A Comparative Analysis of the Stackelberg Game Approach to Green Closed-Loop Supply Chains under Different Recycling Channels

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Abstract. In the face of rapid economic development and increasingly severe environmental challenges, today's society is more critical to creating sustainable green supply chains. The article explores the application of game theory in the green closed-loop supply chain by discussing and analyzing the green closed-loop supply chain. On this basis, the game theory approach is used to construct the green closed-loop supply chain decision model according to the different modes of recycling, and the optimal pricing strategies under other methods are obtained based on the Stackelberg game solution. The impact of the green-related parameters of the products on the decision results is explored. The optimal pricing strategies under different models were obtained based on the Stackelberg game solution. The impact of the green-related parameters on the decision outcome was investigated, which provides a reference for further extension of game theory in green closed-loop supply chain projects.

Keywords: green closed-loop supply chain; recycling channel; Stackelberg game

1 Introduction

In recent years, as the demand for personalized new products increases, the life cycle of various products is also shrinking, all these phenomena make the number of waste products and The number of waste products and the level of environmental pollution gradually increase. Such a social situation has prompted scholars and various sectors at home and abroad to explore and study a new type of environmentally friendly green closed-loop supply chain.

Closed-loop Supply Chain (CLSC) is a series of recycling, testing, reprocessing, redistribution or end-of-life processing operations added to the traditional supply chain, incorporating the reverse product activities into the traditional supply chain system and reorganizing the original process, thus forming a new closed-loop process supply chain so that all materials are circulated in the system. [1] Green Supply Chain Management (GSCM) refers to the design of the entire process of purchasing, manufacturing and consuming raw materials, recycling and reusing waste products for

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environmental protection to achieve the goal of sustainable development for society and enterprises, and through the close connection between various members of the supply chain, the supply chain as a whole in Through the close relationship between the various members of the supply chain, the supply chain as a whole is harmonized in terms of ecology and environmental protection to optimize the environmental benefits of the system.[2] The implementation mechanism is shown in Figure 1.[3]

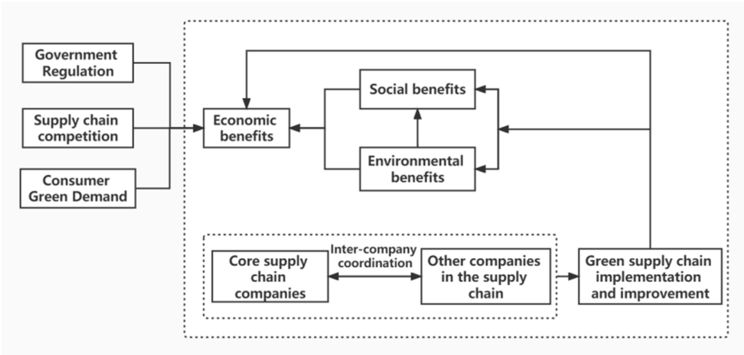

Fig. 1. Green Supply Chain Implementation Mechanisms.

A Green closed-loop supply chain adds the characteristics of a green supply chain based on retaining the attributes of a closed-loop supply chain. Its essential purpose is to achieve the joint maximization of environmental and economic benefits. Its management process is shown in Figure 2.[4] The green closed-loop supply chain is mainly reflected in the innovative green recycling process, comprehensive assessment of the value of waste products, and analysis of the best mode, quantity and cost of recycling.[5]

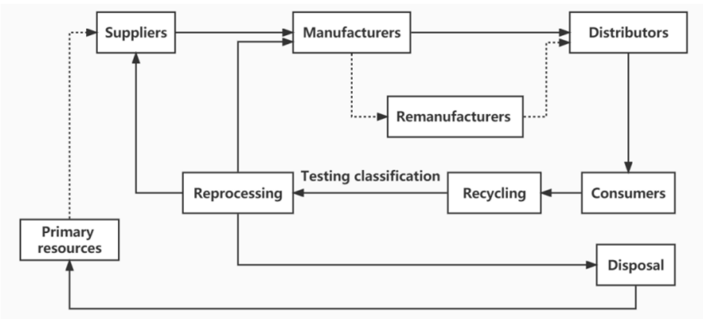

Fig. 2. Green closed-loop supply chain management process.

2 Application of game theory in green closed-loop supply chains

Evolutionary game theory is a research field pioneered by British evolutionary biologist Maynard Smith,6 which is mainly used to analyze the outcome of individual adaptations that take a particular strategy under the influence of other unique plans.

During the study of supply chains, on the one hand, one can look at the essential elements of the study. The upstream and downstream enterprises in the supply chain represent the participants in the game; in the supply chain, each enterprise has different considerations and objectives, and these differences form the strategy space of the game; on this basis, each enterprise gets various benefits in the process of the supply chain, this includes their interest function. The above three points form the game's essential elements and satisfy the game's basic framework.[7] On the other hand, for the problems faced by the research, the core problem of supply chain management is supply chain operation management, including how to choose cooperative suppliers, organize and design the supply chain, and conduct performance incentives and cooperation among members in the alliance.[8] The game theory focuses on the optimal strategies of each member involved in the competition and collaboration and the possible outcomes of these optimal strategies, exploring how these decisions can be balanced when direct interactions between two or more participants are carried out.[9] Both of these reasons conclude that supply chain problems are well suited to be solved using game theory. Different game strategies are often used when facing various supply chain problems.

The Stackelberg game is a duopoly model, the theory proposed by the German economist Heinrich von Stackelberg, and it applies to situations where there is inequality of position between firms.[10] Game theory is often used to analyze inter-firm relationships. It is widely used in various supply chain problems, including multi-decision issues such as inventory, quantity, price, and competition and cooperation problems between supply chain participants.[11]

3 Problem description and basic assumptions

Generally speaking, there are three main recycling methods in the reverse recycling system of a green closed-loop supply chain: manufacturer recycling, retailer recycling and third-party recycling.[12] In this chapter, we build models for these three recycling methods, corresponding to model M, model R and model T below; and set the traditional non-closed-loop supply chain (without recycling process) model N as a control group. In this chapter, the supply chain model is constructed with only one manufacturer and one retailer, and greenness and green investment cost parameters are added to the recycling process. The model construction and comparative analysis of different recycling models based on the Stackelberg game are carried out to investigate the optimal price strategy and the maximum profit available for each green closed-loop supply chain member under different recycling models.

Model N, which represents a traditional supply chain without a recycling mechanism, is used as a control group in this chapter. The process is shown in Figure 3.

Model R, where retailer R acts as a recycler, collects used products from consumers, and sells all used products to manufacturer M, is shown in Figure 3.

Model M, which indicates that manufacturer M acts as the recycler and recycles the used product from the consumer, is shown in Figure 3.

Model T, where a third party, T, acts as a recycler, collects the used product from the consumer, and sells the entire used product to manufacturer M. The process is shown in Figure 3.

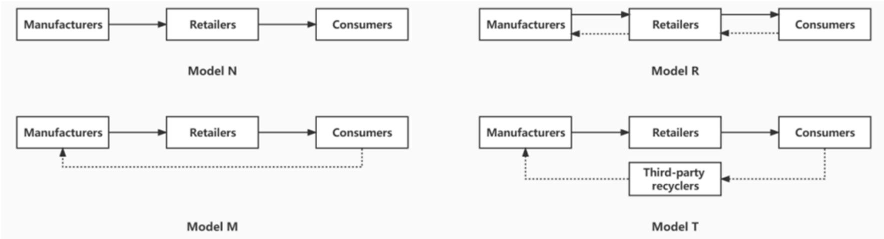

Fig. 3. Flow chart of the four models.

The notation used in building the Stackelberg game model is illustrated in Table 1.

Table 1. Description of symbols.

Symbol	Description
p	The unit retail price of the product.
p_r	Unit recovery prices.
w	The wholesale unit price of the product.
w_r	The unit transfer payment price is paid to the recycler by the manufacturer for the recycled product.
c	The manufacturer's unit cost of producing a new product is constant.
c_r	The unit cost to the manufacturer of remanufacturing the recycled product is constant. If $c_r < c$ show that remanufacturing is profitable, let $\Delta = c - c_r > 0$ denote the unit cost saved by the act of remanufacturing.
c_J	The unit recovery cost of the recycler $J, J \in \{R, T, M\}$, $c_J < \Delta$, indicates that back manufacturing is profitable.
Π_J^M Π_J^R Π_J^T Π_J	Profits for each member and the supply chain in Model $J, J \in \{R, T, M\}$.

The following assumptions were made in the construction of the model.

(i) All recycled waste products will be remanufactured, and there will be no difference between the remanufactured product and the newly produced product with the same retail price,

(ii) Each member makes independent decisions, and manufacturers need to invest in R&D for green products,

(iii) According to Ghosh and Shah's study,13 it is assumed that the market demand function is $D(p) = a - bp + \alpha\theta$, a and b are constants and $a > 0$, $b > 0$, a refers to market volume, b refers to consumer sensitivity to retail price; α refers to the sensitivity coefficient of market demand to the greenness of the product, $\alpha > 0$. θ refers to the innocence of the product as a continuous variable. (In traditional supply chains, $D(p) = a - bp$.)

(iv) Research and development of green products require a certain amount of investment. According to Govindan et al.'s study,14 it is believed that there is a quadratic relationship between the green investment cost of the product and the greenness:$f(\theta) = I\theta^2$, I refer to the green investment parameter, which is the R&D cost invested by the company to improve the innocence of the green product,

(v) Green and non-green products in the market are interchangeable, and consumers will consider the price and greenness of the product when purchasing,

(vi) Let the supply function for the scrap be $S(p_r) = k + \lambda p_r (k \geq 0，\lambda > 0)$; when $p_r = 0$, $S(p_r) = k$, this means that a consumer has agreed to carry out the recycling of waste products at no cost at this time, which can reflect the green consciousness of the consumer,

(vii) The members of the closed-loop green supply chain are in a two-stage Stackelberg game with complete information, containing only the only manufacturer, the only retailer or the only third-party recycler, with the manufacturer as the first mover in the game, and only the recycler differs in each model.

4 Model Construction

4.1 Model N

The model is shown in Figure 3, at which point the profits of each member of the supply chain and the overall are:

$$\Pi_N^R = (p - w)D(p). \tag{1}$$

$$\Pi_N^M = (w - c)D(p). \tag{2}$$

$$\Pi_N = \Pi_N^R + \Pi_N^M. \tag{3}$$

The problem was solved by induction in the reverse direction, with the following results.

$$Max\, \Pi_N^M = \frac{(a-bc)^2}{8b}. \tag{4}$$

$$Max\ \Pi_N^R = \frac{(a-bc)^2}{16b}. \tag{5}$$

$$Max\, \Pi_N = \frac{3(a-bc)^2}{16b}. \tag{6}$$

4.2 Model R

The model is shown in Figure 3, at which point the profits of each member of the supply chain and the overall are:

$$\Pi_R^R = (p - w)D(p) + (w_r - c_R - p_r)S(p_r). \tag{7}$$

$$\Pi_R^M = (w - c)D(p) + (\Delta - w_r)S(p_r) - f(\theta). \tag{8}$$

$$\Pi_R = \Pi_R^R + \Pi_R^M. \tag{9}$$

In this model, a Stackelberg game process arises between the manufacturer and the retailer. The manufacturer must first decide on w, and then the retailer will determine p according to w to maximize its profit; similarly, it is possible to identify w_r and p_r, and the manufacturer needs to take into account the retailer's reaction to its own decision when formulating its strategy. Again solving the problem by induction in the reverse direction, equation (7) yields:

$$\frac{\partial \Pi_R^R}{\partial p} = a - 2bp + \alpha\theta + bw = 0. \tag{10}$$

$$\frac{\partial \Pi_R^R}{\partial p_r} = w_r\lambda - k - \lambda c_R - 2\lambda p_r = 0. \tag{11}$$

It can be solved as follows:

$$p^* = \frac{a+\alpha\theta+bw}{2b}. \tag{12}$$

$$p_r^* = \frac{\lambda w_r - \lambda c_R - k}{2\lambda}. \tag{13}$$

Taking the resulting into equation (8).The following results can be derived.

$$p^* = \frac{3a+3\alpha\theta+bc}{4b}. \tag{14}$$

$$p_r^* = \frac{\lambda\Delta - \lambda c_R - 3k}{4\lambda}. \tag{15}$$

Taking these results into the respective profit functions gives:

$$Max\ \Pi_R^M = \frac{(a+\alpha\theta-bc)^2}{8b} + \frac{(\lambda\Delta+k-\lambda c_R)^2}{8\lambda} - I\theta^2. \tag{16}$$

$$Max\ \ \Pi_R^R = \frac{(a+\alpha\theta-bc)^2}{16b} + \frac{(\lambda\Delta+k-\lambda c_R)^2}{16\lambda}. \tag{17}$$

$$Max\ \Pi_R = \frac{3(a+\alpha\theta-bc)^2}{16b} + \frac{3(\lambda\Delta+k-\lambda c_R)^2}{16\lambda} - I\theta^2. \tag{18}$$

Let:

$$A = \frac{(a+\alpha\theta-bc)^2}{b}, B = \frac{(\lambda\Delta+k-\lambda c_R)^2}{\lambda}. \tag{19}$$

The results are shown in Table 2.

4.3 Model M

The model is shown in Figure 3, at which point the profits of each member of the supply chain and the overall:

$$\Pi_M^R = (p - w)(a - bp + \alpha\theta). \tag{20}$$

$$\Pi_M^M = (w - c)D(p) + (\Delta - p_r - c_M)S(p_r) - f(\theta). \tag{21}$$

$$\Pi_M = \Pi_M^R + \Pi_M^M. \quad (22)$$

In this model, a Stackelberg game process arises between the manufacturer and the retailer. The solution method is the same as in 3.2; the results are shown in Table 2.

4.4 Model T

The model is shown in Figure 3, at which point the profits of each member of the supply chain and the overall:

$$\Pi_T^R = (p - w)(a - bp + \alpha\theta). \quad (23)$$

$$\Pi_T^T = (w_r - p_r - c_T)(k + \lambda p_r). \quad (24)$$

$$\Pi_T^M = (w - c)D(p) + (\Delta - w_r)S(p_r) - f(\theta). \quad (25)$$

$$\Pi_T = \Pi_T^R + \Pi_T^T + \Pi_T^M. \quad (26)$$

In this model, the Stackelberg game process arises between the manufacturer, retailer, and third-party recycler. The solution is the same as in 3.2, and the results are shown in Table 2.

Table 2. Equilibrium solutions and optimal profit values for each decision variable.

	Model N	Model R	Model M	Model T
p	$\frac{3a+bc}{4b}$	$\frac{3a+3\alpha\theta+bc}{4b}$	$\frac{3a+3\alpha\theta+bc}{4b}$	$\frac{3a+3\alpha\theta+bc}{4b}$
p_r	/	$\frac{\lambda\Delta-\lambda c_R-3k}{4\lambda}$	$\frac{\lambda\Delta-\lambda c_M-k}{2\lambda}$	$\frac{\lambda\Delta-\lambda c_T-3k}{4\lambda}$
w	$\frac{a+bc}{2b}$	$\frac{a+\alpha\theta+bc}{2b}$	$\frac{a+\alpha\theta+bc}{2b}$	$\frac{a+\alpha\theta+bc}{2b}$
w_r	/	$\frac{\lambda\Delta+\lambda c_R-k}{2\lambda}$	/	$\frac{\lambda\Delta+\lambda c_T-k}{2\lambda}$
Π_J^M	$\frac{(a-bc)^2}{8b}$	$\frac{A+B}{8}-F$	$\frac{A+2D}{8}-F$	$\frac{A+E}{8}-F$
Π_J^R	$\frac{(a-bc)^2}{16b}$	$\frac{A+B}{16}$	$\frac{A}{16}$	$\frac{A}{16}$
Π_J^T	/	/	/	$\frac{E}{16}$
Π_J	$\frac{3(a-bc)^2}{16b}$	$\frac{3(A+B)}{16}-F$	$\frac{3A}{16}+\frac{D}{4}-F$	$\frac{3(A+E)}{16}-F$

$A = \frac{(a+\alpha\theta-bc)^2}{b}$ $B = \frac{(\lambda\Delta-\lambda c_R+k)^2}{\lambda}$ $D = \frac{(\lambda\Delta-\lambda c_M+k)^2}{\lambda}$ $E = \frac{(\lambda\Delta-\lambda c_T+k)^2}{\lambda}$ $F = I\theta^2$

5 Comparison of models and conclusions

The following conclusions can be drawn from the analysis and comparison of the results in Table 2.

Conclusion 1: The selling and wholesale prices of the products are the same for the models with a recycling step and for the different channels chosen because the recycling rate is not factored into the model.

Conclusion 2: The sales price and wholesale price are somewhat higher in the model with three different recycling models than in the traditional supply chain model N, which does not include a recycling step, but the retailer's profit is somewhat higher; this is because the retailer does not have to pay green costs in our assumptions, in the real world various members of the supply chain may need to share some green fees.

Conclusion 3: The expressions for the transfer price and the recycling price differences between different recycling models further affect the benefits to the individual members within the supplier and the supply chain. The recycling cost of the recycler determines the transfer payment price for the recycled product, so the transfer payment price will change with the recycling cost, so if $c_R = c_T$, for example, the transfer payment price in model R and model T will then be the same.

Conclusion 4: In the $c_R = c_T = c_M$ case, to make the total profit of the green closed-loop supply chain higher than the traditional non-closed-loop supply chain, it is necessary to calculate the green investment parameters and the conditions that the greenness needs to satisfy.

Proof. Let $c_R = c_T = c_M = Z$, then $B = D = E$, yield $\Pi_M > \Pi_R = \Pi_T$; as we require $\Pi_R > \Pi_N$, $\Pi_M > \Pi_N$, $\Pi_T > \Pi_N$; so further need to satisfy:

$$\frac{3(a-bc)^2}{16b} < \frac{3(a+\alpha\theta-bc)^2}{16b} + \frac{3(\lambda\Delta+k-\lambda Z)^2}{16\lambda} - I\theta^2. \tag{27}$$

The calculation can be obtained as follows.

$$I < \frac{\alpha(6a+3\alpha\theta-6bc)}{16b\theta} + \frac{3(\lambda\Delta+k-\lambda Z)^2}{16\lambda\theta^2}. \tag{28}$$

That is, when the green investment parameters and greenness satisfy the conditions of the above equation, the green closed-loop supply chain is profitable compared to the traditional non-closed-loop supply chain.

□

Conclusion 5: If the manufacturer's perspective is used to select its optimal strategy, then.

(i) if $c_R = c_T = c_M$, then $B = D = E$, the choice of model M has the most significant payoff. And for the supply chain as a whole, the most profit is made when model M is used.

(ii) In reality, however, c_R、c_T and c_M are not equal. In this case, it is necessary to compare the manufacturer's maximum profit under the three models to obtain the conditions that c_J needs to satisfy when the optimal choice is model J.

(a) When the model R is the optimal choice, $\Pi_R^M > \Pi_T^M$, $\Pi_R^M > \Pi_M^M$ is necessary, and the calculation can be obtained as follows.

$$c_R < c_T \text{ and } c_R < (1-\sqrt{2})\Delta + \frac{1-\sqrt{2}}{\lambda}k + \sqrt{2}c_M. \quad (29)$$

That is, the manufacturer chooses the retailer for recycling when the recycling cost of each member satisfies the condition in the above equation.

(b) When model M is the optimal choice, $\Pi_M^M > \Pi_T^M$, $\Pi_M^M > \Pi_R^M$ is required, and the calculation can be obtained as follows.

$$c_M < \frac{2-\sqrt{2}}{2}\Delta + \frac{2-\sqrt{2}}{2\lambda}k + \frac{\sqrt{2}}{2}c_T \text{ and } c_M < \frac{2-\sqrt{2}}{2}\Delta + \frac{2-\sqrt{2}}{2\lambda}k + \frac{\sqrt{2}}{2}c_R. \quad (30)$$

That is, when each member's recycling cost satisfies the condition in the above equation, the manufacturer chooses itself to carry out the recycling.

(c) When model T is the optimal choice, it is necessary, and the calculation can be obtained as follows.

$$c_T < c_R \text{ and } c_T < (1-\sqrt{2})\Delta + \frac{1-\sqrt{2}}{\lambda}k + \sqrt{2}c_M. \quad (31)$$

That is, when each member's recycling cost satisfies the condition in the above equation, the manufacturer chooses a third party to carry out the recycling.

Conclusion 6: Increasing the sensitivity coefficient to the greenness of the product has a positive effect on improving the innocence of the product, each decision variable and the profit of each member; however, if the green investment parameter is increased, there will be a reverse effect on the greenness of the product, each decision variable and the profit of each member.

6 Conclusions

Based on the Stackelberg game, this paper has constructed three different models of green closed-loop supply chains with varying models of recycling, compared and discussed their respective pricing strategies, and found that if the recycling cost per unit of product is the same for each member of the supply chain, the optimal decision is for the manufacturer to recycle; and separately calculated that if the recycling cost of each member is different Finally, the impact of green investment parameters and the sensitivity coefficient of green products on the maximum profit and decision variables of each link in the supply chain is analyzed.

Green closed-loop supply chains have been a popular area of research for a short period and have achieved good results in various companies in different countries. However, there are still some shortcomings and limitations in the study on its decision-making game. For example, in this paper, as the green closed-loop supply chain model constructed only contains a sole manufacturer and a sole retailer, the actual supply chain structure is much more complex than these models, and there may be multiple manufacturers, retailers or recyclers, etc. In future research, a more diversified model structure can be constructed; for example, there are n suppliers or n retailers. In future research, we can build a more diversified model structure, for example, a supply chain with n suppliers or n retailers competing with each other, and design a more realistic game model.

In addition, the market demand function set in this paper is only affected by the retail price and greenness. Still, in reality, market demand needs to consider many factors, such as the bullwhip effect, which generates random fluctuations,[15] which can affect the decision-making of each participant in the supply chain. Therefore, to make the research more relevant and realistic, we can explore the situation of uncertainty in market demand to make the research more relevant.

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