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Regulation Research of Coal Market Based on System Dynamics in China

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Abstract: In this paper, we establish a nonlinear dynamic system of coal price, coal supply and economic growth based on the complex relationship of each other. Then we analyze the dynamic behavior of these variables in the system by using Lyapunov exponent and bifurcation diagram. The actual system parameters is determined by genetic algorithm based on the statistical data of China in 1990-2015. Then we simulate the evolution trajectory of coal price, coal supply and economic growth in actual market, analyze the influence of various regulatory policies on the variables and draw a conclusion that the development of new energy sources and the use of clean energy can make the coal market stable.

Keywords: coal market; genetic algorithm; numerical simulation; control strategy

1 Introduction

Coal is one of the most important strategic resources in the world, which can sustain the survival and development of global economy. Since twentieth Century, the development and utilization of coal have been developed rapidly, and have become an important factor in the world economy. Its superiority is very obvious no matter as a kind of power fuel or chemical raw material. With the development of economy, the progress of science and technology, a series of problems such as how to coordinate the price of coal in the coal market, the relationship between coal supply and economic growth, how to study the fluctuation mechanism of coal price deeply and how to evaluate the affect of coal price fluctuations to economic growth are the hot researches on coal market.

In recent years, many domestic and foreign scholars have done a lot of researches on the coal market. Liu constructed a coal price index data information system by building a coal price mechanism of system model and analyzed the control patterns on different economic conditions[1]. Qin expounded the strategy of coal market and stable supply through an in-depth analysis of coal supply and the influence of the national economy, combined with the current China's coal supply and demand, price and consumption problems[2]. Fang etc. proposed a new three-dimensional evolution system of energy saving and emission reduction based on the interdependent relationship among energy saving and emission reduction, carbon emissions and economic growth[3-5]. Chor etc. used the data from 1971-2011 to study the relationship between energy consumption and economic growth in Vietnam[6]. Wonglimpiyarat analyzed the impact of technological progress on energy supply through the use of Kuhn-Schumpeter method, and found that technological innovation can effectively replace coal resources and reduce the risk of coal supply gap[7]. Festic selected the electricity price, coal consumption, the price of oil, natural gas, energy efficiency, nuclear energy and renewable energy consumption as explanatory variables by using principal component analysis method to estimate the trend of fluctuations in coal prices[8].

This paper establishes a nonlinear dynamical system of coal market supply and demand from the mutually interacting relationship of coal price-coal supply-economic growth in order to study the effect of coal price in coal market and gives suggestions for the stable development of the coal market.

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2 Modeling and stability analysis

2.1 Establishment of the model

The coal market is a complex system which includes many factors such as coal price, coal supply and demand, economic growth, coal utilization rate and so on. There is a complex nonlinear relationship among the various variables. Fig.1 below shows the transmission relationship among the various factors, '+'has a positive correlation between the two factors, '-'has a negative correlation between the two factors. According to the causality in the coal market, first of all, $x(t)$ is the

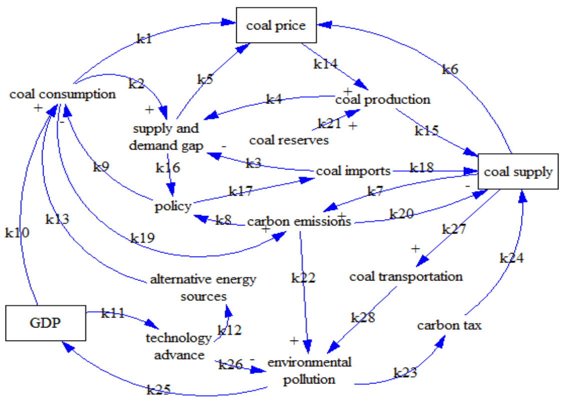


Figure 1: Causal relationship among variables of coal price - coal supply - economic growth

time-dependent coal price in the market, $y(t)$ is the time-dependent coal supply in the market, $z(t)$ is the time-dependent economic growth in the domestic market. We establish a nonlinear system:

$$\begin{cases} \dot{x} = a_1 x + a_2 x(K_1 - y) + a_3 z, & (2.1a) \\ \dot{y} = b_1(x - K_2) - b_2 y - b_3 z(1 - \frac{z}{M}), & (2.1b) \\ \dot{z} = c_1 z(N - z) + c_2 yz. & (2.1c) \end{cases}$$

In the equation, $a_i, b_i, c_j, i = 1, 2, 3, j = 1, 2, K_1, K_2, M, N$ are positive constants. a_1 is the inherent growth of coal price; a_2 is the influence coefficient of coal supply change on coal price; a_3 is the influence coefficient of economic growth on coal price; b_1 is the influence coefficient of coal price change on coal supply; b_2 is the retardation factor of energy supply growth; b_3 is the influence coefficient of economic development on coal supply; c_1 is the coefficient of economic development of its own; c_2 is the influence coefficient of coal supply on economic development; N is the maximum value of regional economic growth under the condition of a determined coal supply; M is the threshold value of coal price affected by economic development; K_1 is the threshold value of coal price affected by coal supply; K_2 is the threshold value of coal price affected by economic development.

The basic idea of the model is as follows:

Eq.$(2.1a)$ indicates that coal price has a growth or decline trend and the coal supply in the market will have an impact on coal price. When $K_1 - y > 0$, it indicates that the coal supply on the market is less than the threshold K_1 of coal demand in the market. At this point the supply of coal can not meet the market demand meanwhile coal prices will show a rising trend in shot supply. With the gradual increase of coal supply, the rising trend of coal price tends to decline. When $K_1 - y < 0$, it shows that the coal supply in the market exceeds the threshold K_1 of coal demand, at this time the coal market over supply which leading to a decline in coal price. $a_1 x$ represents that the price of coal itself has a growth trend. $a_1 z$ represents the rise of coal price due to the increase of economic growth.

Eq.$(2.1b)$: $b_1(x - K_2)$ represents that the rise or fall in coal prices could have an impact on the coal supply (where coal prices rise without regard to major international events such as wars). When $x - K_2 < 0$, the market price of coal is less than its threshold. At this time, the coal supply shows a declining trend which leading a rise in coal price. When $x - K_2 > 0$, the price of coal is greater than the threshold, which will promote the growth of coal supply. $b_2 y$ represents that the coal supply in the market decreases with time due to the continuous consumption of coal. $b_3z(1-\frac{z}{M})$ shows the effect of economic development on coal supply. When the level of economic development is low, i.e. $1-\frac{z}{M}>0$, rapid economic growth will consume large amounts of coal, resulting in a reduction in the supply of coal. When the level of economic development is high, i.e. $1-\frac{z}{M}<0$, the development of clean energy will slow the decreasing trend of coal supply.

Eq.$(2.1c)$: $c_1z(N-z)$ represents the retardation of economic development on its own. The higher the level of economic development, the lower the extent of economic growth; c_2yz shows the role of coal supply in promoting economic development.

2.2 Equilibrium and stability analysis

Let

$$\begin{cases} \dot{x}=a_1x+a_2x(K_1-y)+a_3z=0, \\ \dot{y}=b_1(x-K_2)-b_2y-b_3z(1-\frac{z}{M})=0, \\ \dot{z}=c_1z(N-z)+c_2yz=0. \end{cases} \tag{2.2}$$

Three equilibrium points of the system are obtained: $S_1=(x_1,y_1,z_1)$, $S_2=(x_2,y_2,z_2)$, $S_3=(x_3,y_3,z_3)$, where $x_1=-\frac{a_2(K_1b_2+K_2b_1)}{a_1b_2-a_2b_1}$, $y_1=-\frac{b_1(K_1a_2+K_2a_1)}{a_1b_2-a_2b_1}$, $z_1=0$; $x_2=-\frac{K_1a_2}{a_1}-\frac{Na_2c_1}{a_1c_2}-\frac{a_3(F1+E1)}{2a_1^2c_2b_3}+\frac{a_2c_1(F1+E1)}{2a_1^2c_2^2b_3}$, $y_2=-\frac{Nc_1}{c_2}-\frac{c_1(F1+E1)}{2a_1b_3c_2^2}-\frac{a_3(E1-F1)}{2a_1^2c_2b_3}+\frac{a_2c_1(E1-F1)}{2a_1^2c_1^2b_3}$, $z_2=\frac{E1+F1}{2a_1b_3c_3}$; $x_3=-\frac{K_1a_2}{a_1}-\frac{Na_2c_1}{a_1c_2}-\frac{a_3(E1-F1)}{2a_1^2c_2b_3}$ $y_3=-\frac{Nc_1}{c_2}+\frac{c_1(E1-F1)}{2a_1b_3c_2^2}$, $z_3=\frac{E1-F1}{2a_1b_3c_3}$. Among them, $E1$ and $F1$ are combinations of coefficients in the system.

System (2.1) is a very complex nonlinear dynamic system. When the parameters are different, the system will have different dynamic behaviors. In order to facilitate the study, the parameters of the system are fixed as: $a_1=0.064$, $a_2=0.7001323$, $a_3=0.0051$, $b_1=0.3797$, $b_2=0.1234$, $b_3=0.1689$, $c_1=0.2751$, $c_2=0.0082$, $K_1=0.5122$, $K_2=0.4535$, $M=0.1758$, $N=0.6364$.

In the case of parameter determination, the system has three real solutions: $S_1=(0.7356,0.8681,0)$, $S_2=(-0.1795,0.4504,0.6948)$, $S_3=(-1676.00,-811.16,-23.54)$.

The approximate linear coefficient matrix of the system is $J_i=\begin{pmatrix} a_1 & -a_2 & a_3 \\ b_1 & -b_2 & -b_3+\frac{2b_3z}{M} \\ 0 & c_2z & c_1N-2c_1z+c_2y \end{pmatrix}$.

Case 1 : For equilibrium $S_1(0.7356,0.8681,0)$, the corresponding eigenvalues are $\lambda_1=-0.0297+0.2036i$, $\lambda_2=-0.0297-0.2036i$, $\lambda_3=0.1822$, the system is in an unstable state.

Case 2 : For equilibrium $S_2(-0.1795,0.4504,0.6498)$, the corresponding eigenvalues are $\lambda_1=-0.0190+0.1981i$, $\lambda_2=-0.0190-0.1981i$, $\lambda_3=-0.2002$, the system is in a stable state.

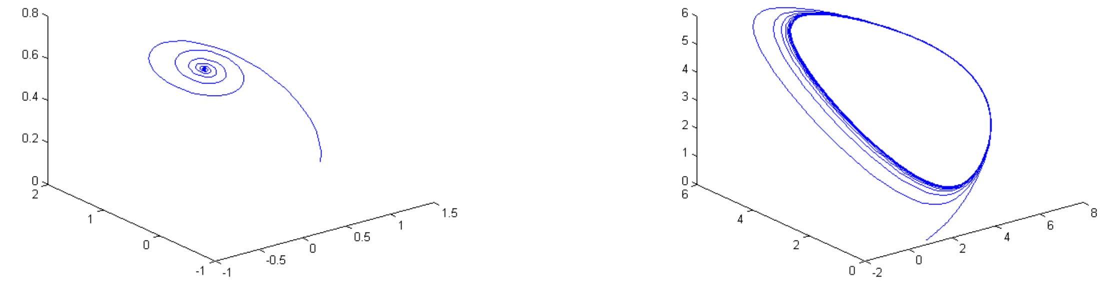
Case 3 : For equilibrium $S_3(-1676.00,-811.16,-23.45)$, the corresponding eigenvalues are $\lambda_1=0.0309$, $\lambda_2=-1.2228$, $\lambda_3=7.6078$, the system is in an unstable state.

According to the above analysis, the state of the system at the equilibrium point depends entirely on the value of the system parameters.

2.3 Numerical simulation

System (2.1) is sensitive to the parameters and initial values, even minor changes in parameters can alter the state of the system. Now we fix the value of parameters as we obtained in Section 2.2, select $(0.86,0.03,0.14)$ as the initial value, draw the images of system under the condition of $a_1=0.064$ and $a_1=0.110$ respectively as shown in Fig.2(a) and Fig.2(b).

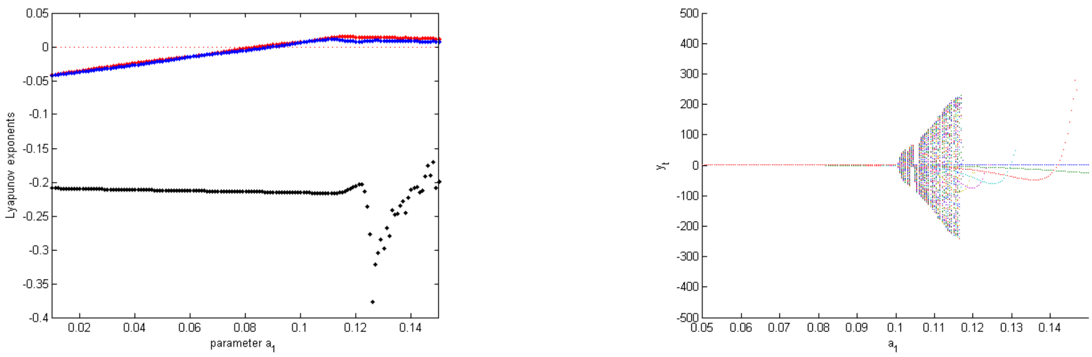
The results show that under the condition of keeping other parameters constant, when $a_1=0.064$, the system exists a fixed point; when $a_1=0.110$, the system exists a limit cycle. The sensitivity of the system to the parameters can also be obtained by Lyapunov exponent and single parameter bifurcation diagram of a_1. In Fig.3(a) we can see that when $a_1=0.064$, the maximum Lyapunov exponent of the system is negative and there exists a stable equilibrium point in the system. In Fig.3(b) we can see that when $a_1=0.116$, the maximum exponent of system is positive and an obvious bifurcation appears. The system is unstable.



(a) a_1= 0.064: fixed point

(b) a_1= 0.110: limit cycle

Figure 2: The fixed point and limit cycle of system



(a) Lyapunov exponents of a_1

(b) Bifurcation of a_1

Figure 3: The Lyapunov exponents and bifurcation of a_1

3 Application of the model

3.1 Parameter identification of the dynamic system

The dynamic evolution system (2.1) is based on the complex relationship among coal price, coal supply and economic growth. The determination of the parameters in the system is very important to the actual coal market. The parameters in the actual situation can obtained with the help of network and genetic algorithm.

First of all, the system is discretized and the difference equation is obtained as follows:

$$\begin{cases} x(k+1) = x(k) + \Delta T[a_1 x(k) + a_2 x(k)(K_1 - y(k)) + a_3 z(k)], \\ y(k+1) = y(k) + \Delta T[b_1(x(k) - K_2) - b_2 Y(k) - b_3 z(k)(1 - \frac{z(k)}{M})], \\ z(k+1) = z(k) + \Delta T[c_1 z(k)(N - z(k)) + c_2 y(k) z(k)]. \end{cases} \quad (3.1)$$

The coal price index, the total coal production and the gross domestic product (GDP) index of China in $1990 - 2015$ is selected as the research object and the data sources were from 'China Statistical Yearbook'. In order to make the variables in the system consistent, the variables are normalized. Using the deviation standardization method, the original data is transformed linearly, so that the data is uniformly mapped to the [0,1] interval. Then we put the parameters into the differential equation of discretization, get the following parameters after several debugging, running when the error reaches 10^{-5} :

$$\begin{cases} a_1 = 0.1088, \quad a_2 = 0.6318, \quad a_3 = 0.1343, \quad b_1 = 0.0986, \quad b_2 = 0.1683, \quad b_3 = 0.1962, \\ c_1 = 0.3164, \quad c_2 = 0.2510, \quad K_1 = 0.1265, \quad K_2 = 0.1420, \quad M = 0.3175, \quad N = 0.2176. \end{cases} \quad (3.2)$$

Putting the above parameters into the system and taking the data of 2000 as the initial condition $[0.2436, 0.1236, 0.4466]$, numerical simulation of the evolution of the relationship among them is shown in Fig.4:

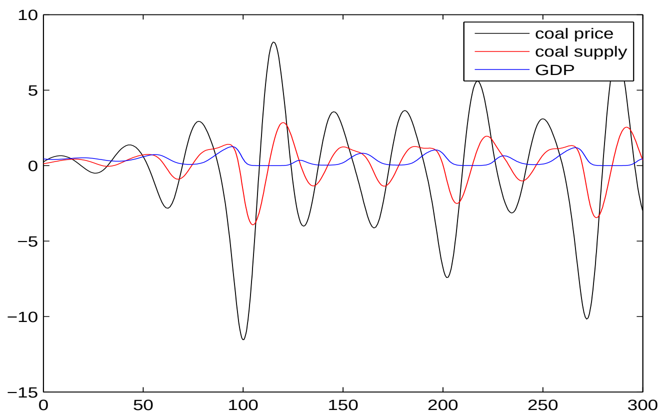
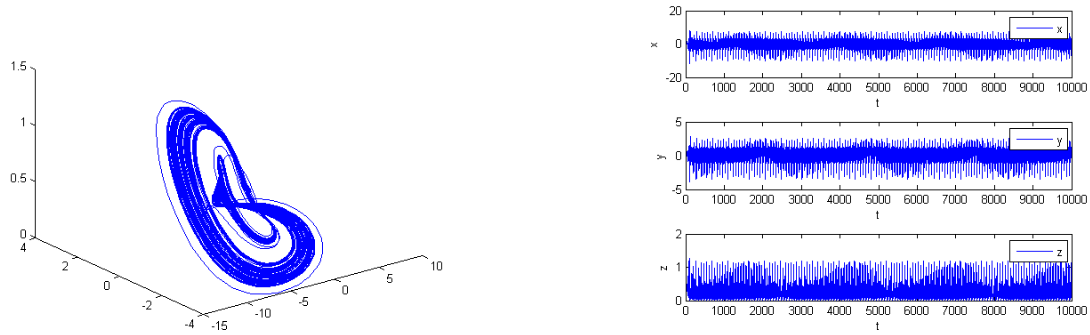


Figure 4: The evolutionary relationship of the actual system

As can be seen from Fig.4, the rise in coal price can promote the rise of coal supply. And the rise of coal supply will promote economic growth and boost gross domestic product. The increase in coal supply has prompted a decline in coal price. Thus it can be seen that there is a complicated nonlinear evolution relationship among coal price, coal supply and the gross domestic product. In the system, coal price, coal supply and GDP can not reach a stable relationship, the system will appear chaotic state as time goes on, as shown in Fig.5(a) and Fig.5(b). In section 3.2, we will study what kind of measures can be taken to make the actual system reach a stable state.

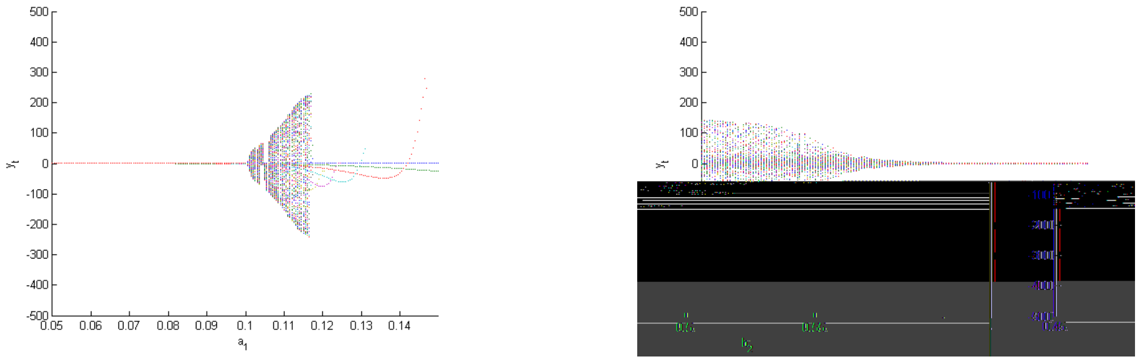
3.2 Control strategy analysis

According to the single parameter bifurcation diagram of a_1 and b_2 in Fig.6, we can know that the development of new energy sources and the use of clean energy can reduce the dependence on coal in the domestic market, which not only



(a) (b)

Figure 5: Chaotic state of the actual system



(a) (b)

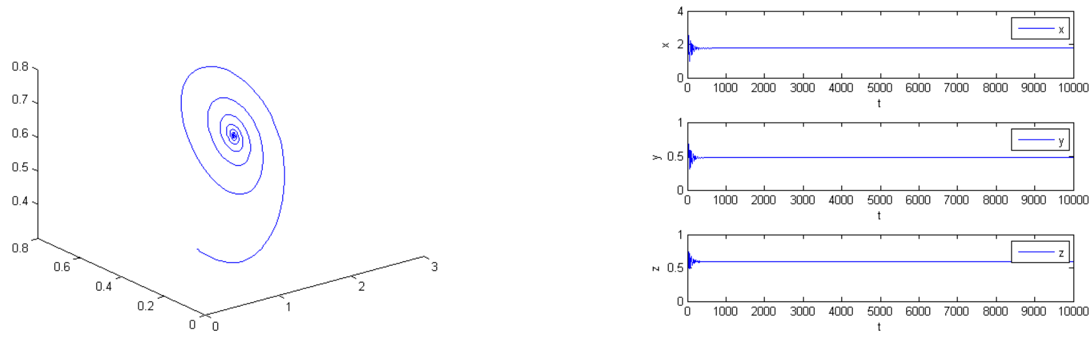
Figure 6: Bifurcation of a_1 and b_2

can diversify the supply of energy but also can reduce the environmental pollution caused by the use of coal. The use of renewable energy sources can make energy supply relatively stable, thus leading to a decrease of the inherent growth rate a_1 of coal, at the same time coal growth retardation coefficient b_2 increase.

As can be seen in Fig.6, the coal market can reach stable when a_1 reduce to the interval $[0, 0.1]$ or b_2 increase to the interval $[0.55, 0.9]$ in the case of other parameters constant. Now we let a_1 drop from 0.1088 to 0.08 and b_2 drop from 0.1683 to 0.56 , other parameters remain unchanged, the system can be obtained as follows: Evolution of the system shows that the initial system is in an unstable state, but as time goes on, the regulatory policy becomes to play a role in the system and the system tends to stable. Thus, the development of new energy sources and the use of clean energy can stabilize the coal market.

4 Conclusions

In this paper, we first analyze the complex dynamics of coal price, coal supply and economic growth from both theory and practice way, and research the evolution behavior of each variable through numerical simulation. Then we get a meaningful system by using the historical data, and confirm that the development of new energy sources and the use of



(a) (b)

Figure 7: Stable state of the actual system

clean energy can promote the coal market to reach a steady state.

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