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Research Article

The Impacts of Fairness Concern and Different Business Objectives on the Complexity of Dual-Channel Value Chains

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This paper considers a Stackelberg game model in a dual-channel supply chain, which is composed of a manufacturer and a retailer. The manufacturer and retailer consider fairness concern in the market competition, and the manufacturer takes market share and profit as his/her business objectives. The entropy complexity and dynamic characteristic of the dual-channel system are analyzed through mathematical analysis and numerical simulation, such as local stability, bifurcation, entropy, and chaos. The results show that, with the increase of price adjustment speed, the dual-channel supply chain is more complex and falls into a chaotic state in which system entropy increases; the stability of the dual-channel supply chain will be robust with the increase of weight of market share and weaken with the increase of the fairness concern level of the manufacturer and retailer. The high level of fairness concern of the manufacturer and retailer is always disadvantageous to the leading manufacturer but not always bad for the follower retailer. The performance of the dual-channel supply chain is improved with a high level of the manufacturer's fairness concern and reduced with a high level of the retailer's fairness concern. We also find the retailer will gain more profits in the chaotic state than the stable state in the Stackelberg game model. The variable feedback control method is applied to control the chaos of the dual-channel supply chain, and choosing appropriate control parameters can make the dual-channel supply chain system return to the stable state from the chaotic state, or delay the system to enter the bifurcation state. The research results can provide a guideline for enterprise decision-making.

1. Introduction

Nowadays, with the development of the e-ecommerce in China, many manufacturers or retailers establish online direct channels which make market competition become more and more tough and complex for participators. Therefore, choosing the proper sales strategies is vital to achieve business objectives for the players.

Firms are mainly concerned with different business objectives, such as maximizing revenues, market shares, sales, or even customer satisfaction [1, 2]. The previous literature assumed the decision-making only caring about profit maximization was an oversimplification view. In practice, a number of decision-makers not only concern on profit but also pay attention to extending the whole market share as can as possible, especially in the oligarchic competitive market.

Business objectives, including profitability, market share, and revenues, have been discussed by many scholars. Tadic et al. [3] studied the effectiveness of business objectives and key performance indicators (KPIs) of the identified business objectives for different types of enterprises. Lohrmann and Reichert [4] developed and shortly evaluated a refined business objective modeling approach. Doyle [5] studied business objectives and explored the approach to measure performance. Keil et al. [6] introduced the impact of business objectives on the pricing behavior.

In addition, some researchers have concentrated on studying profitability and market share. Bell et al. [7] justified that the market share equals marketing efforts divided by the total marketing effort under some assumptions. Szymanski et al. [8] pointed out that market share has a positive effect on business profitability by performing a meta-analysis on 276 market share-profitability findings. Jansen et al. [9] considered a two-stage market share delegation game with two competing firms and believed that if the firm owners choose to hire a manger, then the remuneration of the manager is weighted based on profits and sales or market share. The market share also has been studied extensively in the context of customer satisfaction and relative performance, respectively [10, 11]. Bischi and Kopel [12] established a bridge between gradient dynamics and market share and introduced a dynamic market share model where agents were bounded rational. Li and Ma [13] considered a dual-channel game model with bounded rationality and assumed retailers have different business objectives, and the dynamic behaviors of the system are investigated by numerical simulation. As far as we are concerned, there is no sufficient literature that explored the market share in dynamic scenarios in the dual-channel supply chain.

The researches in recent years focus on the behavior of the decision-maker in market competition. Fairness concern is widely studied by many scholars about the influence on the price decision-making and channel coordination in the supply chain. The fairness is modeled as inequity aversion such that the retailer is willing to give up some monetary payoff to move in the direction of more equitable outcomes. Cui et al. [14] showed that when fairness is concerned by the supply chain members, the manufacturer tends to make simple wholesale price contract to coordinate the supply chain rather than the elaborate one. Du et al. [15] studied how the retailer's fairness concern behaviors influence the coordination of the supply chain. Pavlov and Katok [16] analyzed the fairness concerns with the context of incomplete information and showed fairness would lower the efficiency of the supply chain. Zhang and Ma [17] considered two different pricing policies in a dual-channel supply chain with a fair caring retailer and found that the excessive fairness concern is not always benefit to the retailer. Chen et al. [18] modeled a Stackelberg game model to study the horizontal fairness concern influence on the backup supplier, and Qin [19] showed the fairness concerns of the supplier and retailer cannot change the coordination status of the supply chain in his paper. Tang et al. [20] established two pricing models to study the retailer's fairness concern in a closed-loop supply chain; the result showed that the system profit in a decentralized decision-making situation is less than that in a centralized decision-making situation. Ma et al. [21] investigated closed-loop supply chains under both the centralized and decentralized closed-loop supply chains and furnished the optimal marketing effort, collection rate, and pricing decisions for the supply chain members. Lin and Qin [22] compared the pricing strategies and profits in a two-level supply chain based on absolute fairness concern and relative fairness concern of the retailer. Li et al. [23] studied the impact of the manufacturer's fairness concern on cooperative advertising and analyzed equilibrium problems with retailer services as well as fairness concern in the dual-channel supply chain. Q. H. Li and B. Li [24] developed a game model assuming the private fairness concern is fuzzy and obtained the estimation model by fuzzy theory. Yang and Sun [25] considered the effect of fairness concern in a closed-loop supply chain under two situations and found the result that a fair caring manufacturer or retailer would get more supply chain profits. Qin et al. [26] studied the dynamic evolution of fair preference under the demand of exponential function and pointed out the retailer utility and supply chain utility are increasing with fairness in exponential demand. Sharma et al. [27] developed a behavioral model of fairness in a two-echelon supply chain and found that the supply chain under the channel member's fairness concerns can be coordinated through option contract under certain conditions on the pricing parameters. Zheng et al. [28] investigated the optimal decisions and profits of closed-loop supply chains giving the retailer's distributional fairness concerns and focused on how to allocate maximum profit in a centralized setting. Zhang et al. [29] developed a supply chain system which includes one manufacturer and one retailer and studied how consumer environmental awareness and retailer's fairness concerns affected environmental quality, wholesale price, and retail price of the green product.

According to the research of behavior tendency, people pay attention to the fairness of income distribution quarterly in real life [30]. When the retailers such as Jing Dong, Tmall, and Uniqlo cooperate with their manufacturers, they are very concerned about the fairness of profits. However, few papers discussed the effect of fairness concern and different business objectives simultaneously on the dual-channel supply chain as well as analyzed the dynamic behavior of the complex system.

Complexity generates unpredictability in supply chain behavior, affects customer satisfaction, and increases cost. Relevant literature research attempted to use the optimizing strategy and entropy to enhance the supply chain performance in the system. Martínez-Olvera [31] proposed an entropy-based formulation for comparing different information sharing approaches in a supply chain environment and validated the usefulness of the proposed methodology. Mavi et al. [32] analyzed the problem of supplier selection in the context of supply chain risk management using Shannon entropy for weighing criteria. Raj and Lakshminarayanan [33] aimed to improve supply chain performance through entropy calculations. Qu and Hao [34] established the entropy model of the fractal supply chain network organization structure and showed that the fractal structure had prominent effect of dropping entropy. Meng-Gang et al. [35] built an entropy information diffusion theory model for agricultural flood and drought risk assessment. Zuo and Kajikawa [36] proposed a quantitative metric of entropy to measure the complexity and robustness of supply networks. In order to cope with complex combinatorial problems, Wang et al. [37] developed a cross-entropy algorithm for the first time in closed-loop supply chain design and planning. Kriheli and Levner [38] analyzed the complexity between the supply chain components under uncertainty using the information entropy. Levner and Ptuskin [39] presented the entropy-based optimization model for reducing the supply chain model size and assessing the economic loss. Some scholars analyzed the complexity of supply chain-based entropy theory [40, 41]. Lou et al. [42] analyzed the bullwhip effect in the supply chain with the sales game and consumer returns via the theory of entropy and complexity.

In this paper, a Stackelberg game model is established based on the manufacturer and retailer considering fairness concern and different business objectives. The features of the system are studied via nonlinear theory and entropy theory and investigated by numerical simulations, such as the stable domain, bifurcation, Lyapunov exponent, and entropy. Three-dimensional triangular meshes are carried out to describe the fluctuation of profits and average profits of the system.

This paper is organized as follows: Model assumptions and construction are presented in Section 2. Section 3 mainly analyzes the Stackelberg game model. The dynamic characteristics of the Stackelberg game model are presented in Section 4. Chaos control for the Stackelberg game model is made in Section 5. Section 6 presents the conclusion.

2. Model Assumptions and Construction

This paper considers a manufacturer and a retailer in a two-echelon supply chain; the manufacturer produces a single product and distributes the product though the online direct channel which is built by himself/herself and a traditional retailer channel in which the traditional retailer sells the product via his/her own traditional channel. It means customers not only can purchase the product in the traditional channel but also can buy in the online direct channel.

2.1. Model Assumptions. In order to make this study more realistic, we make the following assumptions:

(1) The manufacturer and the retailer sell the same products from two different channels on the basis of price competition, and the marginal cost of the product is c.

(2) The manufacturer and the retailer can only obtain part of market information and have limited rationality in decision-making [43].

(3) Both manufacturer and the retailer consider fairness concern in the market competition [25].

(4) The retailer only considers the objective of profit maximization, while the manufacturer not only considers the goal of profit maximization but also considers the market share goal under the price strategy [13].

2.2. Model Construction. Based on the previous assumptions and related research [13], the market demands of the manufacturer and the retailer are shown as follows:

$$\begin{cases} D_r = \alpha\theta - b_1 p_r + k p_m, \\ D_m = \alpha(1-\theta) - b_2 p_m + k p_r, \end{cases} \tag{1}$$

where α denotes the potential market size, $\theta(0<\theta<1)$ means the degree of customer loyalty to the traditional channel, and $\alpha\theta$ represents the number of customers preferring the traditional retailer channel, while $\alpha(1-\theta)$ represents the number of customers preferring the online direct channel. b_1 and b_2 are the price elasticity coefficients of customer demands in different channels. The cross-price sensitivity of the manufacturer and retailer is the same and represented by k, $b_1 > k$, $b_2 > k$.

Furthermore, the profit functions of the manufacturer and retailer can be written as follows:

$$\begin{cases} \pi_r = (p_r - w) D_r, \\ \pi_m = D_m (p_m - c) + D_r (w - c). \end{cases} \tag{2}$$

Both the manufacturer and the retailer have fairness concern behavior on the profits gained of their own in the market. According to the literature [14], the retailer's utility function can be described as follows:

$$\begin{aligned} U(w, p) &= \pi(w, p) + f_r(w, p), \\ f_r(w, p) &= -\alpha \max(\gamma\Pi(w, p) - \pi(w, p), 0) \\ &\quad - \beta \max(\pi(w, p) - \gamma\Pi(w, p), 0), \end{aligned} \tag{3}$$

where $\Pi(w, p)$ and $\pi(w, p)$ denote the monetary payoff of the manufacturer and retailer, respectively, and α and β represent the sensitivity coefficient of difference in payoff between $\gamma\Pi(w, p)$ and $\pi(w, p)$. The retailer's fairness feeling depends on the comparison of relative profit of the manufacturer and retailer.

Du et al. [15] also give the retailer's utility function as

$$U_r = \pi_r - \lambda(\pi_m - \pi_r), \tag{4}$$

where π_m and π_r are the profits of the manufacturer and the retailer; the sensitive coefficients about profit and loss are the same and denoted by λ. The fair caring depends on the comparison of the absolute profit between the manufacturer and the retailer; the utility of the manufacturer and the retailer will change if there exists difference in both sides' profits and relative profits.

From the above conditions, the utility functions of the manufacturer and retailer in this paper are as follows:

$$\begin{cases} u_r = \pi_r - \lambda_1(\pi_{md} - \pi_r), \\ u_m = \mu\pi_m + (1-\mu)L_m - \lambda_2(\pi_r - \gamma\pi_{md}), \end{cases} \tag{5}$$

where λ_1 is the fairness concern coefficient of the retailer and λ_2 is the fairness concern coefficient of the manufacturer $(0<\lambda_1<1, 0<\lambda_2<1)$, π_{md} is the manufacturer's profit which is gained from the traditional retailer channel, and $\mu \in (0, 1)$ denotes the manufacturer's balance coefficient between profits and market share; the market share of the manufacturer is as follows:

$$L_m = \frac{D_m p_m}{D_m p_m + D_r p_r}. \tag{6}$$

Let $e_1 = D_m p_m$ and $e_2 = D_r p_r$, then taking the partial derivative of L_m with respect to e_1 yields

$$\frac{\partial L_m}{\partial e_1} = \frac{e_2}{(e_1 + e_2)^2} > 0. \tag{7}$$

Then, the change trends of sales revenue are the same as the market share; this paper uses sales revenue to replace the proportion of market share [8, 14].

3. The Stackelberg Model

In the market competition, the manufacturer is more powerful than the retailer in the dual-channel supply chain. Therefore, we consider that the manufacturer is a game leader, the retailer is the follower, and the game equilibrium is called the Stackelberg equilibrium. In the game model, the manufacturer firstly makes decisions for his/her wholesale price (w) and online direct sale price (p_m), and then the retailer makes the price decision (p_r) on the basis of the manufacturer's decision-making.

3.1. Single Period Game Model

3.1.1. The Retailer's Decision. The retailer's best response can be obtained via setting the wholesale price w and sale price p_m as fixed values, making the first derivative of u_r about p_r as

$$\frac{\partial u_r}{\partial p_r} = a\theta(\lambda_1+1) + b_1(-c\lambda_1 - 2(\lambda_1+1)p_r + 2\lambda_1 w + w) + k(\lambda_1+1)p_m. \tag{8}$$

The second derivative of the retailer's utility function is $(\partial^2 u_r/\partial p_r^2) = -2b_1(\lambda_1+1) < 0$, and the retailer can get global optimal solutions. Letting $(\partial u_r/\partial p_r) = 0$, the retailer's best reply function is obtained as follows:

$$p_r^*(w, p_m) = \frac{a\theta(\lambda_1+1) - b_1 c\lambda_1 + (2b_1\lambda_1 + b_1)w + k(\lambda_1+1)p_m}{2b_1(\lambda_1+1)}. \tag{9}$$

Then, we calculate the first-order partial derivatives of $p_r^*(w, p_m)$ with respect to w and p_m, which can examine the influence of w and p_m on the retailer's best price strategy:

$$\frac{\partial p_r^*}{\partial w} = \frac{1+2\lambda_1}{2+2\lambda_1} > \frac{1}{2}, \qquad 0 < \frac{\partial p_r^*}{\partial p_m} = \frac{k}{2b_1} < \frac{1}{2}. \tag{10}$$

From above inequality equations, we know that the retailer's optimal price increases with the increasing w and p_m, respectively. Therefore, the price strategy of the retailer will be controlled by the manufacturer's price decision-making. If w increases by one unit, p_r^* would increase more than 0.5 units; when p_m increases by one unit, p_r^* would increase less than 0.5 units.

Substituting formula (9) into u_r of formula (5), we obtain the retailer's optimal utility u_r^* which is represented by w and p_m.

3.1.2. The Manufacturer's Decision. Substituting formula (9) into u_m of formula (4), we obtain the manufacturer's optimal utility $u_m^*(w, p_m)$ which is a function with respect to w and p_m. We take the first-order partial derivatives of $u_m^*(w, p_m)$ with respect to w and p_m, respectively, and obtain the following equations:

$$\begin{aligned}\frac{\partial u_m^*}{\partial w} &= \frac{1}{2(1+\lambda_1)^2}\left[a\theta(1+\lambda_1)^2(\lambda_2+\gamma\lambda_2+\mu)\right] + A_0 + A_1,\\ \frac{\partial u_m^*}{\partial p_m} &= -\frac{1}{2(1+\lambda_1)^2}\left\{k^2(1+\lambda_1)\left[p_m(-2+\lambda_2)+c\mu\right]\right\} + A_2 + A_3 + A_4,\end{aligned} \tag{11}$$

where

$$\begin{aligned}A_0 &= b_1\{w(2\lambda_1+1)[2\gamma\lambda_2(\lambda_1+1)+\lambda_2+2\mu(\lambda_1+1)] - c\left[\gamma\lambda_2(3\lambda_1^2+4\lambda_1+1) - \lambda_1^2(\lambda_2-3\mu)+4\lambda_1\mu+\mu\right]\},\\ A_1 &= k(\lambda_1+1)\{p_m[\lambda_1(\gamma\lambda_2+\lambda_2+\mu+2)+\gamma\lambda_2+\lambda_2+\mu+1] - c\mu(2\lambda_1+1)\},\\ A_2 &= a(1+\lambda_1)[2b_1(\theta-1)+k\theta(\lambda_2-1)],\\ A_3 &= -2b_2(1+\lambda_1)(2p_m-c\mu) - ck[\gamma\lambda_2+\mu+\lambda_1(1+\gamma\lambda_2+\mu)],\\ A_4 &= w[\lambda_1(\gamma\lambda_2+\lambda_2+\mu+2)+\gamma\lambda_2+\lambda_2+\mu+1].\end{aligned} \tag{12}$$

When the second-order derivative of the manufacturer's utility function is concave, the manufacturer can get global optimal solutions. The Hessian matrix of u_m is as follows:

$$H(u_m) = \begin{bmatrix} -\dfrac{b_1(2\lambda_1+1)([[2\gamma(\lambda_1+1)+1]+2(\lambda_1+1)\mu]}{2(\lambda_1+1)^2} & \dfrac{k[\lambda_1(\gamma\lambda_2+\lambda_2+\mu+2)+\gamma\lambda_2+\lambda_2+\mu+1]}{2(\lambda_1+1)} \\ \dfrac{k[\lambda_1(\gamma\lambda_2+\lambda_2+\mu+2)+\gamma\lambda_2+\lambda_2+\mu+1]}{2(\lambda_1+1)} & -\dfrac{4b_1b_2+k^2(\lambda_2-2)}{2b_1} \end{bmatrix}. \tag{13}$$

Obviously, the first-order principal minor of the Hessian matrix $H(u_m)$ is

$$H(u_m) = -\frac{b_1(2\lambda_1+1)\{\lambda_2[2\gamma(\lambda_1+1)+1]+2\mu(\lambda_1+1)\}}{2(\lambda_1+1)^2} < 0, \tag{14}$$

where $b_1 = ((k^2\{(\lambda_1[(\gamma\lambda_2+\lambda_2+\mu+2)+\gamma\lambda_2+\lambda_2+\mu+1]\}^2 + A_5)/(4b_2(2\lambda_1+1)A_6))$, in which

$$\begin{aligned}A_5 &= (2\lambda_1+1)(2-\lambda_2)[2\gamma\lambda_2(\lambda_1+1)+1]+2\mu\lambda_2(\lambda_1+1),\\ A_6 &= \lambda_2+2(\mu+\gamma\lambda_2)(\lambda_1+1).\end{aligned} \tag{15}$$

Then, the second-order principal minor is bigger than zero, and $H(u_m)$ is negative definite which indicates the manufacturer can reach the maximum value when making decisions. By solving $((\partial u_m^*)/\partial w) = 0$ and $((\partial u_m^*)/\partial p_m) = 0$, the manufacturer's best reply function (w^*, p_m^*) can be obtained.

Because of the complexity of the model, the expressions of w^*, p_m^*, and p_r^* are very complex, and we cannot see the interaction between variables and parameters. In the next section, in order to analyze and study the stability of the dynamic game model by numerical simulation, we assign parameters according to the actual operation of the market.

3.2. Dynamic Stackelberg Game Model

3.2.1. Model Construction. In this section, a dynamic Stackelberg game model is proposed. As a matter of fact, firms in the real market usually obtain limited information due to the objective condition restriction, and it indicates that decision-makers cannot get the whole market information and the system is not always in the Nash equilibrium state. In order to achieve maximum profit in every competition period, the manufacturer adopts bounded rational expectation and the myopic adjustment mechanism to adjust price decisions dynamically based on partial estimation of the marginal utility of the current period; if the marginal utility in the current period is positive, the manufacturer will raise his/her price in the next period; otherwise, the manufacturer will reduce his/her price in the next period.

The dynamic model can be described as follows:

$$\begin{cases} w(t+1) = w(t) + \alpha_1 w(t) \dfrac{\partial u_m^*(t)}{\partial w(t)}, \\ \\ p_m(t+1) = p_m(t) + \alpha_2 p_m(t) \dfrac{\partial u_m^*(t)}{\partial p_m(t)}, \end{cases} \quad (16)$$

where $\alpha_i > 0$ $(i = 1, 2)$ represent the price adjustment speed of the manufacturer according to his/her marginal profits, which reflect the manufacturer's learning behavior and active managerial behavior.

Then, we can establish the discrete dynamic game model of the dual-channel supply chain considering fairness concern and different business objectives as follows:

$$\begin{cases} w(t+1) = w(t) + \alpha_1 w(t) \left\{ \dfrac{1}{2(1+\lambda_1)^2} \left[a\theta (1+\lambda_1)^2 (\lambda_2 + \gamma\lambda_2 + \mu) \right] + A_0 + A_1 \right\}, \\ \\ p_m(t+1) = p_m(t) + \alpha_2 p_m(t) \left\{ -\dfrac{1}{2(1+\lambda 1)} \left[k^2 (1+\lambda_1) \left[p_m(-2+\lambda_2) + c\mu \right] \right] + A_2 + A_3 + A_4 \right\}, \\ \\ p_r^*(t) = \dfrac{a\theta\lambda_1 + a\theta - b_1 c\lambda_1 + 2b_1\lambda_1 w(t) + b_1 w(t) + k\lambda_1 p_m(t) + k p_m(t)}{2b_1(\lambda_1+1)}. \end{cases} \quad (17)$$

The manufacturer's price strategy is described by the dynamic system (17), and the retailer's price is directly related to $w(t)$ and $p_m(t)$. The parameters α_1 and α_2 have a great impact on $w(t)$ and $p_m(t)$.

3.2.2. Model Analysis. Firstly, making $w(t) = w(t+1)$ and $p_m(t) = p_m(t+1)$, we can get four equilibrium solutions of the dynamic system (17):

$$\begin{aligned} E_1 &= (0, 0), \\ E_2 &= \left(0, \frac{a(\lambda_1+1)[2b_1(\theta-1) + \theta k(\lambda_2-1)] + A_7}{(\lambda_1+1)[k^2(2-\lambda_1) - 4b_1b_2]} \right), \\ E_3 &= \left(\frac{A_8 + A_9}{b_1(2\lambda_1+1)\{\lambda_2[2\gamma(\lambda_1+1)+1] + 2\mu(\lambda_1+1)\}}, 0 \right), \\ E_4 &= (w^*, p_m^*), \end{aligned} \quad (18)$$

where

$$\begin{aligned} A_7 &= c\{b_1[k(\gamma\lambda_1\lambda_2 + \gamma\lambda_2 + \lambda_1\mu + \lambda_1 + \mu) - 2b_2(\lambda_1+1)\mu] \\ &\quad + \mu k^2(\lambda_1+1)\}, \\ A_8 &= (\lambda_1+1)[a\theta(\lambda_1+1)(\gamma\lambda_2 + \lambda_2 + \mu) - ck\mu(2\lambda_1+1)], \\ A_9 &= b_1 c\big(\gamma(3\lambda_1^2 + 4\lambda_1 + 1)\lambda_2 + \lambda_1^2[(3\mu - \lambda_2) + 4\lambda_1\mu + \mu\big]. \end{aligned} \quad (19)$$

Then, we can get the retailer's equilibrium prices as $p_r^{E_1}$, $p_r^{E_2}$, $p_r^{E_3}$, and $p_r^{E_4} = p_r^*$.

Obviously, E_1, E_2, and E_3 are boundary unstable equilibrium solutions because they are partly or entirely zero, and the decision variables obviously are not allowed to be zero in economics for decision-makers. In contrast, E_4 is the unique Stackelberg equilibrium solution. It is meaningless to study the unstable equilibrium solution, so we only analyze the characteristic of the Nash equilibrium solution in the following section.

3.2.3. Stability of the Nash Equilibrium Solution. The Jacobian matrix of the dynamic system (17) is given as

$$J = \begin{bmatrix} 1 + \alpha_1 f_1 & \dfrac{\alpha_1 w\{k[\lambda_1(\gamma\lambda_2 + \lambda_2 + \mu + 2) + \gamma\lambda_2 + \lambda_2 + \mu + 1]\}}{2(\lambda_1 + 1)} \\ \dfrac{\alpha_2 w\{k[\lambda_1(\gamma\lambda_2 + \lambda_2 + \mu + 2) + \gamma\lambda_2 + \lambda_2 + \mu + 1]\}}{2(\lambda_1 + 1)} & 1 + \alpha_2 f_2 \end{bmatrix}, \quad (20)$$

where

$$\begin{aligned} f_1 &= \frac{1}{2(1+\lambda_1)^2}\left[a\theta(1+\lambda_1)^2(\lambda_2 + \gamma\lambda_2 + \mu)\right] + A_{10} + A_1, \\ f_2 &= -\frac{1}{2(1+\lambda 1)}\left\{k^2(1+\lambda_1)[2p_m(-2+\lambda_2) + c\mu]\right\} + A_2 \\ &\quad + A_{11} + A_4, \\ A_{10} &= 2b_1 w(2\lambda_1 + 1)\{\lambda_2[2\gamma(\lambda_1 + 1) + 1] + 2\mu(\lambda_1 + 1)\} \\ &\quad - cb_1\left[\gamma\left(3\lambda_1^2 + 4\lambda_1 + 1\right)\lambda_2 + \lambda_1^2(3\mu - \lambda_2) + 4\lambda_1\mu + \mu\right], \\ A_{11} &= -2b_2(1+\lambda_1)(4p_m - c\mu) - ck[\gamma\lambda_2 + \mu \\ &\quad + \lambda_1(1 + \gamma\lambda_2 + \mu)]. \end{aligned} \quad (21)$$

The characteristic polynomial of the Jacobian matrix (20) is taken as follows:

$$F(\lambda) = \lambda^2 - B_0\lambda + B_1. \quad (22)$$

According to Jury's conditions, the necessary and sufficient condition of asymptotic stability of the system is that all the eigenvalues are inside the unit circle in the complex plane, so the stability of the dynamic system (17) should satisfy the following Jury's conditions:

$$\begin{cases} F(1) = 1 + B_0 + B_1 > 0, \\ F(-1) = 1 - B_0 + B_1 > 0, \\ F(0) = 1 - B_1 > 0, \end{cases} \quad (23)$$

where B_0 and B_1 are the trace and determinant of the Jacobian matrix, respectively. According to condition (23), we can give the stable region of the dynamic system (17) on the adjustment parameters α_1 and α_2. Because the stable condition of the dynamic system (17) is too complicated, we will analyze the stable region and dynamic characteristic of the dynamic system (17) by numerical simulation in the next section.

4. Numerical Simulation

In this section, numerical simulations are carried out to show the influence of parameters on the dynamic characteristic of the dynamic system (17) via bifurcation diagrams, entropy diagrams, largest Lyapunov exponents (LLEs), chaotic attractors, and so on.

Here, we assign values to parameters according to the actual operation of the market in order to facilitate analysis: $a = 100$, $\theta = 0.6$, $b_1 = 2$, $b_2 = 1$, $k = 0.5$, $\gamma = 0.6$, and $c = 10$.

4.1. Stability of the Dynamic System (17)

4.1.1. The Influence of Parameters μ, λ_1, and λ_2 on the Stable Region. Figure 1 clearly presents the influence of the balance coefficient of business objectives on the system stability. When fixing $\lambda_1 = \lambda_2 = 0.2$, the stable region of the dynamic system (17) is the area enclosed by the red line with $\mu = 0.9$, the blue line with $\mu = 0.6$, and the green line with $\mu = 0.4$. It is easy to understand that market share, as one of the business objectives of the manufacturer, has significant impact on the stability of the dynamic system (17), and the stable region of the dynamic system (17) is decreasing with increasing μ. Namely, with the increase of the weight of market share in business objectives, the stable range of the price adjustment speed (α_1, α_2) is extended, which indicates the manufacturer considering market share as part of business objectives makes the market competition more intense.

Fixing $\mu = 0.6$ *an d* $\lambda_2 = 0.2$, Figure 2(a) shows that the stable regions of system (17) are the areas enclosed by the blue line, green line, and red line when $\lambda_1 = 0.2$, 0.5, and 0.9, respectively. Similarly, when $\mu = 0.6$ and $\lambda_1 = 0.2$ are fixed, Figure 2(b) shows the stable regions of the dynamic system (17) are the areas enclosed by the blue line, green line, and red line, respectively, with $\lambda_2 = 0.2$, 0.5, and 0.9. We can see that, with the increasing level of fairness concern, the stable regions of the dynamic system (17) will decrease. The stable scope of α_1 is greatly influenced with increasing λ_2 than with increasing λ_1, and the stable scope of α_2 is less affected by the change of λ_1 and λ_2, which means that the influence of the manufacturer's fairness concerns on the scope of wholesale price adjustment is greater than that of the retailer's fairness concern behavior and the scope of online price adjustment is less affected by the fairness concern behavior of the manufacturer and the retailer.

4.2. The Entropy Complexity Analysis of the Dynamic System (17) with Changing α_2. We know that entropy can measure the chaotic degree of the system, so it is not difficult to find that the entropy of the system is small when the system is in the stable state and the entropy of the system is large when the system is in the chaotic state. On the contrary, the entropy of the system shows the probability of the occurrence of some particular information; when the entropy of

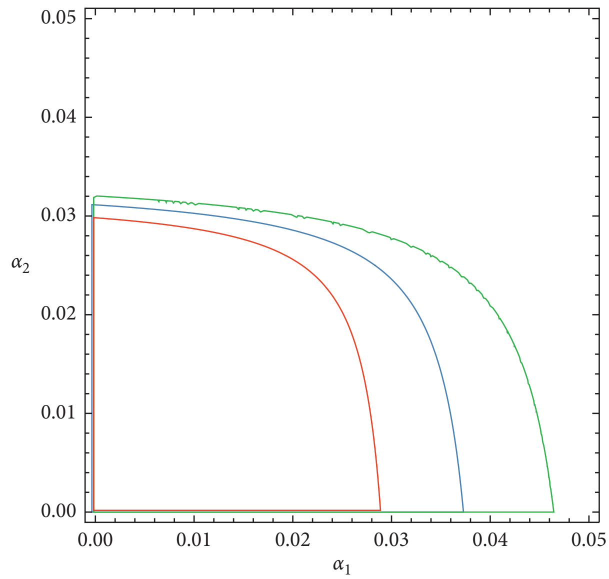


Figure 1: Stable regions of system (17) with different values of μ.

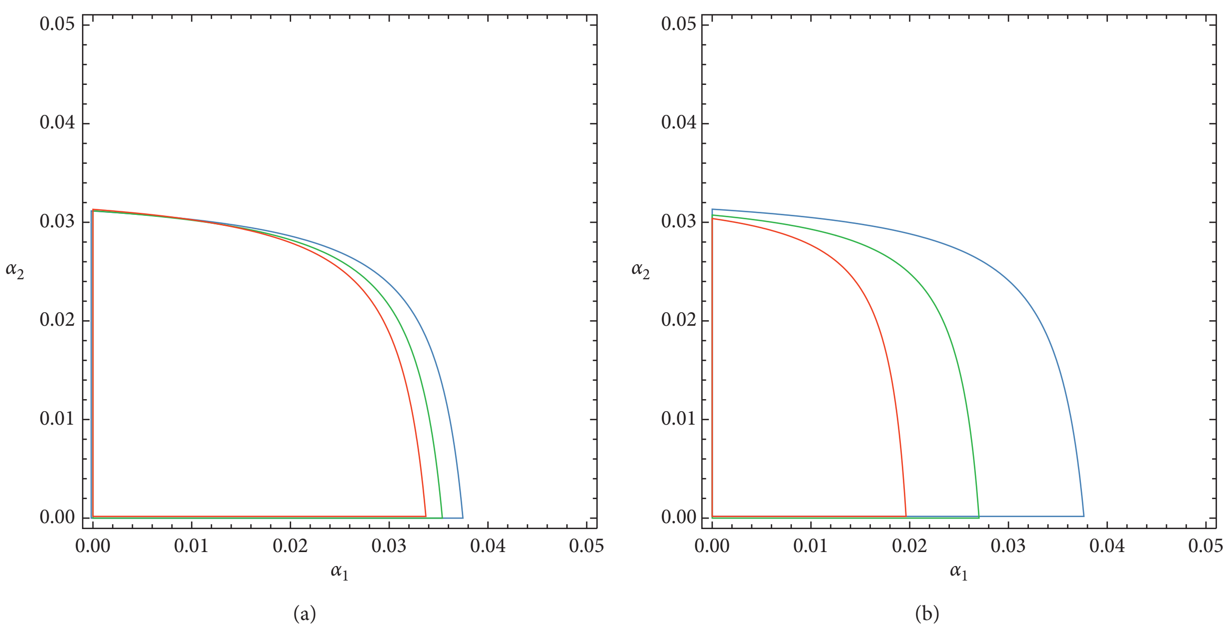


Figure 2: Stable regions of system (17) with different values of (a) λ_1 and (b) λ_2.

the system is high, we need more information to make the system clear. In order to better study the influence of parameters on system stability, we use an entropy graph to show the change of the system's stability.

Figure 3 presents the dynamic evolution process of the dynamic system (17) with $\alpha_1 = 0.02$. From Figure 3(a), we can see that the dynamic system (17) is in the stable state at first, with increasing α_2, and the dynamic system (17) has the first bifurcation at $\alpha_2 = 0.028$ and then falls into chaos finally through a series of period doubling bifurcations. Figure 3(b) is the diagram of the LLE which can reflect the state of the dynamic system (17), and Figure 4 shows the entropy of the dynamic system (17) with $\alpha_1 = 0.02$. We can see from Figures 3 and 4 that when the LLE is negative, the dynamic system (17) remains stable with lower entropy. When the LLE is positive, the dynamic system (17) falls into chaos with higher entropy. In other words, the larger the positive Lyapunov exponent is, the more chaotic the system is and the greater the entropy is.

So we can make a conclusion that irrational changes of price adjustment speed will lead to a large entropy to the system (17) and the manufacturers must get more market information to make a best decision and keep the dynamic system (17) in a stable state.

Figure 5 shows the bifurcation diagram and entropy of the dynamic system (17) with changing α_2 which is in

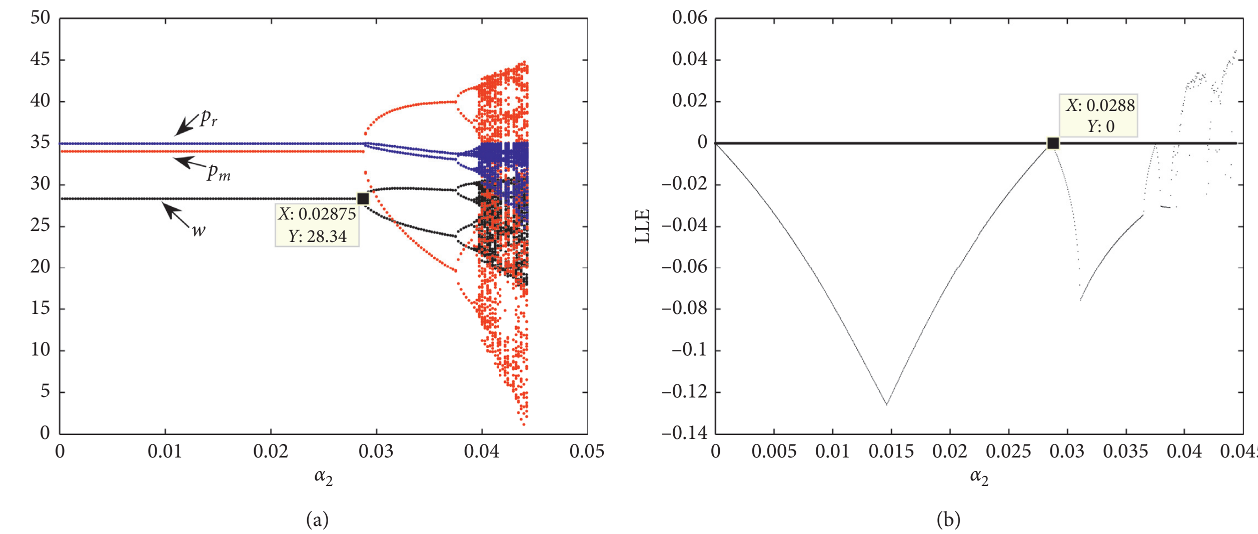


FIGURE 3: Bifurcation diagram and LLE of the system (17) with varying α_2 when $\alpha_1 = 0.02$. (a) Bifurcation diagram when $\lambda_2 = 0.2$. (b) LLE when $\lambda_2 = 0.2$.

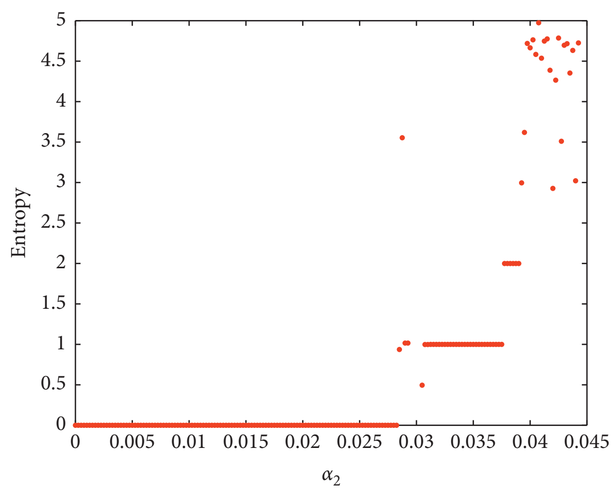


FIGURE 4: Entropy diagram of the system (17) with varying α_2 when $\alpha_1 = 0.02$.

accordance with Figure 2. When $\lambda_2 = 0.6$, the dynamic system (17) has first bifurcation at $\alpha_2 = 0.0245$ and then falls into chaos through the flip bifurcation and N-S bifurcation shown in Figure 5(a), and the entropy of the dynamic system (17) is shown in Figure 5(b). When $\lambda_2 = 0.9$, the system (17) loses its stability at the beginning which is shown in Figure 5(c) and then falls into chaos finally through the N-S bifurcation, and its entropy is shown in Figure 5(d). We can see from Figure 5 that the system (17) remains stable with lower entropy and falls into chaos with higher entropy. In other words, the more chaotic the system (17) is, the greater the entropy is.

From this trend described above, we can draw a conclusion that a faster adjustment speed of direct price or wholesale price will pull the market into chaos through the slip bifurcation or N-S bifurcation; the higher the level of fairness concern from the manufacturer or retailer is, the easier the market falls into chaos. Because the characteristic of the dynamic system (17) is the same as the one when α_1 changes, the characteristic of the dynamic system (17) with changing α_1 is not discussed in this paper.

The state of the system is fixed when stability stays, and the competitors in the market can make a profit in every time period via changing the price. Generally speaking, stability is beneficial for competitors to make the long-term strategies, and the market vibrates regularly in a certain period and returns to the same point in the periodic or limit cycle state; hence, the competitors can forecast the process of market and change their price strategies frequently to gain more profit. Chaos indicates that the market becomes unpredictable and irregular; it is so hard for competitors to achieve their business objectives just relying on the initial value sensitiveness in this situation. In most cases, chaos is an obstacle that the market operates orderly and efficiently.

Figure 6 shows the strange attractors of the dynamic system (17) from the four-period state to limit cycles, which are an important characteristic of the system. Figure 7(a) shows the price changes in the four-period state, and the manufacturer can forecast the tendency of direct price in the next period because the direct price is in a regular change. Figure 7(b) presents the price changes in the chaotic state, and the change of prices becomes irregular and unpredictable. Figure 8 shows the sensitiveness of system to the initial values with w and p_r being fixed and p_m change from 34.01 to 34.02. Figure 8(a) indicates the dynamic system (17) is in four-period bifurcation, and Figure 8(b) displays the dynamic system (17) is in the chaotic state, in which the black line, red line, and blue line represent the fluctuations of w, p_m, *an d* p_r, respectively. Although the difference of the initial value is quite small, the distance between two trajectories becomes large after several iterations. The manufacturer and retailer should pay more attention to the setting of the initial value and the price evolution when the system is in the chaotic state.

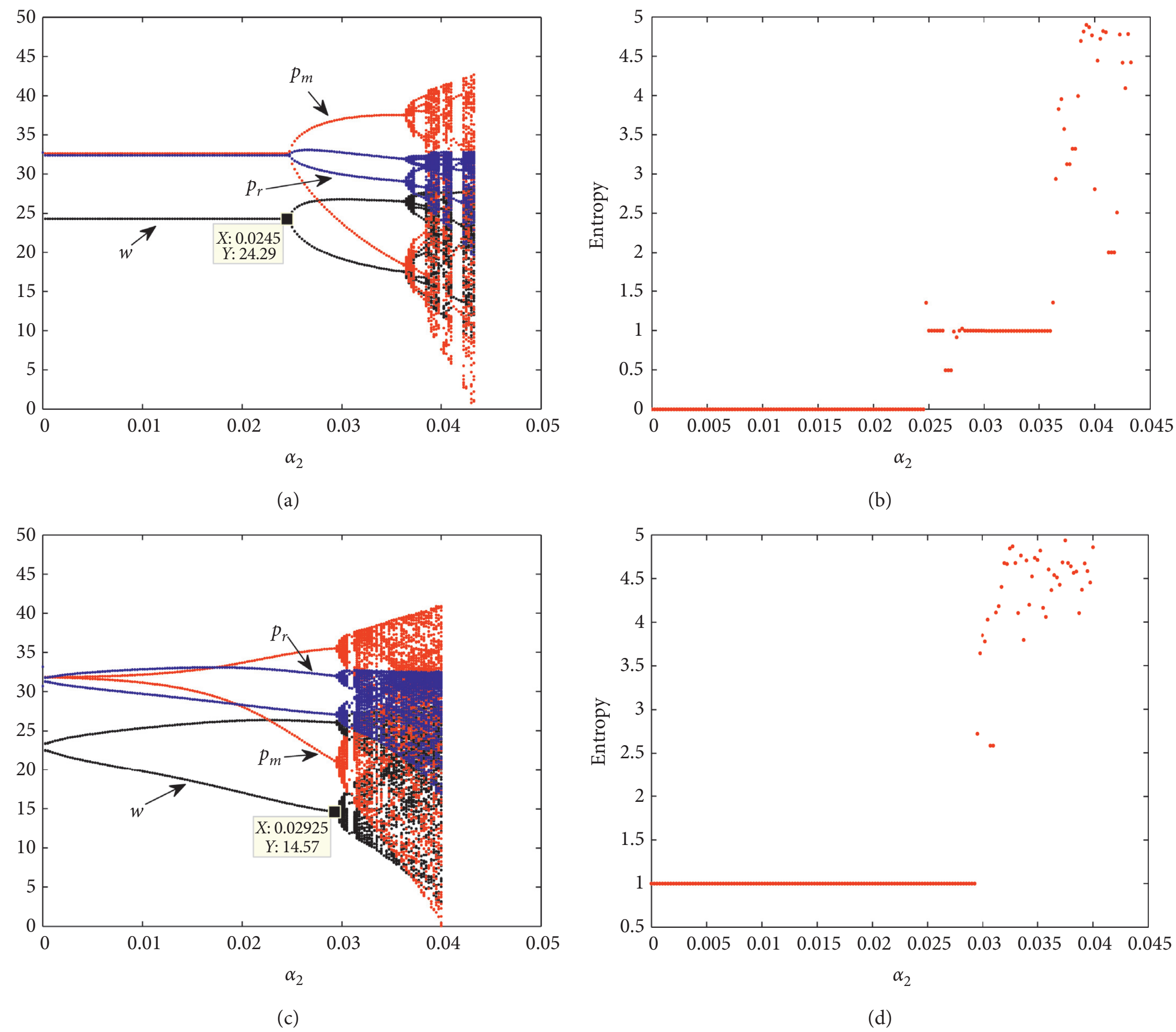


Figure 5: Bifurcation diagram and entropy of the dynamic system (17) with varying α_2 when $\alpha_1 = 0.02$. (a) Bifurcation diagram when $\lambda_2 = 0.6$. (b) Entropy diagram when $\lambda_2 = 0.6$. (c) Bifurcation diagram when $\lambda_2 = 0.9$. (d) Entropy diagram when $\lambda_2 = 0.9$.

4.3. The Influence of Parameters on the Profits. Figure 9 shows the average profits of the manufacturer and the retailer with the change of α_1 and α_2. In the stable state, the average profits of the manufacturer and the retailer are 692.3 and 46.79, respectively; after that, the dynamic system (17) enters 2-period bifurcation and chaotic states eventually with the change of price adjustment speed, the average profit of the retailer increases with increasing α_1 and α_2, but the manufacturer's average profit decreases sharply with increasing α_1 and α_2. In Figure 10(a), the average profits of the manufacturer and the retailer are decreased with increasing λ_1. From Figure 10(b), it is seen that the average profits of the manufacturer and the retailer rise with increasing λ_2 at the beginning, while the average profit of the retailer increases and that of manufacturer declines with increasing λ_2; the performance of the dual-channel supply chain is improved with a high level of the manufacturer's fairness concern and declined with a high level of the retailer's fairness concern. We can obtain that chaos is unfavorable to the leading manufacturer and beneficial to the follower retailer, and the high level of fairness concern of the manufacturer and retailer is always disadvantageous to the leading manufacturer but not always bad for the follower retailer.

Figure 11 shows the influence of α_i and λ_i on the profits of the manufacturer and the retailer using the three-dimensional grid. From Figure 11(a), we obtain that when α_1 and λ_1 are controlled in small values, the profit of the retailer almost remains stable; with fixed λ_1 in a small region, the retailer's profit rises with increasing α_1, but increasing α_1 and λ_1 simultaneously to the larger value range, the dynamic system (17) falls into chaos and the retailer's profit changes violently and even has a great loss; chaos is a great disadvantage to achieving maximizing profit and making a long competition strategy for the retailer in the market.

Similarly, in Figure 11(b), keeping λ_2 in small values, the manufacturer's profits increase with the increase of α_1 which indicates that the lower fairness concern of the manufacturer and the higher adjustment speed of wholesale price for the retailer are beneficial to the manufacturer. The lower level of fairness concern of the retailer and the

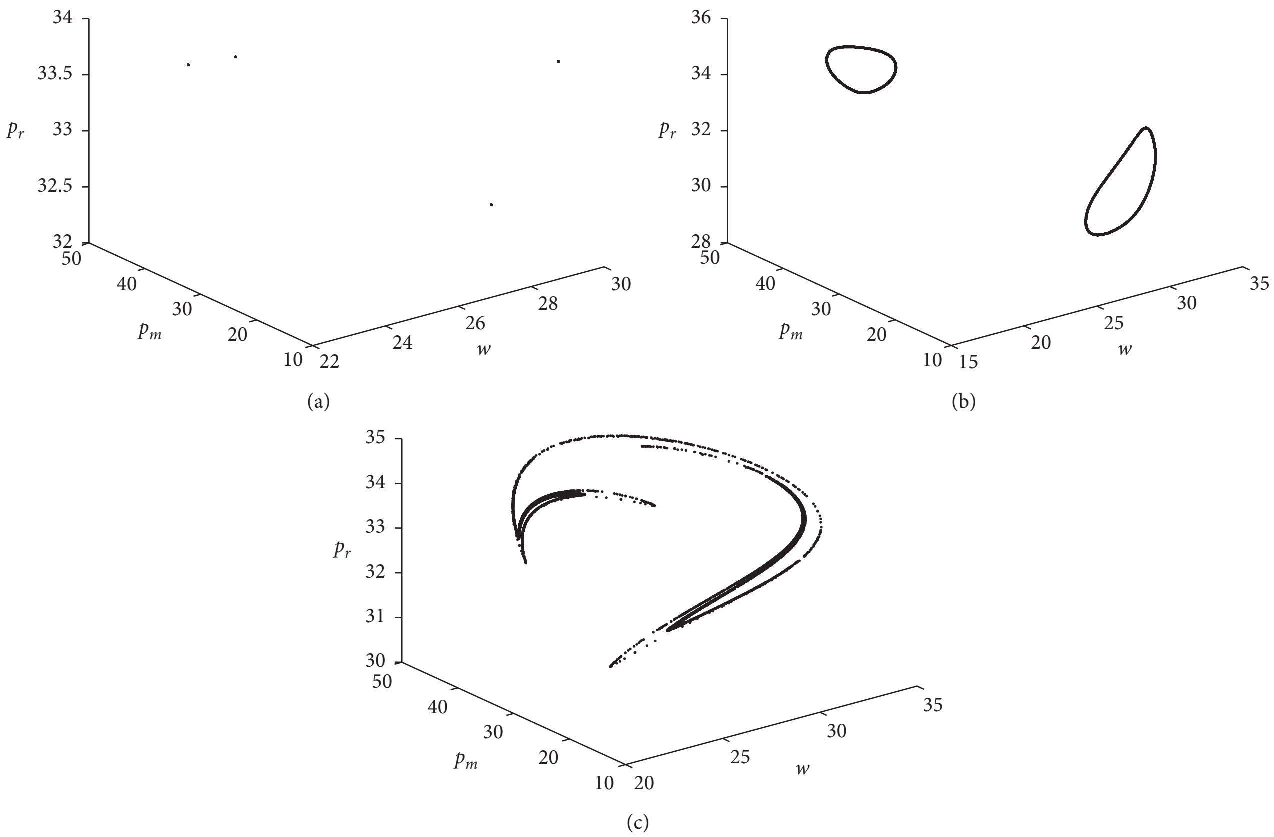


Figure 6: Chaos attractors of the system (17) with (a) $\alpha_1 = 0.02$, $\alpha_2 = 0.038$, (b) $\alpha_1 = 0.03$, $\alpha_2 = 0.035$, and (c) $\alpha_1 = 0.02$, $\alpha_2 = 0.04$.

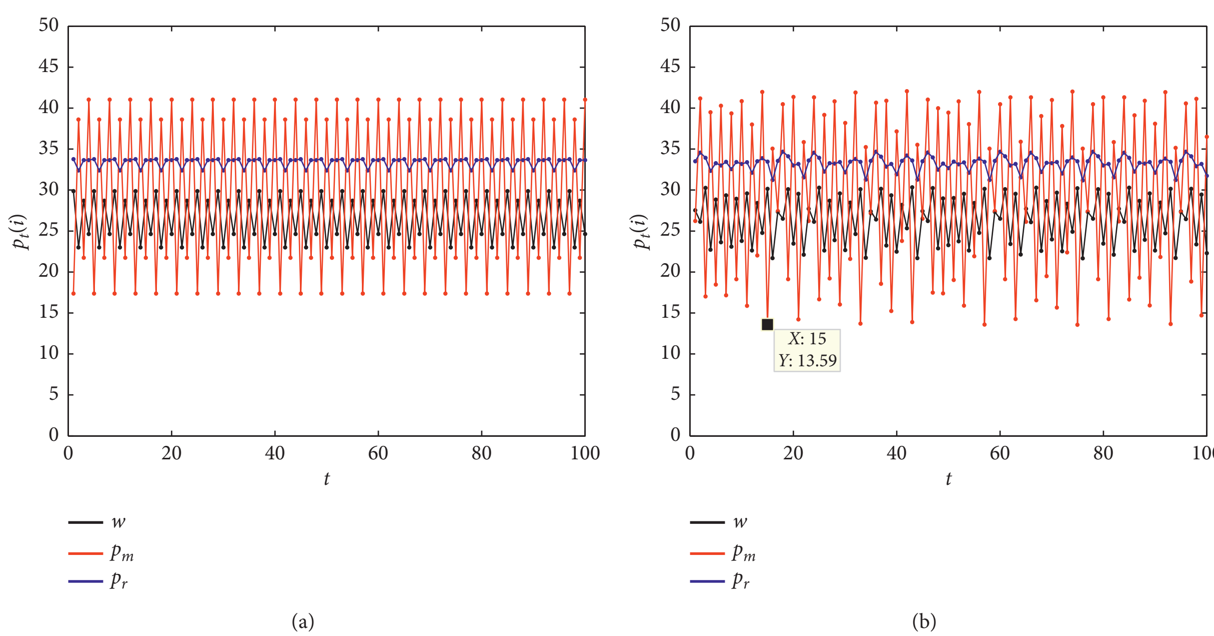


Figure 7: Wave plot of prices with the change of time. (a) $\alpha_1 = 0.02$, $\alpha_2 = 0.038$. (b) $\alpha_1 = 0.02$, $\alpha_2 = 0.04$.

higher adjustment speed of direct selling price for the manufacturer are beneficial to the retailer which is shown in Figure 11(c). Figure 11(d) shows the profit of the manufacturer influenced by α_2 and λ_2; when α_2 stays in small values, the higher fairness concern of the manufacturer is good for himself/herself to obtain the maximum profit. In the market competition, the competitors should pay attention to the range of parameters, and choosing proper values for parameters is indispensable for them to achieve business objectives.

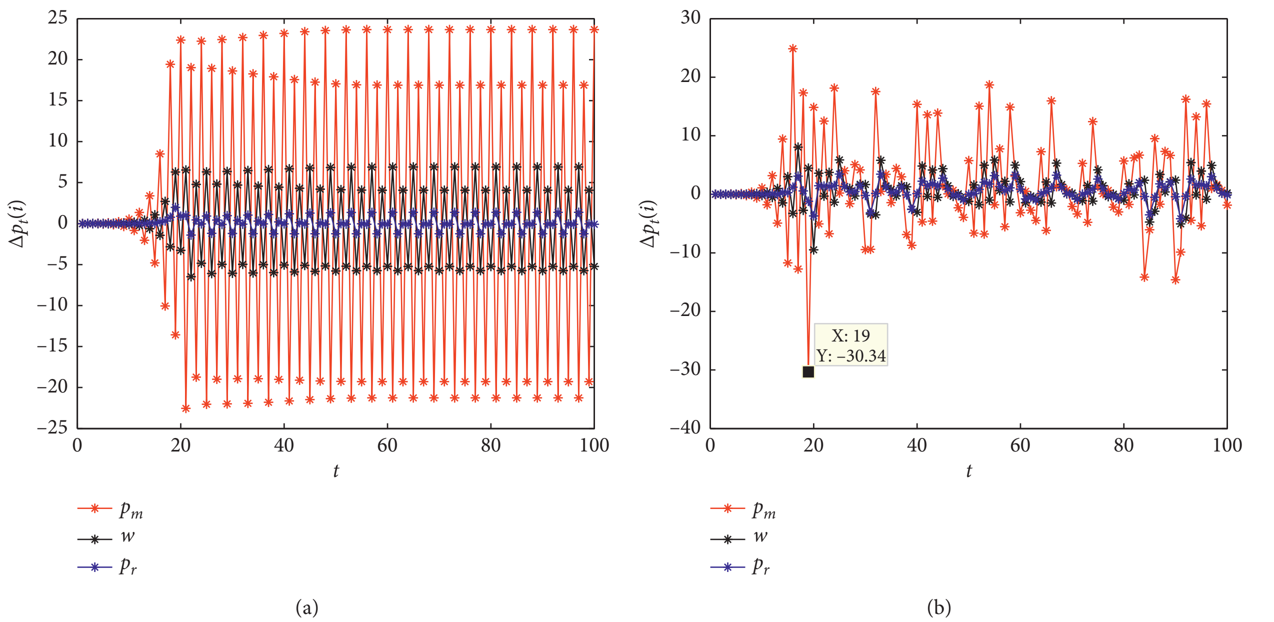


FIGURE 8: Sensitivity to initial values when w, p_m, and p_r are 28.35, 34.01, and 34.95. (a) $\alpha_1 = 0.02$, $\alpha_2 = 0.038$. (b) $\alpha_1 = 0.02$, $\alpha_2 = 0.04$.

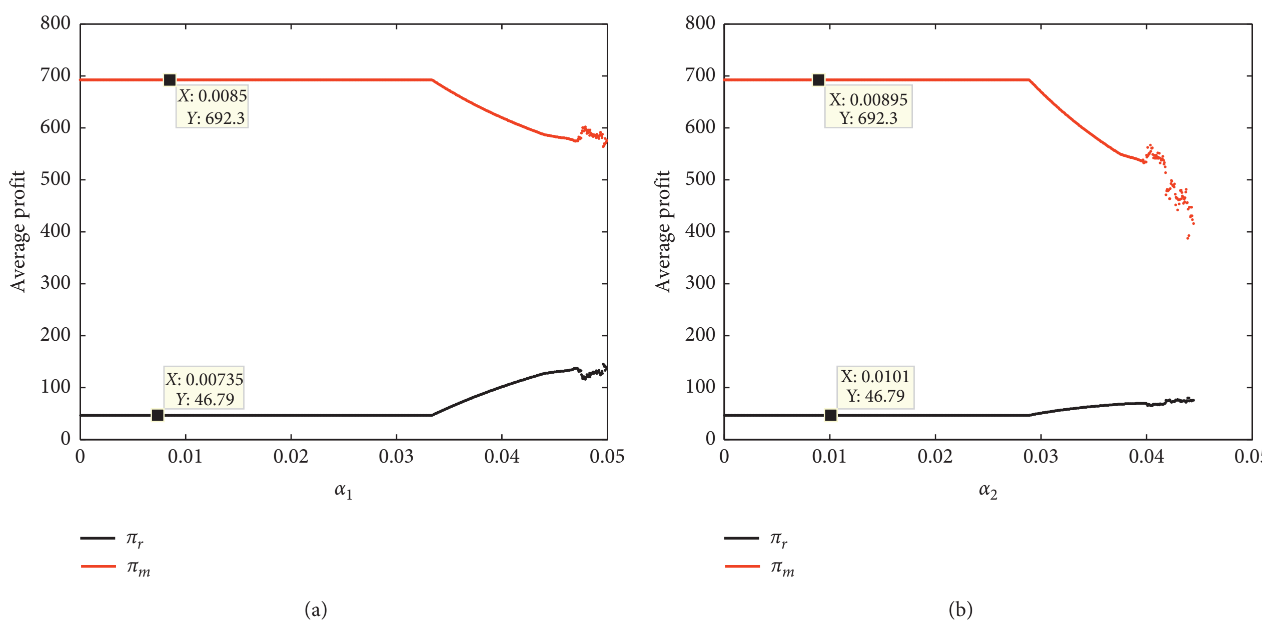


FIGURE 9: Change of average profit with respect to $\alpha_i\,(i = 1, 2)$. (a) $\alpha_2 = 0.02$. (b) $\alpha_1 = 0.02$.

5. Chaos Control

All the participants certainly want to achieve their own business objectives easily and adjust their price decision frequently to adapt the changes of market competition. Once the price adjustment speed is out of control, the market will go out of order and fall into chaos finally which is harmful to the stability of the supply chain. Therefore, some measures should be taken to delay or eliminate the occurrence of bifurcation and chaos.

As far as we are concerned, the method of variable feedback control is widely applied to control the chaos of the supply chain. Ma and Zhang [44] and Ma and Xie [45] have used this method to control the chaos of the insurance market and the supply chain system. The dynamic system (17) under control can be rewritten as

$$\begin{cases} w(t+1) = w(t) + \alpha_1 w(t)\dfrac{\partial u_m^*(t)}{\partial w(t)} - v w(t), \\[2ex] p_m(t+1) = p_m(t) + \alpha_2 p_m(t)\dfrac{\partial u_m^*(t)}{\partial p_m(t)} - v p_m(t). \end{cases} \tag{24}$$

The controlled system (24) can be expressed as follows:

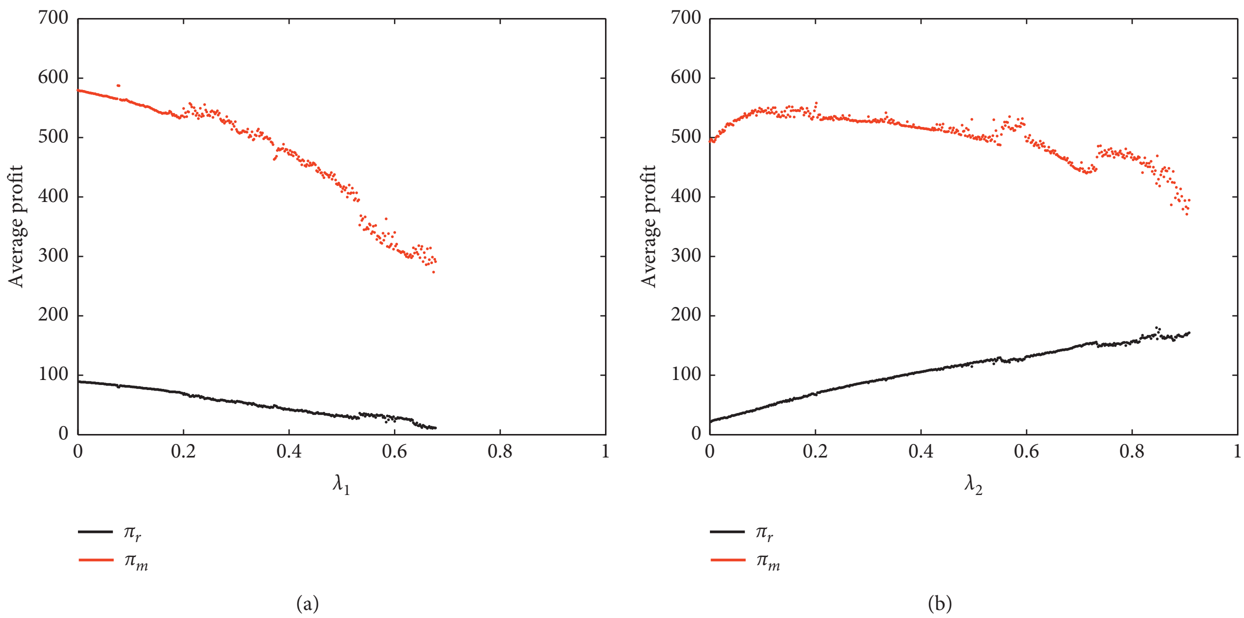


Figure 10: Change of the average profits when $\alpha_1 = 0.02$ and $\alpha_2 = 0.04$.

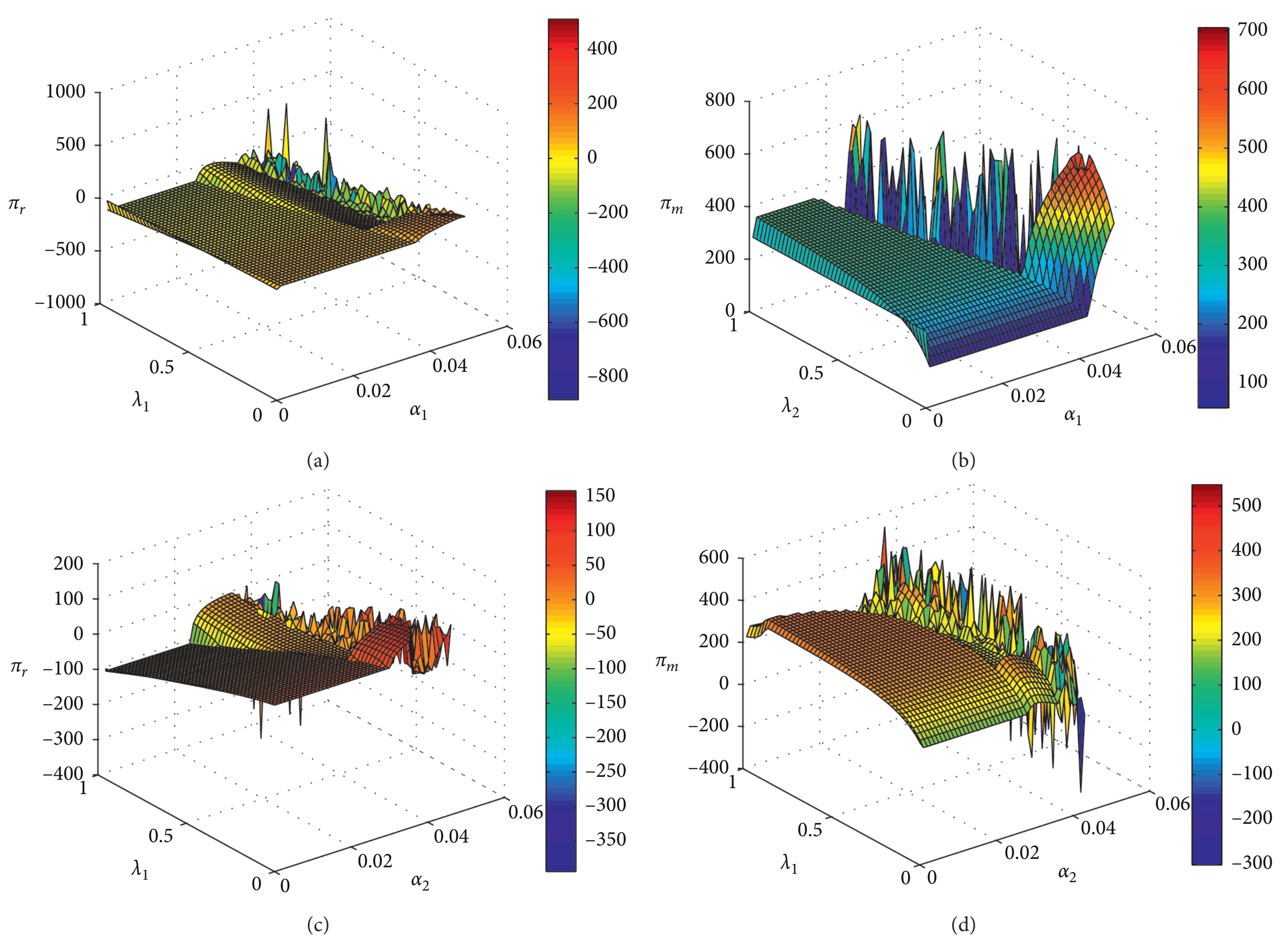
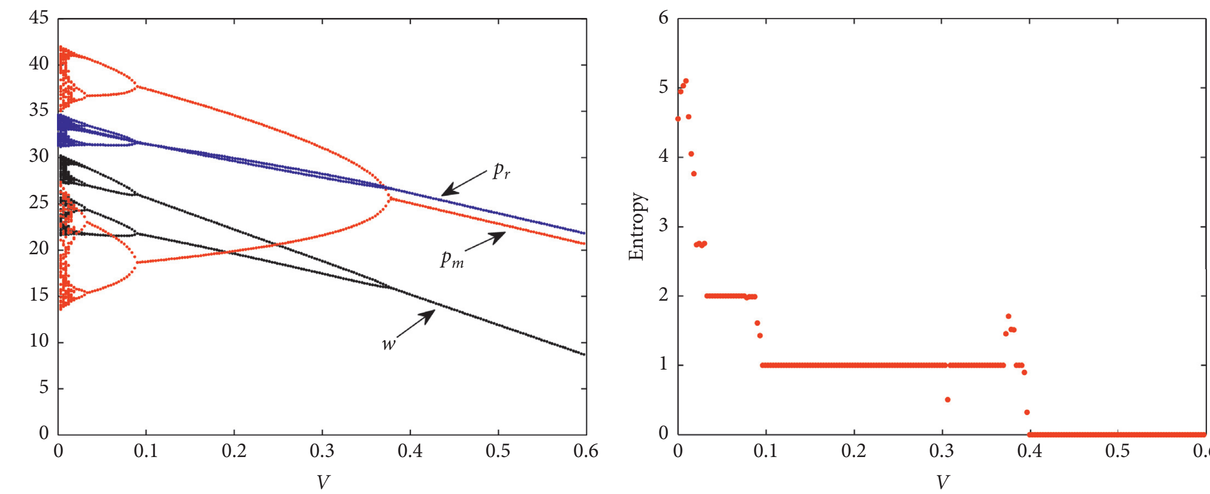
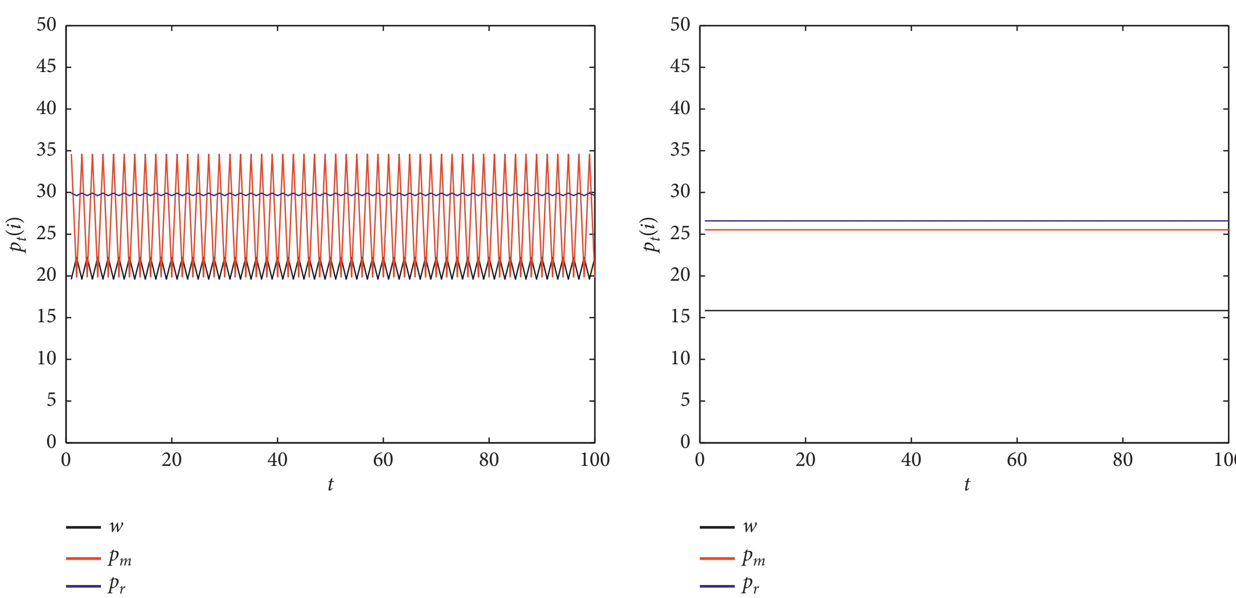


Figure 11: Change of profits with respect to $\alpha_i\,(i = 1, 2)$ and $\lambda_i\,(i = 1, 2)$. (a) Change of profit of the retailer with respect to α_1 and λ_1. (b) Change of profits of the retailer with respect to α_1 and λ_2. (c) Change of profit of the retailer with respect to α_2 and λ_1. (d) Change of profit of the manufacturer with respect to a_2 and λ_2.



(a) (b)

Figure 12: Bifurcation diagram and entropy with the change of v when $\alpha_1 = 0.02$ and $\alpha_2 = 0.04$.



(a) (b)

Figure 13: Price wave plot with the change of time when $\alpha_1 = 0.02$ and $\alpha_2 = 0.04$. (a) $v = 0.2$. (b) $v = 0.38$.

$$\begin{cases} w(t+1) = w(t) + \alpha_1 w(t)\left\{\dfrac{1}{2(1+\lambda_1)^2}\left[a\theta(1+\lambda_1)^2(\lambda_2+\gamma\lambda_2+\mu)\right] + A_0 + A_1\right\} - vw(t), \\ p_m(t+1) = p_m(t) + \alpha_2 p_m(t)\left\{-\dfrac{1}{2(1+\lambda 1)}\left[k^2(1+\lambda_1)(-2+\lambda_2)p_m + c\mu k^2(1+\lambda_1)p_m\right] + A_2 + A_3 + A_4\right\} - vp_m(t), \end{cases} \tag{25}$$

where v represents the control parameter, and selecting an appropriate value for v is essential to delay bifurcation and make the supply chain system return to a stable state.

Next, we examine the influence of the parameter v on the stability of the system (25). Making $\alpha_1 = 0.02$ and $\alpha_2 = 0.04$, Figure 12 shows the bifurcation diagram and entropy with the change of v, the controlled system (25) goes to the stable state from the chaotic state with increasing v, and entropy of the controlled system (25) becomes smaller as the system's instability decreases. In Figure 13(a), when $v = 0.2$ is fixed, the system vibrates in a two-period orbit; then adjusting the parameter $v = 0.38$ (see in Figure 13(b)), the wave plot of prices remains at the determined value and the controlled system (25) returns to the stable state.

From Figure 12, it is seen that the control parameter v will affect the Stackelberg equilibrium value of the controlled system (25), so the manufacturer and retailer should make a good balance between the system's stability and profit maximization.

6. Conclusion

In this paper, we develop a Stackelberg game model in the dual-channel supply chain including a manufacturer and a retailer; both sides consider fairness concern, and the manufacturer has different business objectives. The entropy and complex characteristic of the dual-channel supply chain system are analyzed by nonlinear dynamics theory and entropy theory, such as the entropy diagram, bifurcation diagram, LLE, stable region, and chaos attractors. A three-dimensional triangular mesh is applied to describe the changes of profits of the manufacturer and retailer. The results show that, with the increase of price adjustment speed, the dual-channel supply chain is more complex and falls into a chaotic state in which system entropy increases; the stability of the dual-channel supply chain will be robust with the increase of the weight of market share and weaken with the increase of the fairness concern level of the manufacturer and retailer. The high level of fairness concern of the manufacturer and retailer is always disadvantageous to the leading manufacturer but not always bad for the follower retailer. The performance of the dual-channel supply chain is improved with a high level of the manufacturer's fairness concern and declined with a high level of the retailer's fairness concern. We also find the retailer will gain more profits in the chaotic state than in the stable state in the Stackelberg game model. In addition, the variable feedback control method can effectively control the chaotic behavior of the dual-channel supply chain.

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 that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Qiuxiang Li provided research methods. Yuhao Zhang wrote the original draft. Yimin Huang revised the paper.

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