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Decision models of Multi Periods Closed Loop Supply Chain with Remanufacturing under Centralized and Decentralized Decision Making

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Abstract. The closed-loop supply chains for new products and remanufactured products under uncertain demand are studied. Considering the differences in consumers' "willingness to pay (WTP)" for new products and remanufactured products, the decision models of multi-period closed-up supply chain with remanufacturing under centralized and decentralized decision making are established respectively and optimal decision of each member of the supply chain is obtained. Through comparison between differences in the consumers' WTP for the two types of products, three closed-loop supply chains are established under the condition of the government's reward and punishment mechanism. The game model and numerical experiment dominated by various manufacturers are elaborately analyzed, the interest coordination mechanism is confirmed with Shapley Value Method, and the model is solved and dissected through numerical simulation. The research results show there is benefit loss under decentralized decision making, and a reduction of middlemen can effectively improve benefits of the supply chain. The benefits of closed-loop supply chain with remanufacturing can be distributed with Shapley Value in a rational and effective manner.

Keywords: Closed-loop supply chain, WTP Differentiation, Closed-loop supply chain, Remanufacturing, Reward and punishment mechanism

1 Introduction

Currently, as the contradiction between global resources and environment increasingly intensified, countries in the world put more emphasis on sustainable development and circular economy, and have passed laws successively to enhance and extend the awareness and responsibility for recycling waste products [1]. The operation mode of closed-loop supply chain incorporating traditional forward supply chain and reverse supply chain has become the research hotspot in business circles and academic circles. Decision problems of the traditional supply chain belong to the decentralized decision making. Each enterprise makes the best decisions given the available information without achieving Pareto optimal state. Mutual cooperation among enterprises is needed to realize profit maximization of the entire closed-loop supply chain system, and a reasonable and effective interest coordination mechanism

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will exert direct influence on the operation efficiency of closed-loop supply chain under centralized decision-making. Savaskan conducted a game analysis on problem of the optimal channel structure [1]. Wang Yuyan studied the closed-loop supply chain comprised of a single manufacture and an exclusive retailer, and presented a profit share mechanism distributed by proportion of the system gain [2]. Later on, Wang Yuyan researched the coordination of closed-loop supply chain aimed at recycling mode of the third party – recyclable waste collector, which showed that a greater cooperation among insiders of the closed-loop supply chain can bring more profits through the channel [3]. Sheng Fangzheng discussed the rational benefit allocation method of two-echelon supply chain including a supplier and several retailers [4]. Wang Li constructed the “multi-directional and principal-subordinate mode” three-echelon supply chain and quantitatively analyzed the downstream cooperation profit allocation mechanism [5].

2 Model design

2.1. Decision-making analysis under decentralized decision making

Given the assumptions above, pursuit for profit maximization is set as the decision goal for members of the supply chain, and the manufacturer, the distributer and the retailer constitute a three-stage Stackelberg Game. First of all, the retailer confirms the optimal retail price of new products and remanufactured products are p_{1n}, p_{2n} and p_r in the light of the distributor’s wholesale price w_{1D}, w_{2D} and w_{rD}. Then, the distributor determines the wholesale price depending on order quantity of the retailer and ex-factory price of the manufacturer. Finally, the manufacturer makes the best ex-factory price w_{1S}, w_{2S} and w_{rS} according to cost of production and order quantity.

On account that the retailer merely markets the new products and remanufacturing products, the optimal decision problem of gross profit π_R^D for the retailer within two periods is:

$$\max_{p_{1n},p_{2n},p_r} \pi_R^D = (p_{1n} - w_{1D})q_{1n} + (p_{2n} - w_{2D})q_{2n} + (p_r - w_{rD})q_r$$

Plug the demand function in assumption 3 into the above equation:

$$\max_{p_{1n},p_{2n},p_r} \pi_R^D = (p_{1n} - w_{1D})(1 - p_{1n}) + (p_{2n} - w_{2D})(1 - \frac{p_{2n} - p_r}{1-\beta}) + (p_r - w_{rD})\frac{p_r - \beta p_{2n}}{\beta(\beta - 1)} \quad (1)$$

Evaluate the first-order partial derivatives of p_{1n}, p_{2n} and p_r in equation (1), make them equal to zero, and get response function of the retailer about the wholesale price w_{1D}, w_{2D} and w_{rD}:

$$p_{1n}=\frac{1+w_{1D}}{2}, p_{2n}=\frac{1+w_{2D}}{2}, p_r=\frac{\beta+w_{rD}}{2}$$

Later on, the distributor sets the best wholesale price of products in line with the retailer's decision-making and the gross profit π_D^D can be indicated by:

$$\max_{w_{1D},w_{2D},w_{rD}} \pi_D^D=(w_{1D}-w_{1S})q_{1n}+ (w_{2D}-w_{2s})q_{2n}+(w_{rD}-w_{rS})q_r \qquad (2)$$

Substitute the demand function and the retailer's response function in assumption 3 into equation (2), evaluate the first-order partial derivatives of w_{1D}, w_{2D} and w_{rD}, make them equal to zero, and get the response function of distributor about the ex-factory price w_{1D}, w_{2D} and w_{rD}:

$$w_{1D}=\frac{1+w_{1S}}{2}, w_{2D}=\frac{1+w_{2S}}{2}, w_{rD}=\frac{\beta+w_{rS}}{2}$$

At last, the manufacturer recycles and remanufactures the new products and EOL products on the basis of the distributor's decision-making, and the gross profits π_M^D can be indicated by:

$$\max_{w_{1S},w_{2S},w_{rS},\theta} \pi_M^D=(w_{1S}-c_n)q_{1n}+(w_{2S}-c_n)q_{2n} +(w_{rS}-c_r)q_r-B\theta^2-A\theta q_{1n} \qquad (3)$$

Similarly, plug the demand function and the distributor's response function in assumption 3 into equation (3), evaluate the first-order partial derivatives of w_{1S}, w_{2S}, w_{rS} and θ, make them equal to zero, then:

$$w_{1S}^{D*}=\frac{A^2-8B(1+c_n)}{A^2-16B}, w_{2S}^{D*}=\frac{1+c_n}{2},$$
$$w_{rS}^{D*}=\frac{\beta+c_r}{2}, \theta^{D*}=\frac{(1-c_n)A}{A^2-16B}$$

Substitute the above equation into the distributor's response function, then:

$$w_{1D}^{D*}=\frac{1}{2}+\frac{A^2-8B(1+c_n)}{2(A^2-16B)}, w_{2D}^{D*}=\frac{3+c_n}{4}, w_{rD}^{D*}=\frac{3\beta+c_r}{4}$$

Similarly, plug the above equation into the retailer's response equation, then:

$$p_{1n}=\frac{3}{4}+\frac{A^2-8B(1+c_n)}{4(A^2-16B)}, p_{2n}=\frac{7+c_n}{8}, p_r=\frac{7\beta+c_r}{8}$$

Profits of the manufacturer, the distributor, the retailer and the entire closed-loop supply chain with remanufacturing system can be further obtained:

$$\pi_M^{D*}=\frac{(\beta c_n-c_r)^2}{16\beta(1-\beta)}+\frac{(1-c_n)^2}{16}-\frac{B(1-c_n)^2}{A^2-16B},$$

$$\pi_D^{D*}=\frac{(\beta c_n-c_r)^2}{32\beta(1-\beta)}+\frac{(1-c_n)^2}{32}+\frac{8B^2(1-c_n)^2}{(A^2-16B)^2},$$

$$\pi_R^{D*} = \frac{(\beta c_n - c_r)^2}{64\beta(1-\beta)} + \frac{(1-c_n)^2}{64} + \frac{4B^2(1-c_n)^2}{(A^2-16B)^2},$$
$$\pi_T^{D*} = \frac{7(\beta c_n - c_r)^2}{64\beta(1-\beta)} + \frac{7(1-c_n)^2}{64}$$
$$-\frac{(A^2-28B)B(1-c_n)^2}{(A^2-16B)^2}; \tag{4}$$

2.2 Decision-making under centralized decision making

Under decentralized decision making, members of the supply chain solely make an effort to maximize their profits, in which case the whole supply chain may not achieve the profit maximization. Under centralized decision making (model C), the manufacturer, the distributor and the retailer will make decisions as a whole to fulfill the decision goal of maximizing total profits of the remanufacturing closed-loop supply chain. Under this circumstance, the decision problem can be indicated by:

$$\max_{p_{1n}, p_{2n}, p_r, \theta} \pi_T^C = (p_{1n} - c_n)q_{1n} + (p_{2n} - c_n)q_{2n} + (p_r - c_r)q_r - B\theta^2 - A\theta q_{1n} \tag{5}$$

Plug the demand function in assumption 3 into equation (5), evaluate the first-order partial derivatives of p_{1n}, p_{2n}, p_{2n} and w_{rD}, and make them equal to zero, then:

$$p_{1n}^{C*} = \frac{A^2 - 2B(1+c_n)}{A^2 - 4B}, p_{2n}^{C*} = \frac{1+c_n}{2},$$
$$p_r^{C*} = \frac{\beta + c_r}{2}, \theta^{C*} = \frac{A(1-c_n)}{A^2 - 4B}$$

Substitute the equation above into equation (5) and acquire profits of the entire closed-loop supply chain with remanufacturing:

$$\pi_T^{C*} = \frac{(\beta c_n - c_r)^2}{4\beta(1-\beta)} + \frac{(1-c_n)^2}{4} - \frac{B(1-c_n)^2}{A^2 - 4B}, \tag{6}$$

2.3 Interest coordination mechanism

Under centralized decision making, a reasonable and effective interest coordination mechanism is required to please each member of the supply chain. Because Shapley Value Method must be of the unique solution and is easy to be quantitatively calculated, it is most widely used in game theory, economics and other social studies. Profits of the closed-loop supply chain with remanufacturing will be allocated rationally with Shapley Value Method in this paper.

Suppose the cooperative game $\eta = (N, v)$ wherein $N = \{1,2\cdots,n\}$ refers to a set of participants and n is an integer referring to number of participants. S is the subset of N and refers to the alliance of participants, i.e. $S \subseteq N$. v is an eigenfunction each alliance S in N wants to correspond; $v(S)$ refers to the obtainable utility when the members in alliance S work together; $v(S/i)$ refers to the gettable utility when the member i is removed under the cooperation S. Shapley Values for obtainable utility of each participant under the cooperation N are:

$$\psi_i(v) = \sum_{S\subseteq N, i\subseteq S} \gamma_n(s)(v(S) - v(S/i)), \quad i = 1,2\cdots n$$

Wherein $\gamma_n(s) = ((s-1)!(n-s)!)/n!$, $\psi_i(v)$ refers to the gettable utility of member i under the cooperation N.

$n = 3$ in the game model in this paper. The alliances the manufacturers participate in are $\{M\},\{M,D\},\{M,D,R\}$; the alliances the distributors participate in are $\{D\},\{M,D\},\{D,R\},\{M,D,R\}$; the alliances the retailers participate in are $\{R\},\{D,R\},\{M,D,R\}$. On account that manufacturer M cannot form an alliance with retailer R, $v(\{M,R\})$ are the total profits of manufacturer M and retailer R under decentralized decision-making. Centralized and decentralized decision-making have been discussed above and now it comes to the analysis on decision-making when the manufacturer and the distributor ally, and the distributor and the retailer ally.

3 Conclusions

Based on differences of consumers' WIP for the new products and the remanufactured products, the optimal decision-making of members of the supply chain are respectively researched under centralized and decentralized decision making with multi-period closed-loop supply chain with remanufacturing as the object of study. The benefits of entire closed-loop supply chain with remanufacturing are allocated under centralized decision-making with Shapley Value Method. The study results indicate that centralized decision-making under which Pareto optimal state is achieved is more efficient than decentralized decision-making, the reduction of middlemen can effectively raise the profits of members of the supply chain, and the interest coordination mechanism in view of Shapley Value Method is accessible to each member of the closed-loop supply chain with remanufacturing. All in all, the reward and punishment mechanism of government build on recycling rate is superior to that based upon recycling amount. The above conclusions can function as a theoretical reference for decision makers. The future research will further concern about members in different levels of the closed-loop supply chain, the influence rules of reward and punishment mechanism of the government on supply chain, and the optimal decision-making of the retailer-dominated closed-loop supply chain.

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