest. So it is obvious that supply chain members' paying close attention to the fairness of channel income at the same time is disadvantageous for the pricing and manufacturing of recovered & remanufactured products.

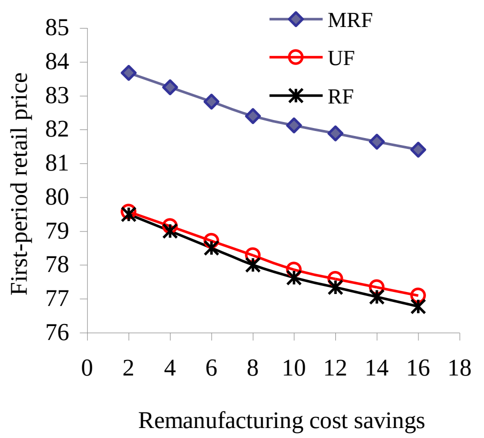

Fig. 3 First-period retail prices vs. δ

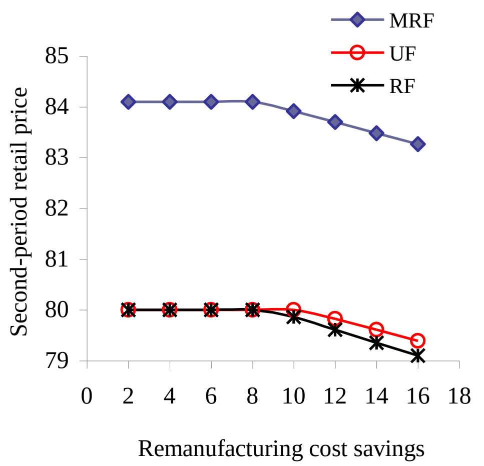

Fig. 4 Second-period retail prices vs. δ

To figure out the effect of degree of fairness concerns on supply chain members and system profits, it's advisable to have other parameter assignments unchanged and assume $\delta = 10$; Figs. 7-8 show the profit change determined for Model RF through sensitivity analysis of the degree of fairness concerns λ_r performed with a step size of 0.2.

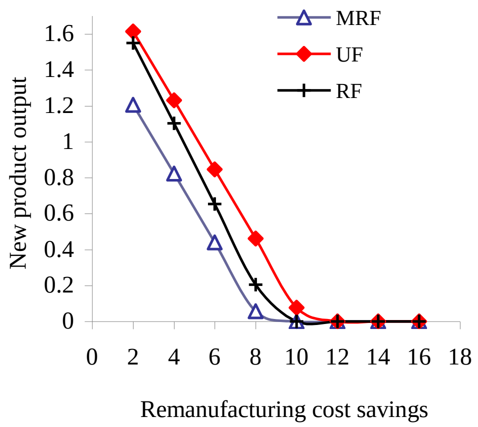

Fig. 5 New product output in period 2 vs. δ

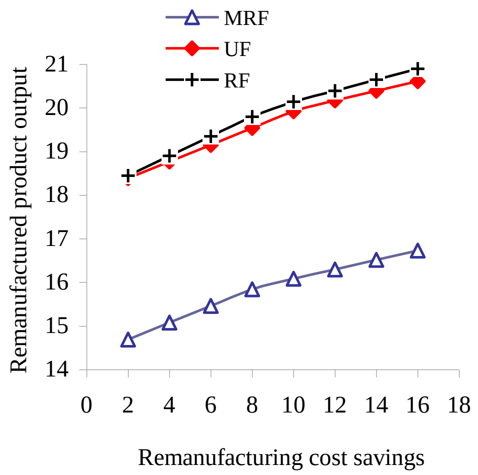

Fig. 6 Remanufactured product output in period 2 vs. δ

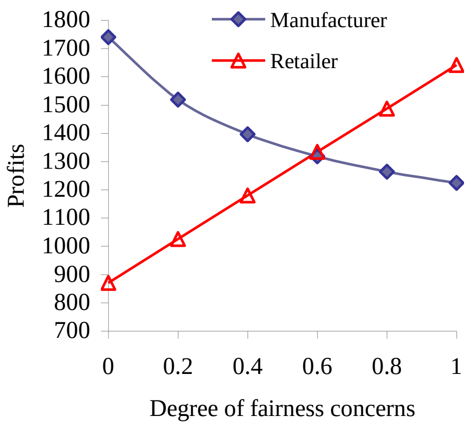

Fig. 7 Members' profits vs. λ_r （Model RF）

According to Figs. 7-8, if manufacturers take no account of fairness concerns, their profits exhibit a tendency of degression with the increase of degree of fairness concerns λ_r by retailers, while retailers' fairness concerns utility increases by degrees there-with; moreover, the profit of supply chain system steps up. It is evident that the system profit in the case without fairness concerns is obtained at $\lambda_r = 0$; it's observed that the system profit is not higher than that in the case without fairness concerns unless the degree of fairness concerns $\lambda_r > 0.5$ by retailers; this demonstrates that the degree of fairness concerns by retailers is directly proportional to their channel profits, of which the improvement facilitates the enhancement of supply chain system profits.

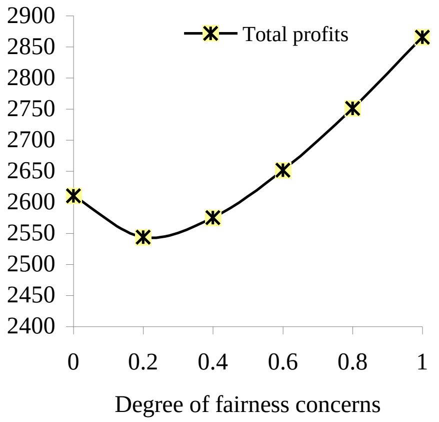

Fig. 8 Total profits vs. λ_r (Model RF)

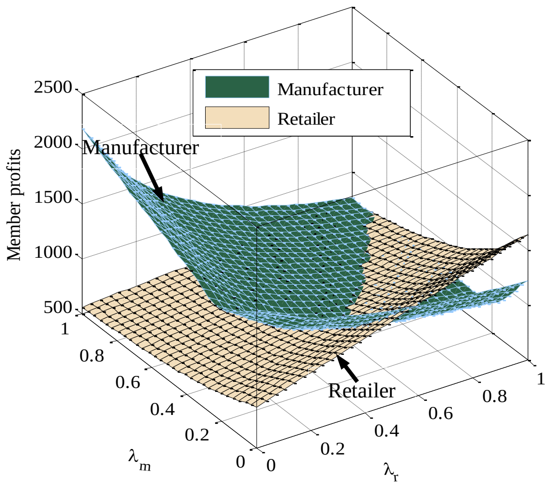

Fig. 9 Members' profits vs. λ_r & λ_m (Model MRF)

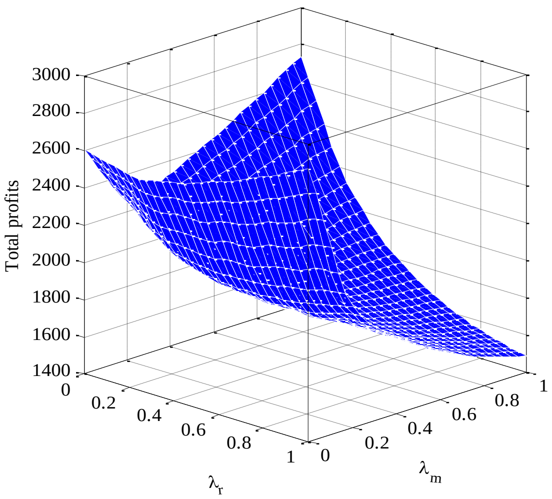

Fig. 10 Total profits vs. λ_r & λ_m (Model MRF)

Then, the effect of change in degree of fairness concerns λ_r and λ_m on supply chain members and system profit is studied for Model MRF (See Figs. 9-10). In addition, since manufacturers and retailers' profit change curves meet at $\lambda_r = 0.6$ according to Fig. 7, the change in degree of fairness concerns λ_m on profit is analyzed with $\lambda_r = 0.6$ all the time (See Figs. 11-12).

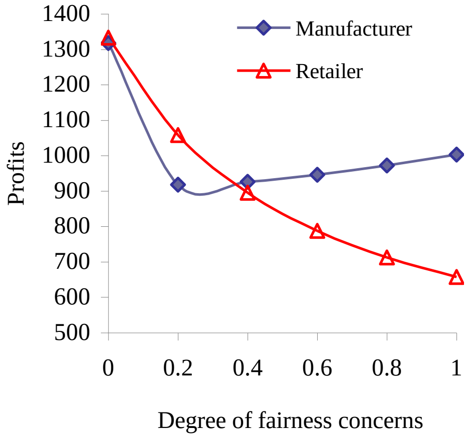

Fig. 11 Members' profits vs. λ_m (Model MRF)

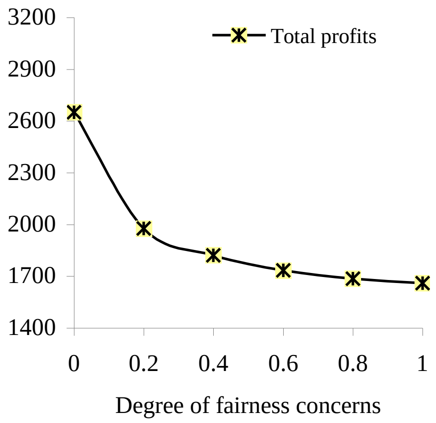

Fig. 12 Total profits vs. λ_m (Model MRF)

According to Figs. 9-12, when manufacturers and retailers pay close attention to the fairness of channel income simultaneously, the party with higher degree of fairness concerns obtains more fairness concerns utility; however, the overall income of closed-loop supply chain system will get impaired and gradually fall below the system profit determined without fairness concerns with the improvement in the degree of fairness concerns by both parties. According to the trend of profit concave surface as shown in Fig. 10, the condition under which only one side of supply chain members tends to get concerned about fairness is the most advantageous for system benefit, because the fact that this members is the gamer concerning about fairness will force the other member to participate in the game and optimize the decision-making so as to get more channel profit; furthermore, the higher the degree of fairness concerns by one side, the more obvious the stimulating effect on the other side, and the more favorable the system benefit; the system profit rising curve in Fig. 8 adequately demonstrates this argument. In general, all supply chain members' showing high degree of fairness concerns is extremely disadvantageous for the channel performance of closed-loop supply chain system.

V. Conclusion

This paper studies the production mode and product pricing of two-period closed-loop supply chain under fairness concerns, presents the thresholds of remanufacturing cost saving in three different models, probes into the effect of remanufacturing cost saving on the selection of production mode in the three models, as well as the equilibrium pricing of multi-period new product and remanufactured item in different production modes. According to the research findings, whether upstream and downstream enterprises are concerned about the fairness of channel income or not, remanufacturing cost saving can affect the selection of production mode by manufacturer under multi-period circumstances. When only one side of closed-loop supply chain members exhibits a high degree of fairness concerns, it's advantageous for the production and pricing of recovered & remanufactured products, in which case the period-specific production mode and product pricing are affected by the degree of fairness concerns and the threshold of remanufacturing cost saving. For example, retailer's unilateral fairness concerns behavior helps to effectively reduce the wholesale price and retail price of product, and is the most advantageous for system performance; it enhances the ability of retailers to bargain with manufacturers in the market, constituting an effective means for retailers to achieve supply chain profit allocation. By contrast, both sides' exhibiting high fairness concerns tendency impairs the channel performance of supply chain system. Added to this, when the recovery rate of used products is relatively high, it's not necessary to set product prices for different periods. Relevant conclusions are useful as a reference for making decisions regarding the promotion of enterprises' recycling & remanufacturing operations and closed-loop supply chain management.

Appendix

Proof in Sub-section A

Proof of Corollary 1. (2.1) According to the result of Proposition 1, when $\eta=1$, the remanufacturing cost saving threshold $(1-\eta)(\phi-c)/\tau\eta^2=0$; since Equation (13) indicates $\delta>0$, manufacturers only employ remanufacturing mode in period 2.

Here, $\hat{p}_2^I=\hat{p}_1^I=[(\tau+1)(3\phi+c)-\tau\delta]/4(1+\tau)$.

(2.2) Based on the optimal decision result of manufacturers and retailers in UF-H mode and UF-R mode, it is obvious that

$$w_2^I-w_1^I=\tau\delta\eta/2\geq 0,$$

$$\hat{w}_2^I-\hat{w}_1^I=[(1-\eta)(1+\tau\eta)(\phi-c)+(1-\eta)\tau\delta\eta]/2(1+\tau\eta^2)\geq 0,$$

$$p_2^I-p_1^I=\tau\delta\eta/4\geq 0,$$

$$\hat{p}_2^I-\hat{p}_1^I=[(1-\eta)(1+\tau\eta)(\phi-c)+(1-\eta)\tau\delta\eta]/4(1+\tau\eta^2)\geq 0.$$

and

$$\hat{w}_1^I-w_1^I=\tau\eta[\tau\delta\eta^2-(1-\eta)(\phi-c)]/2(1+\tau\eta^2),$$

$$\hat{p}_1^I-p_1^I=\tau\eta[\tau\delta\eta^2-(1-\eta)(\phi-c)]/4(1+\tau\eta^2),$$

$$\hat{w}_2^I-w_2^I=-[\tau\delta\eta^2-(1-\eta)(\phi-c)]/2(1+\tau\eta^2),$$

$$\hat{p}_2^I-p_2^I=-[\tau\delta\eta^2-(1-\eta)(\phi-c)]/4(1+\tau\eta^2).$$

Since the remanufacturing cost saving in UF-R mode $\delta>(1-\eta)(\phi-c)/\tau\eta^2$,

$\hat{w}_1^I-w_1^I>0$, $\hat{p}_1^I-p_1^I>0$, and $\hat{w}_2^I-w_2^I<0$, $\hat{p}_2^I-p_2^I<0$.

Proof in Sub-section B

Proof of Proposition 2. First of all, with respect to Eq. (16), we can solve the following simultaneous equations from the first-order conditions of the maximization problem of the retailer

$$\partial U_R/\partial p_1=0,\ \partial U_R/\partial p_2=0.$$

Therefore, the best response function of the retailer can be given as follows

$$\tilde{p}_1=\frac{\phi}{2}+\frac{(1+2\lambda_r)w_1-\lambda_r c}{2(1+\lambda_r)},$$

$$\tilde{p}_2=\frac{\phi}{2}+\frac{(1+2\lambda_r)w_2-\lambda_r c}{2(1+\lambda_r)}. \quad \text{(A1)}$$

Then, substituting Eq. (A1) into Eq. (15), similarly to the analysis of Model UF, the Lagrange function can be expressed as follows

$$\begin{aligned}&L(w_1,w_2,Q_{2r},u_1,u_2)\\&=(w_1-c)[\frac{\phi}{2}-H_1]+\tau[(w_2-c)[\frac{\phi}{2}-H_2]+\delta Q_{2r}]\\&+u_1\left(\eta[\frac{\phi}{2}-H_1]-Q_{2r}\right)+u_2\left([\frac{\phi}{2}-H_2]-Q_{2r}\right).\end{aligned}$$

Correspondingly, the KKT conditions are given below

$$\partial L_1/\partial w_1=\partial L_1/\partial w_2=0 \quad \text{(A2)}$$

$$\partial L_1/\partial Q_{2r}=\tau\delta-u_1-u_2=0 \quad \text{(A3)}$$

$$u_1\left(\eta[\frac{\phi}{2}-\frac{(1+2\lambda_r)w_1-\lambda_r c}{2(1+\lambda_r)}]-Q_{2r}\right)=0 \quad \text{(A4)}$$

$$u_2\left([\frac{\phi}{2}-\frac{(1+2\lambda_r)w_2-\lambda_r c}{2(1+\lambda_r)}]-Q_{2r}\right)=0 \quad \text{(A5)}$$

Solving Eq. (A2), we can get

$$w_1=\frac{(1+\lambda_r)\phi+(1+3\lambda_r)c-(1+2\lambda_r)u_1\eta}{2(1+2\lambda_r)},$$

$$w_2=\frac{(1+\lambda_r)\phi\tau+(1+3\lambda_r)\tau c-(1+2\lambda_r)u_2}{2\tau(1+2\lambda_r)}. \quad \text{(A6)}$$

Recalling Eq. (A3), we have $\tau\delta=u_1+u_2$. The following discussion is launched based on Lagrange multiplier $u_1\geq 0$ and $u_2\geq 0$.

(3.1) RF-H mode: When $u_2=0$ and $u_1=\tau\delta$, manufacturers produce new products and remanufactured items simultaneously in period 2. Here, w_1^{II}, w_2^{II}, p_1^{II}, and p_2^{II} are obtained based on Equations (A6) and (17), and

Q_{2r}^{II} and Q_{2n}^{II} are obtained by substituting w_1^{II} and w_2^{II} into (A4). To ensure $Q_{2r}^{II} \geq 0$ and $Q_{2n}^{II} \geq 0$, the remanufacturing cost saving must meet the condition below

$$\delta \leq \frac{(1-\eta)(1+\lambda_r)(\phi-c)}{(1+2\lambda_r)\tau\eta^2}.$$

That is to say, conclusion (3.1) of Proposition 2 is tenable.

(3.2) RF-R mode: When $u_2 = \tau\delta - u_1 > 0$ and $u_1 > 0$, manufacturers only produce remanufactured items in period 2. Arrange KKT optimization conditions (A2)-(A5) to obtain the following equations

$$u_1^{II} = \frac{\tau(1+\lambda_r)(1-\eta)(\phi-c)+(1+2\lambda_r)\tau\delta}{(1+2\lambda_r)(1+\tau\eta^2)},$$

$$u_2^{II} = \frac{(1+2\lambda_r)\tau^2\delta\eta^2 - \tau(1+\lambda_r)(1-\eta)(\phi-c)}{(1+2\lambda_r)(1+\tau\eta^2)}.$$

Where, the remanufacturing cost saving $\delta > \frac{(1-\eta)(1+\lambda_r)(\phi-c)}{(1+2\lambda_r)\tau\eta^2}$ is obtained based on the fact that $u_1^{II} > 0$ and $u_2^{II} > 0$.

Conclusion (3.2) of Proposition 2 proves to be tenable by substituting results u_1^{II} and u_2^{II} back to KKT optimization conditions.

Proof of Corollary 2. It is obvious that, based on the optimum strategy of Proposition 2

$$\frac{\partial w_1^{II}}{\partial \lambda_r} = -\frac{\phi-c}{2(1+2\lambda_r)^2} = \frac{\partial w_2^{II}}{\partial \lambda_r} < 0,$$

$$\frac{\partial p_1^{II}}{\partial \lambda_r} = -\frac{\tau\delta\eta}{4(1+\lambda_r)^2} < 0,\ \frac{\partial p_2^{II}}{\partial \lambda_r} = 0.$$

$$\frac{\partial \hat{w}_1^{II}}{\partial \lambda_r} = -\frac{(2\tau\eta^2-\tau\eta+1)(\phi-c)}{2(1+\tau\eta^2)(1+2\lambda_r)^2} = \frac{\partial \hat{w}_2^{II}}{\partial \lambda_r} < 0,$$

$$\frac{\partial \hat{p}_1^{II}}{\partial \lambda_r} = -\frac{\tau\delta\eta}{4(1+\tau\eta^2)(1+\lambda_r)^2} < 0,$$

$$\frac{\partial \hat{p}_2^{II}}{\partial \lambda_r} = -\frac{\tau\delta\eta^2}{4(1+\tau\eta^2)(1+\lambda_r)^2} < 0.$$

Proof in Sub-section C

Proof of Corollary 3. (5.1) By substituting $\lambda_m = \lambda_r = 0$ into the optimal decision results of Models RF and MRF, and making comparison with the result of Model UF respectively, it is observed that Model UF is a special case of Model RF when $\lambda_r = 0$, and a special case of Model MRF when $\lambda_m = \lambda_r = 0$. In like manner, by substituting $\lambda_m = 0$ into Model MRF and making comparison with the result of Model RF, it is observed that Model MRF is also the extension of Model RF.

(5.2) Since $\delta^I - \delta^{II} = \frac{(1-\eta)(\phi-c)\lambda_r}{(1+2\lambda_r)\tau\eta^2} \geq 0$, and due to the fact that

$$\delta^{II} - \delta^{III} = \frac{\lambda_m\lambda_r(1-\eta)(\phi-c)}{(1+\lambda_m)(1+2\lambda_r)\tau\eta^2} \geq 0,$$

$\delta^I \geq \delta^{II} \geq \delta^{III}$.

Hence, Corollary 3 is tenable.

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