Research on decision-making of low-carbon and closed-loop supply chain recovery model considering government subsidies

Abstract: considering the low-carbon closed-loop supply chain composed of manufacturers and retailers, this paper constructs four game models in which manufacturers do not participate / participate in cooperative recovery under government subsidies, analyzes the impact of government subsidies on wholesale price, retail price, recovery rate and member profit under different recovery situations, and solves the optimal recovery decision and government subsidy decision. The research shows that: (1) the recovery rate is negatively correlated with the wholesale price, and positively correlated with government subsidies, consumers' low-carbon preference and low-carbon level. (2) Government subsidies play a positive role in the recovery decision-making of closed-loop supply chain members. When the government provides the same subsidy price to the recovery subject, manufacturers prefer to entrust retailers for recovery, and manufacturers' participation in cooperative recovery mode is conducive to improving the product recovery rate of closed-loop supply chain. (3) When the government subsidized price is lower, the manufacturer's task sharing and cooperative recovery is more beneficial to its own recovery rate and profit; On the contrary, cost sharing and cooperative recovery are more beneficial to their own recovery rate and profits.

Key words: closed-loop supply chain; Government subsidies; Recycling mode; Remanufacturing; Cooperative recycling

1 Introduction

The recycling and remanufacturing of waste electrical and electronic products can not only make full use of the added value of old products and reduce production costs, but also the carbon emission in the production process is much lower than that of direct access to resources. Large enterprises such as Lenovo, Huawei, greenmei and TCL have successively built recycling systems. Veolia renewable resources obtained 14.8 tons of renewable resources from 2011 to 2020 by recycling waste electrical and electronic products, which is equivalent to reducing 240000 tons of carbon dioxide emissions. Therefore, with the help of the closed-loop sustainable cycle process of "resources production consumption renewable resources", the government can explore effective ways to solve the problem of environmental pollution, and enterprises can reduce production costs and energy and resource consumption, so as to enhance competitiveness(Xiong, 2014).

However, the recycling channel efficiency of Chinese enterprises is generally not high, and they lack the autonomy of recycling and remanufacturing(Wang, 2020). In 2016, the State Council issued the implementation plan of the extended producer responsibility system, which proposed that "the ways for production enterprises to recycle and dispose of waste products include independent recycling, joint recycling or entrusted recycling". It can be seen that the correct recycling mode has been highly valued by the government and enterprises. In addition, the Chinese government has successively issued policies such as "trade in" subsidy and waste electrical and electronic products treatment fund subsidy to support the development of resource recycling industry. From the perspective of policy effect, the recovery rate and types of recovery in formal channels have increased significantly, and government subsidies provide sufficient external power for enterprise recovery activities. Based on the above, considering government subsidies and further refining the manufacturer's effective recycling mode in the low-carbon background is a practical problem worthy of discussion in the current closed-loop supply chain research.

2 Literature Review

The problems presented in the practice of closed-loop supply chain, such as "who is responsible for recycling, how to effectively recycle, and how to implement government subsidies", have attracted extensive attention of scholars at home and abroad. The decision-making of closed-loop supply chain recycling mode mainly includes single channel independent recycling, multi-agent mixed recycling, online and offline dual channel recycling, etc., which involves discussing the optimal decision of each supply chain member when manufacturers and retailers / third parties are responsible for recycling independently and jointly. For example, Savaskan et al. (2004) constructed a Stackelberg game model with manufacturers as leaders, studied the recycling of waste products in reverse channels, and proposed the recycling mode in the charge of retailers as the optimal choice. After that, he further studied the closed-loop supply chain recycling model under the competition of two retailers. Based on supply chain competition, Lu (2016) and others respectively considered two competitive retailers and the closed-loop supply chain with chain and chain competitive environment, and discussed the selection of the optimal recycling channel from the perspective of win-win of different subjects with the recovery rate as a variable. However, many scholars believe that the independent recycling of a single member is easy to cause it to bear more cost burden and reduce the recycling enthusiasm. Therefore, they suggest that more members participate in recycling activities to improve the recycling rate. Huang Zongsheng (2019) constructed two game models of cost sharing and task sharing to explore the impact of the cooperative alliance between manufacturers and retailers on product recycling. He believes that manufacturers' participation in cooperation is conducive to reducing enterprises' adoption of low price strategy and improving market demand and product recycling range. Gong (2019) and Wen Hui (2020) both discussed the impact of different recycling modes and channel power structure on the optimal decision-making and performance of closed-loop supply chain. The former believes that the hybrid recovery strategy is optimal for both supply chain members. The latter involves the two channel closed-loop supply chain of manufacturers and distributors, and puts forward the contract mechanism.

Generally speaking, manufacturers and retailers are pursuing the maximization of interests and lack the autonomy of recycling and remanufacturing, so they need enough external motivation to stimulate. Therefore, scholars gradually study the impact of external factors such as government subsidies on the recovery decision of closed-loop supply chain. Chen (2016) believes that government subsidies are beneficial to the profits of manufacturers and recyclers, but there is a certain scope of subsidies, and the more the better. Lin (2020) also believes that there is a reasonable range of government subsidies. When the government subsidies are low, it is a better decision for retailers to be responsible for recycling; On the contrary, the third party responsible for recycling is the best choice for decision-makers. Huang (2020) expanded the situation that the government subsidy target is consumers for the two-way dual channel closed-loop supply chain of new energy vehicles, and believed that the government's subsidy policies considering different subsidy targets are conducive to the development of the market. In addition, as carbon emission reduction has become a hot issue, more and more scholars explore the closed-loop supply chain in a low-carbon environment. For example, the impact of government environmental policies on the pricing and production strategies of enterprises in simple linear closed-loop supply chain, and the network equilibrium of complex closed-loop supply chain system under the background of low carbon. For example, scholars introduce factors such as low carbon degree and carbon emission of products to study the decision-making of closed-loop supply chain.

Through the above literature review, we can see that the closed-loop supply chain theory and model of domestic and foreign scholars around government participation behavior have been relatively mature, but there is less research on the cooperative recycling mode between manufacturers and retailers in the low-carbon background. Therefore, based on the research of Huang Hui and Lin Guihua, this paper combines government subsidies with consumers' low-carbon preference behavior, discusses the optimal recycling mode of supply chain members, and further discusses the vertical cooperation between manufacturers and retailers in the case of government subsidies. In view of this, considering the level of carbon emission efforts and consumers' low-carbon preference, this paper constructs four game models of direct recycling by manufacturers, recycling by retailers entrusted by manufacturers, task sharing and cooperative recycling between manufacturers and retailers, and cost sharing and cooperative recycling between manufacturers and retailers in the case of government subsidies, and further discusses "how does government subsidies affect recycling?" "How about the product price, recovery rate and member profit under different recovery modes?" And "does the manufacturer participate in cooperative recycling and what recycling methods do they prefer?" In order to bring new ideas for enterprises to implement the decision-making of recycling mode and the government to seek appropriate subsidies to stimulate the operation efficiency of closed-loop supply chain.

3 Problem Description and Model Description

The two-stage closed-loop supply chain consists of a manufacturer M, a retailer R and consumers. In the supply chain system, the manufacturer is the leader and is responsible for the production of new / remanufactured products; Retailers are followers, responsible for sales activities, and both have the ability to recycle waste products. The government has a preference for carbon reduction and only has a preference for carbon recovery.

3.1 Symbol Description

The main parameter symbols are shown in Table 1.

Table 1. Description of variables and symbols

variable	meaning	variable	meaning
a	Potential market demand	t_2	Unit transfer price paid by the manufacturer
D	Market demand	τ	rate of recovery
p	trade price	L	Recycler fixed cost
w	wholesale price	b	Recovery cost coefficient
c_n	Unit cost of new products	s	Government subsidy for unit recycled products
c_r	Unit cost of reprocessing	λ	Proportion of task sharing
ε	Consumer low carbon preference coefficient	Δ	Cost advantage of Remanufacturing
e	Low carbon level	Π_M	Manufacturer's profit
t_1	Recovery price	Π_R	Retailer's profit

3.2 Model Assumptions

The assumptions of the model are as follows:

(1) There is no significant difference in performance and quality between new products and remanufactured products. Within a reasonable range, consumers have low-carbon preference, and the degree of preference affects the market demand of products. According to the linear demand function model proposed by Pazoki et al., it is assumed that the demand of products is a function of product price and low carbon level, which is $D=a-rw+\varepsilon e$. Where a is the potential market demand, $a>0$; r is the price sensitivity coefficient, $r>0$; ε is low carbon preference coefficient, and e is low carbon level.

(2) Suppose p_i^j 、 w_i^j are the wholesale price and retail price of products in case J under the recovery mode, $i=\{N,C\}$ $j=\{I,II\}$. In addition, t_1 is the market recovery price of the enterprise for consumers; t_2 is the unit price of recycled products purchased by the manufacturer. Referring to the research of Chen Xiaohong and Wang Yuyan, the cost saved by recycling and remanufacturing is set as $\Delta=c_n-c_r$. Since the unit production cost c_n is greater than c_r, and in order to ensure the economy of recycling and remanufacturing activities, there is $\Delta\geq t_2>t_1>0$.

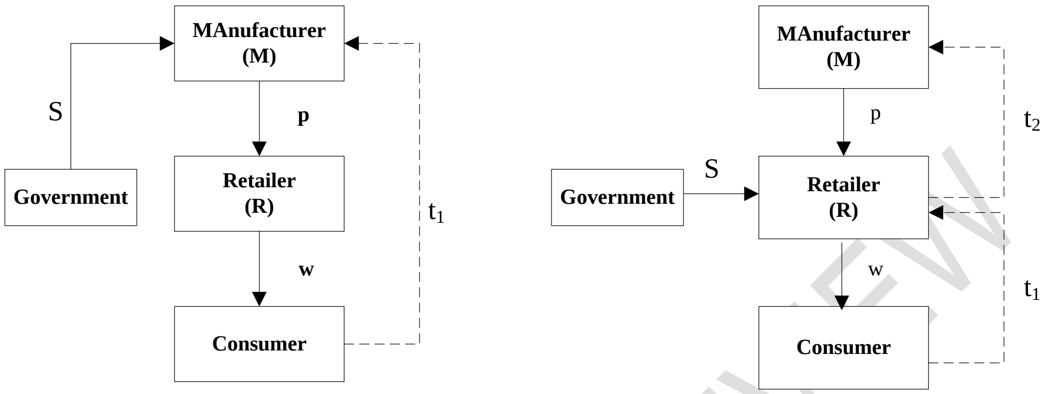
(3) All waste products recovered by enterprises from consumers are used for remanufacturing, and the recovery rate is set as τ ($0\leq\tau<1$) . According to the research of Savaskan, it is assumed that the input cost required by enterprises to participate in recycling activities is $L=b\tau^2$, and b is the recovery cost coefficient.

(4) In order to promote the recycling of waste products, the government only subsidizes the recycling behavior. Assuming that the subsidy price of government units for recycled products under different recycling situations is S_i^j, $i=\{N,C\}$, $j=\{I,II\}$.

3.3 Manufacturer's Recycling model

(1) Manufacturers do not adopt cooperative recycling mode (NC)

Manufacturers can choose to be directly responsible for recycling or entrust retailers to recycle. Both parties bear the recycling costs and enjoy government subsidies. Firstly, this section constructs a model in which manufacturers, retailers and recyclers are respectively responsible for recycling, as shown in i and ii in Figure 1.

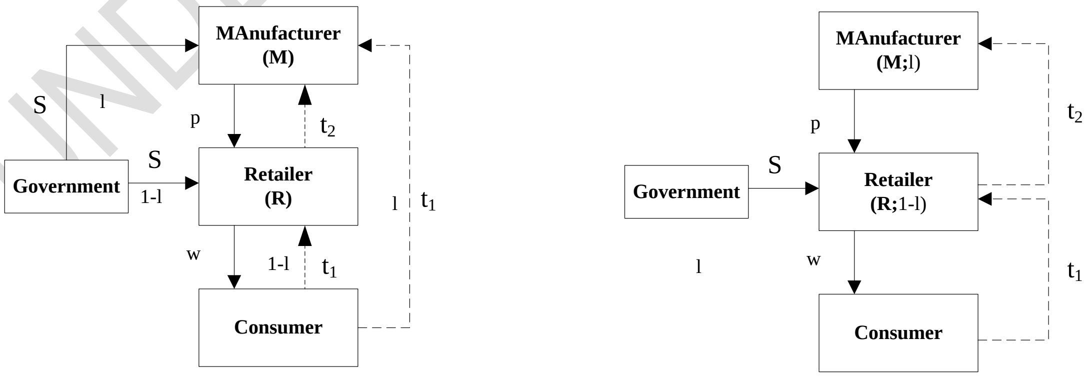


i. Manufacturer's direct recycling model   ii. Manufacturer commissioned retailer recycling model

Figure 1. A closed-loop supply chain model in which manufacturers do not participate in cooperative recycling

(2) Manufacturer participation in cooperative recycling mode (C)

In fact, many manufacturers set up outlets in sales offices and participate in recycling activities themselves, which can be regarded as a task sharing and cooperation mode for recycling; Some manufacturers do not directly participate in recycling activities, but bear the recycling cost in proportion. This part aims to explore whether these two cooperative recycling models are conducive to improving retailers' product recycling enthusiasm, so as to achieve win-win results. Among them, the manufacturer's decision sharing proportion λ, when λ is larger, it indicates that the manufacturer undertakes more tasks, and vice versa, as shown in iii and iv in Figure 2.



iii. The manufacturer carries out task sharing and cooperative recycling model

iv. Cost sharing and cooperative recovery model for manufacturers

Figure 2. A closed-loop supply chain model with manufacturers' participation in cooperative recycling

4 Calculation

4.1 Non-Cooperative mode adopted by manufacturers (C) **(NC)**

4.1.1 Manufacturer's Direct Recycling Model (NC-I)

The decision model are:

$$\max \prod_M^{NC-I} = [p_{NC}^I - c_n + (\Delta - t_1 + S_{NC}^I)\tau_{NC}^I](a - rw_{NC}^I + \varepsilon) - b(\tau_{NC}^I)^2 \quad (1)$$

$$\max \prod_R^{NC-I} = (w_{NC}^I - p_{NC}^I)(a - rw_{NC}^I + \varepsilon) \quad (2)$$

For the convenience of calculation, let $(\Delta - t_1 + S_{NC}^I) = A$.

When $b > \frac{r(\Delta - t_1 + S_{NC}^I)^2}{8}$, the optimal wholesale price, retail price and expected recovery rate when the manufacturer is directly responsible for recovery are:

$$p_{NC}^{I*} = \frac{(4b - rA^2)(a + \varepsilon) + 4brc_n}{r(8b - rA^2)} \quad (3)$$

$$w_{NC}^{I*} = \frac{(6b - rA^2)(a + \varepsilon) + 2brc_n}{r(8b - rA^2)} \quad (4)$$

$$\tau_{NC}^{I*} = \frac{A(a + \varepsilon - rc_n)}{8b - rA^2} \quad (5)$$

The optimal profit pursued by each member of the supply chain are:

$$\prod_M^{NC-I*} = \frac{b(8b - rA^2)(a + \varepsilon - rc_n)^2}{r(8b - rA^2)^2} \quad (6)$$

$$\prod_R^{NC-I*} = \frac{8b^2(a + \varepsilon - rc_n)^2}{r(8b - rA^2)^2} \quad (7)$$

4.1.2 Manufacturer Ccommissioned Retailer Recycling Model (NC-II)

The decision model are:

$$\max \prod_M^{NC-II} = [p_{NC}^{II} - c_n + (c_n - c_r - t_2)\tau_{NC}^{II}](a - rw_{NC}^{II} + \varepsilon) \quad (8)$$

$$\max \prod_R^{NC-II} = [w_{NC}^{II} - p_{NC}^{II} + (t_2 - t_1 + S_{NC}^{II})\tau_{NC}^{II}](a - rw_{NC}^{II} + \varepsilon) - b(\tau_{NC}^{II})^2 \quad (9)$$

For the convenience of calculation, let $(\Delta - t_2) = B_1$; $(t_2 - t_1 + S_{NC}^{II}) = B_2$.

When $b > \frac{r(t_2 - t_1 + S_{NC}^{II})^2}{4}$, the optimal wholesale price, retail price and expected recovery rate when the manufacturer entrusts the retailer to recover separately are:

$$p_{NC}^{II*} = \frac{a + \varepsilon + rc_n}{2r} \quad (10)$$

$$w_{NC}^{II*} = \frac{(3b - rB_2^2)(a + \varepsilon) + brc_n}{r(4b - rB_2^2)} \quad (11)$$

$$\tau_{NC}^{II*}=\frac{B_2(a+\varepsilon e-rc_n)}{2(4b-rB_2^2)} \quad (12)$$

The optimal profit pursued by each member of the supply chain are:

$$\prod_M^{NC-II*}=\frac{b(a+\varepsilon e-rc_n)^2}{2r(4b-rB_2^2)} \quad (13)$$

$$\prod_R^{NC-II*}=\frac{b(a+\varepsilon e-rc_n)^2}{4r(4b-rB_2^2)} \quad (14)$$

4.2 Cooperative mode adopted by manufacturers (C)

4.2.1 Manufacturers and retailers adopt the "task sharing" cooperation mode(C-I)

Manufacturers support retailers with the actual recycling actions of sharing proportion λ and recycling price t_1, and buy back waste products at price t_2 for remanufacturing, forming a closed-loop supply chain. Among them, the government subsidizes according to the amount recovered. The decision model is as follows:

$$\max \prod_M^{C\text{-}I}=[p_C^I-c_n+(c_n-c_r)\tau_C^I](a-rw_C^I+\varepsilon e)+\lambda\tau_C^I(S_C^I-t_1)(a-rw_C^I+\varepsilon e)-(1-\lambda)\tau_C^I t_2(a-rw_C^I+\varepsilon e)-b(\lambda\tau_C^I)^2 \quad (15)$$

$$\max \prod_R^{C\text{-}I}=(w_C^I-p_C^I)(a-rw_C^I+\varepsilon e)+(1-\lambda)\tau_C^I(S_C^{II}+t_2-t_1)(a-rw_C^I+\varepsilon e)-b[(1-\lambda)\tau_C^I]^2 \quad (16)$$

When $b>\frac{r(S_C^{II}+t_2-t_1)^2}{4}$, the optimal wholesale price, retail price and expected recovery rate when the manufacturer entrusts the retailer to recover separately are:

$$p_C^{I*}=\frac{a+\varepsilon e+rc_n}{2r} \quad (17)$$

$$w_C^{I*}=\frac{Z_1(a+\varepsilon e)-b(a+\varepsilon e-rc_n)}{rZ_1} \quad (18)$$

$$\tau_C^{I*}=\frac{(S_C^{II}+a_0-t_1)(a+\varepsilon e-rc_n)}{2(1-\lambda)Z_1} \quad (19)$$

The optimal profit pursued by each member of the supply chain are:

$$\prod_M^{C-I*}=\frac{b(a+\varepsilon e-rc_n)^2[8b(1-\lambda)^2-r(5\lambda^2-6\lambda+2)(S_C^{II}+a_0-t_1)^2+2r(1-\lambda)(S_C^{II}+a_0-t_1)(\Delta-a_0)]}{4r(1-\lambda)^2Z_1^2} \quad (20)$$

$$\prod_R^{C-I*}=\frac{(a+\varepsilon e-rc_n)^2[4b^2-3br(S_C^{II}+a_0-t_1)^2]}{4rZ_1^2} \quad (21)$$

4.2.2 Manufacturers and retailers adopt the " cost sharing " cooperation mode (C-II)

The manufacturer apportions the recovery cost according to proportion λ, and repurchases the waste products at the price for remanufacturing. Among them, the government only subsidizes retailers. The decision model is as follows:

$$\max \prod_M^{C-II}=[p_C^{II}-c_n+(c_n-c_r-t_2)\tau_C^{II}](a-rw_C^{II}+\varepsilon e)-b\lambda(\tau_C^{II})^2 \quad (22)$$

$$\max \prod_R^{C-II}=[w_C^{II}-p_C^{II}+(t_2-t_1+S_C^{II})\tau_C^{II}](a-rw_C^{II}+\varepsilon e)-b(1-\lambda)(\tau_C^{II})^2 \quad (23)$$

When $b>\frac{r(S_C^{II}+t_2-t_1)^2}{4(1-\lambda)}$, the optimal wholesale price, retail price and expected recovery rate when the manufacturer entrusts the retailer to recover separately are:

$$p_C^{II*}=\frac{a+\ae+rc_n}{2r} \quad (24)$$

$$w_C^{II*}=\frac{Z_2(a+\ae)-b(1-\lambda)(a+\ae-rc_n)}{rZ_2} \quad (25)$$

$$\tau_C^{II*}=\frac{(S_C^{II}+a_1-t_1)(a+\ae-rc_n)}{2Z_2} \quad (26)$$

The optimal profit pursued by each member of the supply chain are:

$$\prod_M^{C-II*}=\frac{b(a+\ae-rc_n)^2[8b(1-\lambda)^2-r(\lambda+2)(S_C^{II}+a_1-t_1)^2+2r(1-\lambda)(\Delta-a_1)(S_C^{II}+a_1-t_1)]}{4rZ_2^2} \quad (27)$$

$$\prod_R^{C-II*}=\frac{[4b^2(1-\lambda)^2-3br(1-\lambda)(S_C^{II}+a_1-t_1)^2](a+\ae-rc_n)^2}{4rZ_2^2} \quad (28)$$

5 Comparative Analysis of Results

The optimal p, w, τ and $\prod$ under the four cases of direct recovery by manufacturers under government subsidies, recovery by retailers entrusted by manufacturers, task sharing and cooperative recovery between manufacturers and retailers, and cost sharing and cooperative recovery between manufacturers and retailers are shown in Table 2.

Table 2. Optimal strategies of different recycling modes under government subsidies

	Non-Cooperative mode adopted by manufacturers（NC）		Cooperative mode adopted by manufacturers（C）	
	（NC-I）	（NC-II）	（C-I）	（C-II）
p^*	$\frac{(4b-rA^2)(a+\ae)+4brc_n}{r(8b-rA^2)}$	$\frac{a+\ae+rc_n}{2r}$	$\frac{a+\ae+rc_n}{2r}$	$\frac{a+\ae+rc_n}{2r}$
w^*	$\frac{(6b-rA^2)(a+\ae)+2br}{r(8b-rA^2)}$	$\frac{(3b-rB_2^2)(a+\ae)+brc_n}{r(4b-rB_2^2)}$	$\frac{Z_1(a+\ae)-b(a+\ae-rc_n)}{rZ_1}$	$\frac{Z_2(a+\ae)-b(1-\lambda)(a+\ae-rc_n}{rZ_2}$
τ^*	$\frac{A(a+\ae-rc_n)}{8b-rA^2}$	$\frac{B_2(a+\ae-rc_n)}{2(4b-rB_2^2)}$	$\frac{(S_C^{II}+a_0-t_1)(a+\ae-rc_n)}{2(1-\lambda)Z_1}$	$\frac{(S_C^{II}+a_1-t_1)(a+\ae-rc_n)}{2Z_2}$
$\prod_M^*$	$\frac{b(a+\ae-rc_n)^2}{r(8b-rA^2)}$	$\frac{b(a+\ae-rc_n)^2}{2r(4b-rB_2^2)}$	$\prod_M^{C-I*}$	$\prod_M^{C-II*}$
$\prod_R^*$	$\frac{8b^2(a+\ae-rc_n)^2}{r(8b-rA^2)^2}$	$\frac{(4b^2-brB_2^2)(a+\ae-rc_n)^2}{4r(4b-rB_2^2)^2}$	$\prod_R^{C-I*}$	$\prod_R^{C-II*}$

5.1 impact of government subsidies on closed-loop supply chain when manufacturers do not adopt cooperative recycling strategy

Proposition 1:

(1) $\frac{\partial p^i}{\partial \varepsilon^i} > 0$; $\frac{\partial w^i}{\partial \tau^i} > 0, \frac{\partial w^i}{\partial p^i} > 0, \frac{\partial w^i}{\partial e^i} > 0$; $\frac{\partial \tau^i}{\partial p^i} > 0, \frac{\partial \tau^i}{\partial S^i} > 0, \frac{\partial \tau^i}{\partial \varepsilon^i} > 0, \frac{\partial \tau^i}{\partial e^i} > 0$, and their second derivative exists. This shows that the wholesale price is positively correlated with consumers' low-carbon preference; Retail price is positively correlated with consumers' low-carbon preference, wholesale price and low-carbon level; The recovery rate is negatively correlated with the wholesale price, and positively correlated with government subsidies, consumers' low-carbon preference and low-carbon level.

(2) $\frac{\partial p_{NC}^I}{\partial S} < 0$, $\frac{\partial w_{NC}^I}{\partial S} < 0$, $\frac{\partial \tau_{NC}^I}{\partial S} > 0$. This shows that when the manufacturer recovers directly, the manufacturer's wholesale price decreases with the increase of government subsidies. At this time, the manufacturer's profit mainly comes from the government subsidies for sales and recycling. If the government subsidies are more, it indicates that the manufacturer can make profits in the recycling link. Therefore, reduce the wholesale price to guide the retailer to reduce the retail price and reduce the retail price, and finally expand the product sales volume and increase the recycling quantity of waste products.

(3) $\frac{\partial w_{NC}^{II}}{\partial S} < 0$, $\frac{\partial \tau_{NC}^{II}}{\partial S} > 0$. We know that the wholesale price when the manufacturer entrusts the retailer to recycle has nothing to do with the government subsidy, and with the increase of government subsidy, the retailer's low price strategy is conducive to improving the sales volume and recycling volume.

Proposition 2:

When the government subsidy price is the same, the recovery rate of the manufacturer choosing to entrust the retailer is greater than that of the manufacturer directly responsible for the recovery. When the government's subsidy price for the manufacturer's recycling mode is lower than that of entrusted retailers: when $S_{NC}^I \in (0, S_0)$, the recovery rate of NC-II mode is higher than that of NC-I mode. When the government's subsidy price for manufacturers' direct recovery is high, the recovery rate of nc-i mode is greater than that of NC-II mode.

That is, when the government adjusts the subsidy price, the respective recovery rates of manufacturers and retailers have the following relationship:

（1）When $S_{NC}^I = S_{NC}^{II}$, $\tau_{NC}^{II*} > \tau_{NC}^{I*}$.

（2）When $S_{NC}^I = S_0$, $\tau_{NC}^{II*} = \tau_{NC}^{I*}$.

（3）When $S_{NC}^I \in (0, S_0)$, $\tau_{NC}^{II*} > \tau_{NC}^{I*}$.

（4）When $S_{NC}^{I} \in (S_0, S_{NC}^{II}) \cup (S_{NG}^{II} + \infty)$, $\tau_{NC}^{I*} > \tau_{NC}^{II*}$.

Proposition 3:

When the government adjusts the subsidy price, the retail price under different recovery modes has the following relationship:

（1）When $S_{NC}^{I} = S_{NC}^{II}$, $w_{NC}^{I*} > w_{NC}^{II*}$.

（2）When $S_{NC}^{I} \in (0, S_1)$, $w_{NC}^{I*} > w_{NC}^{II*}$.

（3）When $S_{NC}^{I} \in (S_1, +\infty)$, $w_{NC}^{I*} < w_{NC}^{II*}$.

（4）When $S_{NC}^{I} = S_1$, $w_{NC}^{I*} = w_{NC}^{II*}$.

and, $S_1 = (\sqrt{2} - 1)(\Delta - t_1) + \sqrt{2} S_{NC}^{II}$.

Proposition 4:

When the government adjusts the price change of a party's subsidy, the manufacturer's profits under the three recovery modes have the following relationship:

（1）When $S_{NC}^{I} = S_{NC}^{II}$, 则 $\prod_{M}^{II*} > \prod_{M}^{I*}$.

（2）When $S_{NC}^{I} \in (0, S_1)$, $\prod_{M}^{II*} > \prod_{M}^{I*}$.

（3）When $S_{NC}^{I} \in (S_1, +\infty)$, 则 $\prod_{M}^{I*} > \prod_{M}^{II*}$.

（4）When $S_{NC}^{I} = S_1$时, $\prod_{M}^{II*} = \prod_{M}^{I*}$.

Similarly, $S_1 = (\sqrt{2} - 1)(\Delta - t_1) + \sqrt{2} S_{NC}^{II}$.

Proposition 5:

In terms of the manufacturer's recovery rate and its own profits, when the government adopts the same subsidy strategy, the recovery rate and its own profits under NC-II mode are greater than those under nc-i recovery mode, so the manufacturer tends to choose NC-II mode. When $S_{NC}^{I} > S_1 > S_{NC}^{II}$, NC-I recycling mode is the best choice for manufacturers. When $S_{NC}^{I} < S_0 < S_{NC}^{II}$, NC-II recycling mode is the best choice for manufacturers.

From the perspective of retailers, under the same subsidy strategy, the retail price of nc-i recycling mode is greater than that of NC-II mode; Under the same subsidy background, their own profits fluctuate with the change of government subsidy price. When the government subsidy price is less than the critical value S_a, retailers prefer NC-II recycling mode, on the contrary, they prefer nc-i recycling mode.

$$S_a=\sqrt{\frac{(1+\sqrt{2})b}{8r}}+t_1-\Delta; \quad S_2=\sqrt{8b+\sqrt{32b(4b-r(\Delta-t_1+S_{NC}^{II})^2)}}-\Delta+t_1$$

5.2 impact of cooperative recycling strategy adopted by manufacturers on Closed-loop Supply Chain

Proposition 6:

When the subsidy price provided by the government is the same and there is limit range $(0,S_b)$, e following relationship is established: $\tau_C^{I*}>\tau_C^{II*}>\tau_{NC}^{II*}>\tau_{NC}^{I*}$. This shows that the cooperation between manufacturers and retailers promotes the improvement of product recovery rate in closed-loop supply chain. Therefore, if we want to improve the product recovery rate, on the one hand, the government should adjust the corresponding subsidy price according to the actual situation such as recovery price, sharing proportion and recovery coefficient; On the other hand, within a certain range of government subsidies, manufacturers can choose to share tasks or costs with retailers to provide practical support to retailers. In addition, we can see that the cooperative recycling mode in which manufacturers participate in task sharing is more conducive to the recycling behavior of the closed-loop supply chain. In order to reduce costs, manufacturers will reduce the proportion of task sharing. At this time, the price range of government subsidies will gradually narrow with the reduction of the proportion of sharing. And $S_b=\frac{\alpha+\sqrt{\alpha^2+8r(\Delta-a_1)\beta}}{4r(\Delta-a_1)}$.

Proposition 7:

It can be seen from table 2 that $p_{NC}^{II*}=p_C^{I*}=p_C^{II*}$, that is, the wholesale price will not be affected when the manufacturer adopts the cooperation mode. The wholesale price under different modes has the following relationship: $w_{NC}^{I*}>w_C^{I*}>w_C^{II*}$. That is, when the manufacturer does not participate in the cooperation, the retail price of the retailer is higher than that of the cooperation mode, while when participating in the cooperation, the retail price of the C-I mode is higher than that of the C-II mode.

$$S_c=t_1-a_0+\sqrt{\frac{7b}{2r}}$$

Proposition 8:

When the government grants the same subsidy, the manufacturer's profits under the two recovery modes of C-I and C-II are higher than those under the NC-II mode, that is, $\prod_M^{C-I*}>\prod_M^{NC-II*}$ and $\prod_M^{C-II*}>\prod_M^{NC-II*}$. Therefore, we know that manufacturers' participation in cooperation is conducive to improving manufacturers' own profits.

Proposition 9:

For manufacturers, when the government subsidy is in the range $(0,S_b)$, the cooperative recovery between manufacturers and retailers can improve the product recovery rate of the closed-loop supply chain, and the lower the government subsidy, the C-I recovery mode is more conducive to the recovery behavior of the closed-loop supply chain. On the contrary, manufacturers prefer the C-II recovery mode. For retailers, when the government subsidy is in range $[S_c,+\infty)$, although the retail price of manufacturers participating in cooperation is lower than that of non cooperation mode, manufacturers participating in cooperative recovery share the recovery cost of retailers to a certain extent, which is conducive to the increase of retailers' price and profit. For the government, since $0<S_b<S_d<S_c$, the manufacturer and the government are more willing to promote the task sharing and cooperative recycling mode from the perspective of the government's pursuit of minimum subsidy and higher recovery rate and the manufacturer's pursuit of greater profits.

6 Conclusions and Prospects

With the promotion of the concept of low-carbon environmental protection and green development, the closed-loop supply chain model with the recycling and remanufacturing of waste products as the core has attracted more and more attention from the government. Recycling and remanufacturing of waste products can effectively solve the problem of resource consumption, but at present, Chinese enterprises are still in the initial stage. In order to stimulate the efficient development of closed-loop supply chain, the government has formulated a series of preferential subsidy policies. The results show that: when the manufacturer chooses the closed-loop subsidy, it tends to have the same impact on the recovery rate of products as the retailer. At the same time, when the subsidy price is lower, taking task sharing is more beneficial to the manufacturer's own recovery rate and profit; On the contrary, cost sharing is more beneficial to its own recovery rate and profit. However, for retailers, the profit of retailers with task sharing recycling mode is higher than that without cooperation mode; When the government gives higher subsidies, retailers prefer that manufacturers can take task sharing and participate in cooperative recycling, which is conducive to improving retailers' profits.

This paper studies the cooperative recycling strategy between manufacturers and retailers under government subsidies, and has the following enlightenment: (1) the government's subsidy behavior is conducive to the participation of closed-loop supply chain members in recycling, but it is not that the higher the subsidy, the more effective it is, but the amount of subsidy needs to be adjusted according to the actual situation. (2) It is necessary to promote manufacturers to participate in the vertical cooperation and recycling of retailers, which is not only conducive to the long-term development of enterprises themselves, but also conducive to the recycling of resources. (3) Attention should be paid to considering the low-carbon preference of consumers and the low-carbon level of products. If enterprises do not take the initiative to bear social responsibility, it will hinder the development of closed-loop supply chain system in the future.

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