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THE COMPLEX EVOLUTION OF INFORMATION QUALITY IMPROVEMENT IN COMPETITIVE MARKET

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Abstract. Information is important market resource. High-quality information is beneficial to increase enterprise's reputation and reduce consumer's verification cost. This paper constructs a two-layer dynamic model, in which enterprises simultaneously conduct price and information game. The goal of profit maximization integrates two types of games into one system. The complex evolution of the two-layer system are studied by equilibrium analysis, stability analysis, bifurcation diagram, entropy and Lyapunov exponent. It is found that improving the information quality through regulations will increase involution and reduce stability of the market. Then, the block chain technology is introduced into the model for improving information quality of the market. It is found that increasing enterprises' willingness to adopt block chain can improve the information quality quickly and effectively, and that is verified by entropy value. Therefore, the application and promotion of new technologies are more effective than exogenous regulations for improving information quality in market.

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1. Introduction

At present, the big data, artificial intelligence, cloud computing, and Internet of Things are changing the traditional competitive relationship. The competition is no longer limited to price and output, more companies and platforms rely on information competition. Information includes information volume and information quality. Information competition is embedded in price or output competition and this complex relationship is also called as hyper-competition [1].

Enterprises or platforms often or even continuously disclose information such as the instructions, product specifications, production process, sales records and comments through text, picture, sound, and video for increasing sales and obtaining optimal profits. For example, "Amazon" and "Shopee" attract consumers through disclosing product quality, price, comments. "Tmall" and "Tik Tok" platforms broadcast 24 h a day for expanding customer source. But there may be some inaccurate or false information in these published information. A large amount of low-quality information increases enterprise's cost, reduces enterprise's reputation, and increases consumer verification cost.

Keywords. Competition, information quality, complexity, chaos, involution.

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Informatization makes the interaction of all parties more actively. Various factors are quickly transmitted and amplified through information transmission. The market appears more complex characteristics than before. Recent years, emergencies led to butterfly effect. A sudden initial event may trigger a disaster that is uncertain, unrepeatable, and unpredictable. For example, the COVID-19 hit the global capital markets and cause violent turmoil. On February 3, 2020, a huge amplitude of 7.72% has taken place in Shanghai Composite Index of China (data from Oriental Fortune Online Stock Index). The shock caused price fluctuations in oil, agricultural product, protective product and gold. With the complexity of economic fluctuations, the information defects in the market will be enlarged. How to improve information quality of the market, prevent systemic risks, and ensure the stability of economic models are important issues for all countries.

There are two ways to guarantee the information quality of enterprises in the market:

The first method is government regulation. The government sets standards for the information quality in the market. The second method is block chain that is an effective method to ensure the credibility of information. It has the characteristics of decentralization, non-tampering, traceability, openness and transparency. These characteristics mean "honesty" and "transparency", and build the foundation of information trust [2]. However, there are studies that believed the diffusion of new technologies would lead to market complexity [3].

Then, in the context of the digital economy, when information competition is embedded in traditional competition (price or output competition), how to effectively improve information quality and stabilize market are problems worth studying.

Therefore, based on evolutionary games and complexity theory, the article discusses two evolutionary paths for improving quality of information: "Government setting standard" and "Adopting block chain technology". Especially, quite different from existing methods, the information entropy is used to measure the confusion degree in the process of information quality improvement, and the effective path is analyzed for improving information quality in the competitive market from the perspective of complexity. This research provides a strategic reference for establishing stable market competition under big data background.

2. Related research

There are three types of research relevant to this study: disequilibrium and uncertainty in economy, the complexity of dynamic iterative model, information competition.

2.1. Disequilibrium and uncertainty in economy

Static economics focuses on market equilibrium, but in practice, disequilibrium is the norm. The market evolution from equilibrium to non-equilibrium, and the characteristics of non-equilibrium are focuses of complex economics. Some scholars have discovered that the disequilibrium in the economic and financial system appeared chaotic characteristics. Chaos means random and unstable. In chaotic markets, small initial events can lead to unpredictable outcomes. Ahmad found that when interest rates, savings and investment demand change, the stability of the financial system will evolve into chaotic fluctuations [4]. Through big data technology, Tie found that the chaos degree in the Chinese market increased during the COVID-19, and market fluctuations were related to the domestic macro environment [5]. Rodriguez detected the chaotic fluctuations of Colombia's coffee price by ant colony algorithm [6]. Lahmiri found that Bitcoin's price and number of transactions had chaotic and fractal characteristics through big data analysis [7].

Recent years, extreme events occur frequently. The available labor, raw materials, and demand fluctuate drastically. The violent fluctuations cause uncertainty in the market. Many studies have verified this phenomenon. Using the Time-Varying Parameter Vector Auto Regressive (TVP-VAR) method, Liu found that the panic from the Covid-19 caused complex fluctuations in the prices of Chinese agricultural products, and he concluded that timely information disclosure of agricultural product was beneficial to alleviate farmers' negative emotions [8]. Liao believed that extreme events had systemic impacts on the global financial market, and proved that sudden events have brought huge risks to the oil, gold and stock markets [9]. Ma found that prices of natural resource products were more sensitive to the impact of Covid-19 than other products [10]. Ouzia and Maculan studied the optimal solution of the Euclidean Steiner tree problem with nonlinear characteristics, which is often used for economic optimization problems in network engineering [11]. For system dynamic and complex risks, Kheir and Mahjoub used RGA graph to analyze system complex risk, risk evolution, and risk early warning [12]. Arabadzhyan analyzed the fluctuation of hotel prices in Milan during the Covid-19 outbreak and found that travel restrictions and order cancellations caused hotel prices uncertainty [13].

2.2. The complexity of dynamic iterative model

The dynamic iterative model is usually used to analyze the non-equilibrium of the market. The iterative model is mostly based on differential equations such as dynamic Cournot model, Bernard model and Stackelberg model. Based on the studies from the pioneer scholar Puu [14] and the latest scholars', rapid changes in market price (or output) are the main reason for market equilibrium breaking, periods and random chaotic fluctuations. Other reasons, such as taxation, policy subsidies, etc., can also increase or reduce the complexity. Such as, Askar built a output iterative game model in which one company pursues profit maximization, another company pursues social utility maximization, and analyzed the complex dynamics of the model [15]. In the price competition model, Xi proved that the speed of price adjustment and the intensity of government subsidies could cause uncertainty, the impact intensity was less than the price adjustment speed [16]. Ma studied the complex characteristics of a dual-channel supply chain. In direct sales channels, the price adjustment speed was an important factor that affects the stability of supply chain. In online channels, the service quality adjustment speed was an important factor that affects stability [17].

Some scholars use entropy to measure the complex properties of economic model. Overbury [18] believed that in a closed-loop economic system, minimizing entropy could reduce economic costs, save resources, and control disasters. Teza [19] measured the complexity of national economic efficiency and product diversification through Shannon entropy, and demonstrated its results in a network model between two layers composed of 5016 (products) and 223 (countries) nodes. For waste utilization, Busu [20] constructed a mathematical model of circular economy, based on the second law of thermodynamics, he evaluated the process of circular economy in the EU, and verified the correctness of the results through Shannon entropy. Lou [21] analyzed the bullwhip effect by entropy theory and complexity theory in the dual-channel supply chain system, and found that the bounded rationality parameters had an important impact on the bullwhip effect.

2.3. Information competition

Enterprise competition has the characteristics of diversification, non-linear and non-equilibrium. Price competition, output competition and information competition coexist in the market. Knowledge and information are important sources of enterprises for sustainable competitive. Harvard Business School in the United States regards information competition as one of the major elements of survival (information, talent, capital and technology). D'Aveni believed that enterprise dynamic competition (including price competition, output competition and information competition) is a complex system [22]. The theory of information disclosure believed that market's forces promoted the information disclosure. Jesal believed that high frequency of information disclosure could increase the welfare of information recipients [23]. Information disclosure also exists in the supply chain research. Yu believed that increasing competition degree of the supply chain would reduce participants' willingness to disclose information [24]. In market, the degree of information publicity such as product quality and business reputation would directly affect the equilibrium price in the competition [25]. Fu believed that information disclosure, information collection, and forecasting often occurred before price or output competition [26]. From above studies, traditional competition (price or output game) and information competition constitute a complex economic system. This paper will study the complex characteristics of this multi-layer model. As shown in Figure 1.

The characteristics of the existing studies and their focus are shown in Table 1.

In this study, information competition is embedded into price competition, and the impact of two ways of improving information quality (regulation and block chain technology) on market efficiency is analyzed. The

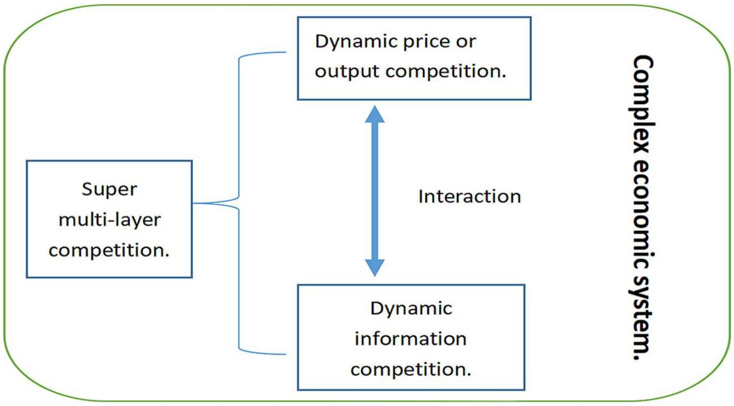

FIGURE 1. The structure diagram of multi-layer competition game.

TABLE 1. The literature review.

Study	Focus point	Comment	This study
Ahmad [4]; Tie [5]; Rodrłguez [6]; Lahmiri [7]	Disequilibrium in the economic system	Equilibrium is infrequent	The complexity of multi-layer price and information competition model
Liu [8]; Liao [9]; Ma [10]; Ouzia and Maculan [11] Kheir *et al.* [12] Arabadzhyan [13]	Uncertainty or nonlinear in system	Uncertainty and nonlinear are always present	
Puu [14]; Askar [15]; Xi [16]; Ma [17]	Complex dynamics in the price (or output) game	Rapid price or output changes can cause chaos	
Overbury [18]; Teza [19]; Busu [20]; Lou [21]	Complex dynamics in economic model	The complexity is measured by entropy	
D'aveni [22]; Jesal [23]; Yu [24]; Alibeiki [25]; Fu [26]	Information competition and price(output) competition coexist	Multi-layer com-petition model	

structure of the article is as follows: the First section is the introduction; the Second section is the literature review; the Third section is the two-layer competition model of price and information; the Forth section is the multi-layer competition model based on block chain technology and the Fifth section is the conclusion.

TABLE 2. The notation declaration.

The notation	The explanation
$\text{info}_1, \text{info}_2$	Information disclosure amount of enterprise 1 and enterprise 2
e	The cross-information sensitivity of information disclosure amount
Q_u	Information disclosure quality
β	The cross-market sensitivity of output
λ	The cross-information sensitivity of output
c_1, c_2	The production cost
c_b	The technology cost of block chain
q_1, q_2	Outputs of enterprise 1 and enterprise 2
Π_1, Π_2	Profits of enterprise 1 and enterprise 2
α, β	Price adjustment speed parameters
ε, η	The adjustment speed parameters of the information publication amount
ω	The adoption rate among companies
ν	$\nu(\nu \in [0,1])$, the degree of information trust
σ	Cross-information sensitivity
τ	$\tau \geq 1$, and τ is a constant
θ	The parameter of choice intensity

3. The notation and explanation

The variables and explanations in Table 2 will be used in Sections 4 and 5.

4. The two-layer competition model of price and information

4.1. The model

Suppose there are two companies that compete on price. "info_1" and "info_2" are the amount of disclosed information in enterprise 1 and enterprise 2, and e is the cross-information sensitivity of information amount. Therefore, $\text{info}_1 = \text{info}_1 + e \times \text{info}_2$, $\text{info}_2 = \text{info}_2 + e \times \text{info}_1$.

The output functions are:

$$q_1 = a - p_1 + \beta p_2 + Q_u(\text{info}_1 - \lambda \times \text{info}_2) \tag{1}$$

$$q_2 = a - p_2 + \beta p_1 + Q_u(\text{info}_2 - \lambda \times \text{info}_1). \tag{2}$$

The profit functions are:

$$\begin{cases} \Pi_1 = (p_1 - c_1 - c_b)q_1 - 0.5\tau \times \text{info}_1^2 \\ \Pi_2 = (p_2 - c_2)q_2 - 0.5\tau \times \text{info}_2^2. \end{cases} \tag{3}$$

Q_u is the quality of disclosed information, and it is assumed that the information quality is improved through government regulations. β is cross-market sensitivity of output, λ is cross-information sensitivity of output, τ is a constant, $c_i (i = 1, 2)$ is production cost, c_b is block chain technology cost.

The company's pricing and information disclosure are aimed at maximizing profits. The explanations of all variables in the model are shown in Table 2.

The bounded rational expectation is the classic expectation rule and it can lead to the complex behavior of dynamic difference models, that is, the decision maker adjusts current output according to the marginal profit of the previous period. The model is as follows:

$$\begin{cases} p_1' = p_1 + \alpha p_1 \frac{\mathrm{d}\Pi_1}{\mathrm{d}p_1} \\ p_2' = p_2 + \varepsilon p_2 \frac{\mathrm{d}\Pi_2}{\mathrm{d}p_2} \\ \mathrm{info}_1' = \mathrm{info}_1 + \eta \times \mathrm{info}_1 \frac{\mathrm{d}\Pi_1}{\mathrm{d}(\mathrm{info}_1)} \\ \mathrm{info}_2' = \mathrm{info}_2 + \mu \times \mathrm{info}_2 \frac{\mathrm{d}\Pi_2}{\mathrm{d}(\mathrm{info}_2)}. \end{cases} \tag{4}$$

p_i' (or info_i') means the unit-time advancement of variable p_i (or info_i), $i = 1, 2$. Parameters α and ε are price adjustment speed parameters. η and μ are the adjustment speed parameters of the information publication amount.

That is,

$$\begin{cases} p_1' = p_1 + \alpha p_1 \{a + c_1 - 2p_1 + Q_u[\mathrm{info}_1 + e \times \mathrm{info}_2 - \lambda(\mathrm{info}_2 + e \times \mathrm{info}_1 + e^2 \times \mathrm{info}_2)] + \beta p_2\} \\ p_2' = p_2 + \varepsilon p_2 \{a + c_2 - 2p_2 + Q_u[\mathrm{info}_2 + e \times (\mathrm{info}_1 + e \times \mathrm{info}_2) - \lambda(\mathrm{info}_1 + e \times \mathrm{info}_2)] + \beta p_1\} \\ \mathrm{info}_1' = \mathrm{info}_1 + \eta \times \mathrm{info}_1 \{Q_u(e \times \lambda - 1)(c_1 - p_1) - [\tau \times (\mathrm{info}_1 + e \times \mathrm{info}_2)]\} \\ \mathrm{info}_2' = \mathrm{info}_2 + \mu \times \mathrm{info}_2 \{-\tau(e^2 + 1)[\mathrm{info}_2 + e(\mathrm{info}_1 + e \times \mathrm{info}_2)] - Q_u(c_2 - p_2)(e^2 - \lambda \times e + 1)\}. \end{cases} \tag{5}$$

4.2. The stability of the model

The Nash equilibrium is considered a strategy group: a change in strategy of either party will not increase the profit of each participant. Therefore, all participants maintain their current strategy for optimal profit. The Nash equilibrium solution of the model is obtained by solving equation (6).

$$\begin{cases} p_1' = p_1 \\ p_2' = p_2 \\ \mathrm{info}_1' = \mathrm{info}_1 \\ \mathrm{info}_2' = \mathrm{info}_2. \end{cases} \tag{6}$$

That is,

$$\begin{cases} \frac{\mathrm{d}\Pi_1}{\mathrm{d}p_1} = 0 \\ \frac{\mathrm{d}\Pi_2}{\mathrm{d}p_2} = 0 \\ \frac{\mathrm{d}\Pi_1}{\mathrm{d}(\mathrm{info}_1)} = 0 \\ \frac{\mathrm{d}\Pi_2}{\mathrm{d}(\mathrm{info}_2)} = 0. \end{cases} \tag{7}$$

In existing research, the equilibrium solution of the model can be obtained by equation (7). But in this study, the model is a complex game with multiple layers and multiple interactions between price and information. The analytical solution obtained by above method is too large for the software to handle. In complex mathematical models, the strategy for cost minimization and profit maximization is usually analyzed by computational experimental methods. Inspired by literatures [27–31], this study will find the optimal solution, perform parameter analysis and stability analysis through mathematical calculation software Matlab.

The comparison between the traditional method and the simulation about the stability of Nash equilibrium is described in Table 3.

4.3. Numerical simulation

4.3.1. The bifurcation

Let $a = 1, \lambda = 0.6, \tau = 0.5, c_b = 0.2, \beta = 0.8, e = 0.35, c_1 = 0.15, c_2 = 0.16.$

TABLE 3. The method comparison.

The step	The existing research	The research method of this article	
	Method	Method	The reason
Step 1. Find the analytical solution of Nash equilibrium	Let the marginal profit equal to zero, that is, "The equation (7) = 0"	Simulation	The multi-layer complex system leads to a huge analytical solution
Step 2. Stability analysis of the Nash equilibrium	1. Find the Jacobian matrix; 2. Build the characteristic equation of the Jacobian matrix; 3. Find the stable region of the Nash equilibrium according to Jury condition [32]	Simulation	The analytical solution is too complicated, and the Jacobian matrix, characteristic equation, Jury condition are beyond the calculation capabilities of software

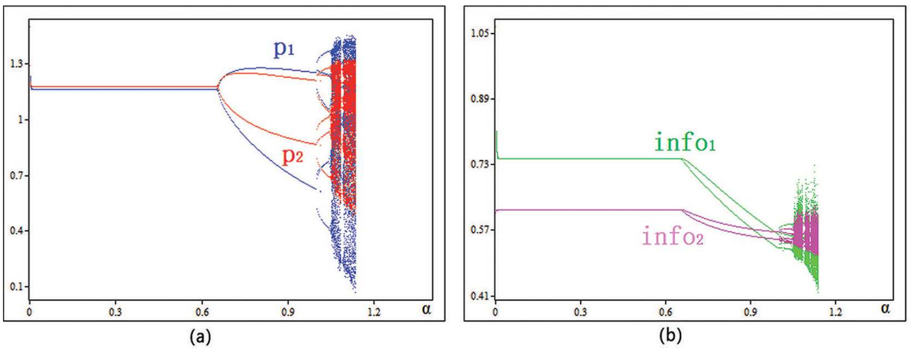

FIGURE 2. The bifurcation diagrams with changing α: (a) p_1 and p_2; (b) info_1 and info_2.

By putting the parameters into the equation (7), the value of the Nash equilibrium is obtained: (p_1, p_2, info_1, info_2), $p_1 = 1.1476$, $p_2 = 1.1621$, $\text{info}_1 = 0.7194$, $\text{info}_2 = 0.6465$.

Figures 2a and 2b are bifurcation diagrams of the model with changing α. It can be seen that the equilibrium point evolves to chaotic fluctuations through periodic bifurcation (*i.e.* Flip bifurcation). Figures 3a and 3b are bifurcation diagrams with changing parameter η. The model enters chaotic fluctuations through Flip (in Fig. 3a) or Neimark-Sacker bifurcation (in Fig. 3b).

4.3.2. Uncertainty measure by entropy

Entropy comes from physics and describes the disorder degree of a system. The essence of things is entropy, that is the availability, state and distribution of energy, not energy itself [33]. The law of increasing entropy is also called "the second law of thermodynamics": any closed system must move towards a state where no valid information is produced anymore. The system shows gradual loss of functionality, increased disorder, and decreased order.

In the economic field, energy in physics becomes price and information amount. The more chaotic the price and the information amount, the higher the entropy; the more stable the price and the information amount, the lower the entropy. An increase in entropy means an increase in involution degree. It means that it is difficult for the market to upgrade to a more advanced model. The entropy value calculation method that is adopted in

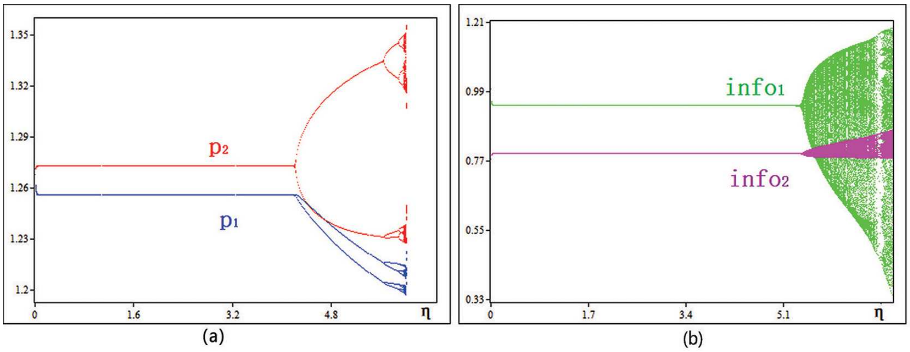

FIGURE 3. The bifurcation diagrams with changing η: (a) p_1 and p_2: the Flip bifurcation; (b) info_1 and info_2: the Neimark-Sacker bifurcation.

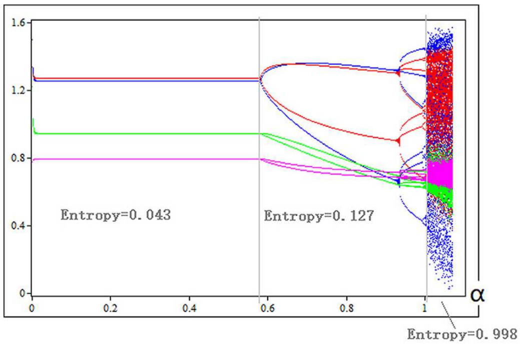

FIGURE 4. Bifurcation and entropy with changing α.

this research as equation (8) described [33–35]:

$$H(x) = -\sum_{i=1}^{n} p(x_i) \log\ p(x_i). \tag{8}$$

"$p(x_i)$" means the probability of a random event "x_i". In this article, random variable "x_i" means price or information amount, and "$p(x_i)$" means a probability function of price or information amount.

The entropy values of bifurcation graph are shown in Figures 4 and 5. In Figure 4, the bifurcation diagram of the market is divided into three stages, equilibrium stage, periodic stage and chaos stage. The entropy value of the Nash equilibrium stage is the smallest: "Entropy = 0.043". In this area, the price, output and information resources of all parties are optimally allocated, and the operation efficiency of the multi-layer competition system is the highest. In periodic fluctuation stage, the average entropy increased to "0.127". In this stage, the demand and supply cannot be well matched, and the price and information fluctuate. In the last stage, the chaotic region has the largest average entropy value: "Entropy = 0.998". Due to the chaos between supply and demand of all parties, it is impossible for companies to make accurate decision for the future. Work efficiency is reduced, resources are wasted, and the entire system is unstable in chaos stage.

Figures 5a and 5b show the same trend. In Figure 5a,

$$\text{“Entropy}_{\text{NashEquibrium}} = 0.034\text{”} < \text{“Entropy}_{\text{Chaos}} = 0.82\text{”}.$$

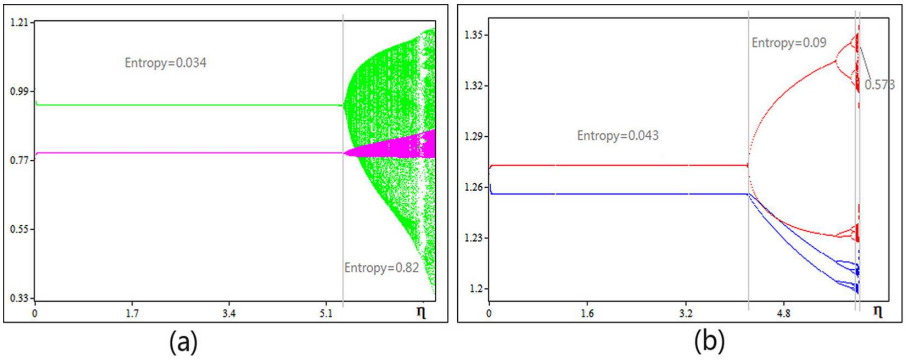

FIGURE 5. Bifurcation and entropy with changing η: (a) info_1 and info_2; (b) p_1 and p_2.

In Figure 5b,

$$\text{“Entropy}_{\text{NashEquibrium}} = 0.043\text{”} < \text{“Entropy}_{\text{Period}} = 0.09\text{”} < \text{“Entropy}_{\text{Chaos}} = 0.573\text{”}.$$

Summarizing the conclusions of Figures 4 and 5:

$$\text{“Entropy}_{\text{NashEquibrium}}\text{”} < \text{“Entropy}_{\text{Period}}\text{” (if it exists)} < \text{“Entropy}_{\text{Chaos}}\text{”}.$$

4.3.3. The parameter basin

Figures 6a–6d are parameter base diagrams of (α, ε) when the information quality equals to 0.2, 0.4, 0.6 and 0.9, respectively. Red means stable, yellow means 2 periods, green means 4 periods, blue means 8 periods, purple means 16 periods, white means chaos. And gray means spillover, that is at least one party exits the market. It can be found from the data on the vertical and horizontal coordinates that the stability domain gradually decreases with increasing the information quality levels set by the government. Blue arrows mean an increase in entropy.

Figures 7a–7c are the parameter base diagrams of (η, μ) when the information quality equals to 0.6, 0.8 and 0.9, respectively. The shape of the stability domain changed from Figures 7a and 7b (Q_u changed from 0.6 to 0.8) and system stability decreased with increasing information quality required through government regulations.

In Figures 6 and 7, the direction of the blue arrow indicates an increase of entropy, that is, the direction of greater internal resource consumption and lower operating efficiency. The stable area in red means predictable and optimized operating efficiency. In the model, the information quality is improved relying on government regulations. It can be concluded that increased outward standards and regulations will weaken market stability. When the entropy value increases, the internal consumption of the market increases, and the waste of resources increases.

In practice, to improve the quality of information, in addition to rules, the market can also rely on technology, such as block chain. In next section, the article will analyze the example of using block chain to improve information quality.

5. Multi-layer competition model based on block chain technology

Block chain technology has unforgettable and traceable characteristics. This section will investigate the dynamic characteristics of the price-information game with block chain technology.

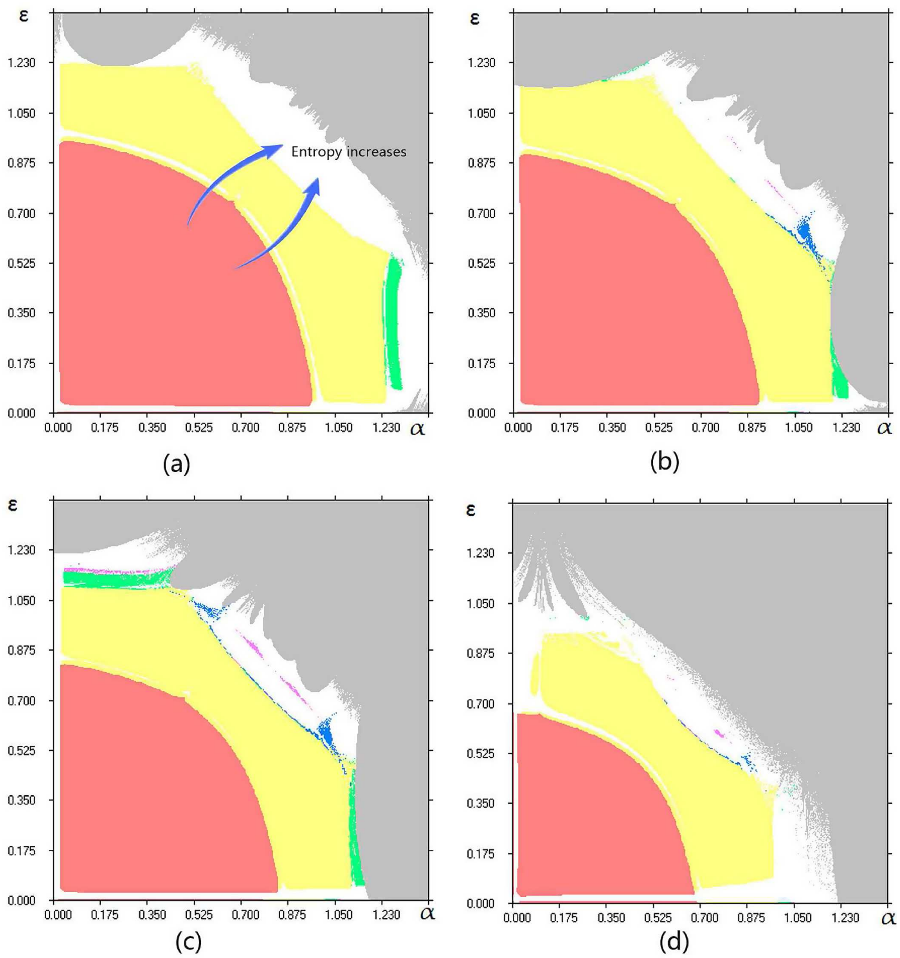

FIGURE 6. The parameter base of (α, ε): (a) $Q_u = 0.2$; (b) $Q_u = 0.4$; (c) $Q_u = 0.6$; (d) $Q_u = 0.9$.

5.1. The model

Suppose there are two types of companies. The first type adopts block chain technology to authenticate its public information, consumers do not have any doubts about the information. The other type does not use block chain technology, and consumers may have doubts about the information. Firms can choose between two categories.

In (9), ω is the adoption rate among companies, which follows the asynchronous update mechanism [3]. Therefore, the dynamic model is

$$\begin{cases} p_i(t+1) = P[p_1(t), p_2(t), \text{info}_1(t), \text{info}_2(t), \omega(t)] \\ \text{info}_i(t+1) = P[\text{info}_1(t), \text{info}_2(t), p_1(t), p_2(t), \omega(t)] \\ \omega(t+1) = \frac{\omega(t) \times e^{\theta \times \Pi_1(t)}}{\omega(t) \times e^{\theta \times \Pi_1(t)} + [1-\omega(t)] \times e^{\theta \times \Pi_2(t)}} \\ i = 1, 2. \end{cases} \tag{9}$$

The output function is:

$$q_1 = a - p_1 + \beta p_2 + \text{info}_1 - \nu\sigma \text{info}_2 \tag{10}$$

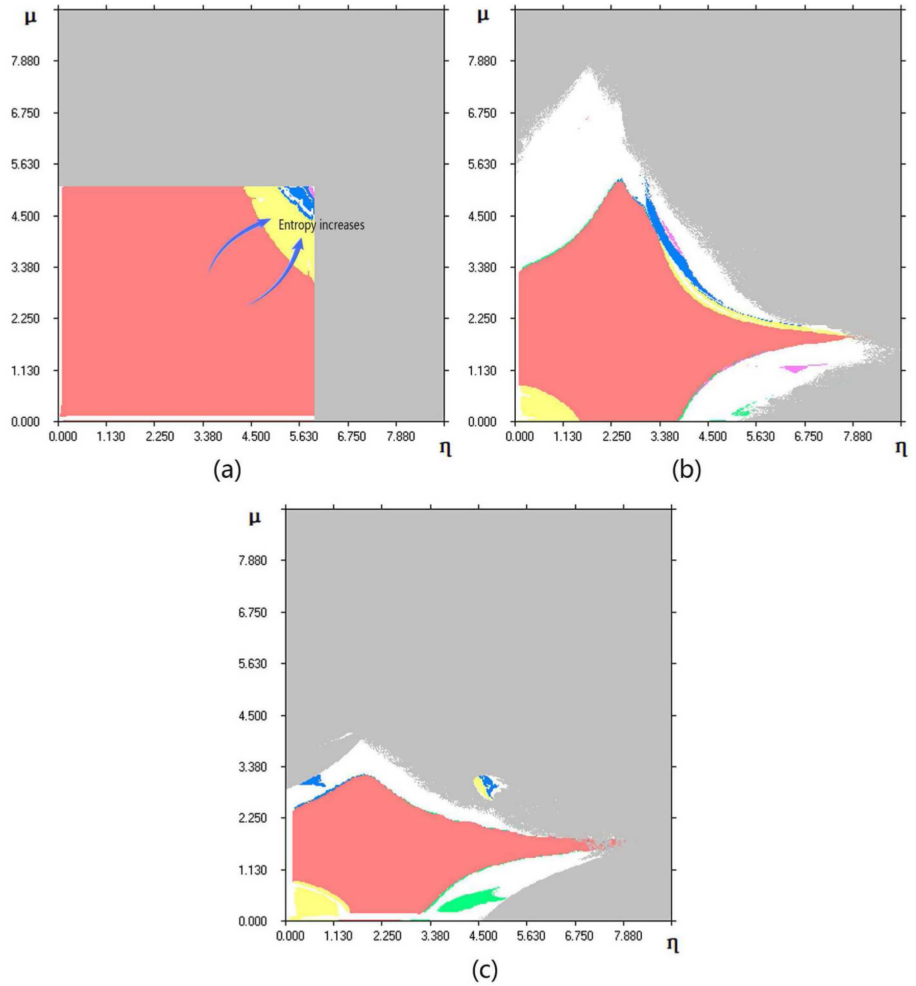

Figure 7. The parameter base of (η, μ): (a) $Q_u = 0.6$; (b) $Q_u = 0.8$; (c) $Q_u = 0.9$.

$$q_2 = a - p_2 + \beta p_1 + \nu \text{info}_1 - \sigma \text{info}_1. \tag{11}$$

In (9) and (10), $\nu(\nu \in [0,1])$ is the degree of information trust. Enterprise 1 adopts block chain technology, the trust level of information is 1. σ is cross-information sensitivity. The cost of public information is $0.5\tau\text{info}_i^2$ that is a universal quadratic form [see Ref. [2]]. $\tau \geq 1$, and τ is a constant.

The profit function is:

$$\begin{cases} \Pi_1 = (p_1 - c_1 - c_b)q_1 - 0.5\tau\text{info}_1^2 \\ \Pi_2 = (p_2 - c_2)q_2 - 0.5\tau\text{info}_2^2. \end{cases} \tag{12}$$

$c_i(i = 1, 2)$ is the cost, c_b is the technical cost of the block chain. Based on bounded rational expectations, the dynamic equation of the system is:

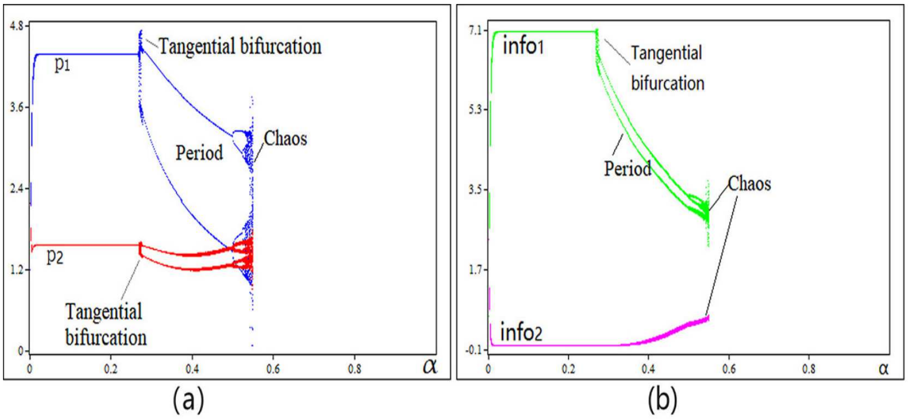

FIGURE 8. The bifurcation diagrams with changing when $\omega = 0.1$: (a) The bifurcation diagram of p_1 and p_2; (b) The bifurcation diagram of info_1 and info_2.

$$\begin{cases} p_1' = p_1 + \alpha p_1\{a + c_1 + c_b + \text{info}_1 - 2p_1 + e \times \text{info}_2 + \beta p_2 - \nu \times \sigma \\ \qquad \times [\text{info}_2 + e \times (\text{info}_1 + e \times \text{info}_2)]\big\} \\ p_2' = p_2 + \varepsilon p_2\{a + c_2 - 2p_2 + \beta p_1 + \nu \times [\text{info}_2 + e \times (\text{info}_1 + e \times \text{info}_2)] - \sigma \times (\text{info}_1 + e \times \text{info}_2)\} \\ \text{info}_1' = \text{info}_1 + \eta \times \text{info}_1 \times [(\nu \times \sigma \times e - 1) \times (c_1 + c_b - p_1) - \tau(\text{info}_1 + e \times \text{info}_2)] \\ \text{info}_2' = \text{info}_2 + \mu \times \text{info}_2 \times \big\{\big[\sigma \times e - \nu \times \big(e^2 + 1\big)\big] \times (c_2 - p_2) - \tau \times \big(e^2 + 1\big) \\ \qquad \times [\text{info}_2 + e \times (\text{info}_1 + e \times \text{info}_2)]\big\} \\ \omega' = \frac{\omega \times e^{\theta \times \Pi_1}}{\omega \times e^{\theta \times \Pi_1} + (1-\omega) \times e^{\theta \times \Pi_2}}. \end{cases} \tag{13}$$

5.2. The simulation

In this section, numerical simulation is used to investigate the dynamic characteristics of the model. Figures 8a and 8b are the bifurcation diagrams of the model with changing the price adjustment coefficient. When $\alpha < 0.27$, the system is in Nash equilibrium. When $\alpha \geq 0.27$, the system undergoes a sudden change through tangential bifurcation, then enters periodic and chaotic fluctuations. Figures 9a and 9b are chaotic attractors.

It can be seen from Figure 10 that adjustment speed factor η of information amount in the first category of enterprises can cause dynamic fluctuations in the product price and information. Similar to Figure 8, tangential bifurcation occurred.

5.3. The entropy of uncertainty

Taking Figure 8 as an example, the bifurcation diagram is divided into four stages, and the average information entropy of each stage is calculated separately (see [35, 36]). The four stages are separated by gray lines. Their average information entropies are 0.026, 0.088, 0.084, 0.342, respectively, as shown in Figure 11. And Figure 12 is the Lyapunov exponent.

The information entropy of the Nash equilibrium is low as 0.026, and the Lyapunov exponent is less than zero at this time. Then, the model appears a sudden change, and the mutation stage marked by tangential bifurcation has a higher uncertainty (Entropy = 0.088) that is only less than the chaotic stage, the Lyapunov exponent in the same period greater than zero. The average entropy of the periodic phase is 0.084 and the Lyapunov exponent is less than 0. In the chaotic state, the average information entropy increases to 0.342 and

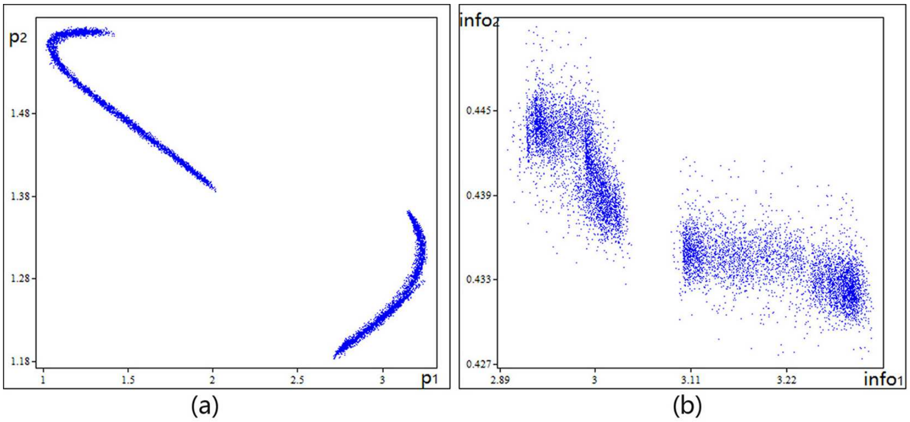

FIGURE 9. The chaotic attractors where $\alpha = 0.54$: (a) (p_1, p_2); (b) $(\text{info}_1, \text{info}_2)$.

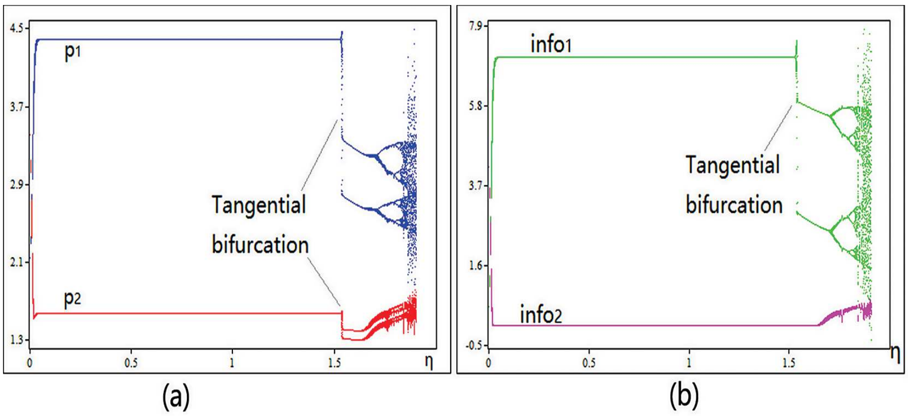

FIGURE 10. The bifurcation diagrams with changing η when $\omega = 0.5$: (a) The bifurcation diagram of p_1 and p_2; (b) The bifurcation diagram of info_1 and info_2.

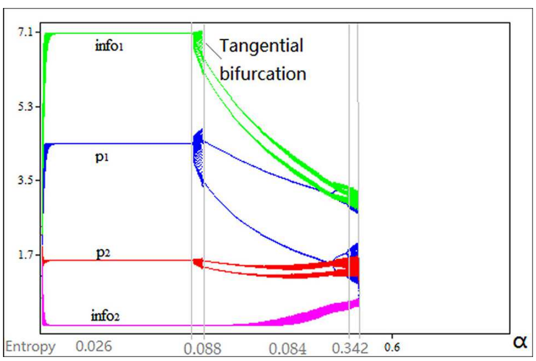

FIGURE 11. The bifurcation diagram with changing α.

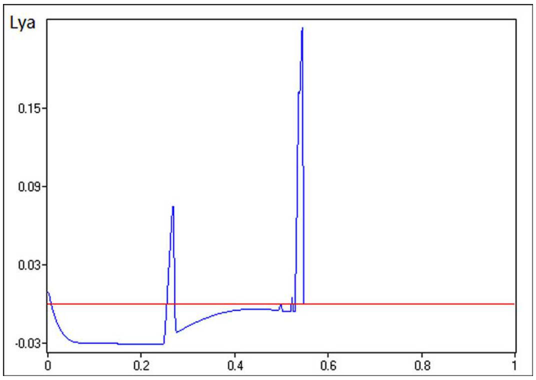

FIGURE 12. The Lyapunov exponent of Figure 11.

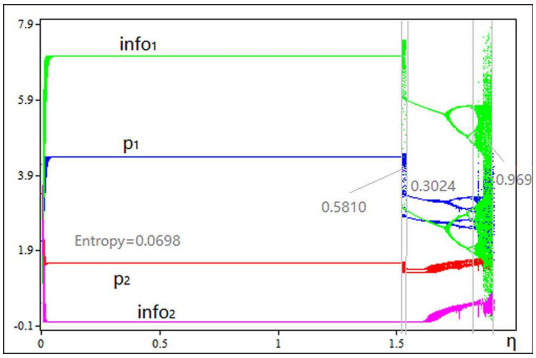

FIGURE 13. The bifurcation diagram with changing η.

the Lyapunov exponent of the model is greater than zero again. The price and information in the market are full of uncertain risks.

Figure 13 is a bifurcation diagram with changing η (information amount adjustment factor). Again, the tangential bifurcation reappears, and it has a relatively high uncertainty: "Entropy = 0.5810". The Lyapunov exponent in Figure 14 also broke through zero during the tangential bifurcation stage, indicating that a brief chaotic fluctuation has occurred. The chaotic region has the largest entropy value: "Entropy = 0.969".

5.4. The adaption rate and its entropy

The adoption rate of a technology is related to its economic position in the market. When the profit of adopting block chain technology is greater than the profit of refusal, players in the market gradually tend to adoption, and the adoption rate gradually evolves to 100%.

Figure 15 is the price and adoption rate of this model when $\theta = 0.1$. "θ" is the parameter of choice intensity. When $\theta = 0$, the enterprise's willingness of adoption remains unchanged "$\omega(t+1) = \omega(t)$". And $\theta = 1$ means that enterprises adopt block chain technology without hesitation.

Then, let adoption intensity coefficients θ equals to 0.1, 0.5, and 0.9, respectively. Observe Figures 16a–16c: as technology adoption intensity increases, the trajectories of adoption rate become thinner during the transition phase from 0% to 100%. In Figure 17, the efficiency of the transition phase is measured by the Shannon entropy.

It can be seen from Figures 17a–17c that the entropy value in the transition phase is continuously decreasing. The three graphs are merged into one graph for comparison, as shown in Figure 18.

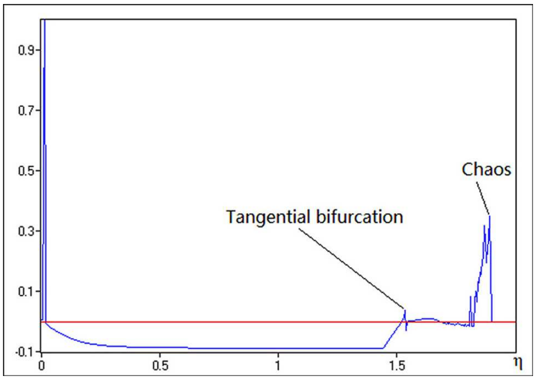

FIGURE 14. The Lyapunov exponent of Figure 13.

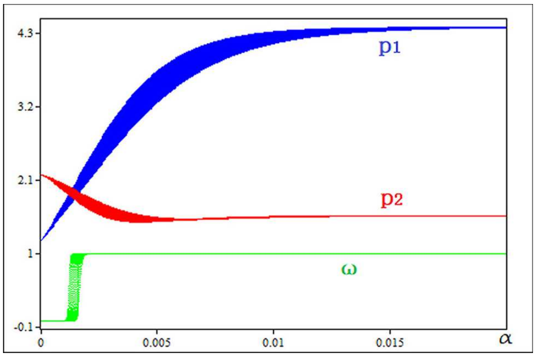

FIGURE 15. Prices and adoption rate with $\theta = 0.1$.

As the adoption willingness parameter θ increases, the entropy value of adoption rate in the transitional stage decreases. A reduction in entropy means a reduction in meaningless consumption. That is to say, a high adoption willingness coefficient can save system resources, reduce unnecessary consumption and improve operating efficiency. The government can enhance the willingness of adopt block chain technology through technical publicity, technical training, successful demonstration, thereby reducing the difficulty of improving information quality in the market.

6. The conclusion

This paper constructs a two-layer dynamic game model, that is a combination of price game and information game. With the goal of maximizing profit, the dynamic evolution of the two-layer model is analyzed. There two ways to improve the quality of market information, including: information quality standard by government and the block chain technology. The complex fluctuation risk and characteristics of two information quality improvement paths are analyzed. The study found that increasing government standards for information quality would reduce market stability. Block chain technology can ensure the quality of information. The stronger the willingness to adopt block chain technology, the higher the upgrading efficiency of block chain technology for market information management. The complex evolutionary of the two pathes are measured by entropy, bifurcation graphs, parameter bases and Lyapunov. The comparison results are shown in Table 4: Strengthening the supervision of information quality will increase meaningless consumption. For improving the quality of

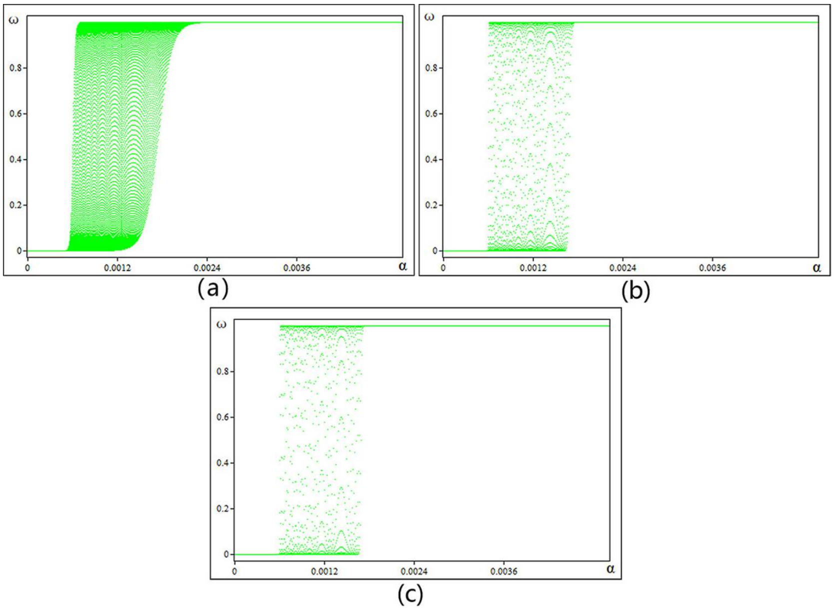

FIGURE 16. Changes in adoption rates: (a) $\theta = 0.1$; (b) $\theta = 0.5$; (c) $\theta = 0.9$.

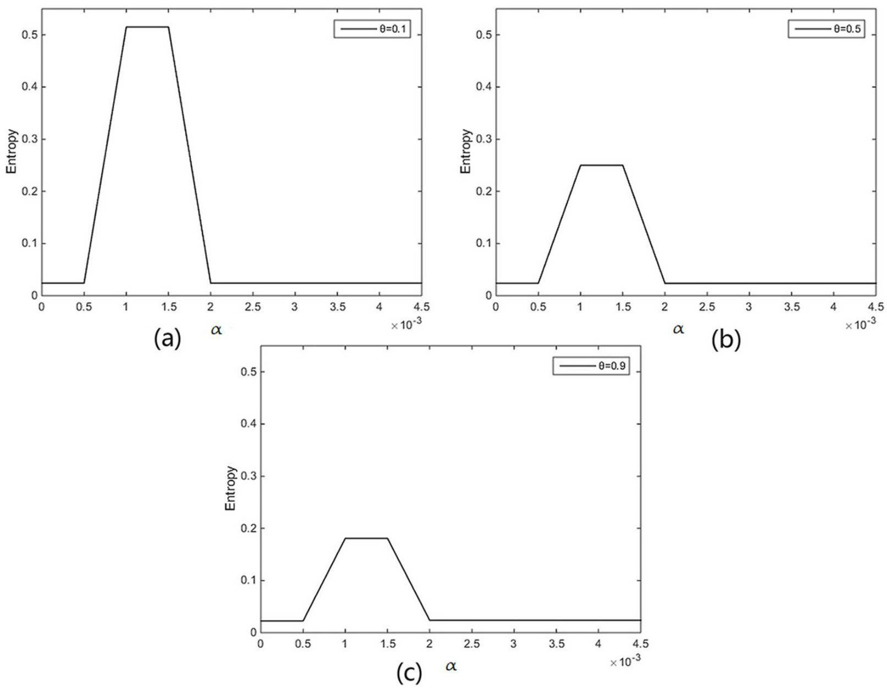

FIGURE 17. The entropy value: (a) $\theta = 0.1$; (b) $\theta = 0.5$; (c) $\theta = 0.9$.

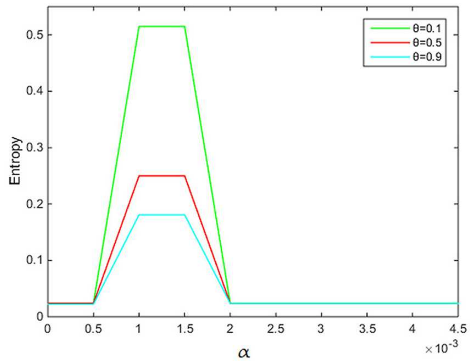

FIGURE 18. The entropy of adaption rate.

TABLE 4. The comparison of entropy.

The model	The key factor	The law of entropy	The result
1. Improve information quality through government regulations	The exogenous factors: government-promulgated quality standards: "Qu"	When the information quality is improved, the system evolves in the direction of decreasing entropy. The internal consumption of the system increases and resources are wasted	Cultivating adopters' sensitivity about technology is more efficient than external information quality regulations
2. Improve information quality through block chain technology	The endogenous factors: willingness of adopting technology: "θ"	The increased willingness of technology choice is conducive to guarantee information quality, and the system evolves in the direction of entropy reduction. Market efficiency is improved and resources are saved	

market information, increasing the willingness of adopting block chain technology is more effective than government regulations. Two models in the article are based on the bounded rational expectations. The expectations theory are the key for firms to learn, imitate, and evolve in the marketplace, and are the main cause of market dynamics. The intelligent market expectation driven by big data and artificial intelligence is the content of the next research. This article provides a reference for the dynamic mechanism of market informatization.

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Conflicts of Interest. The authors declare that they have no conflicts of interest.

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