Research on Closed-loop Supply Chain Recycling Model Considering Carbon Emissions

Wenjing Dong

Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China.

15951751819@163.com

Abstract

In the closed-loop supply chain considering carbon emissions, three recovery game models, manufacturer, retailer and third-party recycling, are established respectively. By comparing and analyzing the emission reduction rate, the recovery rate and the overall profit of supply chain under different recycling models, it is found that the equilibrium outcomes under different recycling models are different. The retailer recycling model has the lowest retail price, the highest recovery rate and emission reduction rate, and the highest overall profit of the supply chain. So considering carbon emissions, retailer recycling is optimal. With the increase of consumers' low-carbon preference, the recovery rate, emission reduction rate and overall profitability in the supply chain increase simultaneously.

Keywords

Recycling model; Carbon emissions; Closed-loop supply chain; Consumer's low-carbon preference.

1. Introduction

In many industries, such as automobiles, home appliances and copiers, closed-loop supply chain management has been successfully implemented. They establish an economically viable production and recycling system.Changhong, Gree and other companies will recover spontaneously. Eastman Kodak Company will recycle through retailers, and the "big three" automakers in the U.S. will start a joint research and remanufacturing partnership with the Dismantling Center. Savaskan (2004) considered three recycling channels of manufacturers, retailers and third parties in the closed-loop supply chain. The results show that different recycling channels will affect the recycling efficiency of used products, which in turn will affect the production and sales efficiency of new re-products.On the other hand, through data surveys of 133 manufacturing companies in Malaysia, Voon-Hsien(2007) conducted an empirical study on low-carbon supply chain management practices, which showing that low-carbon supply chain management such as international environmental management, ecological design, and return on investment can effectively improve the company's efficiency. Bai(2014) theoretically showed that manufacturers can increase market share by investing in low-carbon products.Therefore, different recycling models are studied in a closed-loop supply chain in term of the carbon emissions, and the emission reduction rates of different recovery modes are compared, and the recovery efficiency and applicable conditions of different recycling entities are derived to provide decision reference for supply chain emission reduction and recycling.

2. Problem Description and Conditional Assumptions

2.1 Problem Description

Considering carbon emissions, there are three recycling channels for a closed-loop supply chain: Manufacturer recycling model (M model), retailer recycling model (R model), and third-party recycling model (3P model). Recycler recycles used products from consumer at the unit price a, manufacturer purchases used products from retailers or third parties at recycling subsidies b.When the recycler is a manufacturer, $a = b$. Manufacturer not only produces new products, but also processes used products.Manufacturer sells products to retailer at wholesale prices w, retailer sells products to consumer at retail prices p . π_M , π_R , π_{3P} , π_{SC} representing the profits of manufacturer, retailer, third party and the entire supply chain, respectively.

2.2 Conditional Assumptions

The market demand function is a linear function of price and consumer electricity carbon preferences, so $D(p,e)=\alpha-\beta p+\eta e$, where α represents the basic needs of the market, β represents the price sensitivity factor for consumers, η represents the low carbon preference of consumers and e represents the $\alpha>0,\beta>0,\eta>0,\alpha>\beta p$. In order to reduce carbon emissions and carry out low-carbon production, manufacturers must invest in the production process. It indicates the emission reduction rate of the manufacturer after investing in low-carbon cost. The cost function is expressed as a quadratic function, and this is also the case. Therefore, the low-carbon input cost is expressed as: $c(e)=\frac{1}{2}ie^2$, i is the cost of abatement. Same as the assumption in Savaskan[1], the manufacturer's recycling cost can be expressed as a quadratic function of the recovery rate. k is the cost of abatement, $\tau(0<\tau<1)$ is the recycling rate of used products, $c(\tau)=\frac{1}{2}k\tau^2$. Suppose the unit cost of the manufacturer to produce a new product is c_m ,the unit cost of producing the remanufactured product is c_r . Δ represents the cost saved by the manufacturer using the waste product for remanufacturing, so $\Delta=c_m-c_r$.

3. Model Construction and Analysis

3.1 Model Construction

3.1.1 Manufacturer Recycling Model (Model M)

When the manufacturer recycles the used product, the manufacturer is the leader of the stackelberg game and the retailer is the follower.The manufacturer determines the wholesale price of the product w, the emission reduction level e and recovery rate τ based on the principle of profit maximization. Then the retailer determines the retail price p according to w. The manufacturer's profit function is express as:

$$\pi_M=[(w-c_m)+(\Delta-a)\tau](\alpha-\beta p+\eta e)-\frac{1}{2}k\tau^2-\frac{1}{2}ie^2 \tag{1}$$

The seller's profit function is express as:

$$\pi_R=(p-w)(\alpha-\beta p+\eta e) \tag{2}$$

3.1.2 Retailer Recycling Model (Model R)

When a retailer recycles used product, the manufacturer first determines the the wholesale price of the product w and the emission reduction level e based on the principle of profit maximization. Then the retailer determines the retail price p and recovery rate τ based on the manufacturer's decision. The manufacturer's profit function is express as:

$$\pi_M=[(w-c_m)+(\Delta-a)\tau](\alpha-\beta p+\eta e)-\frac{1}{2}ie^2 \tag{3}$$

The seller's profit function is express as:

$$\pi_R=[(p-w)+(a-b)\tau](\alpha-\beta p+\eta e)-\frac{1}{2}k\tau^2 \tag{4}$$

3.1.3 Third-party Recycling Model (Model 3P)

When a third party recycles used products,the manufacturer first determines the the wholesale price of the product w and the emission reduction level e based on the principle of profit maximization.

Then the retailer determines the retail price p and the third-party recycler determines the recovery rate τ based on the manufacturer's decision. The manufacturer's profit function is express as:

$$\pi_M = [(w - c_m) + (\Delta - a)\tau](\alpha - \beta p + \eta e) - \frac{1}{2} ie^2 \tag{5}$$

Retailer profit function is express as:

$$\pi_R = (p - w)(\alpha - \beta p + \eta e) \tag{6}$$

Third-party profits function is express as:

$$\pi_{3P} = (a - b)\tau(\alpha - \beta p + \eta e) - \frac{1}{2} k\tau^2 \tag{7}$$

All values of the above expressions are listed in Table 1.

Table 1 Results of different recovery game models

	Model M	Model R	Model 3P
τ	$\frac{i\beta(\Delta-b)(\alpha-\beta c_m)}{i\beta D_1 - k\eta^2}$	$\frac{i\beta(\Delta-b)(\alpha-\beta c_m)}{i\beta D_2 - k\eta^2}$	$\frac{i\beta(\Delta-b)(\alpha-\beta c_m)}{i\beta D_3 - 2k\eta^2}$
e	$\frac{k\eta(\alpha-\beta c_m)}{i\beta D_1 - k\eta^2}$	$\frac{k\eta(\alpha-\beta c_m)}{i\beta D_2 - k\eta^2}$	$\frac{2k\eta(\alpha-\beta c_m)}{i\beta D_3 - 2k\eta^2}$
π_M	$\frac{ki(\alpha-\beta c_m)^2}{2(i\beta D_1 - k\eta^2)}$	$\frac{ki(\alpha-\beta c_m)^2}{2(i\beta D_2 - k\eta^2)}$	$\frac{ki(\alpha-\beta c_m)^2}{2(2i\beta D_5 - k\eta^2)}$
π_R	$\frac{k^2 i^2 \beta(\alpha-\beta c_m)^2}{(i\beta D_1 - k\eta^2)^2}$	$\frac{ki^2\beta D_3(\alpha-\beta c_m)^2}{2(i\beta D_2 - k\eta^2)^2}$	$\frac{k^2 i^2 \beta(\alpha-\beta c_m)^2}{(2i\beta D_5 - k\eta^2)^2}$
π_{3P}	–	–	$\frac{ki^2\beta^2(a-b)^2(\alpha-\beta c_m)^2}{2(2i\beta D_5 - k\eta^2)^2}$

3.2 Comparison of Recycling Models

This section analyzes the results summarized in Table 1 and obtains the following conclusions.

Proposition 1. The recovery rate in the three recovery models is: $\tau_R > \tau_M > \tau_{3P}$.

$$\text{proof. } \tau_M - \tau_R = -\frac{i^2\beta^3(\Delta-b)^3(\alpha-\beta c_m)}{(i\beta D_1 - k\eta^2)(i\beta D_2 - k\eta^2)} < 0;$$

$$\tau_{TP} - \tau_M = -\frac{[4ki\beta - k\eta^2]i\beta(\Delta-b)(\alpha-\beta c_m)}{(i\beta D_1 - k\eta^2)(i\beta D_4 - 2k\eta^2)} < 0$$

For the recovery rates, the recovery rate is the highest when the retailer recycles, followed by manufacturer, and the third-party is the lowest. The recovery rate of used products is directly proportional to the marginal revenue of recycling, and the marginal revenue of recycling when third-party recycles is less than the marginal revenue of recycling when the manufacturer recycles. Therefore, the recovery rate when third-party recycles is lower than the recycling rates when the manufacturer recycles. The retailer's recycling marginal revenue is the same as manufacturer's recycling marginal revenue. But when the retailer recycles, the unit cost savings of remanufacturing are only partially reflected in the final price of the product due to the double marginalization. Therefore, the recovery rate when the manufacturer recycles is lower than that when the retailer recycles.

Proposition 2. The emission reduction rate in the three recovery models is: $e_R > e_M > e_{3P}$.

$$\text{proof. } e_M - e_R = -\frac{ki\eta\beta^2(\Delta-b)^2(\alpha-\beta c_m)}{(i\beta D_1 - k\eta^2)(i\beta D_2 - k\eta^2)} < 0;$$

$$e_{TP} - e_M = -\frac{ik\beta^2(\Delta - b)^2(\alpha - \beta c_m)}{(i\beta D_1 - k\eta^2)(i\beta D_4 - 2k\eta^2)} < 0$$

It can be seen from the above proof that the emission reduction rates is related to the recovery model. For the emission reduction rate, the emission reduction rates is the highest when the retailer recycles, followed by the manufacturer recycles, and the third party the lowest.When the retailer recycles, the profit of manufacturer is the highest without carbon emissions. Therefore, in the retailer recycling model, high recycling rates and high emission reduction rates have lead to more recycling and remanufacturing, so the market demand and the overall profit of the supply chain increase.

Proposition 3. The retail price of the product in the three recycling modes is met: when $i\beta > \eta^2$, $p_R < p_M < p_{3P}$;when $i\beta < \eta^2$, $p_R > p_M > p_{3P}$.

Similar to the conclusion 1, the above formula can be proved by a simple operation, and the proof process is abbreviated.

When $i\beta > \eta^2$, the consumer's low carbon preference is small. The retail price is the lowest when the retailer recycles, followed by the manufacturer, and the third party is the lowest. When consumers' low carbon preferences are small, retail price is primarily affected by recycling and remanufacturing.Therefore, the conclusion is closer to literature[1]. When $i\beta < \eta^2$, the consumer's low-carbon preference is large. The retail price is the lowest when the third party recycles and the retail price is the least when retailer recycles. When consumers' low carbon preference is large, retail prices are primarily affected by carbon reductions.

Proposition 4. The profit of the node enterprises in the three recovery models is satisfied: $\pi_{SC}^{R} > \pi_{SC}^{M} > \pi_{SC}^{3P}$.

Similar to the conclusion 1, the above formula can be proved by a simple operation, and the proof process is abbreviated.

For the overall profit of the supply chain, the profit is the highest when the retailer recycles, followed by the manufacturer, and the third party is the lowest. In the retailer recycling model, high recovery and high emission reduction rates have lead to more recycling and remanufacturing. So the market demand and the overall profit of the supply chain increase.

4. Data Analysis

This section compares the decision results of the three recovery models by a numerical example. Set the relevant parameters of the product: $\alpha = 200$, $\beta = 3$, $\eta = 6$, $\Delta = 30$, $i = 200$, $k = 250$. Through calculation, the emission reduction rate, recovery rate and profit results of node enterprises in the three recovery modes are shown in Table 2.

From Table 2, when the consumer's low-carbon preference is stationary, the retailer recycling model has the lowest retail price, the highest recovery rate and emission reduction rate, and the highest overall profit of the supply chain. Therefore, the retailer recycling model is optimal. Regardless of the recycling model, as the consumer's low-carbon preference increases, the retail price, recovery rate, emission reduction rate and overall profit of the supply chain increase.

Table 2 Numerical analysis of different recovery game models

	η	p	τ	e	π_M	π_R	π_{3P}	π_{SC}
Model M	1	68.653	0.573	0.115	229.226	131.362	-	360.588
	2	68.901	0.578	0.231	231.214	133.650	-	364.864
	3	69.326	0.587	0.352	234.604	137.598	-	372.202
	4	69.940	0.599	0.479	239.521	143.426	-	382.947
Model R	1	66.511	0.669	0.134	267.559	134.227	-	391.786
	2	67.027	0.676	0.270	270.270	136.961	-	407.231

	3	67.491	0.687	0.412	274.914	141.708	-	416.622
	4	68.169	0.704	0.563	281.690	148.780	-	430.47
Model 3P	1	69.412	0.267	0.107	213.904	7.149	114.387	335.44
	2	69.650	0.270	0.216	215.633	7.265	116.244	339.142
	3	70.055	0.273	0.328	218.579	7.465	119.442	345.486
	4	70.641	0.279	0.446	222.841	7.759	124.146	354.746

5. Conclusion

This paper discusses three recovery models in a closed-loop supply chain when considering carbon emissions. From an environmental point of view, when retailers recycle, the recovery rate and emission reduction rate are the highest; from an economic point of view, the overall profit of the supply chain is highest when retailers recycle; therefore retailer recycling model is the optimal recycling model. With the increase of consumers' low-carbon preference, the recovery rates, emission reduction rates and overall profitability in the supply chain increase simultaneously. Therefore,in order to achieve a win-win situation between economic effect and environmental protection effects, the government should take appropriate measures to increase consumers' low-carbon preferences.

Of course, this article only considers a single sales channel. In fact, many companies have already opened online sales channels. So, in the future, mixed recycling models should be studied in a closed-loop supply chain considering carbon emissions.

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