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The dynamic decision in risk-averse complementary product manufacturers with corporate social responsibility

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Abstract

Purpose – The problem of manufacturer-customer relationships is becoming the key factor of enterprise development, and the contradiction between manufacturer's objective and customer's satisfaction still exists. Customers claim for product safety from manufacturers, so manufacturers should take corporate social responsibility (CSR) into their company philosophy or even enhance the degree of CSR during their production. The purpose of this paper is to investigate the influences of parameters on the stability of risk-averse complementary product manufacturers.

Design/methodology/approach – In this study, three dynamic game models are developed: manufacturer 1 – leader Stackelberg game model, manufacturer 2 – leader Stackelberg game model and Nash game model. Using bifurcation diagrams, the largest Lyapunov exponent, 0-1 test for chaos and parameter basin plots, the influences of parameters on the complex behaviors of the three models are analyzed.

Findings – The authors demonstrate that the system exists in deterministic chaos when the parameter exceeds a certain value. The lead manufacturer will not be a beneficiary in chaotic state, and when two manufacturers have the same status the stability of the system weakens, which renders it easily chaotic.

Research limitations/implications – In this paper, the authors make some assumptions, which when applied broadly could lead to some findings.

Practical implications – The authors find that the lead manufacturer will derive the greatest profit and will exert the least effort compared with the follower manufacturer, but that both manufacturers will exert greater effort in the Nash game. The two manufacturers should be cautious while selecting the parameter's value so that the stability of the system is maintained.

Social implications – The research will serve as a guide for the two complementary manufacturers in their decision-making process.

Originality/value – The originality and value of the research rest on the use of dynamic thinking in ensuring stability in the quality of complementary products considering the firms' market powers. The research will serve as a guide for the two complementary manufacturers in their decision-making process.

Keywords Operational research, Complexity, Game theory, Simulation

Paper type Research paper

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1. Introduction

With the rapid development of economy, competitions among enterprises become fiercer as the changing environment conditions, such as market uncertainty and risk preference factor. The decision behaviors among these enterprises become more complicated and hard to predict (Ma and Li, 2014). We all know that pricing policy has long been recognized as a significant tool in the profit maximization of firms and applied to revenue or supply chain management (Wei *et al.*, 2013).

A considerable amount of research has been carried out on the problem related to the optimal pricing decision of substitute products. Tang and Yin (2007) developed a base model to establish the relationship between product demand and relative price and examined how a retailer determines the order quantity and the retail price of two substitute products jointly under the fixed and variable pricing strategies. Xia *et al.* (2008) considered competitive system with multiple suppliers and multiple buyers dealing with a single product and obtained the winning supplier offers the lowest price than her closest competitor instead of the lowest price she can offer. Zhao *et al.* (2014) studied pricing decisions in a supply chain which included one common retailer and two competitive manufacturers providing two substitute products, analyzed the effects of the two manufacturers' different competitive strategies and the channel members' different power structures on the optimal pricing decisions. Under cooperative and non-cooperative game, Zhang *et al.* (2014a, b) investigated the pricing and coordination issues of single-period green supply chain in which green product and non-green products co-exist with and substitute each other. Zhang *et al.* (2014a, b) considered a supply chain consisting of a manufacturer and a retailer in a bilateral monopoly setting, and the manufacturer and the retailer independently chose their pricing strategies to optimize their own benefits in the presence of consumers' reference price effects. Yang *et al.* (2014) studied price competition for retailers with both profit and revenue targets. Zhao and Wei (2014) investigated the coordination of a two-echelon supply chain, and the fuzzy demand was dependent on both retail price and sales effort. Kuo and Huang (2012) studied pricing decisions of a retailer who sells products from two different generations for a given period of time, each with limited inventories.

In recent years, the concept of complementary products has obtained a great attention by many scholars. When customers want to obtain the full utility of the products, they may have to buy more than one product at the same time (Yue *et al.*, 2006). So, the marketing decision of one firm would affect the other firm's market performance and vice versa (Mukhopadhyay *et al.*, 2011). In this scenario, the firms selling their products to the same market are interlinked in the sense and the demands for their products in the same market are interrelated. Yan and Bandyopadhyay (2011) presented a profit maximization model to obtain optimal strategies for the complementary products under information asymmetry. Wang *et al.* (2014) considered pricing decisions of two complementary products in a fuzzy environment and analyzed the optimal retail pricing under different decentralized decisions. Wei *et al.* (2013) developed pricing game models with regard to two complementary products in a supply chain with two manufacturers and one common retailer, and obtained the pricing of the individual products plays an important role in the respective demand. Mukhopadhyay *et al.* (2011) developed Stackelberg game models considering a duopoly market where two separate firms offer complementary goods, obtained that information sharing benefits the leader firm and that it is detrimental to the follower firm and the total system if the follower firm shares information unconditionally. These studies, however, only considered the influences of price factor on manager's decisions.

The quality problem, an impact factor influencing manager's decision and customer's demand, has received intensive attention. Forker (1997) studied quality management using process optimization to address both effectiveness and efficiency concerns, and obtained the transaction-specific investments had great influences on system performance. Hsieh and Liu (2010) considered four non-cooperative game models in a supply chain which consist of one supplier and one manufacturer with different degrees of information available about the players' inspection sampling rates and quality investments. Aust *et al.* (2014) proposed modified algorithms to provide the optimal solutions taking the boundary solutions into the consideration. Yu and Ma (2013) studied the impact of decision sequence in a two-echelon system with quality and price dependent. However, to the best of our knowledge, no research has studied the quality problem of complementary products considering the firms' market powers.

The problem of manufacturer-customer relationships is becoming the key factor of enterprise development, and the contradiction between manufacturer's objective and customer's satisfaction still exists. For example, in 2007, Mattel had to recall 20 million children's toys, because some suppliers used materials containing traces of lead; in 1996, Nike was vilified when it was discovered that some of their subcontractors were using child labor (Gimenez and Tachizawa, 2012). Customers claim for product safety from manufacturers, however, high level of corporate social responsibility (CSR) will result in heavy burden on capital. Manufacturers should take CSR into their company philosophy or even enhance the degree of CSR during their production. So, it is urgent and important for manufacturers to find the optimal evolution process of CSR in the decision-making process.

In short, the existing literatures emerged in CSR mainly focus on the area of management, marketing, accounting, finance and default risk (Jiao, 2010; Hori *et al.*, 2014; Boulouta and Pitelis, 2014; Goss and Roberts, 2011; Margolis and Walsh, 2001; Kim *et al.*, 2014; Sun and Cui, 2014). But in response to the rising popularity of CSR in practice, there are only a small number of literature developed game models on CSR to analyze its impact on firm actions and outcomes. The CSR performance of the upper company will eventually influence corporate image, goodwill, cost, and sales of the downstream company. Lambertini and Tampieri (2011) examined the stability conditions of mixed oligopoly firms with CSR and profit-maximizing in the presence of an environmental externality, and obtained the influences of CSR on the Equilibrium. Kopel and Brand (2012) analyzed firms which considered CSR and profit-maximizing, found that the firm considering CSR had a higher market share and even higher profit if the unit production costs of the firms were similar, but the profit was no monotonic in the share of consumer surplus. Xu (2014) applied the CSR to the hospital management considering the price and quality competition. Hsueh (2014) proposed a new revenue sharing contract with CSR in a two-tier supply chain. Ni *et al.* (2010) considered a wholesale price contract with CSR in two-echelon supply chain which consists of an upstream supplier and a downstream firm. In this paper, we will develop dynamic game models with CSR considering a cost sharing contract in complementary products.

In brief, the existing literatures mostly analyze the influences of a firm with CSR or quality investment on the practice or substitute products separately. New models need to be developed to dynamic study the influence of the price, quality investment and CSR on the stability of the system. In this paper, we will present assumptions that two manufacturers (M_1 and M_2) provide two complementary products taking the CSR and quality investment into account, respectively, under different decision criteria, and maximize its profit though, cost sharing and subsidies, respectively. It is an empirical perspective on generalized social responsibility that a manufacturer with CSR may bring benefits to the customers and its complementary enterprise. The dynamic phenomena are obtained through numerical simulation to analyze the influences of the decision parameters on the complex nonlinear dynamics behaviors.

In this paper, the main contributions of this paper lie in two aspects. On the one hand, we simultaneously consider the effects of CSR and cost sharing contract on the level of quality investment and the price, the cooperation relation between the two complementary manufacturers with quality investment and CSR would be complex. On the other hand, we explore the dynamic changes of the system based on Stackelberg dynamic game and Nash dynamic game, analyze the influence of parameters on the system's stability.

The paper is organized as follows: the assumptions, notations and profit functions are described in Section 2. Sections 3 and 4 develop the M_1-leader Stackelberg game model and M_2-leader Stackelberg game model and analyze their dynamic phenomena by numerical simulations. In Section 5, the Nash game model is proposed and its dynamical behaviors are investigated. In Section 6, using parameter basin plot, the influences of the parameters on the system's stability are analyzed. Finally, conclusions are drawn in Section 7.

2. Problem description

Nowadays, the problem of quality level is a popular topic in supply chain. Report of Ford shows 76 percent quality problems of the final product are caused by the faults of suppliers' component quality problem. Toyota Motor Corporation recalled millions of vehicles for various problems from September 2007 to February 2014, including braking software glitches and sticking gas pedals. When a customer makes purchasing decision of a product, he may not only consider the price of the product, but also the quality. Moreover, many leading brands such as Nike, GAP, Adidas, and McDonalds have been urged to incorporate CSR into their supply chains.

In this paper, two complementary product manufacturers (M_1 and M_2) is considered. They provide two complementary product, for example, the elevator and elevator maintenance business; software and software upgrade; purified water system and chemical treatment agent; camera and film. M_1 takes the problem of pricing and CSR as the decision variables, while M_2 takes the problem of pricing and quality investment as the decision variables. M_1 and M_2 have a cooperation relation and selling their respective products to customers. Our main interest is to investigate the system's stability when M_1 and M_2 make their own variable decisions in dynamic game situation facing different market power structures. Three decision scenarios are considered including M_1-leader Stackelberg (M_1S) game, M_2-leader Stackelberg (M_2S) game, and Nash game (NG).

2.1 Assumptions and notations

According to the actual market situation, the models is studied based on the following assumptions:

1. Considering M_1 and M_2 produce two complementary products. Customer demand can be always met and demand function is linear.
2. The consumers demand is stochastic, and M_1 and M_2 are all risk aversion and bounded rationality.
3. M_1 takes the price (p_1) and the CSR level (y) as its decision variables, and give the subsidy "s" per unit product for M_2 who takes price p_2 and quality level (x) as decision variables.
4. M_1 shares the cost of quality investment of M_2, the coefficient of sharing is θ.

2.2 Profit functions

The CSR is always affected by a large number of socio-cultural variables that cannot be accounted or controlled. A survey with well-designed questionnaires may provide some useful information about demand functions. Here, based on literature (Hsieh and Liu, 2010; Aust *et al.*, 2014; Yu and Ma, 2013; Sun and Cui, 2014; Kopel and Brand, 2012; Xu, 2014; Hsueh, 2014), we take the CSR as a decision variable and consider demand functions as follows:

$$\begin{cases} q_1 = \overline{a}_1 - b_1 p_1 - c_1 p_2 + d_1 y + f_2 x, \\ q_2 = \overline{a}_2 - b_2 p_2 - c_2 p_1 + d_2 y + f_1 x, \end{cases} \tag{1}$$

where $\overline{a}_1 > 0,\ \overline{a}_2 > 0$ are the market scales, and $b_1 > 0,\ b_2 > 0,\ c_1 > 0,\ c_2 > 0$ are the price sensitivity of consumers, $d_1 > 0, d_2 > 0$ are the consumer sensitivity of CSR, $f_1 > 0, f_2 > 0$ are the consumer sensitivity of quality investment. In order to capture the uncertainty in market demand resulting from changes in economic and business conditions, we assume that $\overline{a}_1$ is random variables and follow $\overline{a}_1 = a_1 + \varepsilon_1$, here a_1 is the mean of the potential intrinsic demand of M_1 and ε_1 follows a normal distribution such that $E(\varepsilon_1) = 0,\ Var(\varepsilon_1) = \sigma_1^2$, which had been used extensively in the literature. In the same way, $\overline{a}_2 = a_2 + \varepsilon_2$, here a_2 is the mean of the potential intrinsic demand for M_2 and ε_2 follows a normal distribution such that $E(\varepsilon_2) = 0,\ Var(\varepsilon_2) = \sigma_2^2$.

Facing the uncertain demand, the two manufacturers have different financial risk for their products. Therefore, we will consider the effects of the risk attitude of the manufacturer on variable decision. The preference theory provides the framework for incorporating the manufacturer' financial risk propensity into their decision process, the valuation measure we use is known in the preference theory as the certainty equivalent, which is defined as that certain value for an uncertain event which the manufacturer is just willing to accept.

In this paper, we use the exponential utility express the utility function, $U(\pi_i) = -e^{-\pi_i/R_{M_i}},\ i = 1, 2$, where R_{M_i} is the risk tolerance levels of the two manufacturers and e is the exponential constant. π_i is the profit of the firm and follows a normal distribution, the mean is $E(\pi_i)$ and the variance is $Var(\pi_i)$. The certain equivalent of π_i is expressed by the following equation: $E_{U(\pi_i)} = E(\pi_i) - \left(Var(\pi_i)/2R_{M_i}\right)$.

The total expected profit and their expected profit of the two manufacturers, respectively are as follows:

$$\begin{cases} E_{U(\pi_1)} = p_1(a_1 - b_1 p_1 - c_1 p_2 + d_1 y + f_2 x) - \left(\frac{ky^2}{2} + \frac{h\theta x^2}{2}\right) \\ \qquad\qquad -s(a_2 - b_2 p_2 - c_2 p_1 + d_2 y + f_1 x) - \frac{p_1^2 \sigma_1^2}{2R_{M_1}} - \frac{s^2 \sigma_2^2}{2R_{M_1}}, \\ E_{U(\pi_2)} = (p_2 + s)(a_2 - b_2 p_2 - c_2 p_1 + d_2 y + f_1 x) - \frac{h(1-\theta)x^2}{2} - \frac{(p_2+s)^2 \sigma_2^2}{2R_{M_2}}, \\ E_{U(\pi_1+\pi_2)} = E_{U(\pi_1)} + E_{U(\pi_2)}. \end{cases} \tag{2}$$

Fixed costs $\left(ky^2/2\right) + \left(h\theta x^2/2\right)$ and $h(1-\theta)x^2/2$ are increasing and convex in quality level and CSR level, where k, h are fixed constant. R_{M_1} and R_{M_2} are the level of risk preference of M_1 and M_2.

3. $M_1 S$ game model

Suppose that the two manufacturers are all in pursuit of maximum profits as independent subjects, and they make decisions independently. M_1 is the leader and M_2 is the follower, and this relationship implies M_2 makes decision according to the action of M_1. In this game, M_1 first makes decisions of retailer price and the CSR level, then M_2 makes decisions of retailer price and quality level according to the decision of M_1.

3.1 Model and analysis

We can obtain $\boldsymbol{M_2 S}$ marginal profit by the first-order conditions of $E_{U(\pi_2)}$:

$$\begin{cases} \frac{\partial E_{U(\pi_2)}}{\partial p_2} = a_2 - c_2 p_1 - b_2 p_2 - b_2(p_2 + s) - \frac{e_2^2(p_2+s)}{R_{M_2}} + f_1 x + d_2 y, \\ \frac{\partial E_{U(\pi_2)}}{\partial x} = f_1(p_2+s) - hx(1-\theta). \end{cases} \tag{3}$$

The best reply functions of manufacturer M_2 are as follows:

$$\begin{cases} p_2 = \frac{s f_1^2 R_{M_2} + h R_{M_2}(1-\theta)\left(a_2 - c_2 p_1 - b_2 s + d_1 d_2 y - \frac{\sigma_2^2 s}{R_{M_2}}\right)}{h(\theta-1)\left(\sigma_2^2 + 2b_2 R_{M_2}\right) - f_1^2 R_{M_2}}, \\ x = \frac{f_1 R_{M_2}(a_2 - c_2 p_1 + b_2 s + d_2 y)}{R_{M_2}\left(f_1^2 + 2b_2 h(\theta-1)\right) + h(\theta-1)\sigma_2^2}. \end{cases} \tag{4}$$

Similarly, we can get M_1's marginal profit as follows:

$$\begin{aligned} \frac{\partial E_{U(\pi_1)}}{\partial p_1} = {} & a_1 - b_1 p_1 - \frac{\sigma_1^2 p_1}{R_{M_1}} + d_1 y - \frac{f_1 f_2 R_{M_2}(a_2 - c_2 p_1 + b_2 s + d_1 d_2 y)}{R_{M2}\left[f_1^2 + 2b_2 h(-1+\theta)\right] + \sigma_2^2 h(-1+\theta)} \\ & + \frac{c_2 R_{M_2}[f_1 f_2 + c_1 h(-1+\theta)]p_1 - b_1 R_{M_2}\left[f_1^2 + 2b_2 h(-1+\theta)\right]p_1}{R_{M2}\left[f_1^2 + 2b_2 h(-1+\theta)\right] + \sigma_2^2 h(-1+\theta)} \\ & + \frac{\sigma_2^2 b_1 h(-1+\theta)p_1 + c_2 hs\left(\sigma_2^2 + b_2 R_{M_2}\right)(-1+\theta)}{R_{M2}\left[f_1^2 - 2b_2 h(-1+\theta)\right] + \sigma_2^2 h(-1+\theta)} \\ & + \frac{c_1 f_1^2 s + c_1 h(1-\theta)\left(a_2 - c_2 p_1 - b_2 s + d_2 y - \frac{s\sigma_2^2}{R_{M_2}}\right)}{f_1^2 + \frac{h\left(\sigma_2^2 + 2b_2 R_{M_2}\right)(-1+\theta)}{R_{M_2}}} \\ & + \frac{c_2 h\theta f_1^2 R_{M_2}^2(a_2 - c_2 p_1 + b_2 s + d_1 d_2 y)}{R_{M_2}\left[f_1^2 - 2b_2 h(-1+\theta)\right] + \sigma_2^2 h(1-\theta)} \end{aligned} \tag{5}$$

$$\begin{aligned} \frac{\partial E_{U(\pi_1)}}{\partial y} = {} & -ky \\ & + \frac{\sigma_2^2 h d_1(-1+\theta)p_1 + d_1 R_{M_2}\left[f_1^2 + 2b_2 h\right](-1+\theta)p_1 - d_2 R_{M_2}[f_1 f_2 + c_1 h(-1+\theta)]p_1}{R_{M_2}\left(f_1^2 + 2b_2 h(\theta-1)\right) + h\sigma_2^2(\theta-1)} \\ & - \frac{d_2 hs(-1+\theta)\left(\sigma_2^2 + b_2 R_{M_2}\right)}{R_{M_2}\left(f_1^2 + 2b_2 h(\theta-1)\right) + h\sigma_2^2(\theta-1)} - \frac{d_2 h\theta f_1^2 R_{M_2}^2(a_2 - c_2 p_1 + b_2 s + d_2 y)}{R_{M_2}\left(f_1^2 + 2b_2 h(\theta-1)\right) + h\sigma_2^2(\theta-1)} \end{aligned}$$

In the real society, the manufacturers cannot obtain the whole market information and their decisions also show limited rational characteristics, such as risk-aversion behavior. The manufacturers always hope to obtain optimal state through the active managerial behavior. However, it is very much rare for the decision results in an optimal state; this is a long-term game process. How to determine the decision variable values and its adjustment orientation are the focus of this research. In this paper, we consider M_1 makes decisions of price and CSR level based on the limited rational expectation (Guo and Ma, 2013; Wang and Ma, 2013; Ma and Wang, 2013). That is to say, M_1 adjusts $p_1(t)$ and $y(t)$ on the basis of its last period marginal profit, if the marginal profit of t period is positive, M_1 will continue its adjustment strategy in period t+1. Then, the adjustment process can be modeled as follows:

$$\begin{cases} p_1(t+1) = p_1(t)+\alpha_1 p_1(t)\frac{\partial \pi_{M_1}}{\partial p_1}, \\ y(t+1) = y(t)+\alpha_2 y(t)\frac{\partial \pi_{M_1}}{\partial y}, \\ p_2(t) = \frac{s f_1^2 R_{M_2} + h R_{M_2}(1-\theta)\left(a_2 - c_2 p_1(t) - b_2 s + d_1 d_2 y(t) - \frac{\sigma_2^2 s}{R_{M_2}}\right)}{h(\theta-1)\left(\sigma_2^2 + 2 b_2 R_{M_2}\right) - f_1^2 R_{M_2}}, \\ x(t) = \frac{f_1 R_{M_2}(a_2 - c_2 p_1(t) + b_2 s + d_1 d_2 y(t))}{R_{M_2}\left(f_1^2 + 2 b_2 h(\theta-1)\right) + h\sigma_2^2(\theta-1)}, \end{cases} \tag{6}$$

where α_i, $i=1$, 2 is the adjustment speed parameter of decision variables, which reflects the company agents' learning and active managerial behavior.

3.2 Numerical simulation

According to the actual market competition, we simulate the parameter values: $a_1=1$, $a_2=1$, $b_1=0.3$, $b_2=0.3$, $c_1=0.2$, $c_2=0.2$, $d_1=0.3$, $d_2=0.21$, $f_1=0.3$, $f_2=0.21$, $\sigma_1=0.05$, $\sigma_2=0.05$, s = 0.2, $h=1$, $k=1$, $\theta=0.3$, $R_{M_1}=60$, $R_{M_2}=60$ and the initial values $P_1(1)=1.89$, y(1) = 0.4 in the System (6).

Figure 1 shows the bifurcation diagrams of the System (6) with $\alpha_2=1.5$ and α_1 varying from 0 to 2.95. We can conclude that when $\alpha_1 < 1.907$, the System (6) is stable at the Nash equilibrium $(p_1, y, p_2, x, \pi_1, \pi_2) = (1.892, 0.4082, 1.428, 0.6975, 0.5367, 0.6244)$. When $\alpha_1=1.907$, the System (6) makes the first bifurcation, then the System (6) is gradually into the chaotic state with increasing of α_1 after the cycle 2, cycle 4, etc. In chaotic period, *CSR* level and the profit of A is always less than the one of stable state and the profit of B is always greater than the one of stable state. So A is a victim and B is a beneficiary.

The largest Lyapunov exponent is an effective method to verify whether the system is in chaotic state or not. In recent years, some scholars used 0-1 test for chaos to verify system evolution process. The basic idea and the implementation of the 0-1 test refer the literatures (Gottwald and Melbourne, 2009; Sun *et al.*, 2010; Yuan *et al.*, 2013; Armand Eyebe Fouda *et al.*, 2014). $K\approx 0$ indicates regular dynamics and $K\approx 1$ indicates chaotic dynamics.

Figure 2 shows the largest Lyapunov exponent and K of the System (6), which well coincides with the numerical simulation of the bifurcation diagram. When the *LLE* is less than 0 and K approximately equals to 0, the System (6) is in stable state; when the *LLE* is greater than 0 and K approximately equals to 1, the System (6) is in chaotic state.

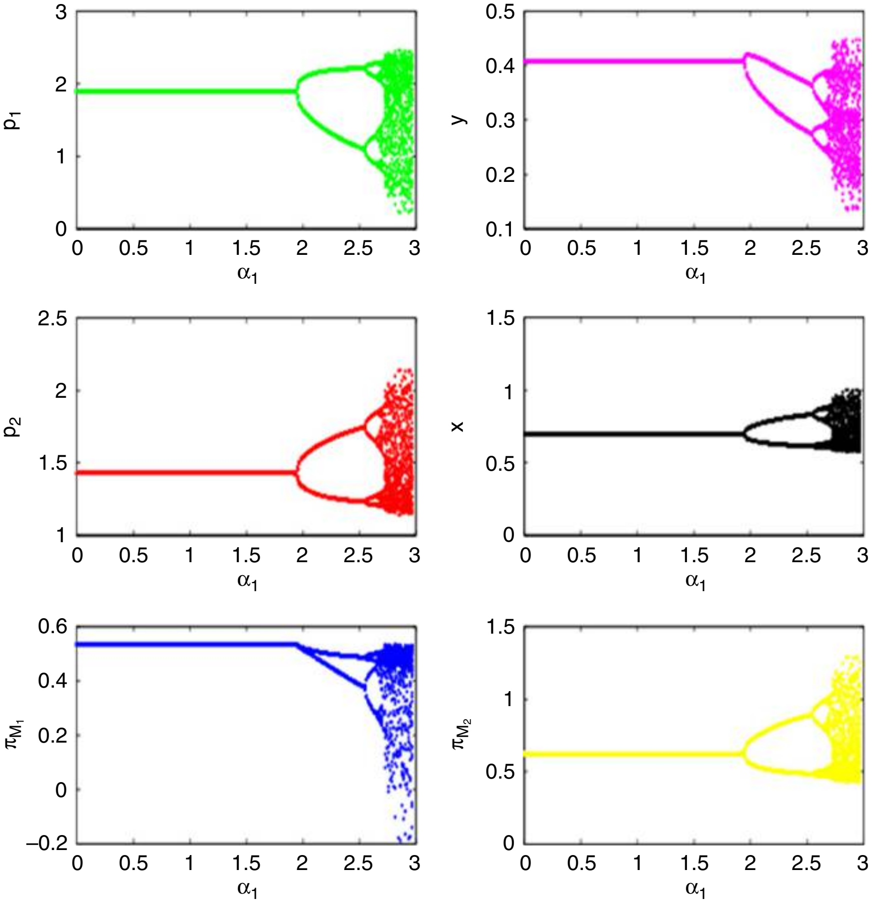
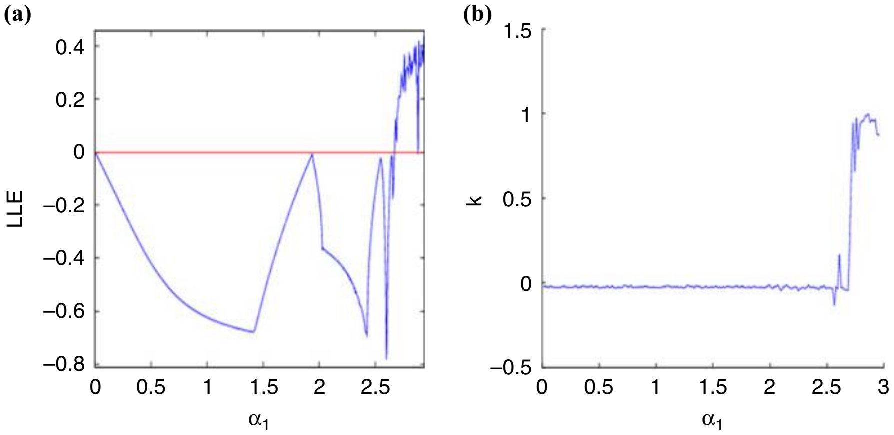


Figure 1. Bifurcation diagrams of the System (6) with $\alpha_2 = 0.8$



Notes: (a) LLE; (b) *K*

Figure 2. The largest Lyapunov exponent (LLE) and *K* of the System (6) vs $\alpha_2 = 0.8$

From Figure 2, it can be found that there is a good agreement between the *LLE* and the median value of correlation coefficient *K*.

Figure 3 is the sensitivity to initial values of System (6) when $\alpha_1 = 2.8$ and $\alpha_2 = 1.5$ and $p_1 = 1.89$ and $p_1 = 1.895$, respectively, we can see that small changes of initial values can cause the butterfly effect which brings the great changes of the system, this is an important symbol of chaotic motions.

4. M_2S game model

Suppose M_2 is the leader and M_1 is the follower and they make decisions independently. This relationship implies M_1 makes decision according to the action of M_2. In this game, M_2 makes decisions of retailer price and quality level, then M_1 makes decisions of retailer price and the CSR's level according to the decision of M_2.

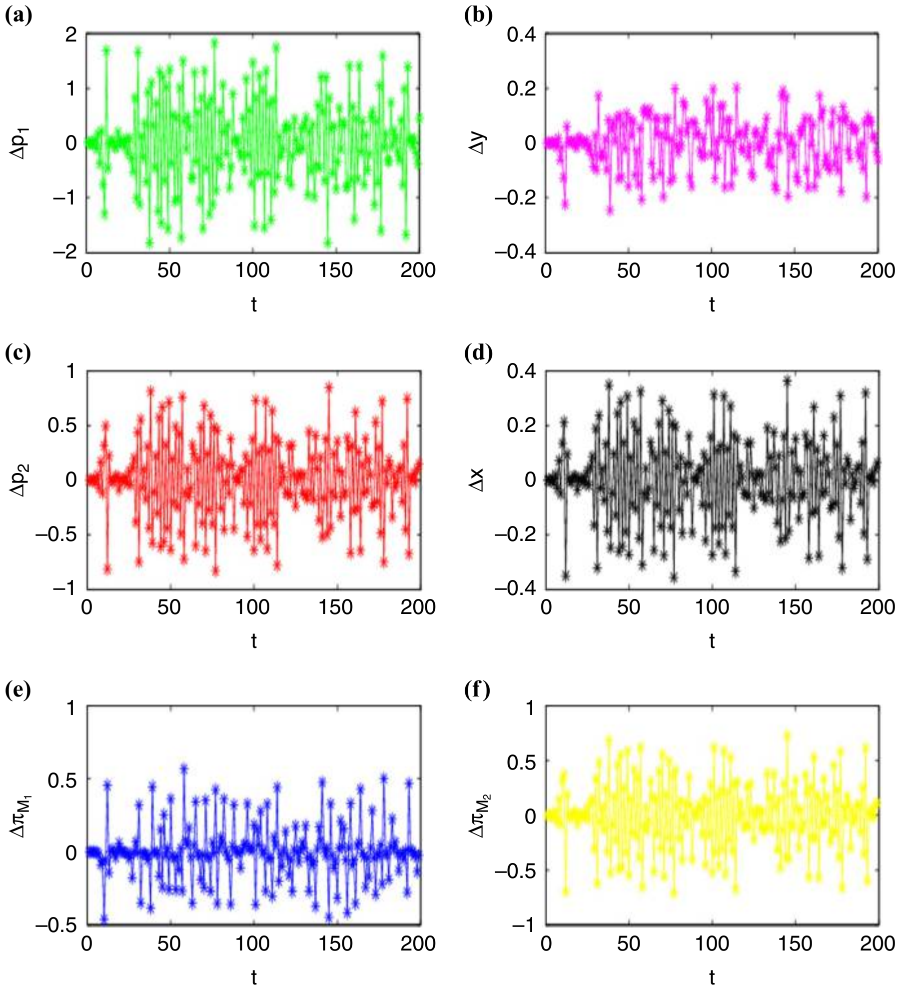


Figure 3. The sensitivity to initial values of System (6) when $\alpha_1 = 2.8$ and $\alpha_2 = 1.5$ and $p_1 = 1.89$ and $p_1 = 1.895$, respectively

4.1 Model and analysis

We can obtain M_1's marginal profit by the first-order conditions of $E_{U(\pi_1)}$:

$$\begin{cases} \frac{\partial E_{U(\pi_1)}}{\partial P_1} = a_1 - 2b_1p_1 - c_1p_2 - \frac{\sigma_1^2 p_1}{R_{M_1}} + c_2s + f_2x + d_1y, \\ \frac{\partial E_{U(\pi_1)}}{\partial y} = d_1p_1 - d_2s - ky, \end{cases} \tag{7}$$

the best reply functions of M_1 as follows:

$$\begin{cases} p_1 = \frac{R_{M_1}(-a_1k + c_1kp_2 + d_1d_2s - c_2ks - f_2kx)}{-\sigma_1^2k + d_1^2R_{M_1} - 2b_1kR_{M_1}} \\ y = \frac{-a_1d_1R_{M_1} + c_1d_1p_2R_{M_1} + d_2s\sigma_1^2 - c_2d_1R_{M_1}s + 2b_1d_2R_{M_1}s - d_1f_2R_{M_1}x}{-\sigma_1^2k + d_1^2R_{M_1} - 2b_1kR_{M_1}} \end{cases} . \tag{8}$$

Similarly, we can get M_2's marginal profit as follows:

$$\begin{cases} \frac{\partial E_{U(\pi_2)}}{\partial p_2} = a_2 - b_2p_2 - (s + p_2)\left(b_2 + \frac{c_1R_{M_1}\left(c_2k - d_1^2d_2\right)}{-\sigma_1^2k + d_1^2R_{M_1} - 2b_1kR_{M_1}}\right) + f_1x - \frac{\sigma_2^2(p_2+s)}{R_{M_2}} \\ \qquad - \frac{c_2R_{M_1}(-a_1k + c_1kp_2 + d_2s - c_2ks - f_2kx)}{-\sigma_1^2k + d_1^2R_{M_1} - 2b_1kR_{M_1}} \\ \qquad \frac{d_1d_2\left(-a_1d_1R_{M_1} + c_1d_1p_2R_{M_1} + d_2\sigma_1^2s - c_2d_1R_{M_1}s + 2b_1d_2R_{M_1}s - d_1f_2R_{M_1}x\right)}{-\sigma_1^2k + d_1^2R_{M_1} - 2b_1kR_{M_1}}, \\ \frac{\partial E_{U(\pi_2)}}{\partial x} = -h(1-\theta)x + (s + p_2)\left(f_1 + \frac{f_2R_{M_1}(c_2k - d_2)}{-\sigma_1^2k + d_1^2R_{M_1} - 2b_1kR_{M_1}}\right). \end{cases} \tag{9}$$

M_2 adjusts $p_2(t)$ and $x(t)$ on the basis of its last period marginal profit, if the marginal profit of t period is positive, M_2 will continue its adjustment strategy in period $t+1$. Then, the adjustment process can be modeled as follows:

$$\begin{cases} p_2(t+1) = p_2(t) + \alpha_1p_2(t)\frac{\partial E_{U(\pi_2)}}{\partial p_2}, \\ x(t+1) = x(t) + \alpha_2x(t)\frac{\partial E_{U(\pi_2)}}{\partial x}, \\ p_1(t) = \frac{R_{M_1}(-a_1k + c_1kp_2(t) + d_1d_2s - c_2ks - f_2kx(t))}{-\sigma_1^2k + d_1^2R_{M_1} - 2b_1kR_{M_1}}, \\ y(t) = \frac{d_1\left(-a_1R_{M_1} + d_2\sigma_1^2s - c_2R_{M_1}s + 2b_1d_2R_{M_1}s + c_1R_{M_1}p_2(t) - f_2R_{M_1}x(t)\right)}{-\sigma_1^2k + d_1^2R_{M_1} - 2b_1kR_{M_1}}, \end{cases} \tag{10}$$

where α_i, $i = 1, 2$ is the adjustment speed parameter of decision variables of M_2, which reflects the company agents' learning and active managerial behavior.

4.2 Numerical simulation

We also set the parameters the same as the System (6) for comparison and the initial values $P_2(1) = 1.3$, $x(1) = 0.6$.

Figure 4 shows the bifurcation diagrams of the System (10) with $\alpha_2 = 1.5$ and $\alpha_1 \in [0, 3.4]$. We can conclude that when $\alpha_1 < 2.17$, the System (10) is stable at the Nash equilibrium point $(p_1, y, p_2, x) = (1.626, 0.4459, 1.674, 0.6523$ and Nash

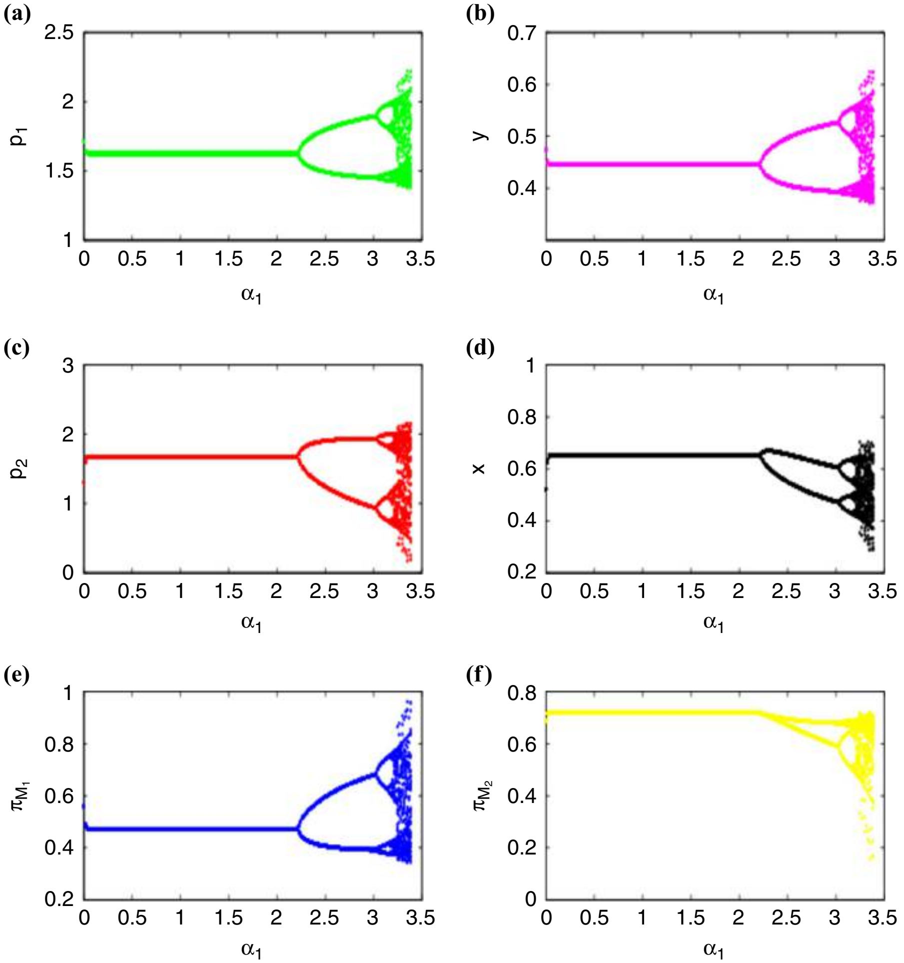
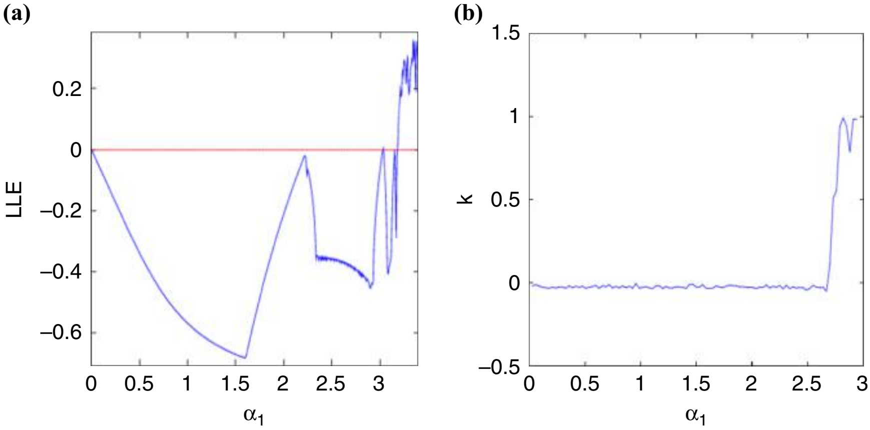


Figure 4.
Bifurcation diagrams of the System (10) with $\alpha_2 = 1.5$ and $\alpha_1 \in [0, 3.4]$

equilibrium profits $(\pi_1, \pi_2) = (0.4729, 0.7165)$. When $\alpha_1 = 2.17$, the System (10) makes the first bifurcation, then the System (10) is gradually into the chaotic state with increasing of α_1 after the cycle 2, cycle 4, etc. In chaotic period, the level of quality and the profit of M_2 is always less than the one of stable state and the profit of M_1 is always greater than the one of stable state. So M_2 is a victim and M_1 is a beneficiary.

Figure 5 shows the largest Lyapunov exponent and K of the System (10), which well coincides with the numerical simulation of the bifurcation diagram. When the *LLE* is less than 0 and K approximately equals to 0, the System (10) is in stable state; when the *LLE* is greater than 0and K approximately equals to 1, the System (10) is in chaotic state. From Figure 5, it can be found that there is a good agreement between the *LLE* and the median value of correlation coefficient K.

Figure 6 is the sensitivity to initial values of System (10) when $\alpha_1 = 3.3$ and $\alpha_2 = 1.5$ and $p_2 = 1.3$ and $p_2 = 1.305$, respectively, we can see that small changes of initial values



Notes: (a) LLE; (b) *K*

Figure 5. The largest Lyapunov exponent (LLE) and *K* of the System (10) vs $\alpha_2 = 1.5$ and $\alpha_1 \in [0, 3.4]$

can cause the butterfly effect which brings the great change of the system, this is an important symbol of chaotic motions.

5. Nash equilibrium game model

With the fully competition of the complementary product market, the status of complementary product enterprises becomes more and more important. Based on this actual situation, we give the Nash equilibrium game model in which M_1 and M_2 make decision simultaneously and do not regard the reaction of the other.

5.1 Model and analysis

The marginal profits of M_1 and M_2 are given as follows:

$$\begin{cases} \frac{\partial \pi_{M_1}}{\partial p_1} = a_1 - 2b_2 p_1 - c_1 p_2 + c_2 s + f_2 x + d_1 y - \frac{\sigma_1^2 p_1}{R_{M_1}}, \\ \frac{\partial \pi_{M_1}}{\partial y} = d_1 p_1 - d_2 s - ky, \\ \frac{\partial \pi_{M_2}}{\partial p_2} = a_2 - c_2 p_1 - 2b_2 p_2 - b_2 s + c_2 s + f_1 x + d_2 y - \frac{\sigma_1^2 (p_2 + s)}{R_{M_2}}, \\ \frac{\partial \pi_{M_2}}{x} = f_1 (p_2 + s) - h(1-\theta) x. \end{cases} \tag{11}$$

One can get the reaction functions of the two manufacturers by solving the Equation (11):

$$\begin{cases} p_1^* = \frac{R_{M_1}(a_1 - c_1 p_2 + c_2 s + f_1 f_2 x + d_1 y)}{\sigma_1^2 + 2b_1 R_{M_1}}, \\ y^* = \frac{d_1 p_1 - d_1 d_2 s}{k}, \\ p_2^* = \frac{a_2 R_{M_2} R_{M_2} - \sigma_2^2 s - b_2 R_{M_2} s - c_2 p_1 + f_1 R_{M_2} x + d_1 d_2 R_{M_2} y}{\sigma_2^2 + 2b_2 R_{M_2}}, \\ x^* = \frac{f_1 (p_2 + s)}{h(1-\theta)}. \end{cases} \tag{12}$$

In this section, we consider M_2 makes decision of price and quality level based on naive expectation (Aust *et al.*, 2014); that is, its variable decisions in period (t+1) is mainly

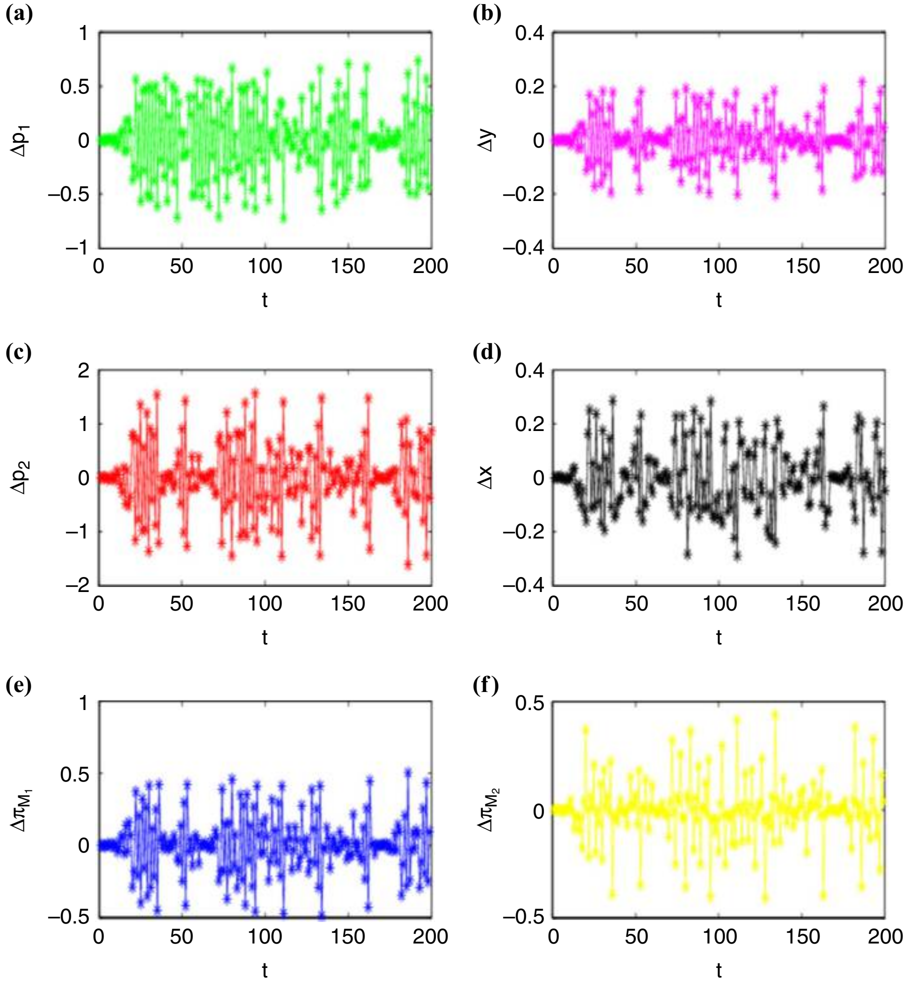


Figure 6.
The sensitivity to initial values of System (10) when $\alpha_1 = 3.3$ and $\alpha_2 = 1.5$ and $p_2 = 1.3$ and $p_2 = 1.305$, respectively

based on its optimal reaction function in period (t), namely $p_2(t+1) = p_2^*(t)$, $x(t+1) = x^*(t)$; and M_1 uses bounded rationality to make its decisions with local information based on its marginal profits, $p_1(t+1) = p_1(t) + \alpha_1 p_1(t)\left(\partial\pi_{M_1}/\partial P_1\right)$, $y(t+1) = y(t) + \alpha_1 y(t)\left(\partial\pi_{M_1}/\partial y\right)$; if the marginal profit is positive (negative), increase (decrease) the values of variables in the next period. Then, the dynamic repeated game can be modeled following nonlinear form:

$$\begin{aligned}
p_1(t+1) &= p_1(t) + \alpha_1 p_1(t)\left(a_1 + c_2 s - \frac{\sigma_1^2 p_1(t)}{R_{M_1}} - 2b_2 p_1(t) - c_1 p_2(t) + f_2 x(t) + d_1 y(t)\right),\\
y(t+1) &= y(t) + \alpha_2 y(t)(-d_2 s + d_1 p_1(t) - k y(t)),\\
p_2(t+1) &= \frac{a_2 R_{M_2} - \sigma_2^2 s - b_2 R_{M_2} s - c_2 R_{M_2} p_1(t) + f_1 R_{M_2} x(t) + d_1 d_2 R_{M_2} y(t)}{\sigma_2^2 + 2b_2 R_{M_2}},\\
x(t+1) &= \frac{f_1(s + p_2(t))}{h(1-\theta)},
\end{aligned} \tag{13}$$

where α_i, $i = 1, 2$ is the adjustment speed parameter of decision variables of M_1, which reflects the company agents' learning and active managerial behavior. In what follows, we will focus on how the adjustment speed (α_1, α_2) effect on the complex dynamics of the System (13).

5.2 Numerical simulation

We also set the parameters same as above to compare with the Systems (6) and (10) and the initial values $P_1(1) = 1.89$, $y(1) = 0.4$, $P_2(1) = 1.3$, $x(1) = 0.6$ in the System (13).

Figure 7 shows the bifurcation diagrams of the System (13) with $\alpha_2 = 1.5$ and $\alpha_1 \in [0, 2.5]$. We can conclude that when $\alpha_1 < 1.414$, the System (13) is stable at the Nash equilibrium point $(p_1, y, p_2, x) = (1.72, 0.4739, 1.53, 0.7414)$ and Nash equilibrium profits $\pi_1, \pi_2 = (0.5199, 0.7054)$. When $\alpha_1 = 1.414$, the System (13) makes the first bifurcation, then the System (13) is gradually into the chaotic state with increasing

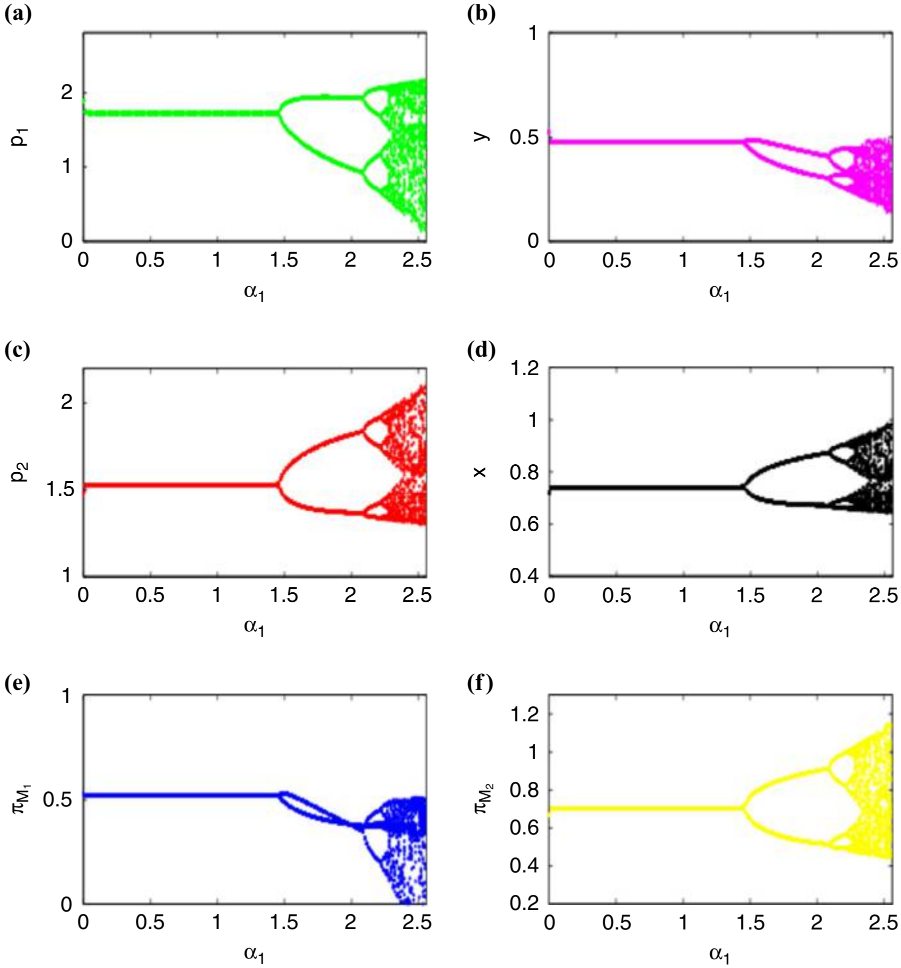


Figure 7. Bifurcation diagrams of the System (13) with $\alpha_2 = 1.5$ and $\alpha_1 \in [0, 2.5]$

of α_1 after the cycle 2, cycle 4, etc. In chaotic period, the level of *CSR* and the profit of *A* are always less than the one of stable state, so *A* is a victim in Nash equilibrium game.

Figure 8 shows the largest Lyapunov exponent and *K* of the System (13), which well coincides with the numerical simulation of the bifurcation diagram. From Figure 8, it can be found that there is a good agreement between the *LLE* and the median value of correlation coefficient *K*, in the chaotic state there exists some *LLE* less than 0 and the value of *K* is not approximately equal to 0, that is to say, there exists stable period in the chaotic state.

Figure 9 is the sensitivity to initial values of System (13) when $\alpha_1 = 3.3$ and $\alpha_2 = 1.5$ and $p_1 = 1.89$ and $p_1 = 1.895$, respectively, we can see that small changes of initial values can cause the butterfly effect which brings the great change of the system, this is an important symbol of chaotic motions.

6. Comparison of the three models

6.1 Performance measures of the three models

We carry out a qualitative study to measure the system's performance in different market structures. The values and the profits in stable state of the three models are shown in Table I. We can see that comparing M_1S with M_2S, M_1 obtains greater profit and makes lower *CSR* level in M_1S market structure, M_2 obtains greater profit and makes lower level of quality in M_2S market structure. M_1 and M_2 exert the best in quality investment and CSR level in *NS* market structure. That is to say, when the manufacturer is a leader, it will get the most profits and pay the smallest efforts. So, the different market structures will lead to the different behaviors for the two complementary manufacturers.

6.2 The comparison of the three models using parameter basin plots

A powerful tool in the numerical analysis of nonlinear dynamic is the parameter basin (Aust *et al.*, 2014), in which different colors express different cycle periods. Next, we will use the parameter basin to express the effects of variable's adjustment speed on system stability.

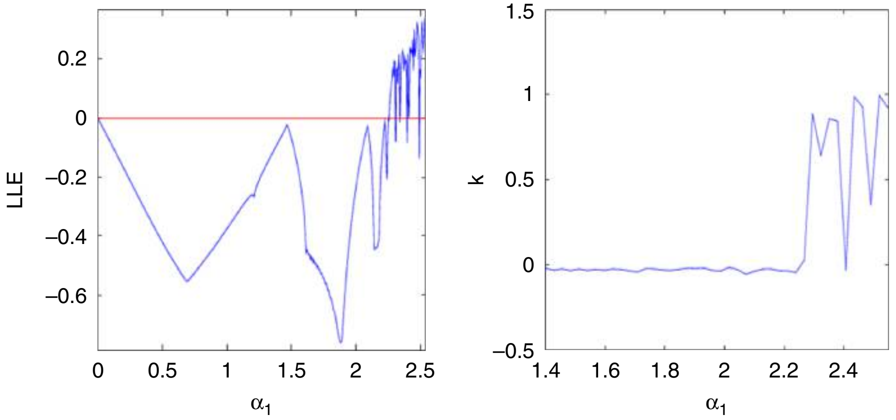


Figure 8.
The largest Lyapunov exponent (LLE) and *K* of the System (13) vs $\alpha_2 = 1.5$ and $\alpha_1 \in [0, 2.5]$

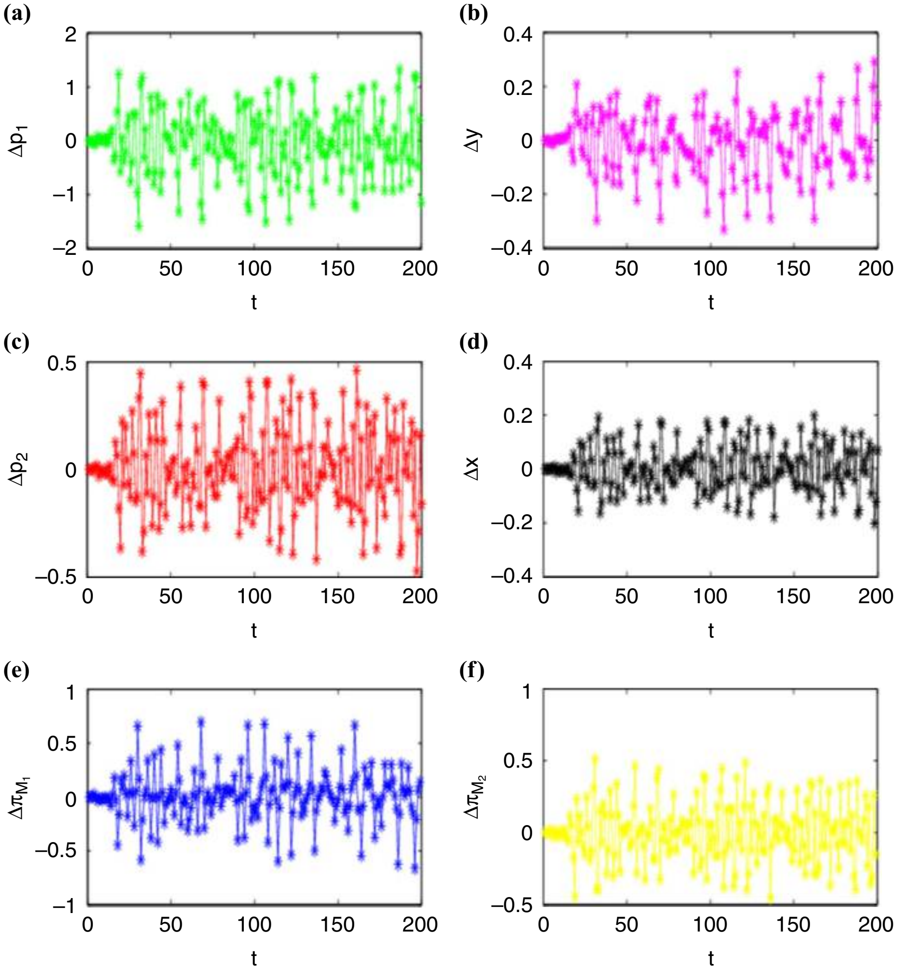


Figure 9. The sensitivity to initial values of System (13) when $\alpha_1 = 2.5$ and $\alpha_2 = 1.5$ and $p_1 = 1.89$ and $p_1 = 1.895$

Table I. The profits and Nash equilibrium value of the three models in stable period

	p_1	y	p_2	x	π_1	π_2
M_1S	1.892	0.4082	1.428	0.6975	0.5327	0.6244
NS	1.72	0.4739	1.53	0.7414	0.5199	0.7054
M_2S	1.626	0.4459	1.674	0.6523	0.4729	0.7165

Figures 10-15, respectively presents the parameter basin plots of Systems (6), (10) and (13) with respect to the parameters (α_1, α_2) and (θ, s), respectively, and assign different colors to stable states (green); periods 2 (blue), 4 (pink), 8 (yellow), chaos (red); and divergence (gray) which means one of the players will be out of the market in economics. We can see that, with the increase of the parameter (α_1, α_2), the three

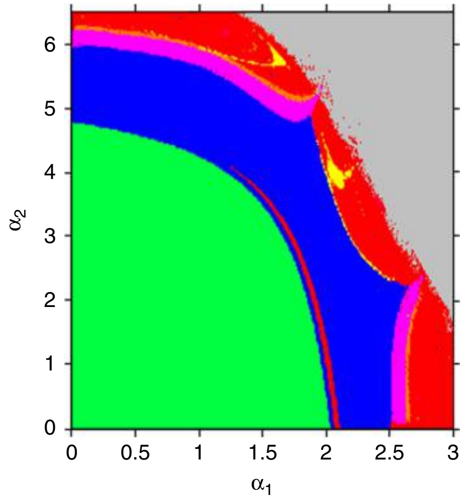


Figure 10.
The parameter basin of System (6)

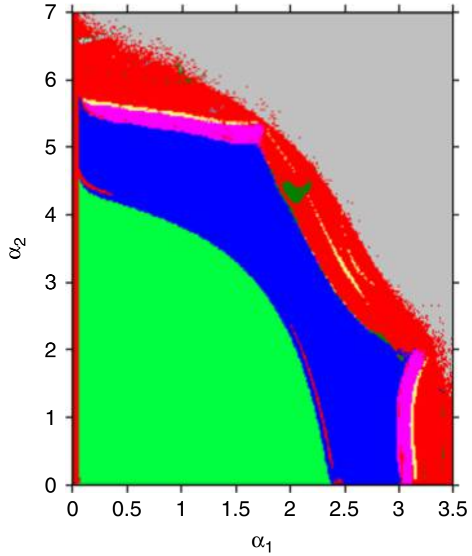


Figure 11.
The parameter basin of System (10)

systems gradually enter into chaos through flip bifurcation (called period-doubling bifurcation in continuous system).

Comparing Figures 10-12, we can find the stable region of System (13) is the smallest; the stable region of System (10) is the largest, which indicates the Stackelberg game model has better stability than the Nash game model. Comparing Figures 10 and 11, we can find the stable region of System (10) is larger than that of System (6), which shows the dominance of M_2 makes the system more stable and weak competitive. We can see that it is easier to enter chaotic state in the Nash game model than in Stackelberg game, which means there has stronger competitive in the Nash game.

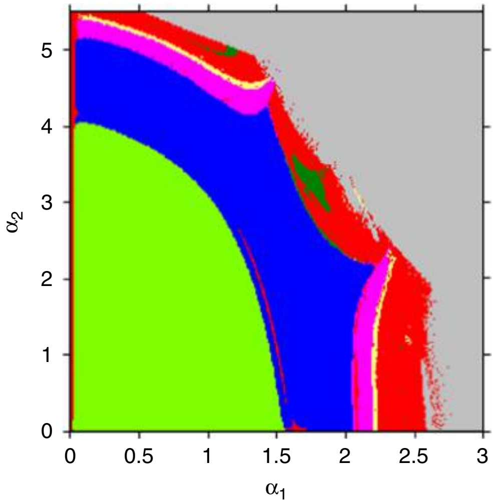


Figure 12.
The parameter basin of System (13)

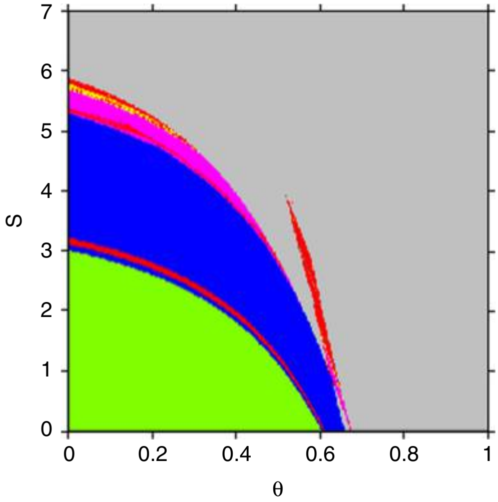


Figure 13.
The parameter basin of System (6) with $\alpha_1 = 1.2$, $\alpha_2 = 1.5$

Comparing Figures 13-15, we can find the stable region of System (13) is the smallest and the chaotic region is the biggest with $\alpha_1 = 1.2$, $\alpha_2 = 1.5$ in (θ, s) plane, which indicates the Stackelberg game model has better stability than the Nash game model with change of s and θ and Nash game is easier to disrupt the system's stability and easier to exit the market.

7. Conclusions

Considering the different competition status of the two manufacturers in the complementary product industry, the three game models are developed, namely M_1S, M_2S and Nash game. The influences of adjustment parameters on the complex nonlinear dynamics behaviors of the three models are investigated using numerable

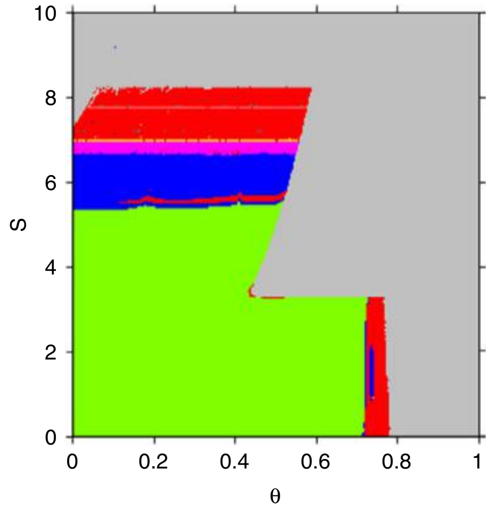


Figure 14.
The parameter basin of System (10) $\alpha_1 = 1.2$, $\alpha_2 = 1.5$

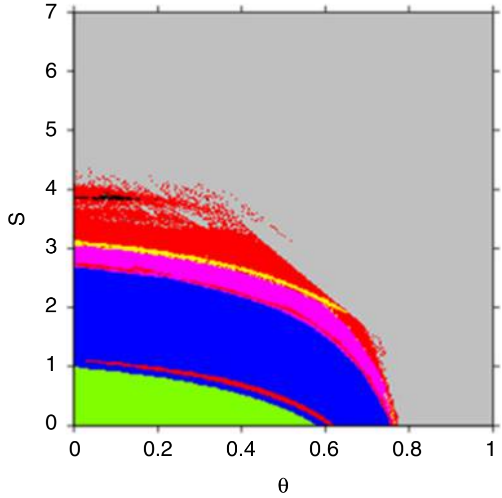


Figure 15.
The parameter basin of System (13) with $\alpha_1 = 1.2$, $\alpha_2 = 1.5$

simulation and the parameter basin plots. The results show that adjustment parameters have great effect on the system stability and should be kept in a certain range, otherwise the systems will enter into chaos through flip bifurcations. With the Nash game model, the stability of the system will become weaken and complicated, the stable range of adjustment parameters will decrease. By comparing the performances of the three models, we can obtain that the leader manufacturer will get the most profit and pay the smallest effort than follower manufacturer, but the two manufacturers will both make more effort in Nash game. The two manufacturers should choose parameter's value more cautious so that the system can be kept in stable state. The research will serve as a good guidance for the two complementary manufacturers to do the best decision making.

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