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Pricing Issues of Plastic Waste Recycling Supply Chain Under Environmental Investment

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Abstract: With the continuous development of the plastic industry, plastic products are everywhere, from production and manufacturing to daily life. At the same time, it is precisely due to the widespread use of plastic that the amount of waste plastic waste generated in China is increasing, which has brought a great burden to the environment. Therefore, this article aims to study the logistics supply chain of plastic waste recycling, solve the problem of plastic waste recycling, and enhance the economic development benefits of all participants. Meanwhile, this article considers different game structures to study the interactions between supply chain participants. Establish a model using nonlinear optimization methods. In order to maximize the total profit of supply chain participants, analytical and closed form methods are used to determine the optimal service price and environmental investment. Taking the data from Hubei Province as an example, it is demonstrated that investment in environmental factors increases the total profit of supply chain partners, and there is an optimal degree, which improves the operational efficiency and efficiency of the entire recycling logistics supply chain.

Keywords: Plastic waste; Game theory; Supply chain management.

1. Introduction

With the rapid rise of the plastic industry, plastic products are everywhere and have gradually penetrated into every corner of society, from the and manufacturing of enterprises to the daily food, clothing, housing, and transportation. According to statistics, the annual output of plastic products in China has increased year by year accumulating to 77.716 million tons by December 2022. The urban domestic waste in China is as high as 249 tons, of which plastic waste accounts for 5%-14%, that is, the total amount of waste plastic waste produced each year is about 12.5 million tons-34.86 million tons. It is precisely because of the large use of plastic products that the phenomenon of a large number of discarded waste in China occurs frequently. This not only poses a serious threat to the growth and development of crops, causing a reduction in crop yields, and the problem of a decrease animal diversity due to animals mistakenly eating plastic, but it is also prone to cause serious environmental and atmospheric pollution problems. The hazards caused have attracted widespread attention from relevant departments society. At the same time, the technology for recycling plastic waste has been upgraded and has become gradually diversified. It has changed from traditional treatment methods such as landfill andineration to thermal cracking, chemical modification, and other methods. The recycling structure of plastic waste is mainly composed of waste PET, waste PE, and waste PP, waste PET plastic, which accounts for 31.9%. It is convenient to recycle and has a high recycling value, and it is one of the main varieties plastic recycling at present. China uses these waste plastic wastes to replace coal and oil, make cement rotary kilns, and generate electricity in many ways, greatly improving the rate of waste plastic wastes in China[1].

At present, there are few relevant documents on the research of plastic waste recycling logistics supply chain in our country. Reverse logistics processes offer companies the opportunity to become more environmentally friendly through reuse, recycling and recovery[2].Referring to the definition of recycling supply chain in literature , we define the plastic waste recycling supply chain as: the process of executing the recycling treatment of plastic waste, which is mainly composed of parts: the generator of plastic waste, the waste transfer station, and the recycling and remanufacturing enterprise.

This paper explores the pricing and environmental investment issues in the plastic waste recycling supply chain, which includes plastic waste generators, logistics providers and recycling and remanufacturing centers. Different from the previous studies, this paper considers different game structures to investigate the interactions among supply chain participants, and uses nonlinear methods to establish the model, and studies the pricing problem in the case of a single logistics provider and a single recycling and remanufacturing center to maximize the total of supply chain participants. Moreover, a numerical analysis and sensitivity analysis are conducted with the data of Hubei Province to explore the relationship between environmental factors and supply chain. Two different game-theoretic methods are adopted, which are Stackelberg game and Nash equilibrium.

2. The Model

This study aims to gain an in-depth understanding of the sustainability investment and pricing of logistics providers and processors. Therefore, we investigated the interactions between in the plastic waste recycling supply chain. In recent decades, game-theoretic approaches have been widely used to analyze supply chain interactions [3]. In general, games be divided into two categories. In cooperative games, players attempt to maximize overall profit. Non-cooperative games, on the other hand, assume that the participants' objective to maximize their individual benefits. Figure 1 illustrates four different games based on the bargaining power between logistics providers and recycling and remanufacturing centers.

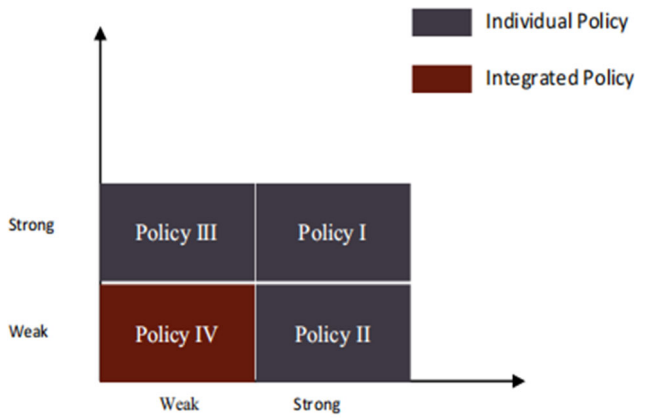


Figure 1. Bargaining Power Relationship

Where the x-axis is the bargaining power of the processor and the y-axis is the bargaining power of the logistics provider. Policy 1 represents the where both the logistics provider and the processor are strong and independent; Policy 2 represents the case where the processor is powerful and acts as a leader; Policy 3 the case where the logistics provider is powerful and the processor is a follower; Policy 4 represents the case where the logistics provider and the processor are weak and equal participants and both are needed to be combined. This paper mainly focuses on the study of non-cooperative games.

2.1. Problem Description

The main challenges of outsourcing waste disposal for plastic waste generators are price and environmental challenges, and the pricing decision is of great importance plastic waste generators, transfer stations, and remanufacturing centers. Moreover, the managers of the plastic waste recycling supply chain always emphasize environmental issues. Transfer stations seek modes with less carbon dioxide emission to transfer plastic waste to disposal facilities. Disposal facilities also seek new technologies to reduce the adverse environmental impact of hazardous plastic waste., service pricing and the degree of environmental investment are the main research objects in this study.

In the general structure of the plastic waste recycling supply chain, there are two related to price: (a) the logistics provider charges the plastic waste generator for the service price and (b) the remanufacturing center charges the logistics provider the disposal price, which is an economic factor. At the same time, toxic gases are produced during the disposal of plastic waste, and even worse, it can cause such as the greenhouse effect and the melting of icebergs, which is an environmental concern, i.e., an environmental factor. Therefore, many supply chain participants must or mandatorily combine pricing issues with investment to reduce the negative environmental impact of waste disposal operations.

In this study, we consider the case of a single logistics provider a single disposal party, where the logistics provider bears the cost of reducing the carbon footprint of waste transportation. At the same time, we study two sub-scenarios where disposal party can choose whether to invest in reducing the negative environmental impact of the disposal of hazardous medical waste. Therefore, we use the following Table 1 to model the problem.

Table 1. The Notation

Parameter	
d	Plastic waste transport demand [tons]
D	Maximum market potential demand [tons]
α	Service price elasticity of demand
λ	Improving the environmental impact of plastic waste treatment process demand elasticity
θ	Logistics companies improve the carbon footprint of plastic waste transportation
μ	The recycling and remanufacturing center improves the level of negative environmental impact of the waste disposal process.
ω	Recycling and remanufacturing center unit processing price [t/yuan]
p	Logistics provider unit service price [t/yuan]
k	Remanufacturing center unit operating cost [yuan]
π_1	Remanufacturing center unit operating cost [yuan]
π_2	Total profit of logistics provider [yuan]
q	Investment factor to reduce the carbon footprint of plastic waste transport
e	Improve investment factors for processing environmental impact
f	environmental impact of processing Logistics fixed profit margin [%]

2.1.1. Scenario 1: treatment without environmental investment

The logistics firm is responsible for transporting the plastic waste to the recycling and remanufacturing center. We assume that the logistics firm invests in the level of carbon footprint impact during transportation, while the recycling and remanufacturing center is not concerned with environmental factors and is not interested in investing in sustainability issues At the same time, we assume an additional demand function that depends on the service price and environmental factors. This type of demand function [4] is common.

$$d = D - \alpha p + \lambda\theta \quad (1)$$

$$\pi_1 = (\omega - k)d \quad (2)$$

$$\pi_2 = (p - \omega)d - q\theta^2 \quad (3)$$

Eq. 1 shows that if the logistics provider's service price increases, the transportation demand for plastic waste will decrease. However, if the logistics provider chooses higher level of environmental factors, the demand will increase.

2.1.2. Scenario 2: treatment with environmental investment

In addition to the logistics provider investing in reducing the level of carbon footprint impact during transportation, the recycling and remanufacturing center invests in the negative environmental impact of plastic waste disposal processes. As a result, the demand function depends on the joint service

price and environmental actions of both the logistics provider and the. The total profit of the logistics provider remains consistent with Eq. 3, while the total profit of the processor will be different.

$$d = D - \alpha p + \lambda(\theta + \mu) \quad (4)$$

$$\pi_1 = (\omega - k)d - e\mu^2 \quad (5)$$

$$\pi_2 = (p - \omega)d - q\theta^2 \quad (6)$$

Eq. 4, similarly, if the processing party chooses a higher level of environmental factors, the demand will increase.

2.2. Solutions

This paper aims to analyze the relationship between the participants in the plastic waste supply chain from the perspective of non-cooperative game theory, using both Stackel and Nash games.

2.2.1. Stackelberg game

The Stackelberg model is a quantity leadership model proposed by the German economist Stackelberg in the 1930s (1934). This model reflects the asymmetric competition between enterprises. In Stackelberg's oligopoly theory the analysis paradigm of positioning the role of oligopolistic firms as "leader" and "follower" was proposed, that is, one is a powerful leader and the is a relatively weak follower. Therefore, the Stackelberg model is a quantity leadership model, and there is a difference in the order of action between firms. The of output follows the following order: the leading firm decides on an output, and then the follower firm can observe this output and then decide its own output based on the of the leading firm. It should be noted that when the leading firm decides its own output, it fully understands how the follower firm will act. This means that the firm can know the reaction function of the follower firm. Therefore, the leading firm will naturally expect the impact of the output it decides on the follower firm. It is this consideration of this impact that the output determined by the leading firm will be a profit-maximizing output constrained by the reaction function of the follower firm. In Stackelberg model, the decision of the leading firm no longer needs its own reaction function.

This game is compatible with Policy 3, which is manifested in the strong power of the logistics provider and the weak bargaining power of the handler, where the logistics provider has power over DF, that is, the logistics provider is the leader and handler is the follower. The leader maximizes its total profit by considering the behavior of the follower.

Therefore, the solution process is that the handler first points out the value of its variable to maximize its total profit. Then, the logistics provider will use these best values to determine its decision variables.

Where, for the sake of simple, we assume that a fixed profit margin f is adopted, and the result of this assumption is that the participants in the strategy do not have pricing power. The service can be expressed as

$$p = \omega(1 + f) \quad (7)$$

Eq. 7 shows the plastic waste generating organization plays the role of both the waste generator and the contractor, so the waste generator does need to pay the logistics provider the service price p. At the same time, the plastic waste disposal party is independent, so the logistics provider has to pay the disposal money ω, so the service price of the logistics provider is to add the profit obtained on the basis of ω.

The final results of θ are shown in Table 2.

Table 2. Final Results

Scenario 1	Scenario 2
$\frac{D\lambda f}{-f\lambda^2 + 4\alpha q(1+f)}$	$-\frac{e\lambda(4De - k\lambda^2)\alpha f(1+f)}{4e^2\lambda^2 f(1+f)\alpha - q(\lambda^2 - 4e(1+f)\alpha)^2}$

2.2.2. Nash game

Taking the price war between two companies as an example, there is a possibility of a lose-lose situation in a price. Under the condition that the other party does not change its price, it is not possible to raise prices, otherwise the market will be further lost; nor can prices lowered, because there will be a loss-selling situation. Therefore, the two companies can change the original pattern of interests and seek a new scheme for the distribution of interests negotiation. The state in which economic agents, assuming that the strategies chosen by other agents are fixed, choose their own optimal strategies is the Nash equilibrium. Therefore, the game theory refers to the situation where there are n players involved in the game, and if no player can increase their payoff by acting alone in a certain situation, that, in order to maximize their own interests, no single party is willing to change its strategy, then this strategy combination is called the Nash equilibrium. All the strategies of players constitute a strategy combination, and the Nash game theory is essentially a non-cooperative game state.

When the Nash equilibrium is reached, it does not mean that both in the game are in a state of inaction. In a sequential game, this equilibrium is reached in the continuous actions and reactions of the players. The Nash equilibrium does not mean that both parties in the game have reached an overall optimal state. The optimal strategy does not necessarily lead to the Nash equilibrium, and the strictly dominated strategy become the best strategy, while the weakly dominant and weakly dominated strategies may lead to the Nash equilibrium.

This game is compatible with policy 1, that is both the logistics provider and the processor are strong, indicating that the logistics provider and the processor are independent entities with the same power, and they are not interested in and seeking to maximize total profits. Participants can make decisions independently at the same time. Therefore, in order to obtain the Nash equilibrium, the profit maximization problems of logistics provider and the processor are solved separately.

The final results of θ are shown in Table 3.

Table 3. Final Results

Scenario 1	Scenario 2
$-\frac{\lambda f(D + k(1+f)\alpha)}{f\lambda^2 - 4\alpha q(1+f)}$	$\frac{\lambda f(k\lambda^2 - 2e(D + k(1+f)\alpha)}{2\lambda^2(q + ef) - 8eq(1+f)\alpha}$

3. Numerical Example Analysis

In this section, we give a numerical example to show the efficiency of the proposed model. Taking the data of plastic waste in Hubei Province an example, we query the national data website and find the amount of domestic waste removed in Hubei Province in the past five years.The average amount of domestic waste removed in these five years is calculated to be 10.3637 million tons.

Both domestic waste and plastic waste need to be collected at the source of waste generation, which is mainly concentrated in residential areas, commercial areas, and, etc.; both need to be transported by vehicles to various waste treatment network nodes. Among them, plastic waste belongs to the components of domestic waste, accounting for about 7% -10%. We roughly calculated the average removal amount of plastic waste as 725459 tons, and for the convenience of calculation we took the integer, so let $D = 72500$ tons. And the values of other data are shown in Table 4.

Table 4. Data Assignment

D	72500
λ	20
f	10%
α	30
k	16
e	12
q	10

To conduct the sensitivity analysis, we first change the value of q and observe the relationship between q and ω under the two game structures. Meanwhile, we consider the logistics provider's marginal profit rate as a constant, we then observe the change of total profit under each game structure when the profit rate f is changed.

Figure 2 shows the relationship between the investment factor to reduce the carbon footprint of plastic waste transportation and the unit processing price of the recycling and remanuring center.

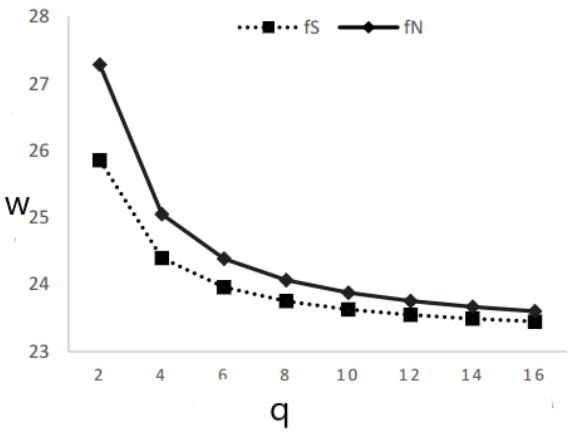


Figure 2. The Relationship Between q And ω

From the Figure 2, it can be seen that as the investment cost to improve the carbon footprint increases, the unit processing price of the collection and remufacturing center decreases. (a) When the cost of carbon reduction increases, the logistics provider will consider reducing the level of sustainability, and therefore, it must consider the price for the plastic waste generator. (b) A higher level of sustainability will provide higher value to the plastic waste generator. This is also a crucial conclusion that decision makers in the plastic waste recycling supply chain manage the economics of their operations.

Figure 3 shows the relationship between the marginal profit margin of logistics providers and total profit.

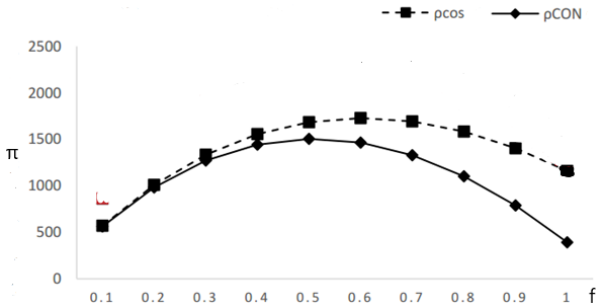


Figure 3. The Relationship Between f And Total Profit

From the Figure 3, it can be seen that the total profit is concave with respect to f, which implies that there is an point for the total profit. The higher the profit margin, the higher the service price, which will have an adverse effect on demand, thereby reducing the total profit.ating this optimal point will have a negative impact on the profits of the participants in the plastic waste supply chain. On the other hand, a lower service price reduces and ultimately reduces the total profit. Therefore, logistics providers should consider this trade-off to determine the optimal service price. At the same time, regardless of the type of, the total profit shows an increasing trend in both games.

When the recycling and remanufacturing center (processor) considers environmental investment, the total profit of both will increase. This result can encourage the processor to invest the fund in more environmentally friendly activities. The results show that it is optimal for the processor to invest in environmental. For logistics providers, there is no significant difference in total profit between the Stackelberg game and the Nash game. In contrast, the processor has a much greater in the Nash game. Logistics providers can focus on environmental impact without worrying about market decision-making power. Being the leader in the supply chain does not provide a significant advantage logistics providers. In contrast, the total profit in the Nash game is higher. This means that logistics providers will not attempt to gain a leading position in the market, the processor can focus on environmental programs that benefit all supply chain participants.

4. Summary

This paper studies the urban plastic waste treatment system, including plastic waste generators, logistics providers, and disposers. We assume that the plastic waste recycling supply chain includes a single logistics provider and a single disposer, and consider two scenarios, one with a disposer who has no willingness invest in the environment, and the other with a disposer who has a willingness to invest in the environment. For these two cases, we use two games, namely Stackelberg game and the Nash game, and use game theory to examine the interaction between participants in the plastic waste supply chain. Finally, we carry out a numerical analysis, and discuss the main insights and findings extracted from the sensitivity analysis of important model parameters.

Plastic waste is generated by many public facilities, such as shopping malls enterprises, and schools, etc. Moreover, plastic waste is usually disposed of by disposal facilities. Due to the special conditions of plastic waste, it is inevitable for urban management companies to consider environmental factors. In addition, determining the optimal service price for plastic waste treatment is the main decision for the recycling and remanufacturing centerdisposal enterprise). In some cases, the center company receives, transports, and disposes of plastic waste. However, in other supply chains, independent individual companies are for the transportation and treatment process.

In addition, the main research of this paper is the optimal service price and environmental investment level for logistics providers and disposers when the profit is maximized. The optimal value is determined according to the bargaining power of the participants in the plastic waste supply chain. The results show that the participants in the waste supply chain can improve their profits through environmental investment, and there is an optimal degree. It also shows that waste generators are willing to pay more for companies that invest improving the environment. At the same time, this paper, on the one hand, explores the different power structures that exist between participants in the plastic waste recycling supply chain On the other hand, it is proposed that service price and environmental investment are key decisions in the plastic waste recycling supply chain. Therefore, our model can help decision makers their position in the market and make the best decision to maximize their total profit.

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