Research Article

Study of the Complexity Game of Supply Chain Green Innovation Introduction under EPR Policy and Government Subsidies

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Nowadays, with global scientific and technological levels rapidly improving, innovation has been a great need for enterprises to solve the dilemma. Combined with EPR (Extended Producer Responsibility) and the topic of remanufacturer, adopting green innovation has been an effective way when green supply chain management is applied. In this paper, we focus on the activity of green innovation and build a model where the manufacturer will invest in green innovation to improve the product availability rate of recycled products and save the cost in the process of remanufacturing. Besides, we take three stages in a cycle into consideration, that is, production/sale, recycling used production, and remanufacture/sale, and meanwhile, the government gives a subsidy to enterprises to encourage the activity of recycling. In the process of model solving, we take a dynamic decision-making way into consideration. We find that the decision adjustment speed of players has a significant effect on the stability, and in a long dynamic repeated game process, with the speed of decision adjustment increasing, the system enters into chaos at the end of the process. It is interesting that when the speed of decision adjustment exceeds the critical point of the bifurcation diagram, the profit of the manufacturer decreases and then enters a chaotic state. Besides, with the level of subsidies increasing, the area of stable region decreases gradually. Certain investment has a positive effect on product selling and recycling as well as the profit, and the government subsidy undoubtedly raises the profit of manufacturers and encourages the activity of recycling. In the end, we make chaos control by adjusting the decision method.

1. Introduction

Due to the increasing environmental preoccupation, the potential economic benefits, and the legislation pressure, supply chain management has changed to focus on environmental impacts of production and Earth resources’ preservation [1]. More and more emphases have been put on a closed-loop supply chain because of its benefit of recycling processes which are the possibility of economic viability and environmental sustainability [2]. As we all know, closed-loop supply chain contains two parts, the forward supply chain and the reverse supply chain, in which the new product development, product design and engineering, procurement and production, marketing, sales, distribution, and after-sale service are realized in the forward supply chain, and then, the reverse supply chain refers to used products’ collection, testing, sorting, refurbishing, recovery, recycling, remarketing, reselling, and so on [3, 4]. The closed-loop supply chain expands the connotation of the traditional supply chain and realizes protecting the environment because it increases the utilization ratio of raw materials and reduces the emission levels. Based on that, the closed-loop supply chain has become a new trend in logistics and supply chain management. In China, the EPR pilot work carried out by the Ministry of Industry and Information Technology, Ministry of Finance, Ministry of Commerce, and Ministry of Science and Technology continues to progress, and the EPR recycling has also achieved periodic results.

Remanufacturing is an important part of the closed-loop supply chain which makes resource sustainable possibly. Remanufacturing is the process in which a used product transforms into a “new” product or into a product satisfying
quality level that meets the recently approved American National Standards Institute definition for remanufacturing [5]. Remanufacturing expands the concept of "product life cycle" which usually refers to product manufacturing, use, and disposal. After the birth of the remanufacturing industry, besides the three phases we said, product maintenance and using advanced remanufacturing technology to repair and reconstruction are also needed to be considered in the product design. The USA is the largest remanufacturer in the world, and the output rose 15 percent to at least $43 billion, supporting 180,000 full-time US jobs by remanufacturing between 2009 and 2012. So, remanufacture benefits not only the environment but also the development of economic. In 2008, the Chinese National Development and Reform Commission launched a pilot program of auto part remanufacturing, and 14 firms were selected and supported to start up remanufacturing, seven of which are auto manufacturers (or their subsidiaries) and the others even are part suppliers [6].

Nowadays, with global scientific and technological levels rapidly improving and to reply to the pressures from customers, competitors, and regulators, innovation has been a great need for enterprises [7, 8]. So, combined with the topic of remanufacturing, adopting green innovation is becoming so important when green supply chain management is applied. Based on what we refer to, the questions we try to answer can be shown as follows. First of all, considering the government's financial intervention and the competition in the market, does a manufacturer need to invest in green innovation to improve the product availability rate of recycled products? Then, how about taking a dynamic decision-making way into consideration? How will product prices evolve in repeated games? What will happen to the stable domain? Besides, what can we do to control chaos?

So, innovation in this paper can be concluded as follows. In our model, we take recycling and remanufacturing into consideration, and there are three stages in a cycle, that is, production/sale, recycling used production, and remanufacture/sale. Then, combined with the recycling of used products, we take manufacturer and supplier into consideration and answer the question of whether a manufacturer needs to invest in green innovation to improve the product availability rate of recycled products. Besides, based on the complex system theory, we take a dynamic decision-making way into consideration instead of limitations into a single period static decision. In the end, the way of controlling chaos is discussed.

The rest of this paper is organized as follows. In Section 2, we review the relevant literature. In Section 3, we describe the problem and show the symbols and assumptions of our model. In Section 4, we build and solve the model and get equilibrium points. Results are also analyzed. In Section 5, through the numerical simulation, we get the bifurcation diagram and stability domain diagram to express chaos. In Section 6, chaos control is made. In the end, we provide the conclusions in Section 7.

2. Literature Review

Innovation pushes society and economics toward development, and under the background of environmental protection and sustainability, green innovation is becoming more and more essential. A lot of literature has researched green innovation investment in recent years. Xie et al. [9] built a dynamic model using data of 28 industries in 10 years and studied green process innovation from the perspective of the financial performance of the manufacturing industry. Ley et al. [10] researched the relationship between energy prices and green innovation activities from an industry level. Olson [11] took the green innovation value chain (GIVC) as the tool to analyze the financial feasibility of green products from the perspective of multiple stakeholders. What has been expressed in many studies is that pressure from regulators has a positive effect on green product innovation [12]. Sheu and Chen [13] also verified that governmental financial intervention has a positive effect on the green profit of the enterprise. Then, Ashkan [14] further expressed the benefit of governmental financial intervention. Generally speaking, there are three kinds of governmental financial interventions which are subsidy, taxes, and insurance [15, 15, 16]. Under a three-stage game framework, Subrata [17] established centralized and decentralized conservation models to gain a fair understanding of the advantages of government subsidies to consumers and manufacturers. By comparing the profit, greening level, consumer surplus, and environmental improvement of each member under two different incentive policies, Nielsen et al. [18] came up with a decision support framework for the selection and successful implementation of environmentally friendly products is obtained. At the same time, Izabela Ewa [18] also compared three kinds of government policies to study issues such as government subsidy policy with optimal pricing in the closed-loop supply chain, investment decision to improve product quality, and product recycling under the goal of social welfare optimization. Huang et al. [19] established a series of game models to study the impact of green loans and government subsidies on enterprises' green innovation activities. Inspired by the above studies, we build a closed-loop supply chain and research the investment of green innovation considering governmental financial intervention.

The closed-loop supply chain has raised much attention from more and more scholars. Remanufacturing is an important process of the closed-loop supply chain that has been put more and more emphasis on. In the study of remanufacturing and closed-loop supply chain management, competition between new and remanufactured products, inventory management, quality, pricing, and who carries out recycling and remanufacturing activities are the five main issues [3, 20–22]. Maiti and Giri [22] built a closed-loop supply chain in which a manufacturer produces new products and sells them to the retailer; besides, he also produces remanufactured products and sells them to the secondary market. They analyzed the model under four different decision structures and got the optimal decision. Turki et al. [1] considering manufacture, remanufacture, transportation, and warehouse built a closed-loop supply chain model and used simulation to obtain the optimal values of decision variables. Hong et al. [2] verified the effect
of technology licensing on supply chain members’ decision. And they built a two-period closed-loop supply chain in which, as for the patent holder, the manufacturer produces new and remanufactured products and, as for the licensee, a remanufacturer collects used products and produces remanufactured products at the same time. Giovanni and Zaccour [3] built a two-period closed-loop supply chain and analyzed whether the remanufacturer should outsource the collection of the used products to the retailer. Hosoda and Disney [23] researched the dynamics of a closed-loop supply chain and got the optimal decision to minimize inventory costs of the manufacturer. Li et al. [20] analyzed the relationship between product quality improvement and remanufacturing making by a monopolist manufacturer. However, there are a lot of studies we can access to discuss remanufacturing, but few scholars researched that supplier is responsible for remanufacturing. Then, we take inspiration from [6] who researched the question about whether the supplier or manufacturer remanufactures in a closed-loop supply chain and built a closed-loop supply chain to discuss who would invest in green innovation and remanufacture on the component level. Tang et al. [24] conducted a Stackelberg game to examine pricing and warranty decisions under two warranty models, which consist of a manufacturer and a retailer. Li et al. [25] have a study about the investigations of product design and its impact on the operations of a two-echelon closed-loop supply chain. Wang et al. [26] examined the benefit of the reward-penalty mechanism in a two-period closed-loop supply chain and analyzed by game models.

By analyzing the above literature, we can find that most scholars assume that the manufacturers are entirely rational. However, in a long time, supply chain members’ decision stage is a dynamic process. They have imperfect information about the market and are bounded rational. So, we introduce nonlinear dynamics theory as a solution. Nonlinear dynamics theory is an effective tool theory and has been widely researched. Bao and Ma [27] studied the quantity decision by considering the product quality in parallel supply chains where two manufacturers produce substitute products and then sell them to their downstream retailers separately; the alternatives are analyzed. Ma and Guo [28] applied nonlinear dynamic theory with different adjustment mechanisms and expectations in a supply chain and analyzed the impacts of key parameters on the stability of the positive Nash equilibrium point. Ma et al. [29] built a closed-loop supply chain model with dual-channel recycling composed of one manufacturer and one-third-party, made a number of simulations [7, 30], analyzed macroeconomic models with Hopf bifurcation theory, and found some phenomenon in these nonlinear dynamic models. Ma and Xie [31] aimed at the color TV recycling market, built the model, and researched related parameters’ effect on the system’s stability; in the end, they made chaos control. Dai et al. [32] constructed a continuous dual-channel closed-loop supply chain model with the delayed decision under government intervention. They analyzed the related parameters’ influence and used delay feedback control method to control the chaos.

3. Model Construction

In this work, we focus on the activity that the manufacturer will invest in green innovation to realize remanufacturing considering government financial intervention. As we all know, extended producer responsibility system, which refers to the responsibility that the producer needs to take not only in the production process but also in the entire life cycle, especially the recycling and disposal, has been recognized by many countries. So based on this, we build a model containing two manufacturers, one of which invests in green innovation, and we take recycling and remanufacturing into consideration. In the first stage, manufacturers produce new products and sell them to consumers; in the second stage, manufacturers, respectively, collect used products they produced from consumers; in the third stage, manufacturers will remanufacture. The whole stages constitute a cycle of production activities in the supply chain. Meanwhile, one of the manufacturers invests in green innovation to improve the product availability rate of recycled products which means that, as for a product, the proportion of its reusable component increases and the manufacturer saves cost during remanufacturing.

The timeline of decision-making is as follows: the activities of a whole cycle can be expressed as three stages and the two manufacturers move simultaneously. In stage 1, manufacturers produce new products, set prices, and then sell them to the market. Manufacturer 1 decides the green innovation level and invests in this stage. In stage 2, manufacturers recycle used products, respectively. In stage 3, manufacturers remanufacture recycled products and sell them to customers again. The timeline of the decision-making process can be described in Figure 1.

In our model, two manufacturers produce two kinds of homogeneous products and the price of new products produced by two manufacturers in the period $t(t = 1, 2, 3, \ldots)$ is $p_1(t)$ and $p_2(t)$. They compete in the market and we use $\theta$ which belongs to $(0, 1)$ for the degree of substitution between two kinds of similar products; these assumptions are similar to some existing papers (such as Xie and Ma, Ma et al. [33], and Ma et al. [29]). In this market, we assume that customers prefer purchasing products having a low price, and the sensitivity to price can be captured by $b$. So, the demand function of each kind of product in the period $t$ is shown as follows:

$$
\begin{align*}
q_1(t) &= \alpha_1 - b(p_1(t) - \theta p_2(t)), \\
q_2(t) &= \alpha_2 - b(p_2(t) - \theta p_1(t))
\end{align*}
$$

where $\alpha_1 (\alpha_2 > 0)$ means the market capacity.

In the second and third stages, manufacturers collect used products from customers and remanufacture them. $p_1(t)$ and $p_2(t)$ are used to represent the price of used products in the period $t$ given by the manufacturer. We assume that based on the producer’s responsibility extension system, the manufacturer only collects used products produced by himself, and meanwhile, all used products collected by the manufacturer will be remanufactured. In the process of recycling, customers also have price sensitivity which is captured by $f$. The recycling market capacity in the period $t$
Period \( t \) starts

Manufacturer 1 decides innovation level and new products price; manufacturer 2 sets new products price

\[ p'_1, p'_2 \]

\[ p_1, p_2 \]

\[ p'_1, p'_2 \]

Period \( t + 1 \) starts

Manufacturers decide recycling price of used products

Sell remanufactured products to customers

\( p_1, p_2 \)

\[ \ldots \]

Figure 1: The timeline of decision-making.

is represented by \( \lambda_1 q_1(t) \) and \( \lambda_2 q_2(t) \), where \( \lambda_i \) is the collection rate of used products and bounded by 0 and 1. Then, the amount of recycled used products by each manufacturer in the period \( t \) which is represented by \( q_1(t) \) and \( q_2(t) \) can be shown as follows:

\[
\begin{align*}
q_1(t) &= \lambda_1 q_1(t) + f p'_1(t), \quad f p'_1(t) < q_1(t - 1), \\
q_2(t) &= \lambda_2 q_2(t) + f p'_2(t), \quad f p'_2(t) < q_2(t - 1),
\end{align*}
\]

With environmental issues getting more and more serious, the government tries to figure out the dilemma of global warming and overexploitation of resources by inducing the manufacturers to produce green products. So, governmental subsidies, a kind of government financial intervention, are adopted when enterprises achieve the governmental goal [13]. In our model, the government encourages enterprises to carry on the activity of recycling. So, it gives a subsidy to enterprises according to the value of recycled used products, which is expressed as follows:

\[
\begin{align*}
\pi_1(t) &= (p_1(t) - c_1)(q_1(t) - q'_1(t)) + (p_1(t) - (1 - \gamma)c'_1 - p'_1(t))q'_1(t) - \beta u^2 + \gamma p'_1(t)q'_1(t), \\
\pi_2(t) &= (p_2(t) - c_2)(q_2(t) - q'_2(t)) + (p_2(t) - c'_2 - p'_2(t))q'_2(t) + \gamma p'_2(t)q'_2(t),
\end{align*}
\]

where \( c_1 \) is the unit cost of production when new products are produced and \( c'_1 \) represents the unit cost of production when remanufactured products are produced. There are some constraints: (1) \( q'_i < q_i, i = 1, 2 \): the number of recycled products cannot be larger than the number of new products manufactured in stage one. (2) \( q'_i, q_i \geq 0, i = 1, 2 \): the output is nonnegative.

Besides the assumptions we mentioned above, there are some other assumptions needed to be clarified. First of all, we ignore the costs of inventory holding, inventory shortage, transportation, and so on to simplify the model. Then, we assume that new products and remanufactured products have the same quality. Recycled products of the same quality can be sold again for the same price. For example, the gold ornament is recycled through channels and can be reprocessed into an ornament for sale. As long as the quality of the gold is the same, the price will be the same. Besides, we assume that the manufacturers in our model are bounded rational.

4. Model Solving

According to what we stated, there are three stages in our model where manufacturers produce new products and sell them to customers, and then, they collect the used products and remanufacture them. We divide the process into two pricing stages in which the new products are priced first and the used products can be priced then. So, we use the classic backward induction to solve this game model. Manufacturers decide their price of used products in the period \( t \) to maximize their profit first; then based on imperfect information, manufacturers are bounded rational.
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rational and decide their price of used products in the period $t + 1$. Substituting equations (1) and (2) into equation (3) and taking the partial derivative of $p_1'(t)$ and $p_2'(t)$, then we get the following:

\[
\begin{align*}
\frac{\partial \pi_1(t)}{\partial p_1(t)} &= c_1 f + c_1' f (-1 + u) + (-1 + \gamma) (2 f p_1'(t) + (\alpha_1 - b p_1(t) + b \theta p_2(t)) \lambda_1), \\
\frac{\partial \pi_2(t)}{\partial p_2(t)} &= c_2 f - c_2' f + (-1 + \gamma) (2 f p_2'(t) + (a_2 - b p_2(t) + b \theta p_1(t)) \lambda_2).
\end{align*}
\]

(4)

We make $(\partial \pi_1(t)/\partial p_1'(t)) = 0$ and $(\partial \pi_2(t)/\partial p_2'(t)) = 0$; then, the result can be shown as follows:

\[
\begin{align*}
p_1'(t) &= \frac{f(c_1 - c_1'(1 - u)) + \lambda_1 (\gamma - 1)(\alpha_1 - b(p_1(t) - \theta p_2(t)))}{2 f (1 - \gamma)}, \\
p_2'(t) &= \frac{f(c_2 - c_2') + \lambda_2 (\gamma - 1)(\alpha_2 - b(p_2(t) - \theta p_1(t)))}{2 f (1 - \gamma)}.
\end{align*}
\]

(5)

Substituting equation (5) into equation (3), then the profit functions can be rewritten as follows:

\[
\begin{align*}
\pi_1 &= (p_1 + \frac{1}{2} c_1 (2 - \lambda_1)) (-b p_1 + b \theta p_2 + \alpha_1) - u^2 \beta + \frac{f c_1^2 - 2 f (1 - u) c_1 c_1' + f (\gamma - 1)(b p_1 - b \theta p_2 - \alpha_1)^2}{4 (1 - \gamma)}, \\
\pi_2 &= (b \theta p_1 - b p_2 + \alpha_2) \frac{1}{2} (c_2 - c_2') (p_2 - c_2) + \frac{f (c_2 - c_2')^2}{4 (1 - \gamma)} + \frac{(\gamma - 1)\lambda_2^2}{4 f} (b \theta p_1 - b p_2 + \alpha_2)^2.
\end{align*}
\]

(6)

The marginal return of manufacturers is

\[
\begin{align*}
\frac{\partial \pi_1}{\partial u} &= \frac{f c_1' (c_1 + (-1 + u) c_1')}{2 (1 - \gamma)} - \frac{\lambda_1 c_1'}{2} (b p_1 - b \theta p_2 - \alpha_1) - 2 u^2 \beta, \\
\frac{\partial \pi_1}{\partial p_1} &= b (c_1 - 2 p_1 + \theta p_2) + \alpha_1 - \frac{1}{2} b (c_1 + (-1 + u) c_1') \lambda_1 - \frac{b (-1 + \gamma)(b p_1 - b \theta p_2 - \alpha_1) \lambda_1^2}{2 f}, \\
\frac{\partial \pi_2}{\partial p_2} &= b (c_2 + \theta p_1 - 2 p_2) + \alpha_2 + \frac{1}{2} b (c_2 + c_2') \lambda_2 + \frac{b (-1 + \gamma)(b p_1 - b p_2 + \alpha_2) \lambda_2^2}{2 f}.
\end{align*}
\]

(7)

In reality, limited to obtaining information, the enterprise cannot learn about the exact innovation output decisions that its rival makes and the decisions are not made by maximizing the profits [7]. Besides, in the long term, the decision process of the manufacturers is dynamic, and manufactures will adjust their decisions every stage. According to the assumptions we made earlier, manufacturers in our model are bounded rational. So, they make decisions in the period $t + 1$ based on price and the marginal profit in the period $t$. The decision variable adjustment
the same strategy would be adopted by the manufacturer in the next period $t + 1$; on the other hand, when the marginal profit in the period $t$ is negative, the manufacturer would adjust his pricing strategy and recycled product availability rate decision. When a manufacturer adjusts pricing and investment decision in the period $t + 1$, the whole system stability will be affected.

To get the equilibrium, we make $u(t + 1) = u(t)$, $p_1(t + 1) = p_1(t)$, and $p_2(t + 1) = p_2(t)$. Then, we obtain eight points. But in our model, we just consider two manufacturers both carried on the competition. So, $u^* = 0$, $p_1^* = 0$, and $p_2^* = 0$ are not taken into consideration. In the end, the equilibrium can be obtained as

$$
(u^*, p_1^*, p_2^*),
$$

where

\[
\begin{align*}
  u^* &= \left( f c_1^*(f c_1(2 f(-4 + \theta^2) + b(-1 + \gamma)\beta(-2 + \theta^2)\lambda_2^2)) - (1 + \gamma)\lambda_1(2 f(b\theta c_2 + a\alpha_1 + \theta a_2) + b\theta(\alpha_2^2 + c_2^2)\lambda_2 - b(\lambda_2 + 1 + \gamma)(2 f + b(-1 + \gamma)\lambda_2^2) + (f(-4 + \theta^2) - b(1 + \gamma)(1 + \theta^2)\lambda_1)\lambda_2^2)) \\
  p_1^* &= \left(2 f\left(4 b(-1 + \gamma) + f c_1^*(2 a\alpha_1 + \theta a_2) + 4 b f\beta(-1 + \gamma) c_1^* \lambda_1 + 2 b\theta(-1 + \gamma)^2 (2 a\alpha_1 + \theta a_2)\lambda_2^2)
  \right.
  \\
  &\quad - b f\theta c_2\left(f^2 c_1^2 + 2 b(1 + \gamma)(2 f + b(-1 + \gamma)\lambda_2^2)\right) - 2(1 + \gamma)(2 f + b(-1 + \gamma)\lambda_2^2) + b\theta c_2\left(f^2 c_1^2 + 2 b(1 + \gamma)(2 f + b(-1 + \gamma)\lambda_2^2)\right)\lambda_2 + b(1 + \gamma)\gamma(1 + \theta^2)\lambda_1^2)\lambda_2^2
  \\
  &\quad + 2 b\beta(1 + \gamma)c_1^2 \lambda_1 + 2 b\beta(1 + \gamma)^2 (a\alpha_1 + \theta a_2)\lambda_2^2 + b f c_1\left(f^2 c_1^2 - 2 b(1 + \gamma)(-2 + \lambda_1)\right)(4 f + b(-1 + \gamma)\lambda_2^2)\lambda_2^2
  \\
  &\quad - b(1 + \gamma)(f(-4 + \theta^2)(4 b(-1 + \gamma) + f c_1^2) + 2 b\beta(-1 + \gamma)^2(-2 + \theta^2)\lambda_1^2)
  \\
  &\quad + b(1 + \gamma)(f(-4 + \theta^2)(4 b(-1 + \gamma) + f c_1^2) + 2 b\beta(-1 + \gamma)^2(-2 + \theta^2)\lambda_1^2)) - 1,
  \\
  p_2^* &= \left(2 f\left(4 b(-1 + \gamma) + f c_1^*(\theta a_1 + 2 a_2) + 2 b f\beta(-1 + \gamma)\theta c_2 \lambda_1 + 2 b\theta(-1 + \gamma)^2 (\theta a_1 + a_2)\lambda_2^2)
  \right.
  \\
  &\quad - 2 b f c_2\left(f^2 c_1^2 + \beta(-1 + \gamma)(4 f + b(-1 + \gamma)\lambda_2^2)\right) - 2(1 + \gamma)(4 f + b(-1 + \gamma)\lambda_2^2) + 2 b f c_2\left(f^2 c_1^2 + \beta(-1 + \gamma)(4 f + b(-1 + \gamma)\lambda_2^2)\right)\lambda_2 + b(1 + \gamma)\gamma(1 + \theta^2)\lambda_1^2)\lambda_2^2
  \\
  &\quad + b(1 + \gamma)\gamma(1 + \theta^2)\lambda_1^2)\lambda_2^2
  \\
  &\quad + b f\theta c_2\left(f^2 c_1^2 - 2 b(1 + \gamma)(-2 + \lambda_1)\right)(2 f + b(-1 + \gamma)\lambda_2^2)
  \\
  &\quad + b(1 + \gamma)(f(-4 + \theta^2)(4 b(-1 + \gamma) + f c_1^2) + 2 b\beta(-1 + \gamma)^2(-2 + \theta^2)\lambda_1^2)
  \\
  &\quad + b(1 + \gamma)(f(-4 + \theta^2)(4 b(-1 + \gamma) + f c_1^2) + 2 b\beta(-1 + \gamma)^2(-2 + \theta^2)\lambda_1^2)) - 1.
\end{align*}
\]
Based on the result, we can obtain the Jacobian matrix of this model as follows:

\[
\begin{pmatrix}
  j_{11} & -\frac{1}{2} buw'j_{1} & \frac{1}{2} buw'tj_{1} \\
  -\frac{1}{2} bc'j_{1} & j_{22} & \frac{1}{2} buw'tj_{1} \\
  0 & \frac{b\theta p_1 v_1 (2f + b(-1 + \gamma)\lambda_2^2)}{2f} & j_{33}
\end{pmatrix}
\]

\[
j_{11} = 1 - 4u\omega \beta + \frac{u'c_1 (-f - 2fu) c_1' - (-1 + \gamma)(bp_1 - b\theta p_2 - \alpha_1) j_{1}}{2(-1 + \gamma)}
\]

\[
j_{22} = 1 + \frac{1}{2} v_1 (b(c_1 - 4p_1 + \theta p_2) + \alpha_1) - b(c_1 + (-1 + u) c_1') j_{1} - \frac{b v_1 j_{2}}{2f} (1 - \gamma)(2bp_1 - b\theta p_2 - \alpha_1)
\]

\[
j_{33} = 1 + v_2 (bc_2 + \theta p_1 - 4p_2 + \alpha_2) - \frac{b\lambda_2 v_2}{2} (c_2 - c_2') - \frac{v_2}{2f} (b(1 - \gamma)(b\theta p_1 - 2bp_2 + \alpha_2) \lambda_2^2)
\]

From the Jacobian matrix of equation (9), we can find the characteristic equation of the matrix. So, we can obtain the characteristic equation of J as follows:

\[
f(\lambda) = \lambda^3 + z_2 \lambda^2 + z_1 \lambda + z_0,
\]

\[
z_2 = -(j_{11} + j_{22} + j_{33}),
\]

\[
z_1 = \frac{b^2 p_1 v_1 (-f u w c_1'^2 \lambda_1^2 + \theta^2 p_2 v_2 (2f + b(-1 + \gamma)\lambda_1^2)), (-2f - b(-1 + \gamma)\lambda_2^2) + j_{22} j_{33} + j_{33} (j_{22} + j_{33})}{4f^2}
\]

\[
z_0 = -j_{11} j_{22} j_{33} + \frac{j_{11} j_{22} j_{33}}{4f^2} \left(\frac{b^2 \theta^2 p_1 p_2 v_1 v_2 (2f - b(1 - \gamma)\lambda_2^2)(2f - b(1 - \gamma)\lambda_2^2)}{4f^2}\right)
\]

\[
+ \frac{1}{8f^2} \left(\frac{b^2 f u w c_1'^2 p_1 v_1 \lambda_1^2 (2f j_{33} + b\theta p_2 v_2 (2f - b(1 - \gamma)\lambda_2^2))}{4f^2}\right).
\]

The stability conditions can be shown as follows, based on the Jury stability criterion [34] and equation (10):

\[
\begin{align*}
  f(1) &= 1 + z_2 + z_1 + z_0 > 0, \\
  f(-1) &= -1 + z_2 - z_1 + z_0 < 0, \\
  |z_0| &< 1, \\
  |z_0 - 1| &> |z_0 z_1 - z_2|.
\end{align*}
\]

**5. Numerical Simulation**

In Sections 2 and 3, we build and figure out the model. Considering the reality, we assume that manufacturers are bound rational because of limited information and they make decisions on the basis of the marginal profit and pricing decision in the period t. They carry on repeated games in a long time. In every stage, the manufacturer constantly adjusts the pricing strategy to get closer to the optimal price of profit maximization. As the results shown in Figure 1, when the speed of price adjustment is too high, the system will become unstable and enter the chaotic state. To understand the process of dynamic change accurately, we do numerical simulations, in which we set \(\alpha_1 = 10, \alpha_2 = 8, b = 1, \theta = 0.6, \lambda_1 = 0.7, \lambda_2 = 0.6, f = 2, c_1 = 2, c_2 = 1.5, c_1' = 0.4, c_2' = 0.4, \beta = 10, \gamma = 0.5, \omega = 1, v_1 = 0.1, \) and \(v_2 = 0.1\). And then, we can get the equilibrium point \((u^*, p_1^*, p_2^*) = (0.11, 7.53, 6.71)\).
5.1. Stability Analysis. There are lots of parameters in the equilibrium of our model and it is difficult to analyze the model directly. So, we verify the stability of this model by doing numerical simulation according to the actual situation. The discrete triangle in Figure 2 is also part of the stability region. Then, the stable region about \( w, v_1, \) and \( v_2 \) is shown in Figure 2:

5.2. Influence of the Speed of Adjustment on the Stability of the System. In Figures 3–5, the bifurcation diagrams and largest Lyapunov exponent describe the change of \( u, p_1, \) and \( p_2 \) with their adjustment parameters. As shown in Figures 3–5, with \( v_1 \) increasing, the status of the system keeps stable at the beginning; then, it becomes bifurcation and ended in chaos. In a stable status, \( p_1 \) from manufacturer 1 is higher than \( p_2 \) from manufacturer 2. When the value of \( w, v_1, \) and \( v_2 \) exceeds the critical points of bifurcation diagram, \( u, p_1, \) and \( p_2 \) bifurcate and then enter a chaotic state.

The largest Lyapunov exponent presents the system’s state. When the largest Lyapunov exponent is smaller than zero, the manufacturers’ decision system is stable. When the largest Lyapunov exponent is equal to zero, bifurcation happens. When the largest Lyapunov exponent is bigger than zero, the manufacturers’ decision system enters chaos. When the values of \( w, v_1, \) and \( v_2 \) are small, the largest Lyapunov exponent is smaller than zero, which means that the system is stable. When the largest Lyapunov exponent is equal to zero first, bifurcation happens in the system. With \( w, v_1, \) and \( v_2 \) increasing continuously, there are some dots above the X-axis; that is, the largest Lyapunov exponent is bigger than zero.

As \( w, v_1, \) and \( v_2 \) change, the profits of the two manufacturers will also fluctuate. In Figures 6–8, we further explore the impact of \( w, v_1, \) and \( v_2 \) on profits.

From Figures 6–8, we can draw a conclusion that the profits of both manufacturers fluctuate with the expansion of the three parameters. This result also shows that excessive adjustment will lead to vicious competition in the market and result in instability. Among them, \( w \) has the least impact on profits, while \( v_1 \) has the greatest impact on profits.

5.3. Influence of the Investment and the Government Subsidy on the Stability of the System. We further analyze the effect of the manufacturer’s investment on the stable region of the system. In our work, one of the manufacturers invests in green innovation to improve the product availability rate of recycled products, which is captured by \( u \). We range \( u \) from 0 to 1 and obtain the 3D stable region with a change of \( v_1, v_2, \) and \( u \) which is shown in Figure 9. By observing Figure 9, we can find that whatever \( u \) is, the stable region stays the same all the time. That is, the product availability rate of recycled products has no effect on the stable region of the system.

Then, we analyze the effect of the government subsidy on the stability of the system. In our model, the government gives a subsidy to the enterprise on the basis of the value of recycled used products and the amount of subsidy is \( \gamma p_1(t)q_1^c(t) \). We change \( \gamma \) from 0 to 1 and get a stable region with a change of \( v_1, v_2, \) and \( \gamma \). By observing Figure 10, we can draw the conclusion that with \( \gamma \) increasing, the area of stable region decreases gradually. To make the result clear, we set \( \gamma = 0, \gamma = 0.3, \gamma = 0.5, \gamma = 0.7, \) and \( \gamma = 0.9 \) and get the stable region with a change of \( v_1 \) and \( v_2 \) which can be seen in Figure 10.

In Figure 11, the red-border area, the blue-border area, the green-border area, the purple-border area, and the black-border area are obtained when we set \( \gamma = 0, \gamma = 0.3, \gamma = 0.5, \gamma = 0.7, \) and \( \gamma = 0.9 \), respectively. It is clear that the bigger the \( \gamma \) is, the smaller the area of the stable region is, which is consistent with the result we get from Figure 11. Based on this result, it can also be concluded that the government needs to set an appropriate level of subsidies to keep the stability of the system.

5.4. Effect of Parameters on the Nonlinear Dynamic Game System. First of all, we focus on the impact of the investment and the government subsidy on the system. We set \( \alpha_1 = 10, \alpha_2 = 8, b = 1, \theta = 0.6, \lambda_1 = 0.7, \lambda_2 = 0.6, f = 2, c_1 = 2, c_2 = 1.5, c_1' = 0.4, c_2' = 0.4, \) and \( \beta = 10 \) and illustrate how the price, demand, recycling price, recycling quantity, and profit go with the investment and government subsidy on the equilibrium point. The price \( p_1 \) with a change of \( u \) is shown in Figure 12.

Figures 13–16 reveal the impact of the investment and government subsidy on manufacturer 1. We find that the effect of the investment on manufacturer 1 is linear. With the increase of the investment, the price of product 1 drops slightly. By contrast, the demand, recycling price, and recycling quantity increase in this process. And the profit increases first but then decreases after reaching the maximum value. Based on those facts, we can draw the conclusion that certain investment has a positive force for product selling and recycling and the profit. However, too much investment will harm the profit of the manufacturer.
Figure 3: Bifurcation diagram and largest Lyapunov exponent of $u$ w.r.t. $w$.

Figure 4: Bifurcation diagram and the largest Lyapunov exponent of $p_1$ w.r.t. $v_1$.

Figure 5: Bifurcation diagram and the largest Lyapunov exponent of $p_2$ w.r.t. $v_2$. 
Compared to the investment, the government subsidy has a contrary impact on the price and the demand. But the government subsidy promotes the recycling price and recycling quantity similar to the way the investment does, but it is not linear. And the government subsidy undoubtedly raises the profit of manufacturer 1.

We further analyze the effect of investment of manufacturer 1 and governmental subsidy on the pricing decision and profit of manufacturer 2. The result can be seen in Figures 17–21. With the product availability rate of recycled products increasing, the price, the demand, and the profit of manufacturer 2 decrease slightly. In our model, manufacturer 1 invests in green innovation to improve the product availability rate of recycled products which leads manufacturer 1 to have an advantage when competing with manufacturer 2. Accordingly, manufacturer 2 is at a disadvantage in the competition. However, with the increase of the investment, both the price and the amount of recycling used products remain unchanged. There is no competition between manufacturers in the recycling market, since we assume that the manufacturer only collects used products produced by himself. Compared to the investment, the government subsidy has a positive impact on the price and has a negative impact on demand. But the government subsidy promotes the recycling price and recycling quantity similar to the result we get earlier. And the government subsidy undoubtedly raises the profit of manufacturer 2.

Next, we will explore the impact of the collection rate on the profits of both manufacturers.

From Figure 22, we can see that when the value of $\lambda_2$ is lower and the value of $\lambda_1$ is higher, the profit of manufacturer 1 is higher. Conversely, when $\lambda_2$ is higher and $\lambda_1$ is lower, manufacturer 2’s profit is higher. This shows that a
A high collection rate is connected with high profits. This is also in line with reality.

In the end, we focus on the impact of the investment, the price sensitivity, and the degree of substitution between two kinds of similar products on the system.

From Figures 23 and 24, we can draw the following conclusions. Among the three decision-making factors, the product substitution rate has the most significant impact on the manufacturer’s profit, followed by the price sensitivity, and the impact of investment is the smallest. Therefore, manufacturers should first pay attention to product innovation and change the substitution rate of products. In addition, manufacturers should set reasonable selling prices to meet consumers’ demand, and finally, manufacturers should invest more in products if they can.

5.5. Change of Pareto Solutions on the Dynamic Game System. In this section, we focus on the effect of the adjustment rates of the two manufacturers on the Pareto solutions.

From Figure 25, we can see that as the period increases, the range of Pareto solutions gradually expands. When the dynamic game reaches a certain period, the range of Pareto solution tends to be stable. When $v_1 < 0.18$ and $v_2 < 0.2$, there are inferior solutions to the system. Therefore, with the development of the dynamic game, the two manufacturers should increase their adjustment rate to avoid the generation of the inferior solution, so as to realize the Pareto optimization of the whole system.

6. Chaos Control

As the result has shown earlier, once the speed of adjustment of the participants in the market exceeds a reasonable
threshold, the market would fall into a state of complex chaos, which will cause disordered fluctuations in the price decision and the amount of recycling used products. As a result, manufacturers are unable to make the optimal response in the current period; thus, their profits will also have violent fluctuations. Considering this result from the chaos, it is necessary to control chaos effectively to ensure the stability of market competition and benefit the whole system. In this section, based on the characteristics of the whole decision-making process, we introduce the method by adjusting the decision method to control the chaos. K hus, the delay control method and the parameter adjustment control method are considered.

Firstly, control analysis is carried out through parameter adjustment control. Managers can control chaotic behavior by introducing a control parameter $g$. Wang [35] realized a chaos control by setting the control parameter as $g$. Under parameter adjustment control, the simultaneous decision system can be expressed as

$$\begin{align*}
 p_1(t+1) &= (1-g)\left( p_1(t) + v_1 p_1(t) \frac{\partial \Pi_1(t)}{\partial p_1(t)} \right) + gp_1(t), \\
 p_2(t+1) &= (1-g)\left( p_2(t) + v_2 p_2(t) \frac{\partial \Pi_2(t)}{\partial p_2(t)} \right) + gp_2(t).
\end{align*}$$

Then, we use the delay control method to control chaos. The core idea of the delay control method is to use feedback to the system after a time delay (2016). That is, we take part of the information that is the output signal of the system into consideration. When making a decision next period, we

\begin{align*}
 p_1^\prime(t+1) &= (1-g)\left( p_1^\prime(t) + v_1 p_1^\prime(t) \frac{\partial \Pi_1(t)}{\partial p_1(t)} \right) + gp_1^\prime(t), \\
 p_2^\prime(t+1) &= (1-g)\left( p_2^\prime(t) + v_2 p_2^\prime(t) \frac{\partial \Pi_2(t)}{\partial p_2(t)} \right) + gp_2^\prime(t).
\end{align*}
Figure 18: The demand $q_2$ with a change of $u$.

Figure 19: The recycling price $p_2'$ with a change of $u$.

Figure 20: The recycling quantity $q_2'$ with a change of $u$. 
Figure 21: The profit $\pi_2$ with a change of $u$.

Figure 22: The profits with a change of $\lambda_1$ and $\lambda_2$.

Figure 23: The effect of $u$, $\theta$, and $f$ on the profit of manufacturer 1. (a) Back. (b) Front.
Figure 24: The effect of $u$, $\theta$, and $f$ on the profit of manufacturer 2. (a) Back. (b) Front.

Figure 25: Continued.
consider the decision in the period, $t$, and decision in the period, $t+1$. Thus, the dynamic adjustment model can be shown as follows:

$$
\begin{cases}
    p_1(t+1) = p_1(t) + v_1 p_1(t) \frac{\partial \Pi_1(t)}{\partial p_1(t)} + \nu(p_1(t+1) - p_1(t)), \\
    p_2(t+1) = p_2(t) + v_2 p_2(t) \frac{\partial \Pi_2(t)}{\partial p_2(t)} + \nu(p_2(t+1) - p_2(t)).
\end{cases}
$$

(15)

We set the same parameters where $\alpha_1 = 10$, $\alpha_2 = 8$, $b = 1$, $\theta = 0.6$, $\lambda_1 = 0.7$, $\lambda_2 = 0.6$, $f = 2$, $c_1 = 2$, $c_2 = 1.5$, $c'_1 = 0.4$, $c'_2 = 0.4$, $\beta = 10$, $\mu = 0.3$, and $\nu = 0.5$ and set $v_1 = 0.5, v_2 = 0.5$. Under this condition, the original system is in a chaotic state. Firstly, we introduce the parameter $g$ to control the system. Through numerical simulation, we draw the bifurcation diagram with the parameter $g$ increasing as follows.

From Figure 26, we can see that with the increase of parameter $g$, the price decision of the two manufacturers gradually gets out of chaos. And when $g = 0.78$, the whole system enters a stable state, and the two manufacturers can have a stable price decision.

Then, we introduce the control parameter $\nu$ and add delayed feedback into the decision signal. Through numerical simulation, we draw the bifurcation diagram with the control parameter $\nu$ increasing as follows.

As is shown in Figure 27, the instability of the system is effectively eliminated after adding delayed feedback into the pricing decision. When $\nu$ is small, the state of the system is chaos. With the control parameter $\nu$ increasing, the state of the system is going into bifurcation and stable gradually. In the end, the system keeps stable when $\nu > 0.34$, where the manufacturers can make effective decisions. We can draw the conclusion that delay control is a good way to control the...
system based on the response of the manufacturers. Li and Yu [36] also prove that delay control can effectively solve the chaotic phenomenon that may arise in the development of the system. So, manufacturers can consider this method to solve the chaos phenomenon in the multiperiod system.

7. Conclusion

Considering the increasing environmental preoccupation, the potential economic benefits, and the legislation pressure, great attention has been paid to green innovation. In this paper, we focus on the activity of green innovation and build a model where the manufacturer will invest in green innovation to improve the product availability rate of recycled products and save the cost in the process of remanufacturing, and the other manufacturers do not invest in green innovation. Besides, we take three stages in a cycle into consideration, that is, production/sale, recycling used production, and remanufacture/sale, and meanwhile, the government encourages enterprises to carry on the activity of recycling and gives a subsidy to enterprises according to the value of recycled used products. In the process of model solving, considering repeated games between two manufacturers in this system, a dynamic decision-making way is used. Then, we analyze the influence of the speed of adjustment on the stability of the system, the influence of the investment, and the government subsidy on the stability of the system and the effect of the investment and the government subsidy on the system. At the end of this research, we make chaos control. The conclusions we made are shown as follows [10, 35, 37–42]:

1. The decision adjustment speed of players has a significant effect on stability, and in a long dynamic repeated game process, with the speed of decision adjustment increasing, the system enters into chaos at last. Besides, when the speed of decision adjustment exceeds the critical point of the bifurcation diagram, the profit of the manufacturer decreases and then enters a chaotic state. So, an appropriate adjustment speed should be adopted.

2. The investment of the product availability rate of recycled products has no effect on the stable region of the system; with the level of subsidies increasing, the area of stable region decreases gradually, so the government needs to set an appropriate level of subsidies to maintain the stability of the system.

3. Certain investment has a positive force for the product selling and recycling and the profit, and the government subsidy undoubtedly raises the profits of manufacturers and encourages the activity of recycling used products.

4. We make chaos control through adjusting the decision method and the result shows that this method really has good control of the chaos of the system.

However, there are still some limitations. For example, the classic linear demand function is adopted in the model; however, there is a certain gap between this linear demand function and the reality; we do not take model structure into consideration. We leave this for the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request. The questionnaire data were acquired mainly through e-mail and filling out paper.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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