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Research Article

Dynamic Investigation in Green Supply Chain considering Channel Service

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Considering firm's innovation input of green products and channel service, this paper, in dynamic environment, studies a dynamic price game model in a dual-channel green supply chain and focuses on the effect of parameter changing on the pricing strategies and complexity of the dynamic system. Using dynamic theory, the complex behaviors of the dynamic system are discussed; besides, the parameter adaptation method is adopted to restrain the chaos phenomenon. The conclusions are as follows: the stable scope of the green supply chain system enlarges with decision makers' risk-aversion level increasing and decreases with service value increasing; excessive adjustment of price parameters will make the green supply chain system fall into chaos with a large entropy value; the attraction domain of initial prices shrinks with price adjustment speed increasing and enlarges with the channel service values raising. As the dynamic game model system is in a chaotic state, the profit of the manufacturer will be damaged, while the efficiency of the retailer will be improved. The system would be kept at a stable state and casts off chaos by the parameter adaptation method. Results are significant for the manager to make reasonable price decision.

1. Introduction

At present, China is the largest producer and consumer of household appliances in the world. The development of the home appliance industry has made great contribution to the economic development. According to the relevant report of China's home appliance market in 2019, the scale of China's home appliance market still keeps rapid growth [1, 2]. However, with people's living standard improving, consumers are no longer satisfied with the low level of retail services but also put forward higher requirements for the environmental performance and technology of products. For household appliance enterprises, increasing their research and development (R&D) investment for green product can not only meet the market demand for intelligent safety products but also improve their independent innovation ability and market competitiveness. In this environment, the dynamic price game of enterprises considering technological innovation and channel service has attracted wide attention from business and academia.

In recent years, many scholars have conducted extensive research on technological innovation for green product in various ways [3–6]. Apte and Viswanathan [7] reviewed the role of strategy and innovation in manufacturing and specifically discussed technology innovation in product and information flow management. Using system dynamic approach, Li and Ma [8] investigated the mechanism of the innovation level on the stability of the dynamic game. By the differential game approach, considering knowledge spillovers are endogenously caused by the R&D process, Lee et al. [9] collected and analyzed data from 133 companies in Malaysia and showed that there is a certain connection between technology innovation input and supply chain practice in manufacturing firms. In three different contract situations, Wang and Shin [10] explored the influence of different contracts with endogenous upstream innovation and found that supply chain decisions (e.g., the innovation input) could be coordinated by the profit-sharing contract considering investment in innovation, whereas the other two contracts would lead to insufficient investment in innovation of supply chains. Verma et al. [11] considered the effects of three factors (e.g., SMAC capabilities, innovation, and advantage in competition) on supply chain performance and showed how three factors improve supply chain revenue. Considering fairness contract and power structure, Kim et al. [12] examined the innovation performance of the supplier in an innovative supply chain. In addition, Song al et al. [13] integrated the technological innovation and advertising strategies of firms into a two-level supply chain and found that the influence of technological innovation investment and advertising level on market demand and optimal marketing decision is more sensitive. In terms of innovation cooperation, Yoon and Jeong [14] put forward the technological innovation coordinative strategies and studied the differences among them in the reverse supply chain. Yan al et al. [15] paid attention to the innovation cooperation of construction industry and discussed the influence of profit distribution and spillover effect on game evolution. Based on the consumer market demand, Aydin and Parker [16] set up a game model and analyzed innovation and technology diffusion in competitive supply chains.

The previous literature has elaborated the influence of innovation factors on the supply chain from various angles in detail, and the conclusions have important reference value for society and enterprises. However, the complexity degree of the supply chain based on the impact of product innovation input on market demand is rarely explored.

In recent years, the supply chain-related problems considering channel service factors have become the focus of the industry and academia [17–20]. Pei and Yan [21] thought that retail service can not only coordinate the conflict between channels but also improve the relationship between channel members. Introducing RLS to substitute naive estimation, Ma and Guo [22] explored the complex dynamic behavior of the game model with service factors. Protopappa-Sieke et al. [23] put forward a two-stage inventory strategy based on multiple service contracts. Jena and Sarmah [24] explored the price and service coopetition between two firms, which competed on price and service level and provided retail service directly to customers by a common retailer. In the omni-channel environment, Chen et al. [25] introduce service cooperation into mixed channels with different power structures. Under the two game structures of centralization and decentralization, Kong et al. [26] paid attention to the pricing and service level decision of the low-carbon closed-loop supply chain and researched the role of related parameters in the system. Zhang and Wang [27] put forward two kinds of dynamic pricing strategies based on the changing market and focused on the mechanism of service factors on pricing. In addition, Zhou et al. [28] found that the retailer's service input is easy to lead to the free-riding effect and further discussed the best service strategy of the supply chain under the free-riding effect. Considering the sensitive factors of consumers to service, Ghosh [29] explored the price and service level strategy of a supply chain including one manufacturer and two retailers. Yang et al. [30] studied the impact of quick response service on supply chain performance with a strategic customer in various supply chain structures and showed that the size of the extra service cost affected the decision-making right structure of the supply chain. Tu et al. [31] studied the effect of coefficient of services on a hybrid supply chains.

Scholars have done some research on price game issues. Xin and Sun [32] studied a differential oligopoly game in which a production-planning single-decision problem is extended to a production-planning and water-saving dual-decision problem, and the decisions are affected simultaneously by both the product and the water right prices. Li et al. [33] studied a Stackelberg game model in a dual-channel supply chain, in which the manufacturer and retailer all considered fairness concern in the price game. Li et al. [34] constructed a dual-channel valued chain in which the manufacturer made green innovation input and the retailer provided channel service, and they make the dynamic price game in decentralized and centralized decisions.

This paper establishes a price game model considering the factors of green innovation input and channel service in decentralized decision scenario. Using game theory and nonlinear dynamics theory, we discuss the equilibrium points and the complex dynamic behaviors of the dynamic system and study the effects of channel service level and risk-aversion level on optimal pricing, stability, and utility of the dual-channel value chain system. The global stability and chaos phenomenon of the dynamic system are analyzed.

Our theoretical contribution is as follows: the first contribution is to the construct dynamic dual-channel supply chain model considering innovation investment and channel service. The second contribution is to analyze the effects of the key parameters on the stability and profitability of the dynamic dual-channel supply chain model.

The rest of this paper is arranged as follows: in Section 2, we present the problem basic description and related hypothesis. Section 3 constructs the static game model and dynamic game model; besides, their stability and the equilibrium solutions are analyzed. Section 4 analyzes the stability characteristics of the dynamic game model. The global stability analysis of the system is given by basins of attraction in Section 5. The control of the chaos phenomenon is made in Section 6. Section 7 presents the conclusions.

2. Model Construction

2.1. Problem Description and Model Assumptions. In a dual-channel green supply chain, to satisfy consumers' demand for intelligent and personalized green products, the manufacturer makes innovative investment in green products, and I_m stands for the amount of innovation input. Two sales channels exist in the dual-channel green supply chain, and one is a traditional channel where the retailer gets green products from the manufacturer and the retailer sells green products to consumers at price p_2; the other is the direct marketing channel where the manufacturer also sells the same green products to the consumer at price p_1 directly. The manufacturer and retailer provide sales services (v_1 and v_2) to win more customer demand, respectively. The manufacturer and the retailer compete for retail prices in the same market. The dual-channel green supply chain system is structured in Figure 1.

To support this research, the following assumptions are made in this paper:

(1) We assume that the participants all show risk-aversion behaviors facing the changing market demand.

(2) In a game cycle, because of difficulty that decision makers grasp the perfect market information through their own abilities, therefore, this paper assumes that the manufacturer and retailer are both bounded rationality and they will make the next decision based on the current marginal utility; as the current marginal utility is more than zero, they would improve selling price in the next period; otherwise, they would reduce selling price.

(3) For the convenience of research, this paper assumes that the unit distribution cost of participants is zero [29] and only considers innovation cost and service cost.

The notations of parameters and its meanings employed in this paper are listed in Table 1.

2.2. Dynamic Game Model. In the market competition, market demand is not only affected by retail price but also by the manufacturer' investment in technological innovation and channel services provided by the participant. In this paper, considering the above factors and relevant literature [29], the market demands from the direct channel and traditional channel can be expressed as follows:

$$\begin{cases} D_m = \theta a - b_1 (p_1 - v_1) + \beta_1 (p_2 - v_2) + \theta Q, \\ D_r = (1-\theta) a - b_2 (p_2 - v_2) + \beta_2 (p_1 - v_1) + (1-\theta) Q, \end{cases} \tag{1}$$

where $b_i > \beta_i$ $(i = 1, 2)$, means that the influence of product price on demand in each channel is greater than that in a competitive channel; $Q = (1/\sqrt{\varepsilon})\sqrt{I_m}$ is the increased market demand for technological innovation investment, and the slowdown of demand growth caused by the increase of technological innovation input is in line with the actual situation of the market.

The connection between service value and service cost of unit product satisfies

$$c_i = \frac{\eta_i v_i^2}{2}, \quad i = 1, 2. \tag{2}$$

Therefore, service cost and service value change in the same direction.

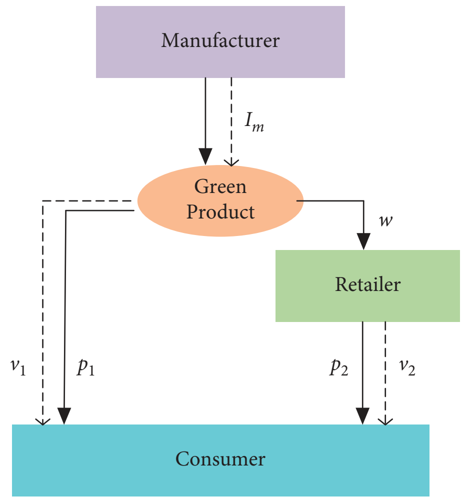


Figure 1: The dual-channel green supply chain system.

Table 1: Notations and their meanings.

a	The basic market scale
$\bar{a}$	The mean of basic market scale
θ	Consumer's preference for direct channel $(0 < \theta < 1)$
w	The wholesale price of product
c	Manufacturing cost per unit product
p_1	Retail price of product in direct channel
p_2	Retail price of product in traditional channel
b_i	Price-sensitive coefficient $(i = 1, 2)$
β_i	Cross-price-sensitive coefficient $(0 < \beta_i \leq 1, i = 1, 2)$
I_m	The scale of innovation input
v_1	Service value of unit product of the manufacturer
v_2	Service value of unit product of the retailer
η_1	Service cost coefficient of the manufacturer
η_2	Service cost coefficient of the retailer
c_1	Service cost of unit product for manufacturer
c_2	Service cost of unit product for the retailer
σ_i	Market demand variance $(i = 1, 2)$
Q	Customer demand created by innovation input
ε	Innovation input coefficient
R_1	Risk attitude of the manufacturer
R_2	Risk attitude of the retailer

Based on the features of this paper, the parameters should satisfy

$$\begin{cases} 0 < c + c_1 < p_1, \\ w + c_2 < p_2, \\ D_m > 0, \ D_r > 0. \end{cases} \tag{3}$$

According to inequality (3), the following conditions can be obtained:

$$\begin{cases} 0 < c < w < p_1 < \dfrac{\theta a b_2 + (1-\theta) a \beta_1 + (1-\theta)(\beta_1/\sqrt{\varepsilon})\sqrt{I_m} + \theta (b_2/\sqrt{\varepsilon})\sqrt{I_m}}{b_1 b_2 (1 - \beta_1 \beta_2)}, \\ 0 < w + c_2 < p_2 < \dfrac{(1-\theta) a b_1 + \theta a \beta_2 + \theta (\beta_2/\sqrt{\varepsilon})\sqrt{I_m} + (1-\theta)(b_1/\sqrt{\varepsilon})\sqrt{I_m}}{b_1 b_2 (1 - \beta_1 \beta_2)} + v_2. \end{cases} \tag{4}$$

The profit functions of firms are as follows:

$$\begin{cases} \pi_m = (w-c)\left[(1-\theta)a - b_2(p_2-v_2) + \beta_2(p_1-v_1) + (1-\theta)\dfrac{1}{\sqrt{\varepsilon}}\sqrt{I_m}\right] \\ +(p_1-c-c_1)\left[\theta a - b_1(p_1-v_1) + \beta_1(p_2-v_2) + \theta\dfrac{1}{\sqrt{\varepsilon}}\sqrt{I_m}\right] - I_m, \\ \pi_r = (p_2-w-c_2)\left[(1-\theta)a - b_2(p_2-v_2) + \beta_2(p_1-v_1) + (1-\theta)\dfrac{1}{\sqrt{\varepsilon}}\sqrt{I_m}\right]. \end{cases} \tag{5}$$

In the face of the uncertain demand, the manufacturer and the retailer have financial risks for their product sales [35]. Therefore, this paper will consider the effect of the risk attitudes of firms on variable decision and the exponential utility is used to express the utility function:

$$U(\pi_i) = -e^{-\pi_i/R_i}, \tag{6}$$

where R_i, $(i=1,2)$ are the risk-aversion levels of the participant and e is the exponential constant; π_i is the profit of the manufacturer and retailer and follows a normal distribution; $E(\pi_i)$ is the mean of π_i, and $\mathrm{Var}(\pi_i)$ is the variance of π_i. The expected utility is as follows:

$$E\left(U_{\pi_i}\right) = E(\pi_i) - \frac{\mathrm{Var}(\pi_i)}{2R_i}. \tag{7}$$

The expected utilities of participants are as follows:

$$\begin{cases} E_m\left(U_{\pi_m}\right) = (w-c)\left[(1-\theta)\overline{a} - b_2(p_2-v_2) + \beta_2(p_1-v_1) + (1-\theta)\dfrac{1}{\sqrt{\varepsilon}}\sqrt{I_m}\right] \\ +(p_1-c-c_1)\left[\theta\overline{a} - b_1(p_1-v_1) + \beta_1(p_2-v_2) + \theta\dfrac{1}{\sqrt{\varepsilon}}\sqrt{I_m}\right] - I_m - \dfrac{(p_1-c-c_1)^2\sigma_1^2}{2R_1} - \dfrac{(w-c)^2\sigma_2^2}{2R_2}, \\ E_r\left(U_{\pi_r}\right) = (p_2-w-c_2)\left[(1-\theta)\overline{a} - b_2(p_2-v_2) + \beta_2(p_1-v_1) + (1-\theta)\dfrac{1}{\sqrt{\varepsilon}}\sqrt{I_m}\right] - \dfrac{(p_2-w-c_2)^2\sigma_2^2}{2R_2}. \end{cases} \tag{8}$$

Making first-order derivatives of $E_m(U_{\pi_m})$ with respect to $\sqrt{I_m}$,

$$\frac{\partial E_m\left(U_{\pi_m}\right)}{\partial\sqrt{I_m}} = \frac{(w-c)(1-\theta)}{\sqrt{\varepsilon}} + \frac{(p_1-c-c_1)\theta}{\sqrt{\varepsilon}} - 2\sqrt{I_m}. \tag{9}$$

Making second-order derivatives of $E_m(U_{\pi_m})$ in $\sqrt{I_m}$,

$$\frac{\partial^2 E_m\left(U_{\pi_m}\right)}{\partial\left(\sqrt{I_m}\right)^2} = -2. \tag{10}$$

From the above analysis, the manufacturer's utility function $E_m(U_{\pi_m})$ is concave and only has a maximum value. Solving $(\partial E_m(U_{\pi_m})/\partial\sqrt{I_m}) = 0$, the optimal technological innovation input is expressed as follows:

$$I_m^* = \frac{\left[\theta(p_1-w-c_1)+w-c\right]^2}{4\varepsilon}. \tag{11}$$

From (11), it is clear that the greater the innovation cost coefficient is, the smaller the optimal technological innovation input is, and it shows that the high innovation cost coefficient has a restraining effect on the technology innovation investment enthusiasm of the manufacturer.

Substituting (11) into (8), the expected utility functions of participants under optimal technological innovation input are obtained:

$$\begin{cases} E_m\left(U_{\pi_m}\right) = (p_1 - c - c_1)\left[\begin{array}{c} \theta\overline{a} - b_1(p_1 - v_1) + \beta_1(p_2 - v_2) + \dfrac{\theta[(p_1 - c_1 - w)\theta + w - c]}{2\varepsilon} \\ +(w - c)\left[(1-\theta)\overline{a} - b_2(p_2 - v_2) + \beta_1(p_1 - v_1) + \dfrac{(1-\theta)[(p_1 - c_1 - w)\theta + w - c]}{2\varepsilon}\right]\end{array}\right], \\ E_r\left(U_{\pi_r}\right) = (p_2 - w - c_2)[(1-\theta)\overline{a} - b_2(p_2 - v_2) + \beta_1(p_1 - v_1)] - \dfrac{(p_2 - w - c_2)^2\sigma_2^2}{2R_2} \\ +(p_2 - w - c_2)\left[\dfrac{(1-\theta)[(p_1 - c_1 - w)\theta + w - c]}{2\varepsilon}\right]. \end{cases} \tag{12}$$

Considering the first-order partial derivatives of $E_m(U_{\pi_m})$ and $E_r(U_{\pi_r})$ in p_1 and p_2, respectively, we can get the related equations in the following equation:

$$\begin{cases} \dfrac{\partial E_m\left(U_{\pi_m}\right)}{\partial p_1} = G_1 + X_1 p_1 + \beta_1 p_2, \\ \dfrac{\partial E_r\left(U_{\pi_r}\right)}{\partial p_2} = G_2 + X_2 p_2 + X_3 p_1, \end{cases} \tag{13}$$

where

$$\begin{aligned} G_1 &= \theta\overline{a} + b_1 v_1 - \beta_1 v_2 + \frac{\theta[(-c_1 - w)\theta + w - c]}{2\varepsilon} + b_1(c + c_1) - \frac{\theta^2(c + c_1)}{2\varepsilon} \\ &\quad + \beta_2(w - c) + (w - c)\frac{\theta(1-\theta)}{2\varepsilon} - \frac{-\theta c + \theta w - \theta^2 c_1 - \theta^2 w}{2\varepsilon} + \frac{\sigma_1^2(c + c_1)}{R_1}, \\ G_2 &= (1-\theta)\overline{a} + b_2 v_2 - v_1\beta_2 + (1-\theta)\frac{(-c_1 - w)\theta + w - c}{2\varepsilon} + b_2(w + c_2) + \frac{(w + c)\sigma_2^2}{R_2}, \\ X_1 &= -2b_1 + \frac{\theta^2}{2\varepsilon} - \frac{\sigma_1^2}{R_1}, \\ X_2 &= -2b_2 - \frac{\sigma_2^2}{R_2}, \\ X_3 &= \beta_2 + (1-\theta)\frac{\theta}{2\varepsilon}. \end{aligned} \tag{14}$$

In multistage game process, participants cannot grasp the perfect market information of the current market, and the grey forecasting model is a good way for the nonlinear system [36], but in this paper, we make price forecasting by bounded rational expectations to obtain profit maximization. As the current marginal utility is more than zero, decision makers would improve price $p_i\ (i = 1, 2)$ in the next period; otherwise, they would reduce them. Then, the dynamic decision-making process of participants can be expressed as follows:

$$\begin{cases} p_1(t+1) = p_1(t) + \delta_1 p_1(t)\left(G_1 + X_1 p_1(t) + \beta_1 p_2(t)\right), \\ p_2(t+1) = p_2(t) + \delta_2 p_2(t)\left(G_2 + X_2 p_2(t) + X_3 p_1(t)\right), \end{cases} \tag{15}$$

where δ_1 and δ_2 represent the price adjustment speeds of decision makers.

3. Equilibrium Points, Conditions for Existence, and Local Stability

For the system disturbed by weak noise, its variation can be seen as the random factors around the deterministic system and transformation between them [33]. When interference factors are very small, the motion state of the system would not be affected by the disturbance term; when interference factors are very large, the state of the system would be changed. Therefore, we first explore the Nash equilibrium solution and the local stability of dynamic system (15).

Based on the theory of the fixed point [37], letting $p_i(t+1) = p_i(t)$, the four possible Nash equilibrium points are obtained as follows:

$$\begin{aligned} \rho_1 &= (0, 0), \\ \rho_2 &= \left(0, -\frac{G_2}{X_2}\right), \\ \rho_3 &= \left(-\frac{G_1}{X_1}, 0\right), \\ \rho_4 &= \left(S_1^*, S_2^*\right), \end{aligned} \tag{16}$$

where $S_1^* = (\beta_1 G_2 - G_1 X_2 / X_1 X_2 - \beta_1 X_3)$ and $S_2^* = -(X_1 G_2 - G_1 X_3 / X_1 X_2 - \beta_1 X_3)$.

Proposition 1. *Nash equilibrium point ρ_1 is an unstable equilibrium point.*

Proof. See Appendix.

Proposition 2. *Nash equilibrium point ρ_2 and ρ_3 are unstable saddle points.*

Proof. See Appendix.

Economically, zero price means nothing to manufacturers and retailers. Next, we will study the stability characteristics of equilibrium solutions (ρ_4).

The Jacobian matrix of dynamic system (15) at ρ_4 can be written as follows:

$$J\left(S_1^*, S_2^*\right) = \begin{pmatrix} 1 + \delta_1\left(G_1 + 2Y_1 S_1^* + \beta_1 S_2^*\right) & \beta_1 \delta_1 S_1^* \\ Y_3 \delta_2 S_2^* & 1 + \delta_2\left(G_2 + 2Y_2 S_2^* + Y_3 S_1^*\right) \end{pmatrix}. \tag{17}$$

The feature equation of the Jacobian matrix can be written as follows:

$$F(\lambda) = \lambda^2 - \operatorname{tr}(J)\lambda + \det(J), \tag{18}$$

where $\operatorname{tr}(J)\lambda = \delta_1(G_1 + 2S_1^* Y_1 + \beta_1 S_2^*) + \delta_2(G_2 + S_1^* Y_3 + 2S_2^* Y_2) + 2$; $\det(J) = [\delta_1(G_1 + 2S_1^* Y_1 + \beta_1 S_2^*) + 1]\ [\delta_2(G_2 + S_1^* Y_3 + 2S_2^* Y_2) + 1] - \beta_1 S_1^* S_2^* Y_3 \delta_1 \delta_2$, $\Delta = (\operatorname{tr}(J))^2 - 4\det(J)$ be its discriminant.

In (18), setting $\lambda = 1$, we can get $F(1) = 1 - \operatorname{tr}(J) + \det(J)$. Therefore, Lemma 1 can be employed to study the eigenvalues of $J(S_1^*, S_2^*)$.

Lemma 1 (see [38]). *Suppose that $F(1) > 0$ and λ_1 and λ_2 are two roots of $F(\lambda) = 0$. Then,*

(1) $|\lambda_1| < 1$ and $|\lambda_2| < 1$ if and only if $F(-1) > 0$ and $\det(J) < 1$

(2) $|\lambda_1| < 1$ and $|\lambda_2| > 1$ (or $|\lambda_1| > 1$ and $|\lambda_2| < 1$) if and only if $F(-1) < 0$

(3) $|\lambda_1| > 1$ and $|\lambda_2| > 1$ if and only if $F(-1) > 0$ and $\det(J) > 1$

(4) $|\lambda_1| = -1$ and $|\lambda_2| \neq 1$ if and only if $F(-1) = 0$ and $\det(J) \neq 0, 2$

(5) λ_1 and λ_2 are complex and $|\lambda_1| = |\lambda_2| = 1$ if and only if $\Delta < 0$ and $\det(J) = 1$

If all eigenvalues of $J(S_1^*, S_2^*)$ are less than one in the modulus, dynamic system (15) will run stably at this equilibrium point. If not, the bifurcation behavior or chaos phenomenon appears in dynamic system (15). Concretely, that flip bifurcation happens as a single characteristic root is equal to −1, while Neimark–Sacker (N–S) bifurcation emerges as two characteristic roots equal one.

4. The Stable Region of Dynamic System (15)

Next, we adopt numerical simulation to indicate how key factors affect the complex dynamical behaviors of dynamic system (15). Taking the current situation and distinguishing the feature of the dual-channel green supply chain into account, parameter values are set as follows: $a = 120, \theta = 0.4, b_1 = 3, b_2 = 3.5, \beta_1 = 1, \beta_2 = 1, \varepsilon = 1.2, v_1 = 1.5, v_2 = 2, \eta_1 = 0.6, \eta_2 = 0.5, c = 6, w = 10, R_1 = 70, R_2 = 60, \sigma_1 = 0.05$, and $\sigma_2 = 0.05$. Thus, the Nash equilibrium solution is $\rho_4 = (15.3102, 18.8588)$ and the optimal innovation input is 7.553.

4.1. The Influence of Key Parameters on Stable Region of Dynamic System (15).

In dynamic system (15), price adjustment speed is regarded as a key factor, which can reflect the type of a decision maker. Radical players prefer to exert a larger adjustment speed to get more benefits in a short time. However, prudent players prefer to choose smaller adjustment speed to avoid risks and obtain stable profits.

Figure 2 shows the stable range of dynamic system (15) as the parameters take the above values; as the adjustment speed is within the light purple scope, dynamic system (15) will return to the Nash equilibrium point after several game cycles. If $\delta_1 > 0.0212$ or $\delta_2 > 0.01483$, dynamic system (15) would enter a bifurcation or chaotic state, and it means that the manufacturer or retailer would face the risk of withdrawing from the market.

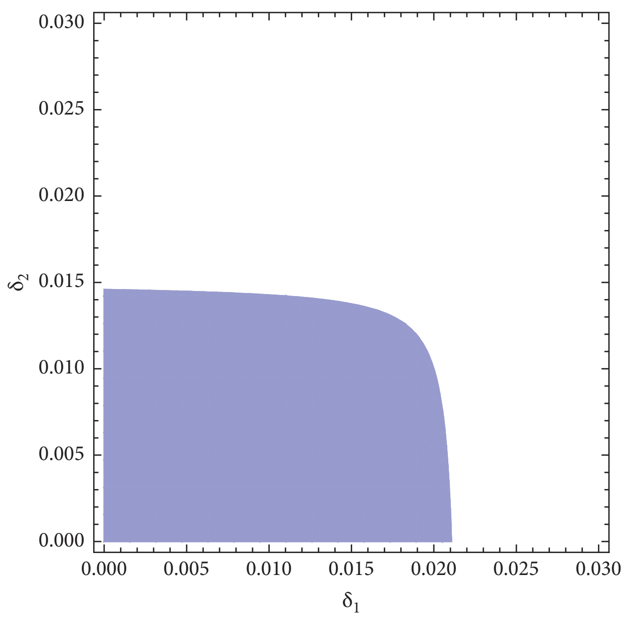


FIGURE 2: The stable region of dynamic system (15).

Figure 3(a) shows the stable regions of dynamic system (15) when $R_2 = 60$ with $R_1 = 10, 35, 60$, respectively, it can be seen that, as $R_1 = 10$, the range of price adjustment speed on the x-axis is $0 < \delta_1 < 0.01948$; when $R_1 = 35$, the range of the price adjustment parameter on the X-axis is $0 < \delta_1 < 0.0204$; when $R_1 = 60$, the range of price adjustment speeds on the X-axis is $0 < \delta_1 < 0.02121$. We conclude that the larger the risk-aversion level of the manufacturer is, the larger the stable range of the price adjustment of the manufacturer is, and the stable range of the price adjustment of the retailer remains unchanged. That is to say, the increase of the manufacturer's risk-aversion level has no effect on the stable range of the retailer's price adjustment but enlarges the stable scope of the retailer's price adjustment.

Figure 3(b) shows that the stability regions of dynamic system (15) decrease gradually in the direction of δ_1, while the stability regions hardly change in the direction of δ_2 when v_1 takes different values. Figure 3(c) shows that the stability scope of dynamic system (15) decreases in the direction of δ_2. However, the stability regions hardly change in the direction of δ_2. That is to say, the service values of the manufacturer and retailer only affect the stable ranges of price adjustment of their own channels but have no effect on other channels.

For understanding better the change process of dynamic system (15), Figure 4 displays the 2D diagram of dynamic system (15) using the parameter basin, which indicates the route of dynamic system (15) to chaos. In Figure 4, different periods are represented by different colors: for a single-cycle state, period-1 (green), period-3 (red), period-5 (purplish red), and period-7 (orange); for a period-doubling state, period-2 (pink), period-4 (blue), period-8 (purple), chaos (grey), and divergence (white). We can see that dynamic system (15) goes through period-doubling bifurcation and goes into a chaotic state. The stable region in Figure 4 is consistent with that in Figure 2.

Figures 5(a)–5(c) show the change process of dynamic system (15) in the (δ_1, δ_2) plane with R_2 having different values, and green areas represent the stable regions of dynamic system (15). The stable scope of dynamic system (15) enlarged with the direction of δ_2 in the increase of risk-aversion level of retailers and almost unchanged in the direction of δ_1. Figures 6(a)–6(c) show the change process of dynamic system (15) in the (v_1, v_2) plane with δ_1 and δ_2 having different values, and areas represent the stable regions of dynamic system (15). We can see that the stable regions of dynamic system (15) shrink in the direction of v_1 and v_2 with price adjustment speeds of participants increasing; that is to say, as the price adjustment speeds are relatively large, the manufacturer and the retailer can choose a smaller service level to make dynamic system (15) stable.

From the above analysis, a conclusion can be drawn that the stability region of dynamic system (15) shrinks with the increase of service values, enlarges in risk-aversion level, when the price adjustment speeds are relatively large. Participants can choose a smaller service level to keep dynamic system (15) stable.

If participants improve their service levels in order to obtain the best utilities, they will consume a lot of manpower and material resources of the dual-channel green supply chain. At this time, the ability of the dual-channel green supply chain system to resist risks will be weakened, which will lead to the decrease of system stability and the increase of vulnerability. Therefore, from the point of view of the supply chain, decision makers should make their own service decisions and price adjustment decisions prudently to make the dynamic system stable.

4.2. Global Stability of Dynamic System (15). The variation of the key parameter affects the stability of system (15). The influence of parameter variation on global stability can be analyzed by the basins of attraction, which includes the attraction domain and escaping area. If the initial values of parameters are set in attraction scope, dynamic system (15) will appear the same attractor after several iterations. If the initial values of parameters are not in the basins of attraction, which is marked by red, dynamic system (15) will evolve from a stable state to a divergent state.

With the same values for parameters, the basins of attraction about initial price p_1 and p_2 are showed in Figure 7, where the red range represents the stable domain of attraction and the white range represents the escape area. We find that the attraction range shrinks as δ_1 and δ_2 increase. Figure 8 indicates the basins of attraction of dynamic system (15) with v_1 and v_2 changing as $\delta_1 = 0.005$ and $\delta_2 = 0.005$. Compared with Figure 7, the stable attraction domain of initial value of p_1 enlarges with v_1 increasing and that of p_2 enlarges with v_2 increasing. If the initial values of p_1 and p_2 are taken in the attraction scope, dynamic system (15) will appear the chaotic attractor after several iterations. Otherwise, dynamic system (15) will fall into divergence at last. From economic perspective, the participant should choose the initial prices in basins of attraction to ensure that the market enters a stable state.

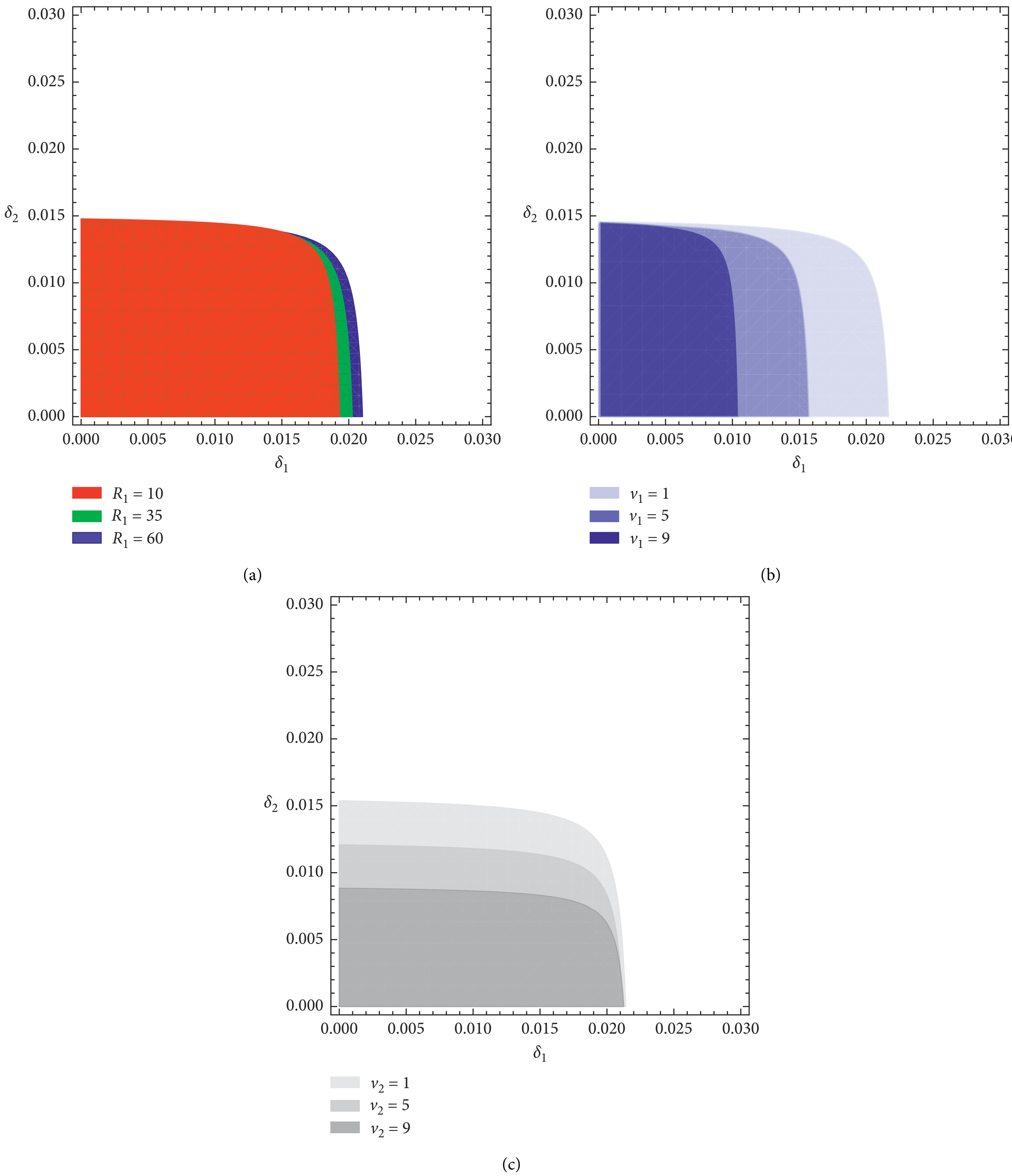


Figure 3: The stable regions of dynamic system (15) with R_1, v_1, and v_2 having different values. (a) R_1. (b) v_1. (c) v_2.

5. The Effect of Parameters on Dynamic System (15)

5.1. The Effect of Price Change on Dynamic System (15). Since the influence of the price adjustment parameters of participants on system behavior is similar, the evolution of system behavior is discussed by taking the price adjustment parameter of the manufacturer as an example. Figure 9(a) shows the effect of δ_1 on price evolution of dynamic system (15) when $\delta_2 = 0.005$. When $\delta_1 < 0.0207$, dynamic system (15) returns to the Nash equilibrium point after several games from the initial state; as $\delta_1 = 0.0207$, dynamic system (15) appears the first bifurcation; after that, dynamic system (15) appears four periodic bifurcations and eight periodic

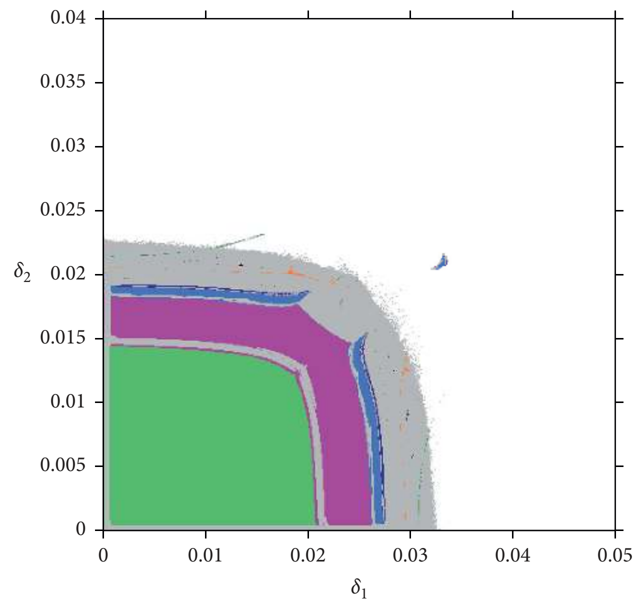
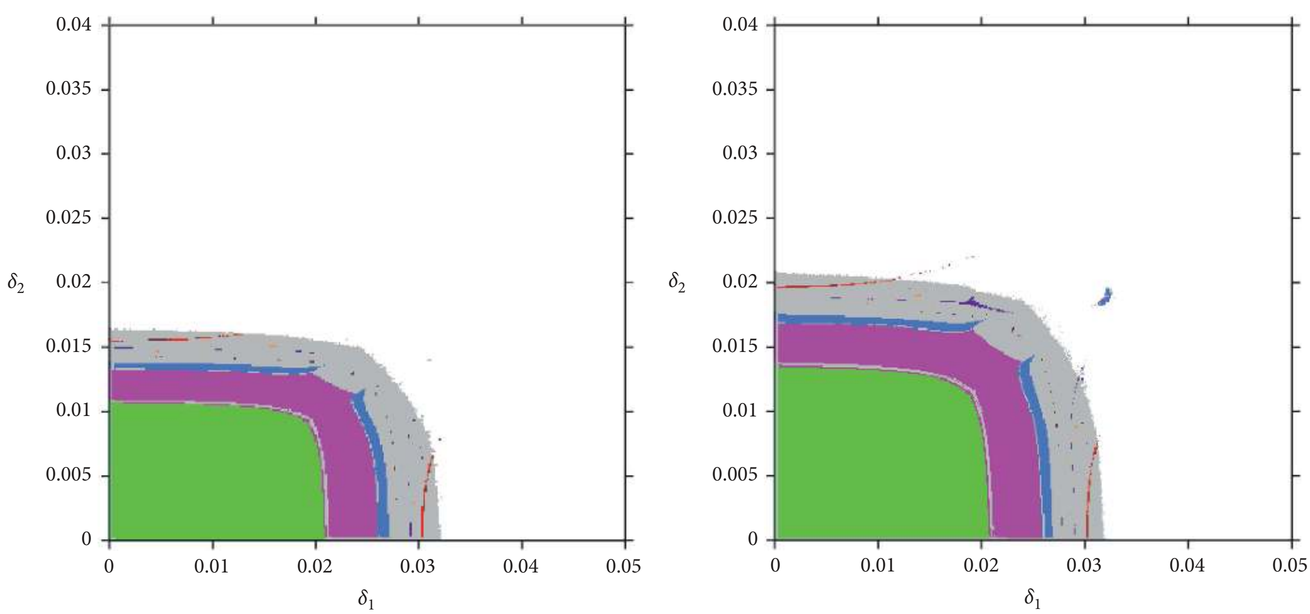
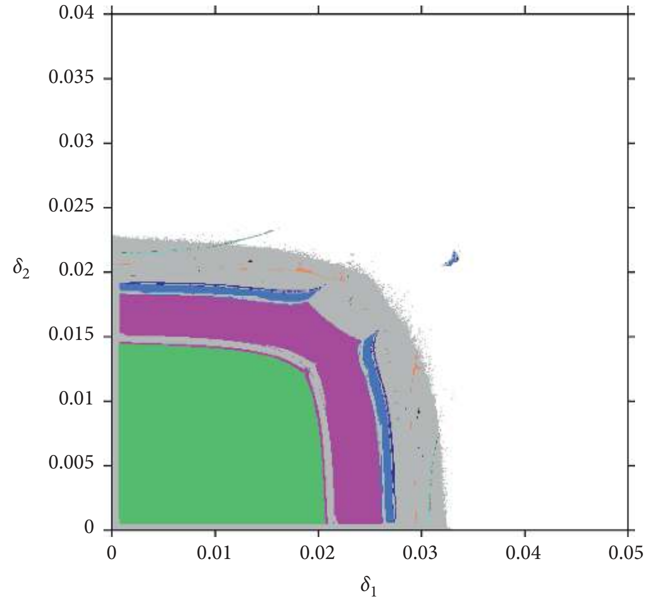


FIGURE 4: The 2D bifurcation diagram of dynamic system (15) in the (δ_1, δ_2) plane.



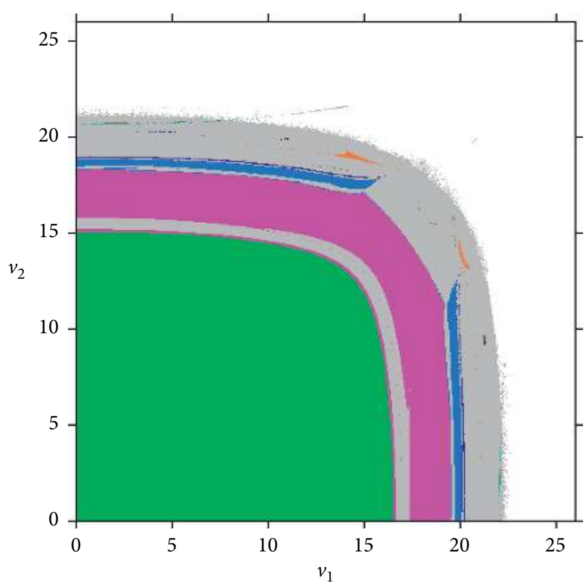
(a) (b)

FIGURE 5: Continued.

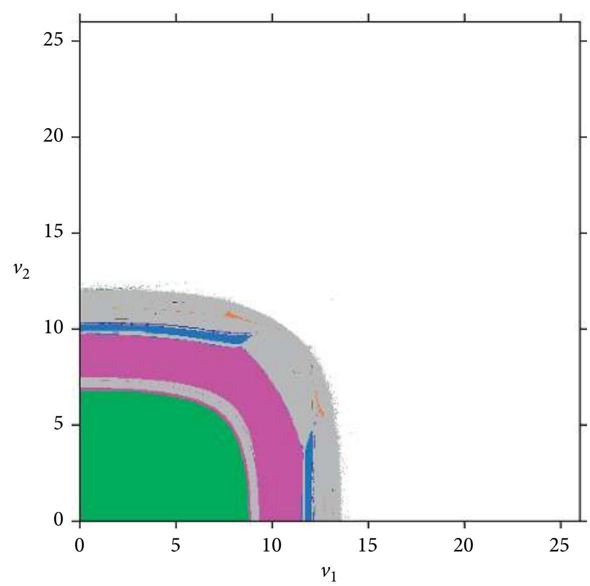


(c)

Figure 5: The 2D bifurcation diagrams in the (δ_1, δ_2) plane with R_r changing. (a) $R_2 = 5$. (b) $R_2 = 30$. (c) $R_2 = 60$.

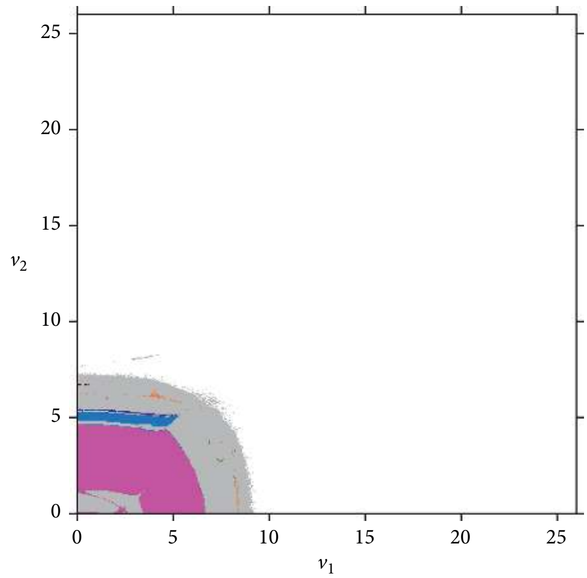


(a)



(b)

Figure 6: Continued.



(c)

Figure 6: The 2D bifurcation diagrams in the (v_1, v_2) plane with δ_1 and δ_1 changing. (a) $\delta_1 = 0.005$ and $\delta_2 = 0.005$. (b) $\delta_1 = 0.01$ and $\delta_2 = 0.01$. (c) $\delta_1 = 0.015$ and $\delta_2 = 0.015$.

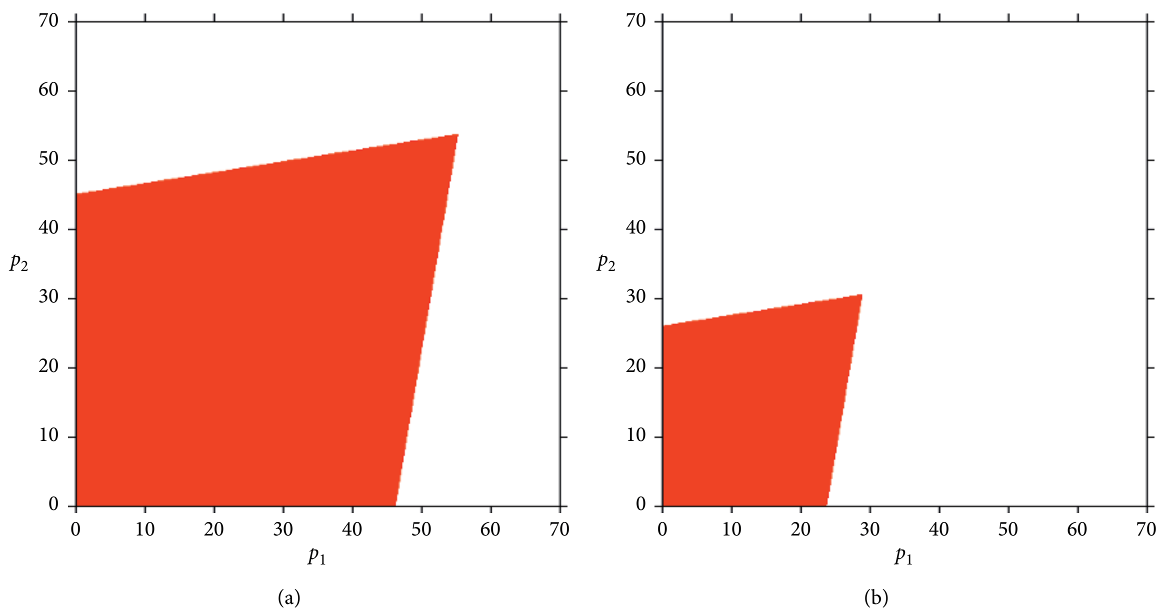


Figure 7: Basins of attraction of dynamic system (15) with δ_1 and δ_2 changing. (a) $\delta_1 = 0.005$ and $\delta_2 = 0.005$. (b) $\delta_1 = 0.015$ and $\delta_2 = 0.015$.

bifurcations and then gradually falls into chaos with δ_1 increasing.

Figure 9(b) shows the entropy change of dynamic system (15) with δ_1 increasing. When the system entropy equals to zero, dynamic system (15) is in the stable state; when the system entropy is greater than zero, dynamic system (15) is in the unstable state.

In order to visually show the effect of service values on the behavior of the system, Figures 10(a)–10(c) indicate that the system evolution process as v_1 has different values. From Figure 10, we can see that, with v_1 varying, the Nash equilibrium value increases, the stability of dynamic system (15) decreases, and market spillover effect appears ahead of time, which is consistent with Figure 3(b).

Figure 11 shows the forming process of the chaotic attractor as dynamic system (15) is in the chaotic state. Figure 11(a) shows the chaotic state of dynamic system (15) in its initial stage, and the orbit of dynamic system (15) is composed of scattered points. When the adjustment parameter increases, the trajectory of the system in the chaotic state presents a preliminary outline shown in Figure 11(b) when $\delta_1 = 0.0285$. From Figure 11(c), it can be found that

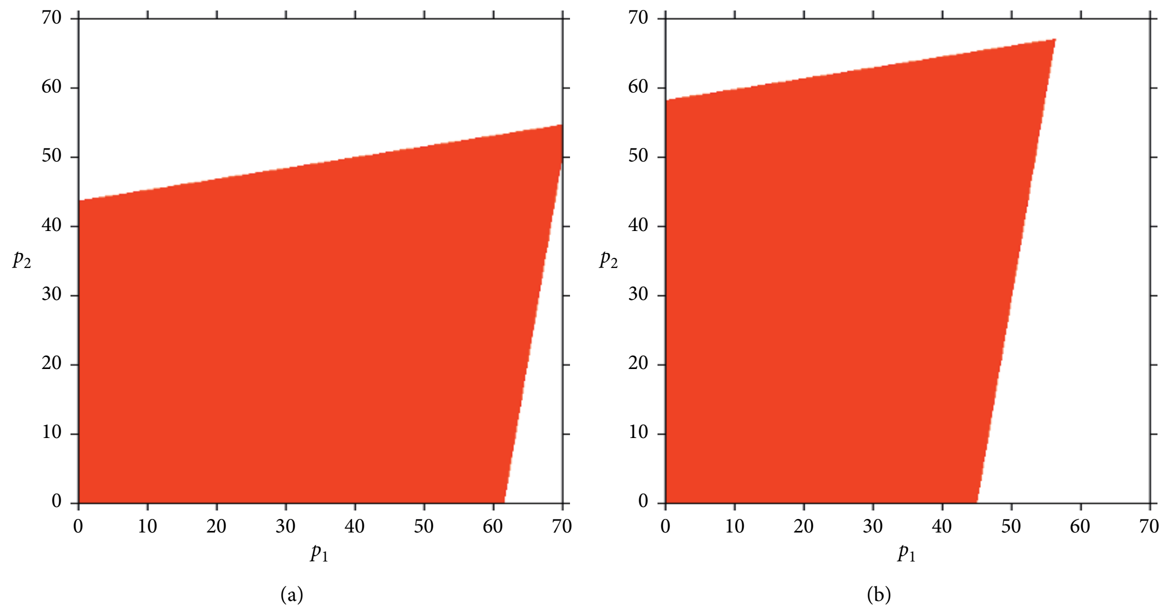


FIGURE 8: Basins of attraction with v_1 and v_2 changing. (a) $v_1 = 9$. (b) $v_2 = 9$.

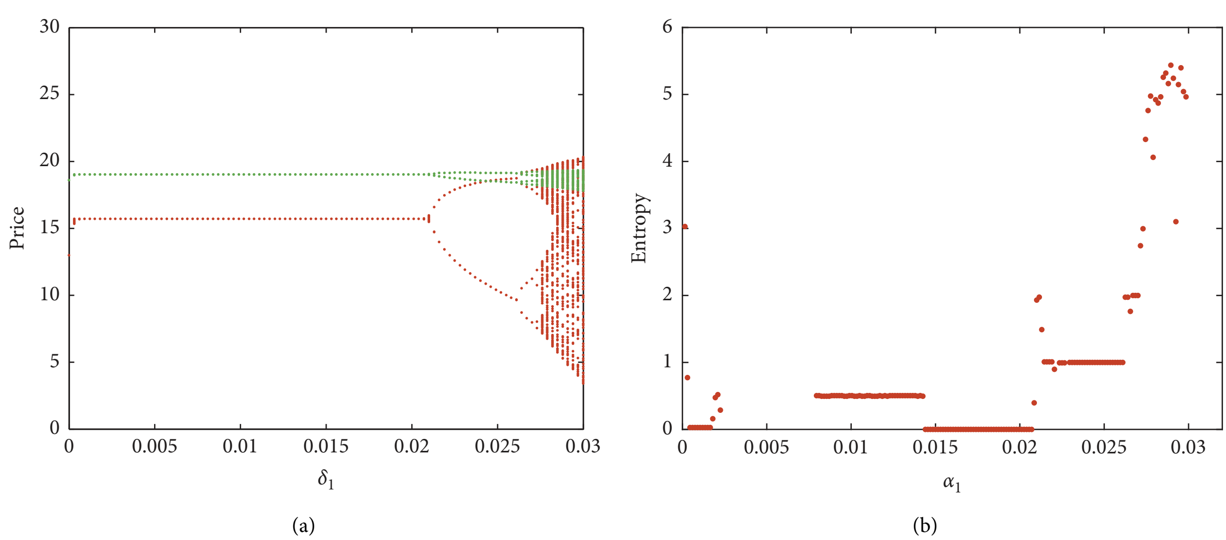


FIGURE 9: The price bifurcation and entropy with δ_1 varying. (a) The price bifurcation. (b) Entropy.

when $\delta_1 = 0.03$, there are countless points in the trajectory of dynamic system (15), and the distribution of countless points is attracted to a certain region.

Figure 11(a) shows the path of the initial chaotic system in phase space. With δ_1 increasing, in Figures 11(c) and 11(b), the chaos degree of dynamic system (15) increases, which can be called as the chaotic attractor.

Sensitivity to the initial value is also an important characteristic of chaotic systems. Figure 12(a) shows the running trend of dynamic system (15) as the initial value of p_1 only changes 0.001. Figure 12(b) shows the running trend of dynamic system (15) as the initial value of p_2 only changes 0.001. We can see that there is almost no difference in the retail prices between participants before 20 time iterations. After 20 time iterations, retail prices began to fluctuate sharply, which indicates that the small difference in the initial value will lead to system instability.

From this, it can be drawn that the sensitivity of the dynamic system in the unstable state is just like the butterfly effect. With the small change of initial conditions, the chaotic system will fluctuate violently with time. In formulating market strategies, decision makers should choose the initial values carefully.

Thus, the excessive price adjustment parameter and larger service value can easily make dynamic system (15) enter the chaotic state and cause disorderly fluctuations. Therefore, managers should reasonably formulate market price strategies in the market competition and should not adjust prices too quickly in order to maximize short-term utility.

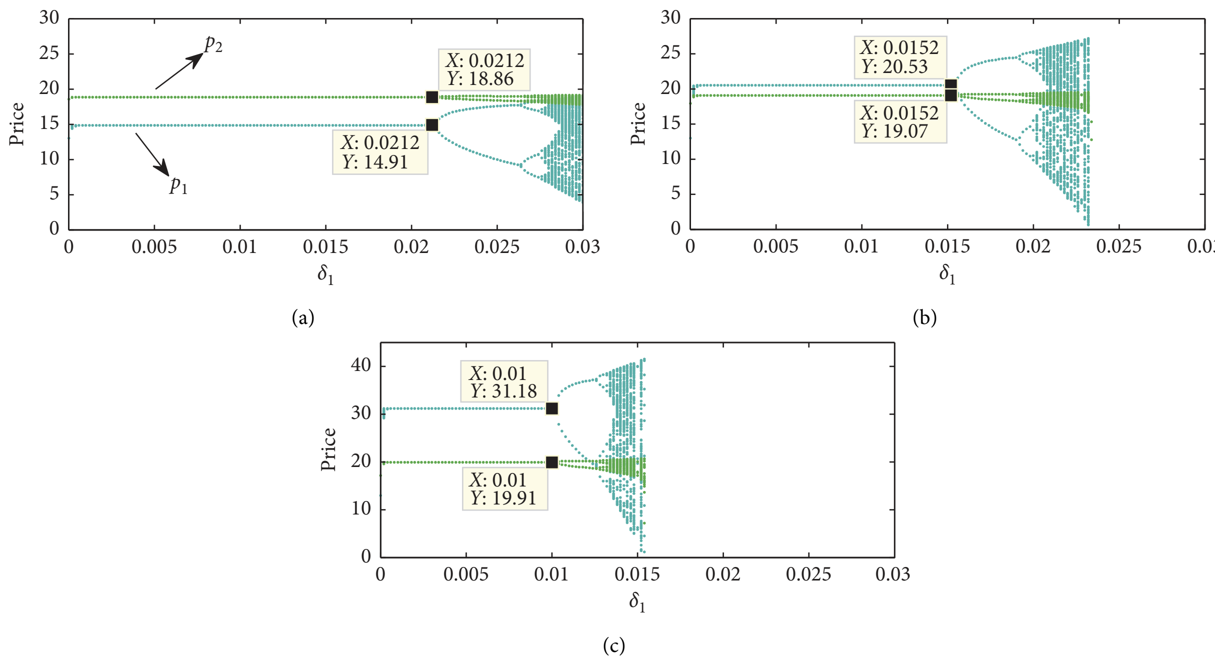


FIGURE 10: The bifurcation diagrams of dynamic system (15) with δ_1 increasing. (a) $v_1 = 1$. (b) $v_1 = 5$. (c) $v_1 = 9$.

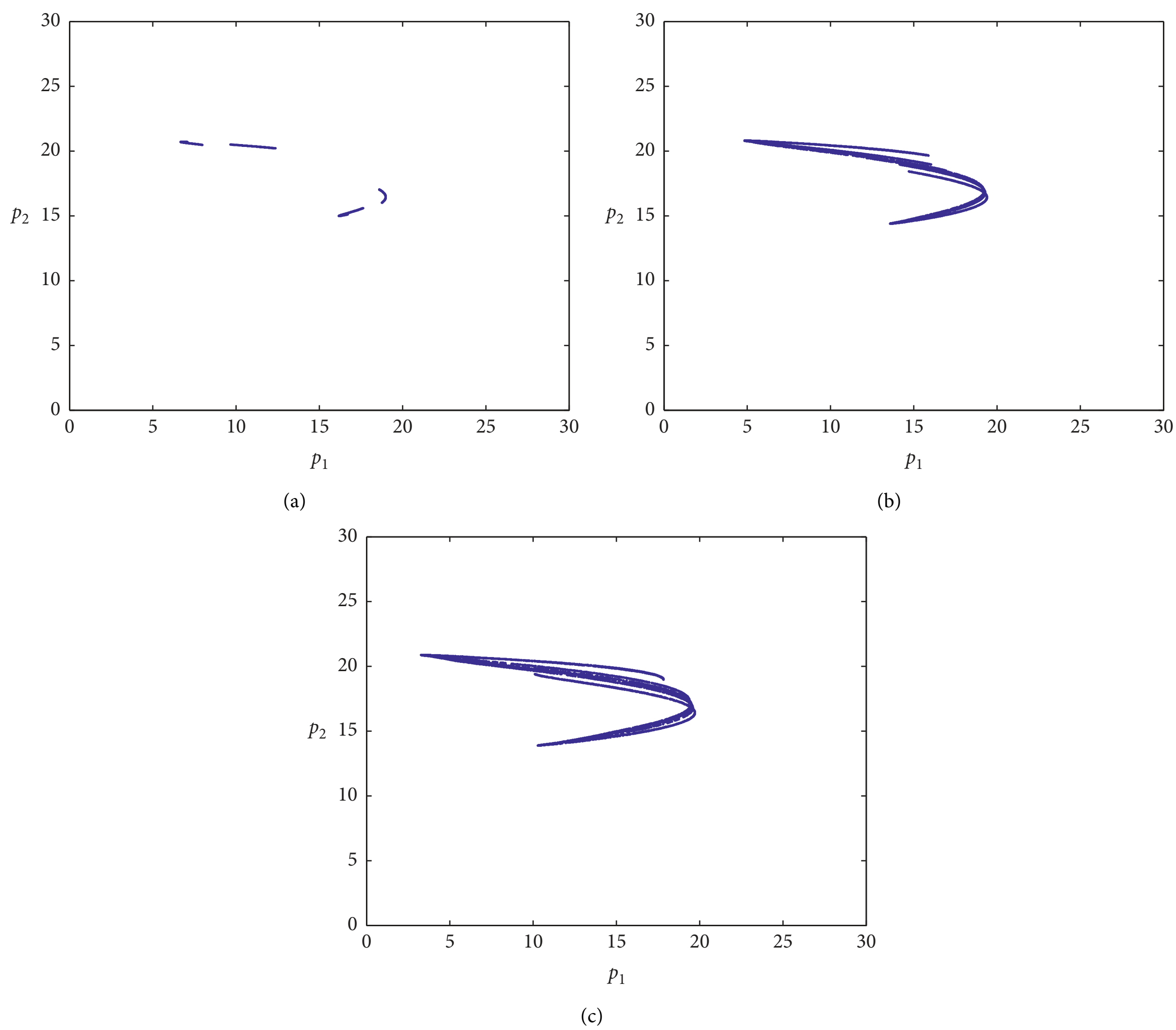


FIGURE 11: The chaotic attractor of dynamic system (15). (a) $\delta_1 = 0.027$. (b) $\delta_1 = 0.0285$. (c) $\delta_1 = 0.03$.

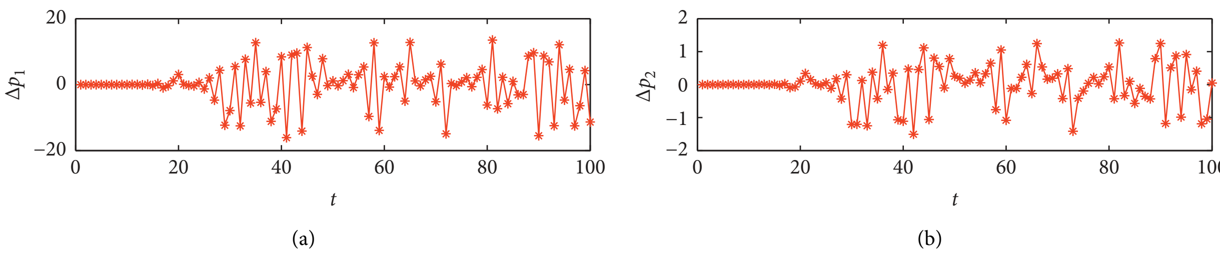


FIGURE 12: Sensitivity of dynamic system (15) to initial price values. (a) Δp_1. (b) Δp_2.

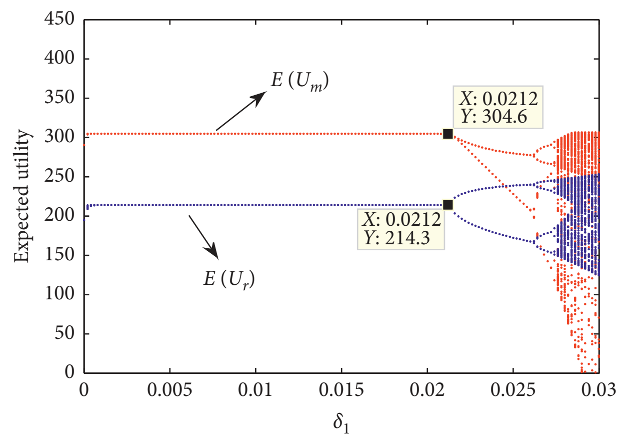


FIGURE 13: The expected utility of dynamic system (15) with δ_1 increasing.

5.2. The Effect of Chaos on the System Efficiency. Figure 13 shows the expected utility of dynamic system (15) and goes into the chaotic state with δ_1 increasing, which is similar to the price evolution process. Figure 14 shows the utility changing of participants over time. As $\delta_1 = 0.005$, the expected utility of the system is a fixed value with time; when $\delta_1 = 0.024$, the expected utility of the system changes periodically; when $\delta_1 = 0.029$, the expected utility fluctuates sharply in Figure 14(c). The expected utility of the system fluctuates in the doubling period and chaotic state, which makes it impossible for two firms to make the next decision according to the current expected utility. In the chaotic state, the expected utility of dynamic system (15) is difficult to measure.

In Figure 15, the red points denote the manufacturer's the expected average utility and the blue line indicates the retailer's expected average utility. With the increase of δ_1, it can be seen intuitively that the average utility of the manufacturer in the unstable state is significantly less than that in the stable state, which means that chaos destroys the effectiveness of the manufacturer; on the contrary, the average efficiency of the retailer in the unstable state is higher than that in the stable state. So, chaos is beneficial for the retailer to achieve high expected utility.

6. Chaos Control

The above research states clearly that the average utility of the manufacturer is higher than that in the stable state, and the one of the retailer is lower than that in the unstable state. In this uncertain situation, it brings great suffering to the participants in making the next price decision. If the chaos phenomenon is not controlled, it will lead to a vicious circle in the market and even lead to the withdrawal of participants from the market competition. In order to restore market stability, it is necessary to control the chaotic market effectively.

Some chaos control methods have been applied to the supply chain, such as modified straight-line stabilization method [39], time-delayed feedback method [40], OGY method [41], and the parameter adaptation method [42] In this section, the parameter adaptation method is adopted to control the market prices of participants. Based on dynamic system (15), the controlled system can be expressed as follows:

$$\begin{cases} p_1(t+1) = (1-\alpha)\delta_1 p_1(t)\left(G_1 + X_1 p_1 + \beta_1 p_2\right) + \alpha p_1(t), \\ p_2(t+1) = \delta_2 p_2(t)\left(G_2 + X_2 p_2 + X_3 p_1\right) + p_2(t). \end{cases} \tag{19}$$

Figures 16(a) and 16(b) show the dynamic process of control system (19) with the adjustment parameter δ_1 increasing when $\alpha = 0.1$ and $\alpha = 0.4$, respectively. It can be seen that controlled system (19) appears the first bifurcation at $\delta_1 = 0.024$ when $\alpha = 0.1$; and the first bifurcation of controlled system (19) is delayed again when $\alpha = 0.4$.

When $\delta_1 = 0.03$ and $\delta_2 = 0.005$, the market is in a chaotic state. As α increases, the game evolution of controlled system (19) is shown in Figure 17(a). When $\alpha = 0$, controlled system (19) is chaos; as $0 < \alpha \le 0.31$, controlled

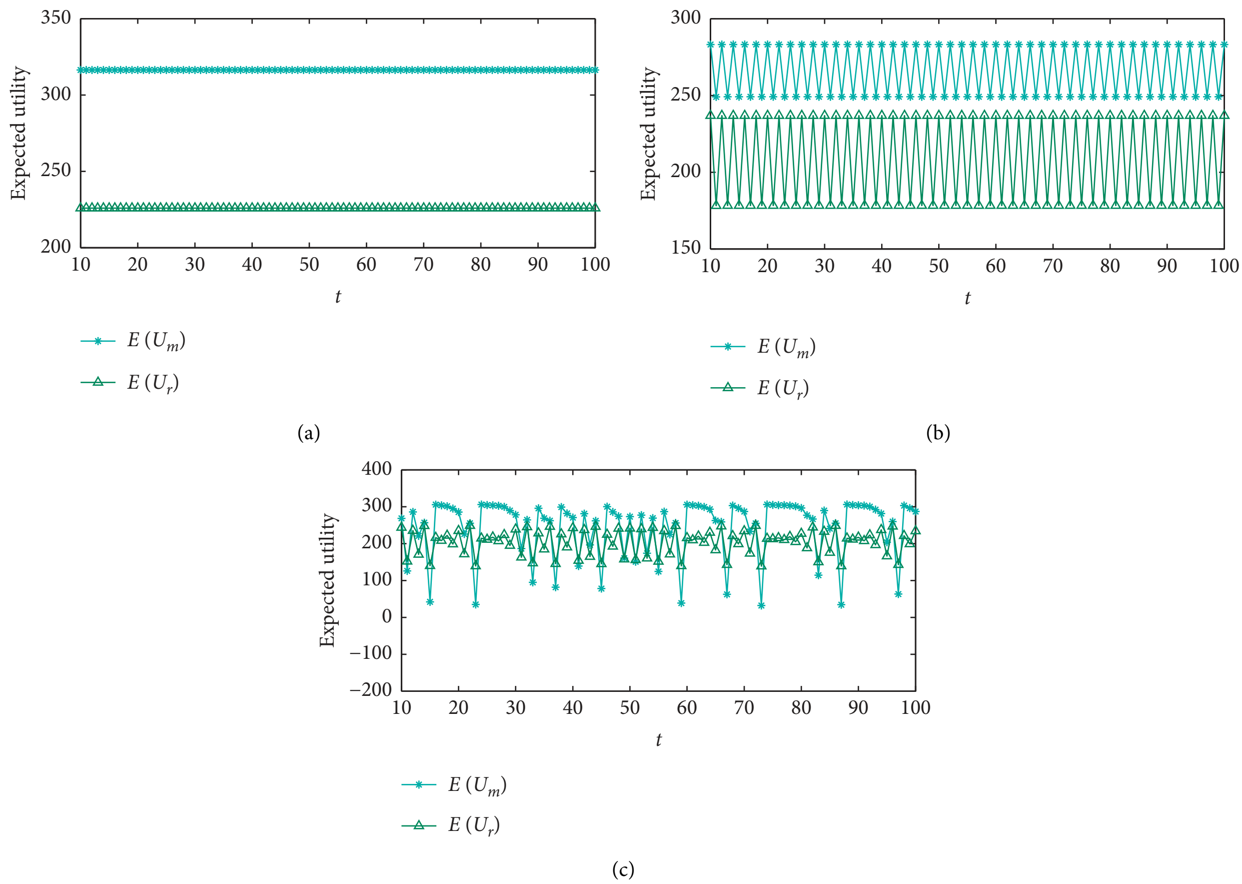


Figure 14: The evolution of expected utility over time in different periods. (a) $\delta_1 = 0.005$. (b) $\delta_1 = 0.024$. (c) $\delta_1 = 0.029$.

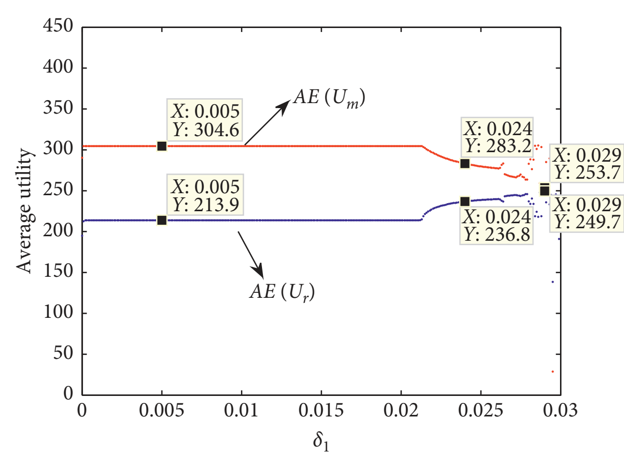


Figure 15: The average utility diagram with δ_1 varying.

system (19) gets rid of the chaotic state and enters a period-doubling bifurcation state; as $\alpha > 0.31$, the dynamic system is completely controlled in the stable period. Correspondingly, Figure 17(b) indicates the entropy of system (19); as $0 < \alpha \leq 0.31$, the entropy value is larger than one and system (19) is in the state of chaos and periodic doubling state; when $\alpha > 0.31$, the entropy value is equal to 0.5 or 0 and controlled system (19) is in the stable state.

In market competition, chaos has an important effect on the utility of participants. However, due to the market complexity and the difference of decision makers, the behavior of the decision makers may make the stable market into a bifurcation state or even chaotic state in pursuit of maximizing their utilities. At this time, it is necessary for participants to cooperate and coordinate to hold the system in a stable state, or for the government to

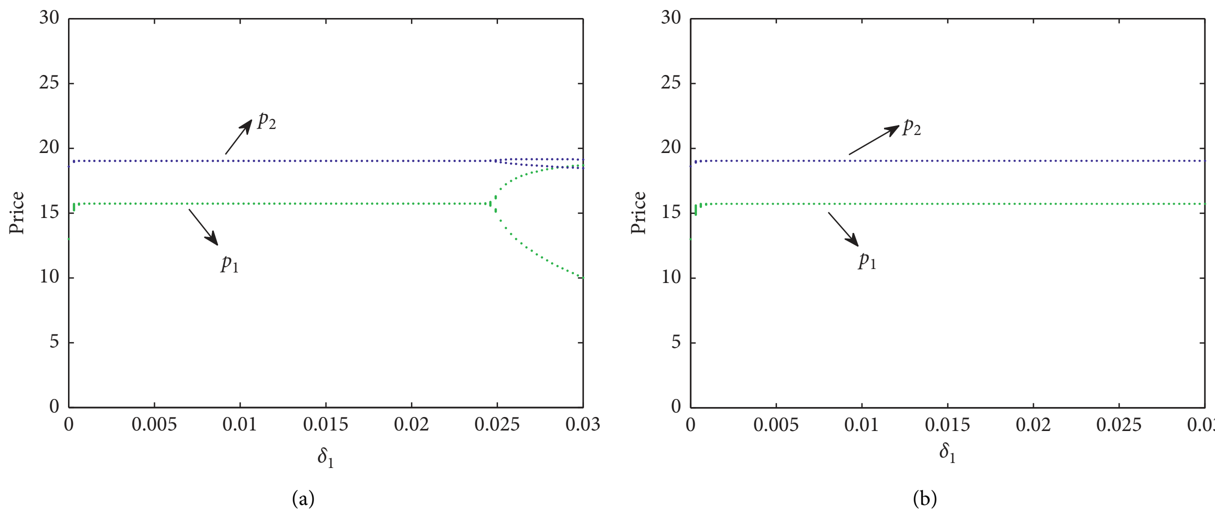


FIGURE 16: The bifurcation diagram of controlled system (19) with δ_1 varying. (a) $\alpha = 0.1$. (b) $\alpha = 0.4$.

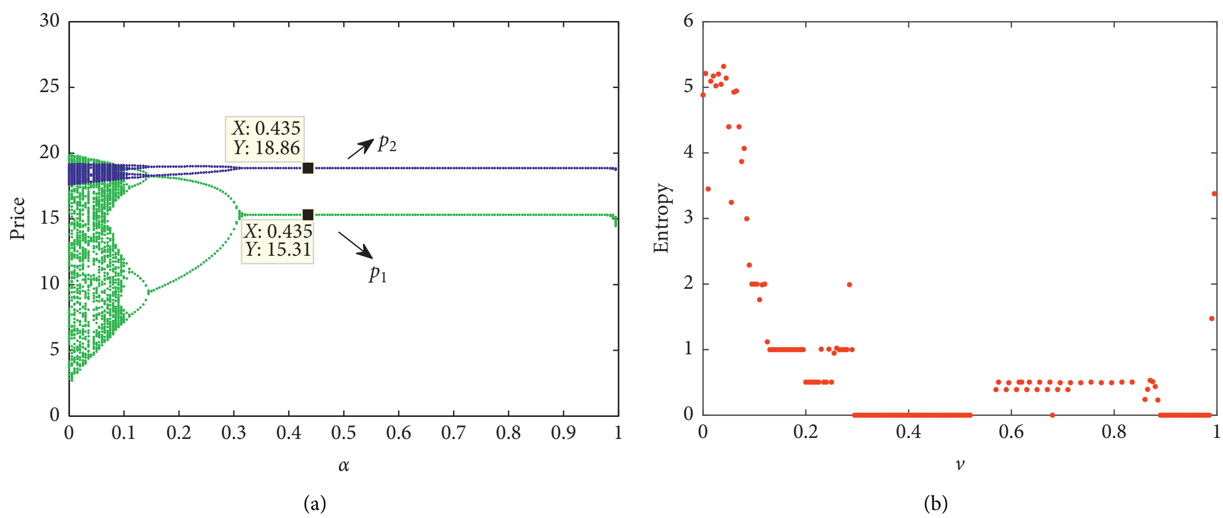


FIGURE 17: The price bifurcation diagram and entropy of controlled system (19) with α varying. (a) The price bifurcation diagram. (b) Entropy.

control the chaotic market and create a good market competition environment.

7. Conclusions

Considering the innovation input for green products and channel service, this article establishes a dynamic game model under the optimal innovation input and focuses on the influence of key factors on the pricing decisions and complexity of the dynamic system. Firstly, equilibrium points, conditions for existence, and local stability of the dynamic system are discussed. Secondly, the complexity dynamics of the dynamic system (the influence of parameters on prices, utilities, and global stability of the dynamic system) are studied by employing dynamic theory. Finally, the parameter adaptation method is employed to restrain chaos of the system. The results are summarized as follows:

(1) The stable range of the dynamic dual-channel green supply chain system enlarges with the increase of risk-aversion levels of participants, shrinks with service value increasing. In addition, the retailer's channel service will only decrease the stable scope of its own channel price adjustment speed and brings no influence on the manufacturer's decision range of channel price adjustment speed.

(2) The dynamic system experiences flip bifurcation and enters into chaos as the adjustment speed increasing. In stable range, the retail prices and the utilities of participants are fixed values, and the entropy value of the dynamic dual-channel green supply chain system is low. In the chaotic state, the average utility of the manufacturer declines and that of the retailer improves. The entropy value of the dynamic dual-channel green supply chain system is high. So, chaos

is beneficial for the retailer and is harmful to the manufacturer to achieve high expected utility.

(3) The attraction domain of initial prices shrinks with price adjustment speed increasing and enlarges with the channel service values increasing. The dynamic system, from chaos, can run to a stable state again using the parameter adaptation method.

There are some shortcomings in this paper, and we can study from the following aspects in the future: (1) one can consider the nonlinearity of market demand, which is more in line with the market competition environment. (2) One can consider the cost sharing of innovation input based on the cooperation of participants.

Appendix

Proof of Proposition 1. the Jacobian matrix of dynamic system (15) can be expressed as follows:

$$J(p_1, p_2) = \begin{pmatrix} 1 + \delta_1 (G_1 + 2X_1 p_1 + \beta_1 p_2) & \beta_1 \delta_1 p_1 \\ X_3 \delta_2 p_2 & 1 + \delta_2 (G_2 + 2X_2 p_2 + X_3 p_1) \end{pmatrix}. \tag{A.1}$$

Substituting the values of ρ_1 into the Jacobian matrix, the two eigenvalues of the Jacobian matrix of dynamic system (15) are $\lambda_1 = 1 + \delta_1 G_1$ and $\lambda_2 = 1 + \delta_2 G_2$. Because $G_1 > 0$ and $G_2 > 0$, we can verify that all the eigenvalues of the Jacobian matrix are more than 1, so ρ_1 is an unstable equilibrium point.

The proof of Proposition 2. substituting $\rho_2 = (0, -(G_2/X_2))$ and $\rho_3 = (-(G_1/X_1), 0)$ into the Jacobian matrix, the Jacobian matrix of dynamic system (15) can be expressed, respectively, as follows:

$$J(\rho_2) = \begin{pmatrix} 1 + \delta_1 \left(G_1 - \beta_1 \dfrac{G_2}{X_2} \right) & 0 \\ -\dfrac{X_3 \delta_2 G_2}{X_2} & 1 - \delta_2 G_2 \end{pmatrix},$$
$$J(\rho_3) = \begin{pmatrix} 1 - \delta_1 G_1 & -\dfrac{\beta_1 \delta_1 G_1}{X_1} \\ 0 & 1 + \delta_2 \left(G_2 - \dfrac{X_3 G_1}{X_1} \right) \end{pmatrix}. \tag{A.2}$$

The eigenvalues of the matrix $J(\rho_2)$ are $\lambda_1' = 1 - \delta_2 G_2$ and $\lambda_2' = 1 + \delta_1 G_1 - (\beta_1 G_2 \delta_1 / X_2)$. The eigenvalues of the matrix $J(\rho_3)$ are $\lambda_1'' = 1 - \delta_1 G_1$ and $\lambda_2'' = 1 + \delta_2 G_2 - (b_2 G_1 X_3 / X_1)$.

According to the previous restrictions on the parameters, it can deduce that $\lambda_1' < 1$, $\lambda_2' > 1$, $\lambda_1'' < 1$, and $\lambda_2'' > 1$. The eigenvalues of the Jacobian matrix $J(\rho_2)$ and $J(\rho_3)$ are not less than 1. So, ρ_2 and ρ_3 are unstable saddle points.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Li Qiuxiang provided research methods, Huang Yimin wrote the original draft, and Li Mengmeng revised the paper.

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