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Research on Coupled Relationships among Supply, Demand and Price of Oil

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Abstract: In 2014, the international oil price fluctuated violently and all aspects of life were deeply affected has become the focus of current research that how the international oil supply, oil demand and oil price affect and restrict each other. The coupled relationships among oil supply, oil demand and oil price are studied by establishing a novel three-dimensional nonlinear dynamic system of oil supply-demand-price (S-D-P) in this paper. The dynamical behaviors of this system are analyzed. The dynamic evolution of various factors in the system is studied by numerical simulation. The actual system parameters are determined by neural network and genetic algorithm based on the statistical data of international oil market from January 1997 to November 2016. Based on the results of parameter identification, the characteristics of system parameters and difference among the parameters are analyzed. In particular, how the oil supply and demand situation affect oil price and how the oil price react to oil supply and demand are studied.

Keywords: supply-demand-price model; genetic algorithm; numerical simulation; parameter identification

1 Introduction

As the blood of industry, oil is an indispensable strategic resource [1] for national survival and development. Oil supply, oil demand and changes in oil price have a profound impact on the international oil market as well as political [2], economic [3] and other aspects [4-7]. As can be seen from Fig.1, the international oil price fluctuated violently in 2014. It fluctuated by more than 50 US dollars / barrel. The international oil price maintained high price shocks by influences of the Ukrainian crisis, the turmoil in Libya and other geopolitical events in the first half of 2014. Brent price have remained at around 108 US dollars / barrel. In the second half, the international oil price plunged to less than 60 US dollars / barrel, which is the first time since the international oil market began to recover from 2009. The reasons for the sharp decline in the international oil price, the impact and the corresponding measures have become hot issues. The evolution of oil price is the result of oil supply, oil demand, energy efficiency, energy strength and other factors. Correspondingly, the evolution of oil price also reflects a variety of information in the oil market and plays an important role in the oil market as an invisible hand [8]. Oil supply and demand pattern changes rapidly with the rapid change of oil supply, oil demand and oil price. It is a hot topic to study the mechanism of oil supply and demand influence on oil price and to evaluate the reaction mechanism of oil price fluctuation to oil supply and oil demand in oil market.

In recent years, many scholars have carried out a lot of researches on these issues. M. [9] used the data of 2004-2008 to study the impact of oil price volatility on income distribution in Malaysia by introducing an extended social accounting matrix (SAM) and compared it with China and India. Tang and Tan Eu [10] studied the relationships between electricity consumption and economic growth, energy price and technological innovation according to the data of 1970- 2009. The above researches all tested the relationships among the energy price, supply, demand and other aspects by means of empirical analysis. The results of researches vary depending on time and region of studies. The scientific question needs to be solved is how to describe the complex relationships between oil supply, demand and price in the energy market by establishing a nonlinear model.

We will first draw the causal graph among the factors of international oil market. Secondly, we build a three-dimensional nonlinear dynamic system among oil supply, demand and price to explore the dynamic characteristics of

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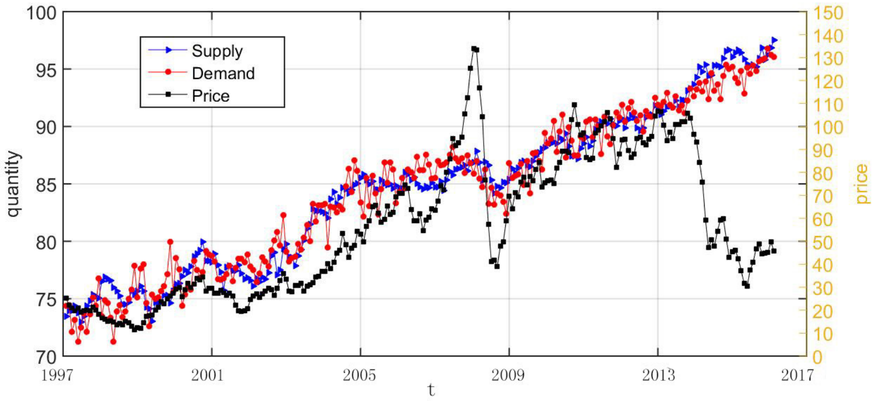


Figure 1: Actual evolution map of oil supply, demand and price from 01/1997 to 11/2016.

the system, and find that the system shows stable state, periodic change state and chaotic state under different parameters or initial values by numerical simulation. It shows that this system is sensitive to parameters and initial values. Finally, we simulate the evolution of oil supply, demand and price through differential equation, and find that there is a high degree of coincidence between simulation results and actual data. The results show that this system can effectively reflect the complex relationship among supply, demand and price in the international oil market.

2 Oil supply-demand-price model

Oil S-D-P system is a complex system in it that includes oil demand, oil supply, oil price, economic growth, energy efficiency, energy intensity, national policy and many other factors. There are very complex relationships among each factor. As can be seen from Fig.2, $k_i, i = 1, 2, ...35$ indicates the relationships among the factors, '+' indicates a positive correlation, '-' indicates a negative correlation [11-16].

As can be seen from Fig.2, oil supply has a trend of increase or decrease. The increase in oil production and oil import will lead to an increase in oil supply and a decrease in the difference between supply and demand [17], which will reduce the oil price. The decline in oil price will cut back the oil production, which will lead to an increase in dependency. The increased dependence will promote government departments to adjust the oil structure accordingly, which will lead to the reduction of energy strength and improve the energy efficiency of oil use effectively, then the economic development will be promoted. Oil consumption and oil demand will also increase along with the development of economic. Oil consumption and oil demand will increase along with the rapid economic development, which will lead to further expansion of the difference between supply and demand. The rapid economic growth will also promote scientific and technological progress. The advanced technical means will effectively improve the amount of oil can be mined, and thus promote the growth of oil production. The technological progress can promote the development of oil and reduce the cost of alternative energy, thereby reducing carbon emissions and oil demand. In addition, technological progress can also improve energy efficiency effectively. Energy efficiency can reduce the energy strength effectively, thereby promoting economic development [18]. Thus, oil supply, oil demand and oil price show a complex relationships through direct or indirect links.

2.1 Model description

The S-D-P model consists of three variables: oil supply, oil demand and oil price, which are denoted by x, y and z respectively. We use K to denote the initial price in order to avoid the negative of the differential equation, then the price of K is $z - K$. We substitute the variable $X = x, Y = y, Z = z - K$.

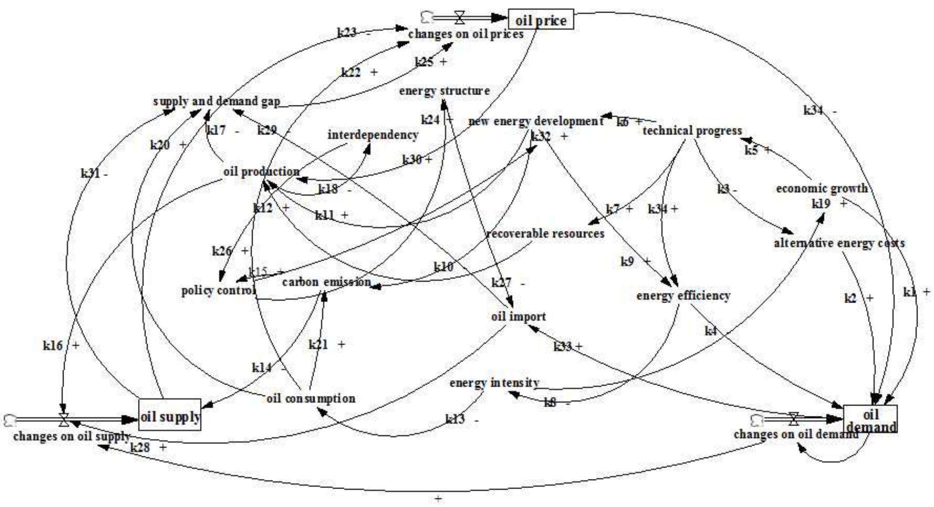


Figure 2: The causal relationship among the variables of oil S-D-P system.

2.2 Mathematical model and symbol explanation

According to the equilibrium price theory, we can see that the price of the commodity declines when the supply exceeds demand and the price rises when the supply exceeds the demand. Oil as one of the commodities also has a similar law.

$$\begin{cases} \dot{X} = a_1 X \left(\frac{Z}{P} - 1\right) + a_2(Y - X) + a_3 Z & (1,a) \\ \dot{Y} = b_1 Y \left(1 - \frac{Z}{P}\right) - b_2 Z & (1,b) \\ \dot{Z} = c_1(Y - X)(1 - \frac{Z}{P})^2 + c_2(\dot{Y} - \dot{X}) + c_3 Z \left(1 - \frac{Z}{P}\right) & (1,c) \end{cases} \qquad (1)$$

X is the oil supply; Y is the oil demand; Z is the oil price (relative to the initial price K). a_1 indicates the impact of the oil price deviation from the ideal price on oil supply. a_2 represents the impact of the difference between supply and demand on oil demand. a_3 represents the impact of oil price on oil supply. b_1 represents the impact of oil price deviation from the ideal price on oil demand. b_2 represents the impact of oil price on oil demand. c_1 indicates the impact of the difference between supply and demand and the oil price deviation from the ideal price on oil price. c_2 shows the impact of oil demand and the difference between change rate of oil supply and demand. c_3 represents the natural growth rate of oil price. P represents the ideal price of oil at a certain stage.

The first term of the Eq. $(1,a)$ represents that the rate of change in oil supply $\dot{X}$ is proportional to the current oil supply X and the degree of the oil price deviating from the ideal price. If $Z > P$, the market price of oil is greater than the ideal price, then the supplier will increase the supply of oil in order to seek benefits. When $Z = P$, the oil price in the market is equal to the ideal price, and the oil price has no influence on the supply behavior. Suppose $Z < P$, that is the oil price is less than the ideal price, then the supplier will reduce the supply of the oil to avoid risks. The second term indicates that the rate of change in oil supply $\dot{X}$ is proportional to the difference between oil supply and demand $(Y - X)$. When $Y > X$, oil market is in short supply, then the oil supply will increase. If $Y = X$, supply and demand are balanced in the energy market, then the oil supply will remain unchanged. When $Y < X$, the oil supply exceeds demand, then the supplier will slow down the oil supply to reduce losses. The third term indicates that the rate of change in oil supply $\dot{X}$ is proportional to the current oil price Z.

The first term of the Eq. $(1, b)$ represents that the rate of change in oil demand $\dot{Y}$ is proportional to the current oil demand Y and the degree of the oil price deviating from the ideal price. When $Z > P$, the oil price in the market is greater than the ideal price, the consumers will reduce the consumption of oil or seek alternative energy, which will lead oil demand Y to reduce. When $Z = P$, the oil price will not affect demand behavior. When $Z < P$, the price of oil in the market is less than the ideal price, the consumers will increase the consumption of oil, which will lead to an increase in demand. The second one shows the rate of change in oil demand $\dot{Y}$ is negatively correlated with the current oil price Z. When the oil price is at a high level, it will promote changes in oil demand; on the contrary, it will slow down changes in oil demand.

The first term of the Eq. (1,c) denotes that the change of oil price Z is proportional to the difference between oil supply and demand $(Y - X)$ and the degree of oil price deviating from the ideal price $(1 - Z/P)^2$. When $Y > X$, the oil market is in short supply, then the oil price Z will show an upward trend. Suppose $Y = X$, the oil supply and demand are balanced, then the oil prices will not fluctuate. When $Y < X$, there is an oversupply in oil market, which will lead the oil price to go down. When the oil price Z is close to the ideal price P, the effect on the change of oil price will be weaken. Conversely, if the degree of the oil price deviating from the ideal price $(1 - Z/P)^2$ increases, the impact on the change of oil price $\dot{Z}$ will increase. The second term indicates that the rate of change in oil price is proportional to the difference between change rate of oil supply and demand $\dot{Y} - \dot{X}$, it is used to indicate that not only the difference between oil supply and demand impacts on oil prices, but also the difference between the rate of change in oil supply and demand will also have an impact on oil prices. People adjust their behaviors of supply and demand according to the current situation of oil supply and demand, even if the difference between supply and demand is minor will lead to larger changes on oil prices correspondingly. When $\dot{Y} - \dot{X} > 0$, the oil price will have an upward trend; if $\dot{Y} - \dot{X} < 0$, the oil price will have a downward trend. The third term implies that the rate of change in price satisfies $Logistic$ growth, and the oil price Z will continue to grow at a price that dose not exceed the ideal price P; on the contrary, it will continue to decline.

3 System dynamics analysis

Let $\dot{X} = 0, \dot{Y} = 0, \dot{Z} = 0$. We can get the equilibrium points of nonlinear equations:

$$\begin{cases} a_1 X\,(Z/P - 1) + a_2(Y - X) + a_3 Z = 0 \\ b_1 Y\,(1 - Z/P) - b_2 Z = 0 \\ c_1(Y - X)(1 - Z/P)^2 + c_2(\dot{Y} - \dot{X}) + c_3 Z(1 - Z/P) = 0 \end{cases} \tag{2}$$

The S-D-P system has two equilibrium points $O(0,0,0)$ and $S_1(x_1, y_1, z_1)$, where $x_1 = \frac{M_2}{M_1 M_3}(a_3 b_1 b_2 c_1^2 - a_1 b_2^2 c_1^2 + a_3 b_1^2 c_1 c_3 - 2a_1 b_1 b_2 c_1 c_3 - a_1 b_1^2 c_3^2)$, $y_1 = \frac{b_2 c_1 M_2}{M_3}$, $z_1 = \frac{M_2}{M_1}$. Respectively, M_1, M_2, M_3 are the combination of system parameters, where $M_1 = a_3 b_1 c_1 - a_1 b_2 c_1 - a_1 b_1 c_3$, $M_2 = (a_3 b_1 c_1 - a_1 b_2 c_1 - a_1 b_1 c_3 - a_2 b_1 c_3)P$ and $M_3 = a_2 b_1^2 c_1 c_3$.

3.1 Equilibrium points and dissipation

In order to facilitate the analysis, the system parameters are fixed as shown in Table 1.

Table 1: Value of parameters.

a_1	a_2	a_3	b_1	b_2	c_1	c_2	c_3	P
0.758	0.008	0.19	0.13	0.025	0.89	0.06	0.11	0.4

The Jacobian matrix at $O(0,0,0)$ is

$$J_0 = \begin{pmatrix} -a_1 - a_2 & a_2 & a_3 \\ 0 & b_1 & b_2 \\ (a_1 + a_2)c_2 - c_1 & (b_1 - a_2)c_2 + c_1 & c_3 - (a_3 + b_2)c_2 \end{pmatrix}.$$

The characteristic roots of J_0 are $\lambda_{1,2} = -0.00984598 \pm 0.105564i$, $\lambda_3 = -0.519208$, and the system is stable at the equilibrium point $O(0,0,0)$. Let $c_3 = 0.14$ and fixing the other parameters, the characteristic roots of J_0 are $\lambda_{1,2} = 0.0131719 \pm 0.127718i$, $\lambda_3 = -0.535244$, and the system is unstable at the equilibrium point $O(0,0,0)$.

Therefore, the S-D-P system may be in a stable state or in an unstable state at the equilibrium point $O(0,0,0)$, it depends entirely on parameters in system 1.

For simplicity, the system parameters are fixed as shown in Table 2.

Table 2: Value of parameters.

a_1	a_2	a_3	b_1	b_2	c_1	c_2	c_3	P
0.1583	0.0883	0.2071	0.0667	0.0288	0.9812	0.9784	0.2150	0.9594

We get one equilibrium point as (1.2857, 1.8138, 0.7810).

The Jacobian matrix at $S_1(x_1, y_1, z_1)$ is

$$J_1 = \begin{pmatrix} -0.2262 & 0.0833 & 0.4192 \\ 0 & 0.0124 & -0.1549 \\ 0.0813 & -0.0404 & -0.8975 \end{pmatrix}.$$

The characteristic roots of J_1 are $\lambda_1 = -0.952497$, $\lambda_2 = -0.17333$, $\lambda_3 = 0.0145269$, and the system is unstable at the equilibrium point $S_1(x_1, x_2, x_3)$.

It can be seen from the above analysis that the equilibrium point of the oil S-D-P system may be stable or unstable, which indicates that the oil S-D-P model has complicated dynamical behaviors. The dissipation is

$$\begin{aligned}\Delta V &= \frac{\partial \dot{X}}{\partial X} + \frac{\partial \dot{Y}}{\partial Y} + \frac{\partial \dot{Z}}{\partial Z} \\ &= b_1 + c_3 - a_1 - a_2 - a_3c_2 - b_2c_2 + \frac{2c_1 - a_2c_2}{P}X \\ &- \frac{2c_1 + b_1c_2}{P}Y + \frac{a_1 - b_1 - 2c_3}{P}Z + \frac{2c_1}{P^2}Z(Y - X) \end{aligned} \tag{3}$$

It is difficult to prove the dissipation of this system theoretically because of the existence of cross-terms. But we can analyze the dissipation at some point. For example, the dissipation of the system at the point of $O(0,0,0)$ is

$$\Delta V_{(0,0,0)} = b_1 + c_3 - a_1 - a_2 - a_3c_2 - b_2c_2 < 0.$$

Obviously, the system is dissipative if the parameters meet the condition $b_1 + c_3 < a_1 + a_2 + a_3c_2 + b_2c_2$.

3.2 Numerical simulation

In this section, we will conduct numerical simulation

Case 1 Stable point

Set parameters as shown in Table 3 and take $(0, 0.4899, 1)$ as initial value. The system is stable and converges to $S_1(x_1, y_1, z_1)$, which can be observed from Fig. 3.

Table 3: Value of parameters in Case 1.

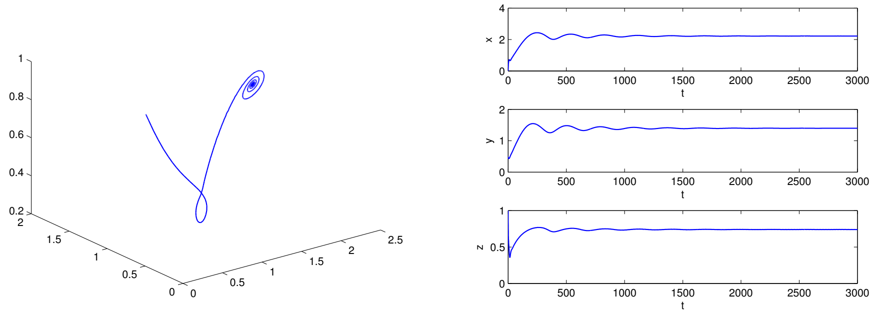
a_1	a_2	a_3	b_1	b_2	c_1	c_2	c_3	P
0.1583	0.0883	0.2071	0.0667	0.0288	0.9812	0.9784	0.25	0.9594

Case 2 Limit cycle

Let c_3 be 0.2150 and fixing other parameters as shown in Table 3.

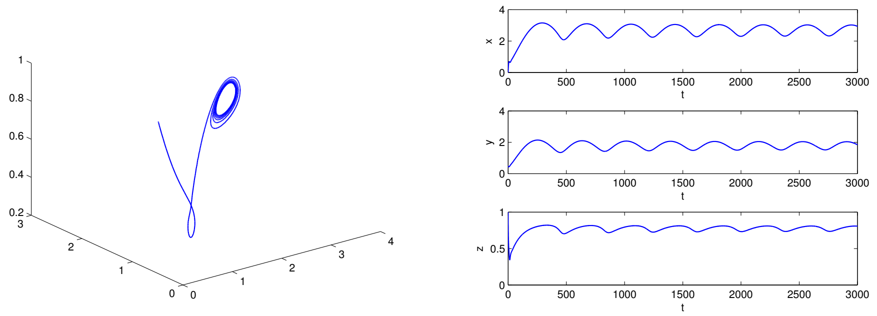
Case 3 Chaotic attractor

Set parameters as Table 4 and take (0.09,0.01,-0.1) as initial value.



(a) Three-dimensional phase diagram (b) Trajectory of case 1 versus time

Figure 3: The evolution results of system 1 in case 1.



(a) Three-dimensional phase diagram (b) Trajectory of case 2 versus time

Figure 4: The evolution results of system 1 in case 2.

Case 4 Limit cycle

c_3 is changed to 0.135, and initial value is changed to $(0.05, 0.03, 0.04)$, fix other parameters as shown in Table 4.

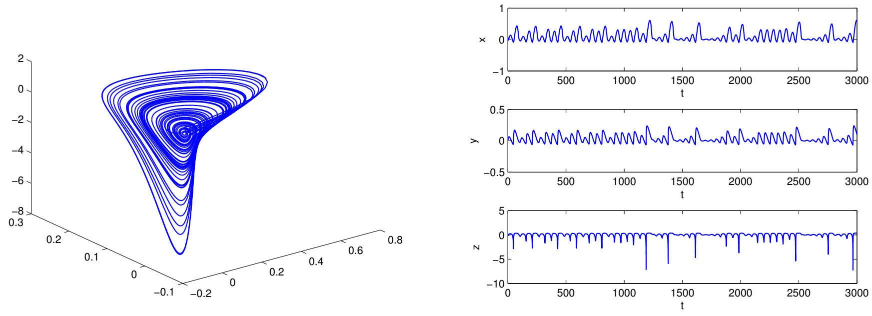
The results of numerical simulation show that there is a very complex nonlinear relationship among oil supply, oil demand and oil price. This complexity is closely related to the value of parameters in the model 1. The value of these parameters will be adjusted, which depends on different periods and backgrounds. The different values will lead to stable state, periodic change state and chaotic state. Also, the results of numerical simulation show that the system exhibits different nonlinear dynamical behaviors on different initial conditions even if the parameters are fixed, which indicates that the system has strong initial sensitivity.

4 Empirical analysis

Three-dimensional S-D-P model 1 has been established based on the complex relationships among oil supply, oil demand and oil price. The determination of parameters in S-D-P model 1 is of great significance to oil supply, oil demand and oil price in real situation. Genetic algorithm with the characteristics of tiny errors [19,20] is an effective method to identify the system parameters. Genetic algorithm will be used to identify the parameters.

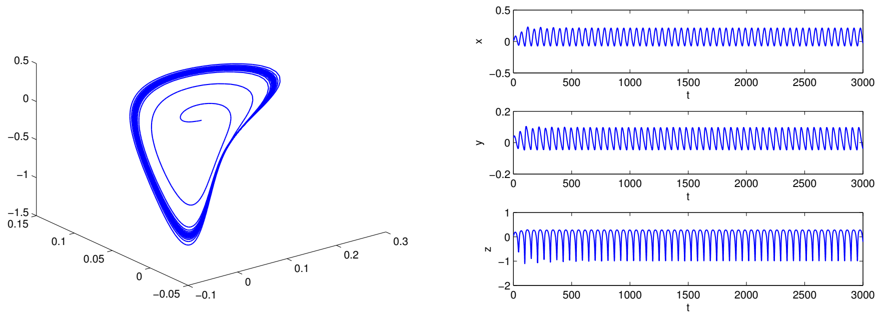
Table 4: Value of parameters in Case 3.

a_1	a_2	a_3	b_1	b_2	c_1	c_2	c_3	P
0.758	0.008	0.19	0.13	0.025	0.89	0.06	0.141	0.4



(a) Three-dimensional phase diagram (b) Trajectory of case 3 versus time

Figure 5: The evolution results of system 1 in case 3.



(a) Three-dimensional phase diagram (b) Trajectory of case 4 versus time

Figure 6: The evolution results of system 1 in case 4.

4.1 Data sources

The data of international 01/1997-11/2016 monthly oil production, oil consumption and WTI crude oil price is selected as the research object in this section. We select the data from EIA. We set the international oil production as the oil supply, the international oil consumption as the oil demand and the international oil price as the oil price with the symbol X, Y and Z.

4.2 Genetic algorithm

Genetic algorithm is a kind of randomized search method which evolved from the evolutionary law of biology. Its main method is to manipulate structural objects directly. It has inherent implicit parallelism and good global optimization ability. It can guide the optimization of the search space and adjust the search direction automatically. These properties make the genetic algorithm effectively identify the parameters of the system.

The following formula is used to normalize the data for inconsistent units,

$$x_i^* = \frac{x - x_{min}}{x_{max} - x_{min}},$$

where x_i^* represents the data, x_{min} represents the minimum value in x_i, and x_{max} represents the maximum value in x_i.

The S-D-P system can be written as vector fields:

$$\dot{X}(t) = f(X(t), \alpha)$$

where X represents the state of the system, α is the system parameter. The system is described

$$X(k+1) = X(k) + f(X(k)) = F(X(k), \alpha)$$

The parameter identification of the system is equivalent to the nonlinear optimization problem:

$$min \quad \frac{1}{2}\sum_{k=1}^{T}\|X(k+1)-F(X(k),\alpha)\|^2$$

$$s.t. \quad \alpha_i > 0$$

The genetic algorithm is used to solve the optimal solution α^*. After repeated attempts, the population size is 200, the crossover probability is 0.7, the mutation probability is 0.3, and the number of evolution is 1400.

4.3 Parameter identification

The results of parameter identification are shown in Table 5.

Table 5: The results of parameter identification.

a_1	a_2	a_3	b_1	b_2	c_1	c_2	c_3	P
0.0103	0.0065	0.0073	0.0011	0.0233	0.0847	0.0809	0.0169	29.3238

As can be seen from the results of parameter identification, the values of a_2, a_3 are small, which reveals that the oil price and the difference between supply and demand have little influence on the oil supply. The change of the oil supply is mainly affected by the deviation of the oil price from the ideal price. The value of b_1 is relatively small, which demonstrates that the impact of the oil price deviating from the ideal price on oil demand is less, and the change of oil demand is mainly affected by oil price. The values of c_2, c_3 are relatively large, which indicates that the difference between supply and demand, the deviation of the oil price from the ideal price and the difference between the rate of change in oil demand and oil supply are very important factors in the process of fluctuations in oil prices. The comparison of actual data and simulation results are shown in Fig. 7, there is a high degree of coincidence between simulation results and actual data.

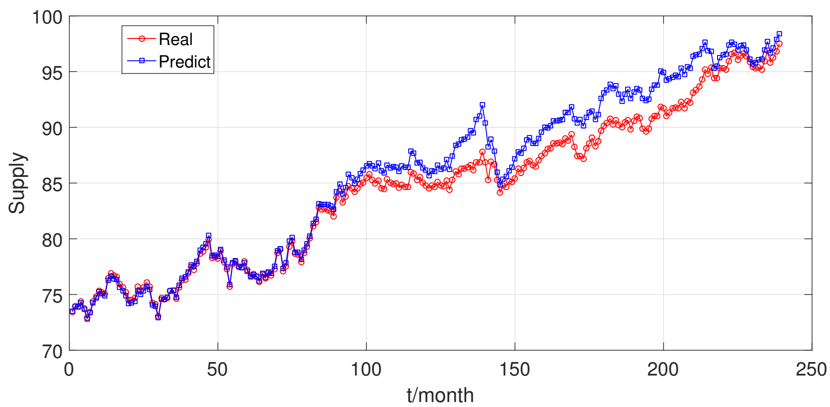


Figure 7: Comparison of actual data and simulation results from 01/1997 to 11/2016.

5 Conclusion

In this paper, a new model of oil supply, oil demand and oil price was proposed on the background of the interdependent relationships among supply, demand and price in the oil market. The difference between the rate of change in oil supply and oil demand was introduced as a new influencing factor, so this model can better characterize the evolution relationships of oil supply, oil demand and oil price compared to other models. The basic dynamics of oil S-D-P system was analyzed

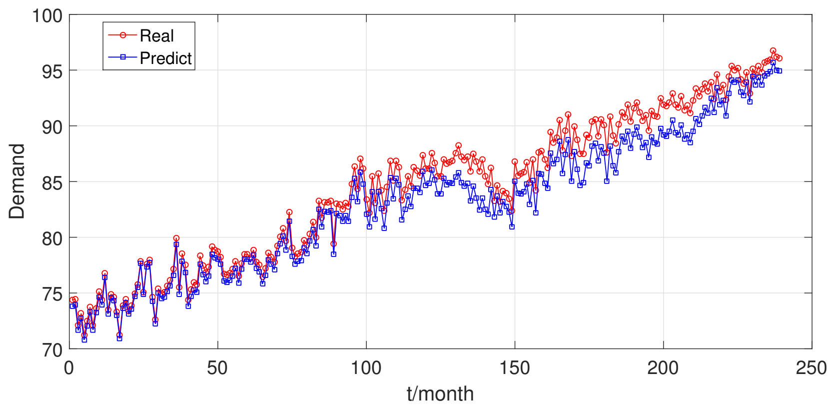


Figure 8: Comparison of actual data and simulation results from 01/1997 to 11/2016.

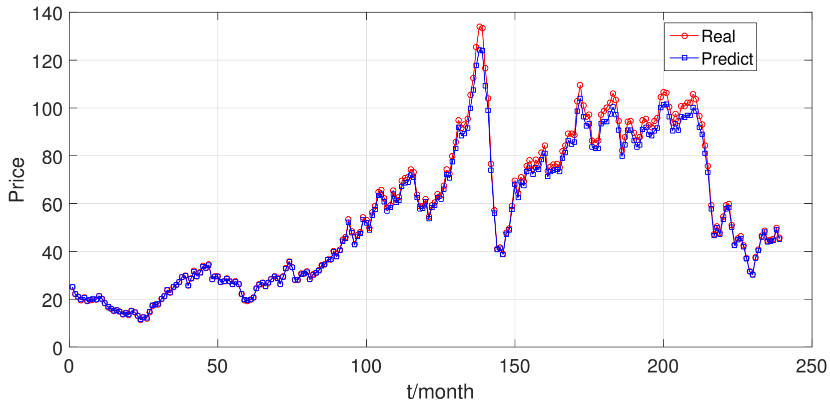


Figure 9: Comparison of actual data and simulation results from 01/1997 to 11/2016.

theoretically. The evolutionary behaviors between variables was studied by numerical simulations. The system parameters of the whole stage were identified by genetic algorithm. The result of parameter identification was compared with the actual data. There is a high degree of coincidence between simulation results and actual data, which shows that this system can effectively reflect the complex relationships among supply, demand and price in the international oil market.

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