Research on the Dynamic Pricing and Service Decisions in the Reverse Supply Chain considering Consumers’ Service Sensitivity

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Abstract: In this work, considering consumers’ service sensitivity for the third-party collector in the reverse supply chain, a game model (including a manufacturer and a third-party collector) with dual-channel recycling structure was established. Based on the bounded rationality, we used dynamics theory to analyze the dynamic service and pricing decisions of the manufacturer and the third-party collector in the process of collecting waste products. The results showed that adjustment speeds of pricing and service decisions have great effect on the stability of recycling market, and the recycling market is most sensitive to the change of third-party collectors’ service decision. When the recycling market is in chaos, it has a strong initial value sensitivity. In addition, we found that increase of consumers’ service sensitivity and service cost parameter had negative effect on stability of the recycling market; there is a reverse relationship between price adjustment parameters and the service adjustment parameter. With the increase of service adjustment parameter, the bifurcation point of the system will appear more quickly. Finally, chaotic market can be controlled by the feedback control method.

Keywords: pricing decision; service decision; dual-channel; bounded rationality; reverse supply chain

1. Introduction

With the rapid development of technology, the speed of upgrading products becomes faster. A large number of products are eliminated every year. These waste products are usually abandoned casually or disposed of in inappropriate ways, which causes great damage to the environment and people’s health. Along with the shortage of natural resources, enterprises need to change their traditional production mode and consider a sustainable development mode. Thus, the closed-loop supply chain (CLSC) appears; in contrast to traditional supply chains, CLSC contains the process of collecting waste products from consumers and remanufacturing [1], which is regarded as the reverse supply chain [2]. Collecting and remanufacturing waste products can effectively reduce environmental pollution and bring economic benefits to enterprises [3]. In recent years, remanufacturing has been successful in many areas such as computers, cameras, and car batteries. For example, Apple Inc. makes great profits through the business of recycling used mobile phones, and it is constantly expanding its recycling business [4,5].

The collection of waste products is an important part of the reverse supply chain and ensures the continuation of the remanufacturing activities, and it can be done by different members in the supply chain. Savaskan [6] introduced three different recycling models (manufacturer recycling, retailer recycling, and the third-party recycling) and studied the forward supply chain pricing decision under different recycling channels. These three ways of recycling are common and effective in the
real world. However, with the rapid development of production, these single recycling modes are gradually unable to meet the demand for recycling. Then, dual-channel recycling model appeared. Compared with the single-channel recycling structure, the dual-channel recycling structures tend to be more effective [7]. In this paper, we considered the dual-channel recycling structure. Specifically, we focus on the mode of joint recycling by the manufacturer and the third-party collector.

In recent years, many independent third-party collectors have appeared in the recycling market and make great contributions to the collection of waste products. They make profit by collecting or handling waste products. Furthermore, different from the recycling way of manufacturers and retailers, third-party collectors always provide different service for consumers. For example, Aihuishou.com not only bears the postage cost of consumers but also provides pick-up service [8]. Service is an important factor in supply chain, which can improve consumer satisfaction and increase profit [9], and it is also helpful to promote the demand of products [10–12]. The study of supply chain considering the factor of service has been an issue of concern. Ren et al. [13] analyzed the return strategy of customers when service level competition was considered in the model. Dan [14] found that the profit of the manufacturer and the sales service integrator are positively correlated with the consumer’s sensitivity coefficient to the service level. Therefore, besides the pricing decision, we also consider the service decision of the third-party collector in the reverse supply chain.

When studying pricing and service decisions in the supply chain, much of the literature assumed that participants are completely rational and pursue individual interests. Hence, the optimal decision is often obtained during the single period. Without a doubt, the supply chain is a complex economic system, and it is difficult for decision makers to know all the market information. Especially in the recycling market, the decision maker can hardly know the complete market information such as potential total waste products quantity, consumers’ different preferences, and strategies of competitors. Hence, the participants tend to be bounded rationality. Along with incomplete information, the behavior of participants in the recycling market tends to be complex and the result may not converge to the Nash equilibrium, and complex phenomena like bifurcation and chaos may occur [15]. In this case, traditional static optimization methods are not suitable and dynamic game model should be established to analyze the supply chain.

By the above discussion, we found that the recycling mode, service, and bounded rationality have great effect on the optimal operational decision in the supply chain. The main purpose of this paper is to analyze the dynamic change of pricing and service decisions under bounded rationality in the reverse supply chain and discuss how consumers’ service sensitivity affect the decision. Then, a dynamic model which described the recycling market was established. By analyzing the local stability of equilibrium point and simulation, this study discussed the dynamic evolution of pricing and service decisions and the influence of different adjusting parameters and parameters related to service on the stability of the recycling market.

In this study, we will address the following questions.

1) In the dual-channel recycling supply chain, how do adjustment parameters of recycling price and service affect the stability of the recycling market in the dynamic evolution? Does the market have initial value sensitivity when in chaotic state?

2) How does consumer service sensitivity and service cost parameter influence the stable region of the system?

3) In a long-term game, how does the adjustment speed of service influence profits of the third-party collector and the manufacturer?

4) How can the chaotic phenomena be controlled if chaos occurs?

The rest of the paper is organized as follows. After a review of relevant literatures in Section 2, the assumptions and notations are described in Section 3. Then, we analyze the equilibrium point of the game model and local stability range of the equilibrium point in Section 4. In Section 5, a numerical study is given to analyze the complexity of the market. A method of chaos control is given in Section 6, and in Section 7 we draw the relevant conclusions.
2. Literature Review

This section mainly reviews literature relevant to this study. Three main streams of research are related to our work: research on supply chain with dual-channel recycling structure, pricing or service decisions in supply chain, and dynamic game with bounded rationality in supply chain.

There are a growing number of research papers on dual-channel recycling supply chain in recent years. Different structures of recycling modes can affect the operation of the supply chain. Gong [8] analyzed optimal decisions under different recycling modes and channel power structures and found that hybrid recycling is more effective. Ranjbar [16] studied optimal pricing and recycling strategies under the competitive recycling of the retailer and the third party, and found that the overall recycling rate of the supply chain is the highest under the leadership of retailers. He [17] established a closed-loop supply chain model with competitive recycling and proposed two coordination mechanisms in the case of centralized decision-making and decentralized decision-making. Zhao et al. [18] established two models considering the competition in collecting channels, and analyzed the optimal choice of the collecting channel as well as the optimal operational decisions. Liu [19] considered recycling innovation input for the collector and found that the manufacturer prefers the hybrid recycling mode. Moreover, the collection rate was the highest under the hybrid model compared with other cases.

Besides the research on dual-channel recycling supply chain, the service decision in supply chain has attracted extensive attention from academia. With the improvement of people’s living standards, people’s sensitivity to services has also become higher. Dumrongsiiri [20] thought that service has become an important factor which affects the behavior of the customer. Zhou [21] analyzed the impact of free riding on supply chain members’ service strategies and profits in the case of differential pricing and non-differential pricing. Yan and Pei [22] found that improved retail services effectively alleviated the channel competition and conflict and improved the supply chain performance in a competitive market. Wu [23] obtained optimal service and pricing decisions in a dual-channel reverse supply chain by using the Stackelberg model, and found that the improvement of service level can maximize the profit of the recycling center. In this paper, we discussed the service decision of the third-party collector and customers’ service sensitivity was also considered in the model.

Most of the above literature assumes that members in supply chains are completely rational. When considering the bounded rational of the members in supply chains, the optimal decisions tend to be more complicated. Some studies focused on the dynamic duopoly games of Bertrand and Cournot [24–26]. Elsadany [27] established a bounded rational duopoly game with delay to analyze its complexity and the local stability of the equilibrium points. Xue [28] established a dynamic model to identify the effect of retailer-led recycling and how contracts affect different retail modes. Li [29] studied a recycling price game model in the long-term competition and analyzed the stability of the system. Furthermore, he considered the fair concern of a recycler in a competitive reverse supply chain and analyzed how fair concern influenced the stable area [30].

By reviewing literature, although some aforementioned literature have drawn valuable conclusions in above three streams, most of the literature [10,12,14,21] relevant to the service focused on the service in the forward supply chain. While Wu [23] and Kong [31] considered the level of service in the reverse supply chain, they ignored the bounded rationality of the supply chain member. Thus, the research concerned with service decision and pricing decision in reverse supply chain under bounded rationality is valuable. Based on the above discussion, from the perspective of bounded rationality, this study considered the dynamic change of the pricing and service decision under the mode of joint recycling by the manufacturer and third-party collector. The present paper contributes to the literature in three aspects. First, to the best of our knowledge, this is the first research to consider the dynamic change of the third-party collector’s service decision in the reverse supply chain. Second, we focus on the dynamic pricing and service decisions in the process of recycling and analyze the stability of the recycling market under different parameters. Third, this research enriches the theory of the recycling market with a dual-channel recycling structure.
3. Model Notation and Assumptions

In this section, a game model which describes the process of recycling was established. As shown in Figure 1, a third-party collector and a manufacturer were contained in the model. Collection is done by both the manufacturer and the third-party collector. In this model, the manufacturer set up his own collecting channel to collect waste products from consumers at price $P_2$, and the third-party collector collected waste products from consumers at price $P_1$. Different from the way of collection by remanufacturers and retailers, professional third-party collectors also pay attention to service provided to the customers in order to obtain more waste products. Therefore, we assumed the service level provided by the third-party collector is $s$, and the cost for the third-party collector to achieve service level $s$ is $\sigma s^2/2$, where $\sigma$ is the parameter of the service cost [32–34].

![Figure 1. Supply chain structure.](image)

The notations in this study are listed below:

- $P_1$: Recycling price of the third-party collector per unit.
- $P_2$: Recycling price of the manufacturer per unit.
- $P_m$: The subsidy given by the manufacturer to the third-party collector per unit.
- $s$: The service level of the third-party collector.
- $k_1$: The recycling quantity when the third-party collector’s recycling price is 0.
- $k_2$: The recycling quantity when the manufacturer’s recycling price is 0.
- $C_1 / C_2$: The collection cost of the third-party collector/manufacturer per unit.
- $M$: The production cost saved by waste product per unit.
- $\pi_{3p}$: The profit of the third-party collector.
- $\pi_m$: The profit of the manufacturer.
- $G_1$: The recycling quantity function of the third-party collector.
- $G_2$: The recycling quantity function of the manufacturer.

The following are some assumptions that need to be illustrated specifically.

**Hypothesis 1 (H1).** The recycling quantity function is a linear function of the recovery price and service level.

The remanufacturer and the third-party collector can be regarded as duopoly in the recycling market; they decide recycling price and level of service at the same time. According to the study of Huang and Wang [35], we assumed that the recycling quantity function in the market was a linear function of the recycling price and there had price competition between the third-party collector and the manufacturer. In addition, following the literature [31,36,37], the improvement of service level has a positive effect on the recycling quantity function. Therefore, recycling quantity functions of the third-party collector and manufacturer are:

$$G_1 = k_1 + aP_1 + \gamma s - \beta P_2$$ (1)

$$G_2 = k_2 + aP_2 - \beta P_1$$ (2)

Here, the parameter $a$ represents the consumers’ sensitivity to recycling price, the parameter $\beta$ represents the price cross parameter between response channels, and the parameter $\gamma$ represents...
consumers’ sensitivity to the service level of the third-party collector. We assumed $\alpha > \beta$, which means the channel’s own price has a greater impact on the recycling quantity function.

**Hypothesis 2 (H2).** We assume that all waste products collected by the manufacturer and the third-party collector are valuable. To ensure the collection and remanufacturing can bring benefit to both manufacturer and third-party collection, similar to study of Savaskan [6], the condition $M > \max\{P_2 + C_2, P_m\}$ is always true. Respectively, for simplification of the analysis, we assume $C_1 = C_2 = c = 0$ [30].

**Hypothesis 3 (H3).** Neither the manufacturer nor the third-party collector can totally know the market information, and they are bounded rational.

4. Dynamic Model Construction and Analyzation

According to the above assumptions, the profit functions of the third-party collector and the manufacturer are:

$$
\pi_{3p} = G_1(P_m - P_1 - C_1) - \frac{\sigma^2}{2} = (k_1 + \alpha P_1 + \gamma s - \beta P_2)(P_m - P_1) - \frac{\sigma^2}{2} \quad (3)
$$

$$
\pi_m = G_1(M - P_m) + G_2(M - P_2 - C_2) = (k_1 + \alpha P_1 + \gamma s - \beta P_2)(M - P_m) + (k_2 + \alpha P_2 - \beta P_1)(M - P_2) \quad (4)
$$

In the profit functions, the decision variables of the third-party collector are the recycling price $P_1$ and service level $s$. This paper is aimed to study the dynamic changes in the process of collection, $P_m$ is regarded as a constant [30]. Therefore, the decision variable of the manufacturer is the recycling price $P_2$.

4.1. Methodology

In the recycling market, the third-party collector and the manufacturer can be regarded as the duopoly in the reverse supply chain, and the game model is similar to the Bertrand model. In the dynamic process, let $P_1(t)$, $P_2(t)$, and $s(t)$ represent recycling prices and service level during period $t = 0, 1, 2 \ldots$ Then, profits of the third-party collector and the manufacturer in a single period are Equations (3) and (4). According to the literature [38,39], the recycling price and service level for period $t + 1$ are decided by solving the optimization problem:

$$
\begin{align*}
P_1(t + 1) &= \arg\max_{P_1, P_2(t + 1), s(t)} \pi_{3p}(P_1(t), P_2(t + 1), s(t)) \\
\gamma(t + 1) &= \arg\max_{P_1, P_2(t + 1), s(t)} \pi_{3p}(P_1(t), P_2(t + 1), s(t)) \\
P_2(t + 1) &= \arg\max_{P_1, P_2(t + 1), s^*(t + 1)} \pi_m(P_1(t + 1), P_2(t), s^*(t + 1)) \\
\end{align*}
$$

where $P_2^*(t + 1)$ represents the expectation of the third-party collector about the recycling price of the manufacturer, $P_1^*(t + 1)$ represents the expectation of the third-party collector about the recycling price of the third-party collector, and $s^*(t + 1)$ represents the expectation of the manufacturer about the service level of the third-party collector.

Due to the bounded rationality and uncertainty of the recycling market, the manufacturer and third-party collector cannot completely know the market information. Thus, they will make decisions according to the local estimation of marginal profit. Such decision-making based on the bounded rationality is common in practice [40,41]. If the marginal profit in period $(t)$ is positive, the manufacturer or the third-party collector will correspondingly increase the recycling price or service level in period $(t + 1)$. Otherwise, the manufacturer or the third-party collector will decrease the recycling price or service level.
4.2. Model Construction

According to the above profit functions and methodology, the model can be constructed as follows.

\[
\begin{align*}
P_1(t+1) &= P_1(t) + g_1 P_1(t) \frac{\partial \pi_1}{\partial P_1} \\
s(t+1) &= s(t) + g_2 s(t) \frac{\partial \pi_2}{\partial s} \\
P_2(t+1) &= P_2(t) + g_3 P_2(t) \frac{\partial \pi_2}{\partial P_2}
\end{align*}
\]

(6)

System (6) gives the dynamic price and service decision, and the decision variables directly relate to the positive parameter \(g_i\) \((i = 1, 2, 3)\), which represents the price and service adjustment speed. By solving the first-order condition \(\frac{\partial \pi_1}{\partial P_1}, \frac{\partial \pi_2}{\partial s}, \frac{\partial \pi_2}{\partial P_2}\), the marginal profit functions are:

\[
\begin{align*}
\frac{\partial \pi_1}{\partial P_1} &= \alpha (P_m - P_1) - (k_1 + \alpha P_1 + \gamma s - \beta P_2) \\
\frac{\partial \pi_2}{\partial s} &= \gamma (P_m - P_1) - \sigma s \\
\frac{\partial \pi_2}{\partial P_2} &= \alpha (M - P_2) - \beta (M - P_m) - (k_2 + \alpha P_2 - \beta P_1)
\end{align*}
\]

(7)

When substituting expression (7) into (6), we gain the three-dimensional discrete dynamical system (8):

\[
\begin{align*}
P_1(t+1) &= P_1(t) + g_1 P_1(t) [\alpha (P_m - P_1) - (k_1 + \alpha P_1 + \gamma s - \beta P_2)] \\
s(t+1) &= s(t) + g_2 s(t) [\gamma (P_m - P_1) - \sigma s] \\
P_2(t+1) &= P_2(t) + g_3 P_2(t) [\alpha (M - P_2) - \beta (M - P_m) - (k_2 + \alpha P_2 - \beta P_1)]
\end{align*}
\]

(8)

4.3. Equilibrium Points and Local Stability

According to the definition of the equilibrium points, in order to guarantee the practical significance, we assume that all the equilibrium points are non-negative. By setting \(P_1(t+1) = P_1(t), s(t+1) = s(t),\) and \(P_2(t+1) = P_2(t)\), we obtained the following eight equilibrium points:

\[
\begin{align*}
R_1(0, 0, 0), \ R_2(0, \frac{\gamma P_m}{\sigma}, 0), \ R_3(0, 0, \frac{H}{2 \alpha}), \ R_4(0, \frac{\gamma P_m}{\sigma}, \frac{H}{2 \alpha}), \\
R_5(\frac{\alpha P_m - k_1}{2 \alpha}, 0, 0), \ R_6(\frac{\alpha \sigma P_m - \gamma^2 P_m - \sigma k_1}{2 \alpha \sigma - \gamma^2}, \frac{\gamma \alpha P_m + \gamma k_1}{2 \alpha \sigma - \gamma^2}, 0), \ R_7(\frac{T}{4 \alpha^2 - \beta^2}, 0, \frac{N}{4 \alpha^2 - \beta^2}), \\
R_8(\frac{\sigma T - 2 \alpha \gamma^2 P_m}{F}, \frac{\gamma(4 \alpha^2 P_m - \beta^2 P_m - T)}{F}, \frac{\sigma N - \gamma^2 H - \beta \gamma^2 P_m}{F})
\end{align*}
\]

where

\[
\begin{align*}
H &= M(\alpha - \beta) + \beta P_m - k_2 \\
T &= M(\alpha \beta - \beta^2) + (2 \alpha^2 + \beta^2) P_m - 2 \alpha k_1 - \beta k_2 \\
N &= 2M \alpha (\alpha - \beta) + 3 \alpha \beta P_m - 2ak_2 - \beta k_1 \\
F &= 4 \alpha^2 \sigma - 2 \alpha \gamma^2 - \beta^2 \sigma
\end{align*}
\]

Obviously, \(R_i\) \((i = 1, 2, 3, 4, 5, 6, 7)\) are boundary equilibrium points. When \(F > 0, \sigma T - 2 \alpha \gamma^2 P_m > 0, 4 \alpha^2 P_m - \beta^2 P_m - T > 0,\) and \(\sigma N - \gamma^2 H - \beta \gamma^2 P_m > 0,\) \(R_8\) is the Nash equilibrium point.

In order to analyze the stability of the equilibrium point, we obtain the Jacobian matrix of system (8):

\[
J = \begin{bmatrix}
J_{11} & -\gamma g_1 P_1 & \beta g_1 P_1 \\
-\gamma g_2 s & J_{22} & 0 \\
\beta g_3 P_2 & 0 & J_{33}
\end{bmatrix}
\]

(9)
Theorem 1. The boundary equilibrium points, \( R_i (i = 1, 2, 3, 4, 5, 6, 7) \) of system (8) are unstable equilibrium points.

Proof. In order to prove this result, we find the eigenvalues of the Jacobian matrix at each boundary equilibrium points \( R_i (i = 1, 2, 3, 4, 5, 6, 7) \). The Jacobian matrix at \( R_1 \) is:

\[
J(R_1) = \begin{bmatrix}
1 + g_1[aP_m - k_1] & 0 & 0 \\
0 & 1 + g_2\gamma P_m & 0 \\
0 & 0 & 1 + g_3[aM - \beta(M - P_m) - k_2]
\end{bmatrix}
\]

One eigenvalue of \( J(R_1) \) is: \( \lambda_2 = 1 + g_2\gamma P_m > 1 \), therefore, \( R_1 \) is an unstable equilibrium point.

The Jacobian matrix at \( R_2 \) is:

\[
J(R_2) = \begin{bmatrix}
1 + g_1[aP_m - \left(k_1 + \frac{g^2P_m}{\sigma}\right)] & 0 & 0 \\
0 & 1 - g_2\gamma P_m & 0 \\
0 & 0 & 1 + g_3H
\end{bmatrix}
\]

One eigenvalue of \( J(R_2) \) is: \( \lambda_3 = 1 + g_3H \), since \( H > 0 \), we obtain \(|\lambda_3| > 1 \), \( R_2 \) is an unstable equilibrium point.

The Jacobian matrix at \( R_3 \) is:

\[
J(R_3) = \begin{bmatrix}
1 + g_1[aP_m - k_1 + \frac{\beta H}{2\sigma}] & 0 & 0 \\
0 & 1 + g_2\gamma P_m & 0 \\
\frac{\beta g_3H}{2\sigma} & 0 & 1 + g_3[aM - \beta(M - P_m) - k_2 - 2H]
\end{bmatrix}
\]

One eigenvalue of \( J(R_3) \) is: \( \lambda_1 = 1 + g_1[aP_m - k_1 + \frac{\beta H}{2\sigma}] \), since \( aP_m - k_1 > 0 \), \( H > 0 \), we obtain \(|\lambda_1| > 1 \), \( R_3 \) is an unstable equilibrium point.

Similarly, other boundary equilibrium points can be proved to be unstable equilibrium points. \( \square \)

Theorem 2. If the system parameters satisfy \( F > 0 \), \( \sigma T - 2a\gamma^2P_m > 0 \), \( 4a^2P_m - \beta^2P_m - T > 0 \), \( \alpha N - \gamma^2H - \beta\gamma^2P_m > 0 \) and the Jury conditions, the Nash equilibrium point \( R_8 \) is locally asymptotically stable.

Proof. In contrast to the boundary equilibrium, the stability of the Nash equilibrium point is difficult to determine by the eigenvalue because of the complexity of the calculation, but the local stability of the Nash equilibrium point can be obtained by using the Jury condition [42]. By substituting \( R_8 \) into (9), we can obtain:

\[
J(R_8) = \begin{bmatrix}
J_{11} & -\gamma g_1P_1^* & \beta g_1P_1^* \\
-\gamma g_2s^* & J_{22} & 0 \\
\beta g_3P_2^* & 0 & J_{33}
\end{bmatrix}
\]

where \[
J_{11} = 1 + g_1[a(P_m - 3P_1^*) - (k_1 + aP_1^* + \alpha s - \beta P_2^*)] \\
J_{22} = 1 + g_2[\gamma(P_m - P_1^*) - 2\alpha s^*] \\
J_{33} = 1 + g_3[a(M - 3P_2^*) - \beta(M - P_m) - (k_2 + aP_2^* - \beta P_1^*)]
\]

We gain the characteristic equation from matrix (10); the characteristic equation is as follows:

\[
\lambda^3 + a_2\lambda^2 + a_1\lambda + a_0 = 0
\]
When we found that the maximum Lyapunov exponent of the system (8) reached the first peak when the parameters, we can obtain the Nash equilibrium point. When the bifurcation point appeared. It was followed by periods 2, 3, 4... and gradually descended into chaos when $g_2 > 0.1639$, the maximum Lyapunov exponent in Figure 3 was larger than 0, and system (8) occurred chaos and appeared complex dynamic states.

$$\begin{align*}
a_2 &= -(J_{11} + J_{22} + J_{33}) \\
a_1 &= J_{22}J_{33} + J_{11}J_{22} + J_{22}J_{33} - \gamma^2 g_1 P_1^* g_2^* s^* - \beta^2 g_1 P_1^* g_3^* P_2^* \\
a_0 &= -J_{11}J_{22}J_{33} + \beta^2 g_1 P_1^* g_3^* P_2^* J_{22} + \gamma^2 g_1 P_1^* g_2^* J_{33}
\end{align*}$$

By using the Jury condition, the sufficient and necessary condition for the Nash equilibrium point $R_8$ to be stable is:

$$\begin{align*}
1 + a_2 + a_1 + a_0 &> 0 \\
-1 + a_2 - a_1 + a_0 &< 0 \\
|a_0| &< 1 \\
|a_0^2 - 1| &> |a_0 a_2 - a_1|
\end{align*} \tag{12}$$

The stable region of the Nash equilibrium point $R_8$ is defined by (12). However, beyond the stability region more complex phenomena such as bifurcation and chaos will occur. Moreover, the local stability of the system in $R_8$ can be affected by consumers’ service sensitivity parameter $\gamma$ and service cost parameter $\sigma$. Based on inequalities (12), the three-dimensional stability domains of the system (8) are simulated when $\gamma$ and $\sigma$ take different values (as shown in Section 5.3). $\square$

5. Numerical Simulation

In this section, numerical simulations were carried out to show the dynamic change in the system (8). The dynamic characteristics of the system will be analyzed by bifurcation diagram, maximum Lyapunov exponent, and strange attractor. Both the manufacturer and third-party collector can observe the influence of the adjustment on the system (8). The main purpose of the numerical simulation is to analyze the local stability of the equilibrium point and simulate the dynamic evolution of the pricing and service decisions under different adjustment parameters. Similar to the numerical simulation section in literatures [29,30,39,43], the values of parameter just need to meet the model assumptions. Hence, we set the parameter values as follows: $\alpha = 0.6, \beta = 0.3, \gamma = 3, M = 40, k_1 = 5, k_2 = 3, \sigma = 50, P_m = 30$; these data were close to the real-world condition. According to these parameters, we can obtain the Nash equilibrium point $R_8$ is (12.8,1.03,18.2).

5.1. The Impact of Adjustment Parameters on the Stability of the System

When the adjustment parameter of the third-party collector $g_1$ changed in the range of [0.02, 0.18], Figure 2 showed the bifurcation diagrams of $P_1$ and $P_2$ in (a) and $s$ in (b) with respect to $g_2 = 0.01$ and $g_3 = 0.01$. When $g_1 < 0.1255$, the system (8) was in the stable region, the Nash equilibrium point was locally stable. When $g_1 = 0.1255$, the system (8) will deviate from the stable region and the phenomenon of bifurcation appears. Corresponding to the maximum Lyapunov exponent in Figure 3, we found that the maximum Lyapunov exponent of the system (8) reached the first peak when the bifurcation occurred. When $g_1$ increased to the value of 0.157, the second bifurcation occurred in Figure 2 (corresponding to the second peak in Figure 3). When $g_1 > 0.1639$, the maximum Lyapunov in Figure 3 was larger than 0, and system (8) occurred chaos and appeared complex dynamic states.

Figure 4 showed the bifurcation diagrams of $P_1$ and $P_2$ in (a) and $s$ in (b) with respect to adjustment parameter $g_2$ while $g_1 = 0.1$, $g_3 = 0.01$. When the parameter $g_2$ belonged to the stable region ($g_2 \in [0.01, 0.0252]$), the Nash equilibrium point was locally stable. Corresponding to the maximum Lyapunov exponent in Figure 5, we found the maximum Lyapunov exponent of the system (8) reached the first peak when $g_2 = 0.0252$. Then, the system (8) will deviate from the stable region and the first bifurcation point appeared. It was followed by periods 2, 3, 4... and gradually descended into chaos when $g_2 > 0.0375$ (the maximum Lyapunov exponent in Figure 5 is larger than 0).
The dynamic change in the system (8) will be analyzed by bifurcation diagram. When the adjustment parameter of the third region and the phenomenon of bifurcation equilibrium point was locally stable. When the parameter values just descended into chaos when the maximum Lyapunov exponent of the system (8) reached the stable region more complex phenomena such as bifurcation and chaos will occur. Moreover, the numerical simulation is to analyze the local stability of the equilibrium point and simulate the dimension stable domains of the service sensitivity parameter.

(a) (b)

Figure 2. The bifurcation diagram of the system (8) when \( g_1 \) changes: (a) \( P_1 \) and \( P_2 \); (b) \( s \).

Figure 3. The maximum Lyapunov exponent when \( g_1 \) changes.

(a) (b)

Figure 4. The bifurcation diagram of system (8) when \( g_2 \) changes: (a) \( P_1 \) and \( P_2 \); (b) \( s \).
Figure 5. The maximum Lyapunov exponent when $g_2$ changes.

Figure 6 showed the bifurcation diagrams of $P_1$ and $P_2$ in (a) and $s$ in (b) with respect to adjustment parameter $g_3$ while $g_1 = 0.1$, $g_2 = 0.01$. When the parameter $g_3 < 0.07$, the Nash equilibrium point was locally stable. It was found that the bifurcation point appeared when $g_3 = 0.07$. Then, the system (8) will deviate from the stable region and gradually descended into chaos when $g_3 > 0.1057$ (the maximum Lyapunov exponent in Figure 7 is larger than 0).

Both the maximum Lyapunov exponent and the strange attractor are important indexes of the system dynamics. For example, Figure 8 showed the strange attractor under different value of $g_1$ corresponding to Figure 2. From Figure 8a, it can be found that when the system (7) was locally stable, the strange attractor will evolve to the Nash equilibrium point $R_6(12.8, 1.03, 18.2)$. When $g_1 > 0.1255$, like the situation in Figure 8b, the Nash equilibrium point begins to change into a branch state for the first time (the system appears the first bifurcation point corresponding to Figure 2). Figure 8c shows when $g_1 > 0.1639$, the system (8) is in completely chaotic state and the stranger attractor is an irregular shape.

Figure 6. The bifurcation diagram of system (8) when $g_3$ changes: (a) $P_1$ and $P_2$; (b) $s$. 

Through the above numerical simulation analysis, it can be concluded that the adjustment speeds $g_1$, $g_2$, and $g_3$ had great effect on the stability of system (8). If the manufacturer and third-party collector adjusted their price or service strategies too fast, the recycling market will be in a chaotic state. Once chaos occurred in the economic system, it was difficult for the game player to make a correct prediction. Furthermore, by comparing bifurcation diagrams of the system under different adjustment parameters, it was found that even if the service adjustment parameter of the third-party collector changed in a very small range, chaos may occur in the recycling market. Therefore, the system (8) is
most sensitive to the change of the third-party’s service decision. The third-party collector should not adjust his service decision too quickly.

5.2. Sensitivity Analysis of Initial State in the System

In this section, we explored the sensitivity of initial value in the system (8). First, we compared the slight difference of initial value when the system (8) is in a stable state. From Section 4.1, it can be seen that when $g_1 = 0.1$, $g_2 = 0.01$, and $g_3 = 0.01$, the system was locally stable. Here we took a group of initial values as baseline data, i.e., $P_1 = 11$, $s = 0.7$, and $P_2 = 15$. Then, we added value of 0.001 to the three initial values separately. The difference in recycling prices and service after 30 iterations is shown in Figure 9. It was found that when the initial value of the baseline data was changed by 0.001, the system tended to a slight difference at the beginning. As iterations increased, the difference gradually became 0 and the value was equal to the Nash equilibrium point. It showed that even if there was a little deviation in the initial value when system (8) in the stable state, with the increase of iterations, the influence brought by the deviation could be eliminated.

![Figure 9](https://example.com/figure9.png)

**Figure 9.** Sensitivity of initial values in the system (8) when in stable state: (a) $s = 0.7$, $P_2 = 15$; (b) $P_1 = 11$, $P_2 = 15$; (c) $P_1 = 11$, $s = 0.7$.

Then, we studied the sensitivity of the initial value when the system (8) was in chaotic state. Based on Section 4.1, when $g_1 = 0.18$, $g_2 = 0.01$, and $g_3 = 0.01$, the system (8) appeared chaotic. We still took the same baseline data, i.e., $P_1 = 11$, $s = 0.7$, and $P_2 = 15$. Figure 10 shows the sensitivity of the system (8) to initial values when in chaotic state. It was obvious that the value of recycling prices and service level in the system (8) tended to be significantly different over time. We can conclude that the chaotic system was highly sensitive to the initial value. Even if the initial value changed slightly, the result would change a lot. Therefore, the third-party collector and manufacturer should...
pay more attention to choosing the initial price and service strategies when the recycling market is in chaotic state.

**Figure 10.** Sensitivity of initial values in the system (8) when in chaotic state: (a) $s = 0.7, P_2 = 15$; (b) $P_1 = 11, P_2 = 15$; (c) $P_1 = 11, s = 0.7$.

5.3. The Impact of Consumers’ Service Sensitivity and Service Cost Parameter on the Stable Region of the System

Different from former literature, this study focused on the dynamic evolution of the third-party collector’s service decision in reverse supply chain. From Section 4.1, we found that the adjustment parameter of service decision had a great effect on the stability of the recycling market. Actually, consumers’ service sensitivity is also an important factor which influences the service decision. From the recycling quantity function of the third-party collector in Assumption 1, it is clear that the more sensitive consumers are to the service, the more quantity of waste products the third-party collector can collect. Hence, the value of consumers’ service sensitivity parameter also plays a significant role in the recycling market.

First, we analyzed the impact of consumers’ service sensitivity on the stable region of the system (8). Inequalities (11) showed the stable region of the system (8) under adjustment speed parameters $g_1$, $g_2$, and $g_3$. Here, we took three different values of the service sensitivity parameter, i.e., $\gamma = 1$, $\gamma = 3$, and $\gamma = 5$. We divided consumer service sensitivity into three levels corresponding to the different value of parameter $\gamma$, i.e., weak, middle, and strong. When other parameters are fixed, the stable region for the Nash equilibrium point under different values of $\gamma$ are shown in Figure 11. From the stable region in Figure 11a–c, with the increase of parameter $\gamma$, the stable region of the system (8) decreased. Therefore, from the perspective of the recycling market, the increase in consumers’ service sensitivity is not conducive to stability of the market. By comparing the stable range of adjustment speed parameters under different parameter $\gamma$, we found that the increase of consumers’ service sensitivity can expand the stable range of adjustment parameters.
sensitivity can expand the stable range of adjustment parameters \(g_1\) and \(g_3\) while narrowing the stable range of the adjustment parameter \(g_2\). Therefore, if consumers have strong sensitivity to a third-party collector’s service, the third-party collector should maintain his service decision because the change in service decision may cause great fluctuations in the recycling market.

![Graph](image_url)

**Figure 11.** 3D stable region for \(g_1\), \(g_2\), and \(g_3\) under different values of \(\gamma\): (a) \(\gamma = 1\), (b) \(\gamma = 3\), (c) \(\gamma = 5\).

The Nash equilibrium points corresponding to Figure 11 are as follows: \(R_8(15.29, 0.29, 18.82)\) in Figure 11a, \(R_8(12.8, 1.03, 18.2)\) in Figure 11b, and \(R_8(4, 2.6, 16)\) in Figure 11c. By analyzing the changes in the value of three Nash equilibrium points, we found that when consumers’ service sensitivity increased, the recycling price of the manufacturer and the third-party collector decreased while the service level increased. The result indicates that when consumers have a strong sensitivity to the service provided by the third-party collector, in order to obtain more waste products from consumers, the third-party collector tends to improve his service level. Under this situation, the third-party collector does not need to set a high recycling price to attract consumers, and the third-party collector will reduce his recycling price. In the process of collection, there occurs price competition between the manufacturer and the third-party collector. When the recycling price of the third-party decreases, the price competition from the third-party becomes weak and the manufacturer also reduces his recycling price.

Besides the parameter of consumer service sensitivity, the value of the service cost parameter \(\sigma\) can affect the stable region of the system (8) at the same time. When other parameters are fixed, the stable region for the Nash equilibrium point under different values of \(\sigma\) are shown in Figure 12. The stable region of the system (8) decreased when the parameter \(\sigma\) increased. By comparing the stable range of adjustment speed parameters under different value of parameter \(\sigma\), we found that the increase
of service cost parameter can narrow the stable range of adjustment parameters \( g_1 \) and \( g_3 \) while expanding the stable range of the adjustment parameter \( g_2 \). Furthermore, the Nash equilibrium point corresponding to Figure 12 changed from \( R_8(12.8, 1.03, 18.2) \) in Figure 12a to \( R_8(14.3, 0.47, 18.57) \) in Figure 12b. The result indicates that the third-party collector will reduce the types of services provided to consumers if service cost is high. In this situation, both the manufacturer and the third-party collector will increase their recycling price to obtain more waste products. Since the value of the service cost parameter is dependent on the third-party collector, the third-party collector can take management, innovation, and other means to reduce the service cost and make the recycling market more stable.

\[ R_8(12.8, 1.03, 18.2) \]

\[ R_8(14.3, 0.47, 18.57) \]

![Figure 12](image-url)

**Figure 12.** 3D stable region for \( g_1 \), \( g_2 \), and \( g_3 \) under different values of \( \sigma \): (a) \( \sigma = 50 \), (b) \( \sigma = 100 \).

### 5.4. The Impact of Service Adjustment Parameter on the Profit in Supply Chain

From the previous analysis, we found that the value of adjustment parameters, consumer service sensitivity, initial value, and service cost parameter are crucial to the stability of the market. In this section, we analyzed how the increase of the service adjustment speed influences game players’ profits. When parameter \( g_1 \) changes, Figure 13a,b showed the dynamic change of game players’ profit when \( g_2 = 0.01 \) and \( g_3 = 0.01 \), and Figure 13c,d showed the dynamic change of game players’ profit when \( g_2 = 0.02 \) and \( g_3 = 0.01 \). The result showed that no matter what the service adjustment parameter \( g_2 \) is, when the market is in a stable state, the profits of the manufacturer and third-party collector depend on the value of the Nash equilibrium point \( R_8 \). With increase of the adjustment parameter \( g_1 \), the profit of the manufacturer and third-party collector began to diverge and gradually become a chaotic state. Furthermore, when the adjustment parameter of service increased to 0.2, the bifurcation point of Figure 13a,b shifted to the left in Figure 13c,d. The result shows that there was a reverse relationship between parameters \( g_1 \) and \( g_2 \). According to the recycling quantity function in Assumption 1, the increase change of service leads to the great changes in recycling quantity of the third-party collector. In order to maintain profit, the third-party collector tends to accelerate its recycling price adjustment. As a result, it may lead the market into the chaotic state more quickly. Hence, when the third-party collector adjusted service decision more quickly, the collector should control recycling price from a long-term perspective and take scientific methods to avoid chaos.

When parameter \( g_3 \) changes, Figure 14a,b shows the dynamic change of game players’ profit when \( g_1 = 0.1 \) and \( g_2 = 0.01 \), and Figure 13c,d shows the dynamic change of game players’ profit when \( g_1 = 0.1 \) and \( g_2 = 0.02 \). The result shows that when the system (8) is in stable state, the profits of the manufacturer and third-party collector depend on the value of the Nash equilibrium point \( R_8 \). With the increase of the adjustment parameter \( g_3 \), the profit of the manufacturer and third-party collector began to diverge gradually toward a chaotic state. Furthermore, when the adjustment parameter of service increased to 0.2, the bifurcation point of Figure 14a,b shifted to the left in Figure 14c,d. There was also a reverse relationship between the parameters \( g_2 \) and \( g_3 \). Therefore, when the service adjustment
parameter of the third-party collector increases, the stable range of adjustment parameters $g_1$ and $g_3$ will narrow. Once chaos appears in the market, the profit of the manufacturer and the third-party collector are difficult to predict.

Figure 13. The bifurcation diagrams of players’ profit when $g_1$ changes: (a,b) $g_2 = 0.01, g_3 = 0.01$; (c,d) $g_2 = 0.02, g_3 = 0.01$.

Figure 14. Cont.
Figure 14. The bifurcation diagrams of players’ profit when $g_3$ changes: (a,b) $g_1 = 0.1, g_2 = 0.01$; (c,d) $g_1 = 0.1, g_2 = 0.02$.

5.5. Discussion

Under bounded rationality, the pricing and service decisions in the reverse supply chain tend to be complicated in the dynamic evolution. During the decision-making process, the participants adjust their decisions according to the marginal profit. According to the numerical simulation, the recycling market is always stable when the adjustment parameters meet the inequalities (12). Once the speed of adjustment is too fast, the recycling market will get out of the stable state and gradually become chaos. The chaotic system has strong initial sensitivity, which is similar to the conclusion of Zhang [39] and Xi [44]. Different from Li’s study [29], besides the pricing decision, the third-party collectors’ service decisions also affect the stability of the recycling market. Furthermore, the market is more sensitive to the change in service decision compared with the pricing decision. In addition, the stable area of the system (8) has strong connection with the consumers’ service sensitivity and the service cost parameter. The stable region of the system (8) decreases when these two parameters increase. By analyzing the change in the Nash equilibrium point, the increase of consumer service sensitivity promotes the improvement in third-party collectors’ service and weakens the recycling price competition between the manufacturer and the third-party collector. On the contrary, the increase of service cost parameter reduces the service level of the third-party and strengthens the recycling price competition between the manufacturer and the third-party collector, both of whom need to increase recycling price to obtain more waste products.

When discussing the profit situation in the reverse supply chain, we found an interesting result that there was a reverse relationship between the adjustment parameters of pricing decision and the adjustment parameter of service level, the increase of service adjustment will lead to the recycling market loss of control and the occurrence of chaos. In a chaotic state, the profit of the manufacturer and the third-party collector become disordered. The chaotic state is harmful to the development of the manufacturer and the third-party. In the next section, we will find measures to avoid chaos.

6. Chaos Control

Chaos is harmful to an economic system. When the market is in a chaotic state, members of the system are unable to accurately analyze the current market and make right price and service decisions. Therefore, certain measures should be taken to prevent and avoid the phenomenon of chaos. There are some methods to avoid chaos, for example, Zhang [43] used the delayed feedback control method to control the chaos in a nitrogen emissions system. In this paper, we used the variable feedback control method [45] to control the recycling market.
We expressed the discrete dynamic system (8) without control as:

\[
\begin{align*}
P_1(t+1) &= g_1(P_1(t), s(t), P_2(t)) \\
s(t+1) &= g_2(P_1(t), s(t), P_2(t)) \\
P_2(t+1) &= g_3(P_1(t), s(t), P_2(t))
\end{align*}
\]  
(13)

By adding control parameter \( L \) into system (13), the new system can be expressed as:

\[
\begin{align*}
P_1(t + 1) &= (1 - L)g_1(P_1(t), s(t), P_2(t)) + LP_1(t) \\
s(t + 1) &= (1 - L)g_2(P_1(t), s(t), P_2(t)) + Ls(t) \\
P_2(t + 1) &= (1 - L)g_3(P_1(t), s(t), P_2(t)) + LP_2(t)
\end{align*}
\]  
(14)

From Section 5.1, it is clear that when \( g_1 = 0.18, g_2 = 0.01, \) and \( g_3 = 0.01, \) the system (8) becomes chaos. By using the variable feedback control method, Figure 15 shows the bifurcation diagram for control parameter \( L. \) As is shown in Figure 15, \( L_0 = 0.285 \) is corresponding to the bifurcation point of the system (14). When \( L < L_0, \) the system (14) is still in the state of bifurcation or chaos. The smaller \( L \) is, the less stable the system (14) is. When \( L = 0, \) the system (14) is completely in chaos. When \( L > L_0, \) the system (14) tends to be stable.

![Figure 15](image-url)

**Figure 15.** The bifurcation diagram of system (14) when \( L \) changes: (a) \( P_1 \) and \( P_2; \) (b) \( s. \)

In order to further illustrate the effectiveness of the control method, we drew the strange attractors of system (14) under the conditions of \( L = 0.1 \) and \( L = 0.4. \) As is shown in Figure 16a, when \( L = 0.1 < L_0, \) system (14) was still in a chaotic state. From Figure 16b, when \( L = 0.4 > L_0, \) system (13) was effectively controlled, and the strange attractor will evolve to the Nash equilibrium point \( R_8. \) The control parameter \( L \) can be understood as an internal or external factor. Internal factors can be understood as the learning ability of enterprises. In order to strengthen the control of chaos, the enterprise can predict the market information through big data analysis. External factors can be understood when enterprises lack learning ability, the government enters the recycling market by means of policy regulation to maintain the market order.
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7. Conclusions

This study established a game model with dual-channel recycling structure. With the rapid development of the independent third-party collector, we considered the situation that the manufacturer and the third-party collector collect waste products at the same time. Different from manufacturers and retailers, third-party collectors always provide different service for consumers. Hence, we considered the service decision of the third-party collector. Based on bounded rationality, we analyzed the dynamic change of the service and price decisions in the recycling market. Then, we analyzed equilibrium points of the system and stable condition for the Nash equilibrium point. In the section of numerical simulation, we analyzed the dynamic characteristics of the system. Finally, we used the feedback control method to control the chaotic market.

The conclusions are as follows. (1) The adjustment speeds of the third-party and the manufacturer have great effect on the stability of the system. If the adjustment parameter is too large, the system will evolve to chaotic state. Furthermore, the market is most sensitive to the change of third-party collectors’ service decisions. (2) When the recycling market is in a stable state, the slight deviation of the initial value will be eliminated by increasing iterations. When the market is in a chaotic state, the small deviation of the initial value will be gradually amplified with the increase of iterations. The chaotic system has a strong sensitivity to the initial value. (3) The stable region of the dynamic system shrinks with the increase of consumer service sensitivity and the service cost parameter. Furthermore, the increase of consumer service sensitivity can expand the stable range of price adjustment parameters while narrowing the stable range of the service adjustment parameter. On the contrary, the increase of the service cost parameter can narrow the stable range of price adjustment parameters while expanding the stable range of the service adjustment parameter. (4) There was a reverse relationship between price adjustment parameters and the service adjustment parameter. With the increase of service adjustment parameter, the bifurcation point of the system will appear more quickly. (4) Chaotic systems can be controlled by the feedback control method.

Figure 16. Strange attractor of the system (13): (a) $L = 0.1$; (b) $L = 0.4$. 

(a) (b)
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