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Research Article

Research on the Influence of Bounded Rationality and Product Differentiation on the Stability of Steel Industry Market

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At present, the problems of homogenization and low quality in China's iron and steel industry are particularly prominent and the ability of the enterprises to cope with change is insufficient. Adopting product differentiation strategy and dynamic adjustment strategy can allow steel enterprises and the industry to better adapt to future changes. By introducing the product differentiation degree (substitution coefficient) and the bounded rationality strategy to simulate these two strategic means, this paper constructs an extended two-stage dynamic game model to analyse the dynamic game scenarios and steel market stability in China. As new findings, we report the following: (1) The system is more likely to fall into an unbalanced state when multiple enterprises adopt the policy of dynamic output adjustment simultaneously. (2) Enterprises with large output and small output have different output adjustment policies. When enterprises with big-scale output adopt a bit larger adjustment policies, enterprises with small output will be strongly impacted, and the available adjustment space will be sharply compressed. (3) The gradual increase in the difference between products reduces the stability of the market. (4) When product differentiation and bounded rationality strategies coexist, the steel market may fall into an unbalanced state when the degree of product difference increases excessively and the enterprise adopts more drastic output adjustment policies. Therefore, there are pros and cons to product differentiation strategy and bounded rationality adjustment strategy. When each steel oligopoly enterprise formulates a production plan, it needs to comprehensively consider the output changes of the other enterprises and carefully weigh the strategic issues.

1. Introduction

The steel industry is an important basic industry for the national economy. For a long time, it has provided important raw material guarantees for national construction which have strongly supported the development of related industries.

Although China has become the world's largest producer of steel products, the shortcomings of China's steel industry are obvious: the problems of homogenization and low quality are still grim. Steel enterprises lack the ability to adjust to problems such as overcapacity and sluggish returns. In the future, the relationship between supply and demand in the steel market will be more comprehensive. Therefore, "stand still" or complacent and conservative behaviours will seriously affect the survival and development of steel enterprises. Hence, how to adopt product differentiation strategy and dynamic adjustment strategy to make steel enterprises and industries more adaptive to future changes and related new research will become a difficulty faced by the steel industry and a focus for additional research.

At present, emission reduction policies such as carbon trading and carbon taxation mechanisms have not been fully implemented, and their impact on the production level and economic profit of enterprises and the steel industry is still unclear. However, it is clear that the emission reduction targets will be more and more restrictive in the energy conservation and emission reduction tasks for steel enterprise. Facing the future steel industry's more diversified and more complex market competition environment, the industry's development should start from the perspectives of energy conservation and emission reduction, product structure, and corporate decision-making simultaneously. Based on the ideas above, this paper will focus on the complex changes to various steel oligopoly enterprises under different economic conditions and the emission reduction policy, and then, it will analyse the dynamic production adjustment game situation and the stability of the steel market.

2. Literature Review

2.1. Product Differentiation Theory and Application. Shaw was the first scholar to conduct product differentiation research, he [1] believed that product differentiation should be used to better meet human needs, and not for increased competition. Chamberlin [2] discussed that the scale of an enterprise is related to the degree of product differentiation. Due to product differentiation, small and medium-sized enterprises (SMEs) have gained a living space and may have monopoly power. Although the existence of this monopoly power leads to efficiency loss, product differences meet the diverse needs of customers. Porter [3] believed that product differentiation results from the physical characteristics of the product and other market mix factors.

Product differentiation models are widely used in industrial economics and other disciplines. The basic theoretical models are the Bowley model [4], the Shubik and Levitan model [5], and the Hotelling model [6]. Early product differentiation research was mostly derived and extended from these theoretical models. Since the middle and late twentieth century, due to the continuous development of game theory, product differentiation has gradually become a hot research topic in industrial economics. In related research, product differentiation theory is usually studied together with other theoretical combinations as a comparison with homogeneous products. Table 1 shows the literature combining product differentiation theory with other theories.

In the industry sector especially in China, the application of product differentiation theory is very extensive. Table 2 shows the literature related to industry application.

2.2. Bounded Rationality and Application. Bounded rationality is a rationality between certain rationality and incomplete rationality. Simon [32] believed that what people are looking for in their actual decision process is not a "maximum" or "optimal" standard, but a "satisfactory" standard. Due to its closeness to reality, bounded rationality has gradually attracted more scholars' attention and application, and various bounded rational models have been created. At the same time, scholars have combined the theory of bounded rationality with product differentiation theory, repeated game, evolutionary game, nonlinear theory, chaos theory, chaos control, delay strategy, etc. in comparison with complete rationality. Table 3 shows the literature combining bounded rationality with other theories. Table 4 shows the literature related to industry application.

2.3. Summary of Literature Review. From the literature review, it can be seen that product differentiation and bounded rational expectation strategies have been widely applied to the study of complex market economy changes and equilibrium stability domains. However, the literature is mostly based on theoretical research and is rarely applied to production problems. Numerical analysis is mostly based on random values, and there is still a definite gap between present work and manufacturers' real situations. For steel industry, there are little theoretical literatures on product differentiation and bounded rationality, and most papers consist of narratives and policy descriptions.

Table 1: The literature and summary information combining product differentiation theory with other theories.

Researcher	Main theory
Shaked and Sutton [7]	Product differentiation + three-stage game model
Chang [8]	Product differentiation + collusion
Goldberg [9]	Product differentiation + oligopoly competition
Zhang et al. [10]	Product differentiation + two-stage stochastic programming model
Zhao and Du [11]	Product differentiation + heterogeneous expectations
Meng et al. [12]	Product differentiation + horizontally competitive + carbon tax
Li and Chen [13], Raza and Govindaluri [14]	Product differentiation + supply chain
Ivanova and Ushchev [15]	Product differentiation + CES model
Wang et al. [16]	Product differentiation + endogenous product substitutability theory
Zhou et al. [17]	Product differentiation + bifurcation, intermittent chaos, and multi-stability
Askar and Al-Khedhairi [18]	Product differentiation + nonlinear duopoly games

Table 2: The literature and summary information about product differentiation theory in industry application.

Researcher	Industrial sector	Qualitative or quantitative analysis
Li et al. [19]	Textile and garment industry	Qualitative
Ma [20]	Textile and garment industry	Quantitative
Bronnmann and Hoffmann [21]	Drink market	Quantitative
Yang [22]	Tourism industry	Quantitative
Fu et al. [23]	Transportation industry	Quantitative
Lv [24]	Transportation industry	Quantitative
Gebauer et al. [25]	Manufacturing industry	Quantitative
Zeng and Liu [26]	Fast food industry	Quantitative
Altug [27]	Semiconductor industry	Quantitative
Chen [28]	Digital content rental market	Quantitative
Ma [29]	Steel industry	Qualitative
Feng [30]	Steel industry	Qualitative
Li [31]	Steel industry	Qualitative

Table 3: The literature and summary information combining bounded rationality with other theories.

Researcher	Main theory
Bischi and Naimzada [33]	Bounded rationality + duopoly game model
Elsadany [34]	Bounded rationality + three oligarchs game model
Elettreby and Hassan [35]Askar and Al-Khedhairi [36]	Bounded rationality + four oligarchs game model
Ahmed et al. [37], Puu [38]	Bounded rationality + heterogeneous products + delay bounded rationality
Agiza et al. [39]	Bounded rationality + multi-oligarch Bowley game model
Yassen and Agiza [40], Hassan [41], Matsumoto and Szidarovszky [42], Ma and Pu [43]	Bounded rationality + nonlinear game model
Wang and Ma [44]	Bounded rationality + duopoly Cournot model, Bertrand model, and Cournot–Bertrand mixed model
Yu and Yu [45, 46]	Bounded rationality + product differentiation
Yu and Yu [47]	Bounded rationality + Stackelberg triopoly game
Ma and Wu [48]	Bounded rationality + three oligarchs game model + product differentiation
Zhao et al. [49]	Bounded rationality + nonlinear analysis + chaos control
Li and Wang [50]	Bounded rationality + duopoly Cournot model + constant conjectural variation
Dong [51]	Bounded rationality + Stackelberg model
Li et al. [52]	Bounded rationality + Markov logic networks

Table 4: The literature and summary information about bounded rationality in industry application.

Researcher	Industrial sector
Ji [53]	Electricity industry and electricity market
Ding et al. [54]	Electricity system
Sun and Ma [55]	Steel industry and steel market
Tan and Liang [56]	Coal industry and coal market
Tu [57]	Power and renewable resources industry
Dang and Hong [58]	Glass substrates industry
Li et al. [59]	Tourism industry
Yu [60]	Transportation industry
Zhang [61]	Carbon trade market
Zhao [62]	Carbon trade market
Sang et al. [63]	Shipbuilding industry
Di et al. [64, 65]	Transportation planning

In developing countries like China, there are significant regional differences and regional economic development imbalances. Thus, some areas' parameters and data, including those of the steel industry, need to be supplemented. And with the merger and reorganization, the remaining steel enterprises inevitably have to compete in production and price. This high-dimensional, large-scale steel market cannot be simulated with random value figures. On this basis, there is basically no relevant research on how the steel market changes after introducing product differentiation theory and bounded rational expectation and implementing different emission reduction policies.

In summary, the product differentiation strategy and the production or price adjustment strategy are important means for the steel industry to enhance its competitive advantage. Steel enterprises and industries should immediately pay attention to these two strategic means. This paper organizes energy, environment, and economic data from the six main steel-producing areas in China. By introducing the degree of product differentiation (substitution coefficient) and bounded rationality strategy, a two-stage dynamic game model is constructed. Then, this paper analyses the influence of product differentiation degree and production adjustment coefficient on the dynamic game of steel enterprises' output. It also studies the unbalanced conditions, in order to provide reasonable policy recommendations for the transformation and upgrading of China's steel market and the maintenance of market stability.

Therefore, the remainder of this paper is organized as follows: Section 3 establishes a dynamic output selection model based on bounded rationality and introduces the differentiated product policy scenario and data sources. In Section 4, based on accounting data and statistical analysis, we present and discuss our results in detail. Section 5 provides conclusions and policy recommendations for China's steel industry.

3. Methods

3.1. Notations and Explanations. As shown in Figure 1, according to the traditional Chinese geographical division method and reference to Duan et al. [66], China is divided into six regions. For data reasons, Tibet, Hong Kong, Macau, and Taiwan are not included. In this paper, regions are presented by subscripts: 1 represents North China, 2 represents Northeast China, and so on.

The main research focus of this paper encompasses the government and the above six regions. The regional steel industry data are regarded as presenting a steel enterprise entity. Since this paper only introduces the theory of product differentiation and bounded rationality based on the basic model, the basic model structure and main hypothesis do not change.

Similar to Duan et al. [66], the government emission reduction policy is a double game problem. Firstly, there is a

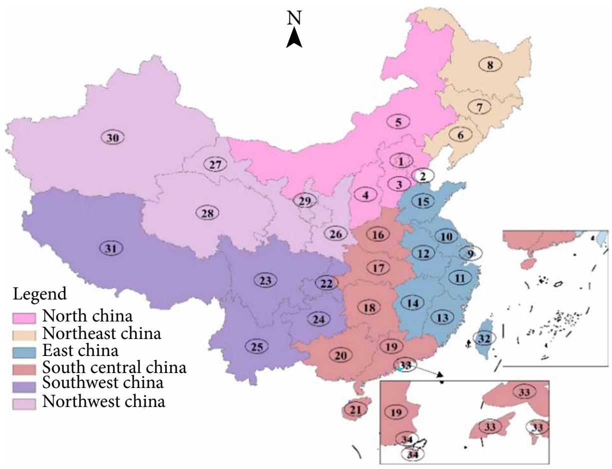

FIGURE 1: Regional division of China in this paper.

decomposition game between the government and regional enterprises: the government stipulates the emission reduction target for a certain period, after which the regional enterprises should determine their respective reduction ranges according to their own cost curves. Secondly, there is a game of product output between the six regions, and the different targets for each regional enterprise will affect their respective output levels and market competitiveness.

This paper adopts the inverse method in solving the two-stage game problem. On the basis of Duan et al. [66], this paper introduces some new parameters such as product differentiation degree and expands the notations and explanations, which are shown in Table 5.

3.2. Game Analysis of Production Decision Model under Product Differentiation Conditions. The main body of this paper includes the government (steel industry) and the steel companies in the six regions. After merger and reorganization, each of the six regions has a single large-scale steel production enterprise. The steel production level of each enterprise represents the level of steel production in the region. The technical level indicators, such as CO_2 emission intensity of each enterprise, represent the technology level in that region. In one cycle, the sales volume of the product is equal to the production volume; that is, a production and sales balance is reached.

The six regional oligopoly enterprises produce a product at the same time, and the products produced by each enterprise are substitutable but have certain differences. The coefficient of l_{ji} (the substitution coefficient) indicates the degree of substitution of enterprise j's product for enterprise i's product. The process takes the output as the decision variable and achieves the balance of production and sales in one cycle. In this paper, the set reduction scenario is: carbon tax as the only emission reduction policy, at a certain time point K in the future where the CO_2 emission intensity will decrease by R from CO_2 emission intensity in 2010.

In the second stage of the game, the basic form of the profit function of each enterprise according to the Bowley model is as follows:

TABLE 5: Notations and explanations used in this paper.

Notations	Explanations
Q	Steel production
P	The price of steel
α	The constant of the market inverse demand curve
β	The primary coefficient of the market inverse demand curve
q_i	Steel production of region i
$e_{2015,i}$	The region i CO_2 emission intensity of per ton steel in 2015
e_i	The region i CO_2 emission intensity of per ton steel at some stage
r_i	The decline range of CO_2 emission intensity of per ton steel in region i at some stage
R	The decline target of national CO_2 emission intensity of per ton steel at some stage
MAC	Marginal abatement cost curve in steel industry
a_i	The quadratic coefficient of steel industry's MAC in region i
b_i	The primary coefficient of steel industry's MAC in region i
C_i	The cost function of steel industry in region i
$C_{0,i}$	The production cost of steel industry in region i
c_i	The cost of base period emission reduction in region i
T	The total carbon tax
t	The unit value of carbon tax
W	Social welfare function
CS	Consumer surplus
PS	Producer surplus
$D(E)$	Total macro external environment loss of CO_2 emission
θ	The external loss parameter of CO_2
π_i	The profit function of steel industry in region i
E	The total CO_2 emissions in steel industry
l_{ji}	The extent to which products produced by j can replace those produced by i
ξ_i	The adjustment coefficient, rate of output adjustment

$$\begin{aligned}\pi_i &= P(Q)q_i - C_i q_i = (\alpha - \beta Q)q_i \\ &\quad - q_i C_{0,i} - q_i \lambda\left(c_i + \int_0^{r_i} MAC_i(r)dr\right) - te_i q_i \\ &= (\alpha - \beta Q)q_i - q_i C_{0,i} - q_i \lambda\left(c_i + \int_0^{r_i} MAC_i(r)dr\right) \\ &\quad - te_{2015,i}(1 - r_i)q_i \end{aligned} \tag{1}$$

and,

$$\begin{aligned}\pi_1 &= [\alpha - \beta(q_1 + l_{21}q_2 + l_{31}q_3 + l_{41}q_4 + l_{51}q_5 + l_{61}q_6)]q_1 \\ &\quad - \left(C_{0,1} + \lambda\left(c_1 + \int_0^{r_1} MAC_1(r)dr\right) + te_{2015,1}(1 - r_1)\right)q_1, \\ \pi_2 &= [\alpha - \beta(q_2 + l_{12}q_1 + l_{32}q_3 + l_{42}q_4 + l_{52}q_5 + l_{62}q_6)]q_2 \\ &\quad - \left(C_{0,2} + \lambda\left(c_2 + \int_0^{r_2} MAC_2(r)dr\right) + te_{2015,2}(1 - r_2)\right)q_2, \\ &\cdots \\ \pi_6 &= [\alpha - \beta(q_6 + l_{16}q_1 + l_{26}q_2 + l_{36}q_3 + l_{46}q_4 + l_{56}q_5)]q_6 \\ &\quad - \left(C_{0,6} + \lambda\left(c_6 + \int_0^{r_6} MAC_6(r)dr\right) + te_{2015,6}(1 - r_6)\right)q_6. \end{aligned} \tag{2}$$

Let $\partial\pi_i/\partial q_i = 0$ and $\partial\pi_i/\partial r_i = 0$, the corresponding reduction range of emission intensity (r_i) and output (q_i) of steel enterprises in each region can be obtained.

Under the carbon tax value t, the total carbon tax revenue is $T_i = \sum_{i=1}^{6} te_i q_i = \sum_{i=1}^{6} te_{2015,i}(1-r_i)q_i$. The external macroscopic loss caused by CO_2 emissions to the environment is $D(E) = \theta E = \theta\sum_{i=1}^{n} e_i q_i = \theta\sum_{i=1}^{n} e_{2015.i}(1-r_i)q_i$. Then,

$$\begin{aligned} W &= CS + PS + T - D(E) \\ &= \int_0^Q P(q)dq - P(Q)Q + \sum_{i=1}^{6}\pi_i + \sum_{1}^{6} T_i - \theta E \\ &= \int_0^Q (\alpha - \beta q)dq - \left(\alpha - \beta\sum_{i=1}^{6} q_i\right) \\ &\quad \cdot \sum_{i=1}^{6} q_i + \sum_{i=1}^{6}\pi_i + \sum_{i=1}^{6} te_{2015,i}(1-r_i)q_i \\ &\quad - \theta\sum_{i=1}^{6} e_{2015,i}(1-r_i)q_i. \end{aligned} \tag{3}$$

In the first stage, the regional enterprises obtain the profit function by selecting the decline in emission intensity and production output, as a response to the government's corresponding emission reduction policy and emission reduction target R. The government's decision can be expressed as:

$$\begin{aligned} &\max W, \\ s.t.\ &\frac{\sum_{i=1}^{6} e_{2015,i}(1-r_i)q_i}{\sum_{i=1}^{6} q_i} = e_{2010}(1-R), \\ &0 < r_i < 1, \\ &e_i > 0, \\ &q_i > 0, \\ &t \geq 0, \\ &i = 1,2,3,4,5,6. \end{aligned} \tag{4}$$

3.3. Local Stability Analysis of Dynamic Decision Model Based on Bounded Rationality. In the actual steel market, the game between enterprises is going on constantly. It is necessary to establish a dynamic game model based on bounded rationality. In the proposed approach, we will improve and supplement the model according to the processing method of reference [34, 39, 40, 42–47] and then analyse the dynamic system.

In the second stage of the game, the respective profit function is derived, and the marginal profit of the enterprise i in period K is:

$$\frac{\partial\pi_i(q_i(k), q_j(k))}{\partial q_i(k)} = \alpha - C_i - \beta\sum_{j=1, j\neq i}^{6} l_{ji} q_j(k) - 2\beta q_i(k). \tag{5}$$

The product takes production as the decision variable. When the marginal profit of the base period is positive (negative), the enterprise will increase (decrease) the output of the next period. The output of enterprise i in period $K+1$ is:

$$q_i(k+1) = q_i(k) + \xi_i q_i(k)\frac{\partial\pi_i(q_i(k), q_j(k))}{\partial q_i(k)}, \tag{6}$$

where $\xi_i > 0$, and ξ_i indicates the output adjustment coefficient, the speed of production adjustment. For six enterprises, there are:

$$\begin{aligned} q_1(k+1) &= q_1(k) + \xi_1 q_1(k)[\alpha - C_1 - \beta(l_{21}q_2(k) + l_{31}q_3(k) \\ &\quad + l_{41}q_4(k) + l_{51}q_5(k) + l_{61}q_6(k)) - 2\beta q_1(k)], \\ q_2(k+1) &= q_2(k) + \xi_2 q_2(k)[\alpha - C_2 - \beta(l_{12}q_1(k) + l_{32}q_3(k) \\ &\quad + l_{42}q_4(k) + l_{52}q_5(k) + l_{62}q_6(k)) - 2\beta q_2(k)], \\ &\cdots \\ q_6(k+1) &= q_6(k) + \xi_6 q_6(k)[\alpha - C_6 - \beta(l_{16}q_1(k) + l_{26}q_2(k) \\ &\quad + l_{36}q_3(k) + l_{46}q_4(k) + l_{56}q_5(k)) - 2\beta q_6(k)]. \end{aligned} \tag{7}$$

After a limited number of repeated games, the steel market stabilizes, and the output of steel oligopoly enterprises in various regions reaches a balance. When $q_i(k+1) = q_i(k)$, there are:

$$\begin{aligned} &\xi_1 q_1(k)[\alpha - C_1 - \beta(l_{21}q_2(k) + l_{31}q_3(k) + l_{41}q_4(k) \\ &+ l_{51}q_5(k) + l_{61}q_6(k)) - 2\beta q_1(k)] = 0, \\ &\xi_2 q_2(k)[\alpha - C_2 - \beta(l_{12}q_1(k) + l_{32}q_3(k) + l_{42}q_4(k) \\ &+ l_{52}q_5(k) + l_{62}q_6(k)) - 2\beta q_2(k)] = 0, \\ &\cdots \\ &\xi_6 q_6(k)[\alpha - C_6 - \beta(l_{16}q_1(k) + l_{26}q_2(k) \\ &+ l_{36}q_3(k) + l_{46}q_4(k) + l_{56}q_5(k)) - 2\beta q_6(k)] = 0. \end{aligned} \tag{8}$$

Among the 64 analytical solutions obtained, there is a Nash equilibrium point $E^*(q_1, q_2, q_3, q_4, q_5, q_6)$ (this paper considers only the nonnegative equilibrium solutions as having economic significance). However, the production adjustment coefficient affects the stability of the steel market and increases the complexity of the system. Therefore, it is necessary to study the local stability of the Nash equilibrium point.

For the stability of the six-dimensional linear discrete system $q_i(k+1) = f(q_i(k))$, it can be judged by the eigenvalue of its Jacobian matrix. The Jacobian matrix J is,

$$J = \begin{pmatrix} J_{11} & J_{12} & J_{13} & J_{14} & J_{15} & J_{16} \\ J_{21} & J_{22} & J_{23} & J_{24} & J_{25} & J_{26} \\ J_{31} & J_{32} & J_{33} & J_{34} & J_{35} & J_{36} \\ J_{41} & J_{42} & J_{43} & J_{44} & J_{45} & J_{46} \\ J_{51} & J_{52} & J_{53} & J_{54} & J_{55} & J_{56} \\ J_{61} & J_{62} & J_{63} & J_{64} & J_{65} & J_{66} \end{pmatrix}, \tag{9}$$

among this,

$$
\begin{aligned}
J_{11} &= 1+\xi_1[\alpha - C_1 - \beta(l_{21}q_2 + l_{31}q_3 + l_{41}q_4 + l_{51}q_5 + l_{61}q_6)] - 4\xi_1\beta q_1,\\
J_{12} &= -\xi_1\beta l_{21}q_1, J_{13} = -\xi_1\beta l_{31}q_1, J_{14} = -\xi_1\beta l_{41}q_1, J_{15} = -\xi_1\beta l_{51}q_1, J_{16} = -\xi_1\beta l_{61}q_1,\\
J_{22} &= 1+\xi_2[\alpha - C_2 - \beta(l_{12}q_1 + l_{32}q_3 + l_{42}q_4 + l_{52}q_5 + l_{62}q_6)] - 4\xi_2\beta q_2,\\
J_{21} &= -\xi_2\beta l_{12}q_2, J_{23} = -\xi_2\beta l_{32}q_2, J_{24} = -\xi_2\beta l_{42}q_2, J_{25} = -\xi_2\beta l_{52}q_2, J_{26} = -\xi_2\beta l_{62}q_2,\\
J_{33} &= 1+\xi_3[\alpha - C_3 - \beta(l_{13}q_1 + l_{23}q_2 + l_{43}q_4 + l_{53}q_5 + l_{63}q_6)] - 4\xi_3\beta q_3,\\
J_{31} &= -\xi_3\beta l_{13}q_3, J_{32} = -\xi_3\beta l_{23}q_3, J_{34} = -\xi_3\beta l_{43}q_3, J_{35} = -\xi_3\beta l_{53}q_3, J_{36} = -\xi_3\beta l_{63}q_3,\\
J_{44} &= 1+\xi_4[\alpha - C_4 - \beta(l_{14}q_1 + l_{24}q_2 + l_{34}q_3 + l_{54}q_5 + l_{64}q_6)] - 4\xi_4\beta q_4,\\
J_{41} &= -\xi_4\beta l_{14}q_4, J_{42} = -\xi_4\beta l_{24}q_4, J_{43} = -\xi_4\beta l_{34}q_4, J_{45} = -\xi_4\beta l_{54}q_4, J_{46} = -\xi_4\beta l_{64}q_4,\\
J_{55} &= 1+\xi_5[\alpha - C_5 - \beta(l_{15}q_1 + l_{25}q_2 + l_{35}q_3 + l_{45}q_4 + l_{65}q_6)] - 4\xi_5\beta q_5,\\
J_{51} &= -\xi_5\beta l_{15}q_5, J_{52} = -\xi_5\beta l_{25}q_5, J_{53} = -\xi_5\beta l_{35}q_5, J_{54} = -\xi_5\beta l_{45}q_5, J_{56} = -\xi_5\beta l_{65}q_5,\\
J_{66} &= 1+\xi_6[\alpha - C_6 - \beta(l_{16}q_1 + l_{26}q_2 + l_{36}q_3 + l_{46}q_4 + l_{56}q_5)] - 4\xi_6\beta q_6,\\
J_{61} &= -\xi_6\beta l_{16}q_6, J_{62} = -\xi_6\beta l_{26}q_6, J_{63} = -\xi_6\beta l_{36}q_6, J_{64} = -\xi_6\beta l_{46}q_6, J_{65} = -\xi_6\beta l_{56}q_6.
\end{aligned}
\tag{10}
$$

The characteristic equation of the Jacobian matrix equilibrium point is:

$$f(\lambda) = \lambda^6 + \mu_1\lambda^5 + \mu_2\lambda^4 + \mu_3\lambda^3 + \mu_4\lambda^2 + \mu_5\lambda + \mu_6 = 0 \tag{11}$$

Next, let

$$
\begin{aligned}
&\varphi_0 = \mu_6^2 - 1,\ \varphi_1 = \mu_6\mu_5 - \mu_1,\ \varphi_2 = \mu_6\mu_4 - \mu_2,\\
&\varphi_3 = \mu_6\mu_3 - \mu_3,\ \varphi_4 = \mu_6\mu_2 - \mu_4,\ \varphi_5 = \mu_6\mu_1 - \mu_5,\\
&\gamma_0 = \varphi_0^2 - \varphi_5^2,\ \gamma_1 = \varphi_0\varphi_1 - \varphi_4\varphi_5,\ \gamma_2 = \varphi_0\varphi_2 - \varphi_3\varphi_5,\\
&\gamma_3 = \varphi_0\varphi_3 - \varphi_2\varphi_5,\ \gamma_4 = \varphi_0\varphi_4 - \varphi_1\varphi_5,\\
&\upsilon_0 = \gamma_0^2 - \gamma_4^2,\ \upsilon_1 = \gamma_0\gamma_1 - \gamma_3\gamma_4,\ \upsilon_2 = \gamma_0\gamma_2 - \gamma_2\gamma_4,\ \upsilon_3 = \gamma_0\gamma_3 - \gamma_1\gamma_4,\\
&\varepsilon_0 = \upsilon_0^2 - \upsilon_3^2,\ \varepsilon_1 = \upsilon_0\upsilon_1 - \upsilon_2\upsilon_3,\ \varepsilon_2 = \upsilon_0\upsilon_2 - \upsilon_1\upsilon_3.
\end{aligned}
\tag{12}
$$

Edelstein [67] pointed out that according to the Jury stability criterion, the necessary and sufficient condition for stability of the equilibrium point is that all zeros of the characteristic equation fall within the unit circle on the complex plane, at which time:

$$
\begin{aligned}
&1 + \mu_1 + \mu_2 + \mu_3 + \mu_4 + \mu_5 + \mu_6 > 0,\\
&1 - \mu_1 + \mu_2 - \mu_3 + \mu_4 - \mu_5 + \mu_6 > 0\\
&|\mu_6| < 1,\\
&|\varphi_0| > |\varphi_5|,\ |\gamma_0| > |\gamma_4|,\ |\upsilon_0| > |\upsilon_3|, |\varepsilon_0| > |\varepsilon_2|.
\end{aligned}
\tag{13}
$$

Then, in the space $(\xi_1, \xi_2, \xi_3, \xi_4, \xi_5, \xi_6)$, the initial value of arbitrary output passes the finite-order game and finally reaches the Nash equilibrium state. At that time, the Nash equilibrium point is locally stable. The result is the equilibrium output of steel companies in the presence of product differentiation. Once the parameter adjustment of an enterprise exceeds the stable region, the stable state of the Nash equilibrium will be destroyed, and the system may be bifurcated and even evolve into a chaotic state, which means that the market will fall into disorderly competition and unbalanced production.

When the market is in a stable state, q and r in period K can be expressed in t, and also, period $K+1$ can be expressed in t. Values such as q and r can be obtained by the reverse order solution. From the expressions of the output and the decline in CO_2 emission intensity, the results in the market steady state are the same as the single static game.

Since the decision-making ability of each oligarch is different, ξ_i is also different, which has a very important impact on the outcome of the game. Therefore, after obtaining the local stability domain, it is necessary to analyse the complex dynamic characteristics of the system. It is usually described using the system's output bifurcation diagram and the Lyapunov exponent. Therefore, in the results and discussion section, we will discuss the results in two parts: (1) analysis of the factors affecting the stability of the stability domain (l_{ji} and ξ_i) and (2) description and analysis of the dynamic characteristics of the system (bifurcation diagram and Lyapunov exponent).

3.4. Data Sources. The statistics in this paper are from the China Statistical Yearbook [68], China Industrial Statistical Yearbook [69], China Energy Statistical Yearbook [70], China Steel Yearbook [71], and the statistical yearbooks of the various provinces. Relevant economic data are equivalent to comparable prices in 2010. The time span is from 2005 to 2016.

In addition, CO_2 emissions in industrial production (IPPU CO_2), which also produce large amount of CO_2, are included in this paper. Therefore, CO_2 emission accounting, emission intensity, and descent amplitude are based on energy consumption + IPPU CO_2 emissions.

Due to data availability, the steel industry's relevant energy consumption and economic data are derived from the ferrous metal smelting and calendering processing industry in the Statistical Yearbook. The CO_2 accounting of fossil energy consumption and IPPU refer to IPCC 2006 [72] and Duan et al. [73].

4. Results and Discussion

4.1. The Results of Parameter Fitting. In this paper, referring to the research of Ma and Li [74], the market demand for steel industry is expressed by the apparent consumption, and the product price is obtained by dividing the industrial output value by the output. In the selection of the curve form, the inverse demand curve can be approximated as a straight line inclined to the lower right. The inverse demand curve fitting equation is as follows:

Table 6: Some parameter values.

Notations	Unit		$i=1$	$i=2$	$i=3$	$i=4$	$i=5$	$i=6$
$e_{2015,i}$	t CO_2/t		2.3344	3.5698	2.9040	2.8779	3.2202	4.5864
a_i			11661	17208	16932	12952	6397	3485
b_i			−169.76	8876.70	−166.92	1483.60	502.52	421.13
c_i	Yuan		2168.20	3511.10	2165.40	3325.10	2368.70	3814.30
$C_{0,i}$	Yuan	2015	2833.15	4898.47	3453.53	4153.15	3799.03	3832.38
		K	2124.86	3918.77	2590.15	2491.89	3609.08	3640.76

$$P=\alpha-\beta Q=15769.56-1.13\times 10^{-5}Q. \quad (14)$$

In 2010, the average level of CO_2 emissions in China's steel industry was 3.1710 ton CO_2/ton steel (the same below, omitted). According to the collection and calculation, the average level of CO_2 emission in 2015 was 2.8210. Correspondingly, the CO_2 emission levels of the six regions in 2015 were $e_1=2.3344, e_2=3.5698, e_3=2.9040, e_4=2.8779, e_5=3.2202$, and $e_6=4.5864$.

The calculation method of MAC refers to Duan et al. [75], Färe et al. [76], and Lee et al. [77] (the data are updated to 2016, and the function form is slightly changed). The relationship between the reduction of emission intensity in each region and the marginal abatement cost of CO_2 is shown in Table 6. It should be pointed out that due to the estimation of shadow price, the error and uncertainty of the CO_2 marginal abatement cost curve are increased. This leads to a certain gap between the calculated abatement cost and the real abatement cost. In order to reduce the error, this paper uses $\lambda\left(c_i+\int_0^{r_i}MAC_i(r)dr\right)$ to represent the actual emission reduction cost, with $\lambda=0.5$, in order to reduce the error.

In setting the CO_2 emission intensity reduction target, this paper refers to Steel Industry Adjustment and Upgrade Plan (2016–2020). The target of 2020 is about 85% of the energy consumption level in 2010. Therefore, this paper sets the CO_2 emission intensity of the steel industry in period K to be 15% lower than that in 2010. In terms of the value of production costs, this paper assumes that in the period K, the production costs in North China, East China, and South Central China will decrease significantly, and the production costs in Northeast China, Southwest China, and Northwest China will decrease somewhat less. The external macro-environmental loss parameters of CO_2 emissions refer to the study of Guenno and Tiezzi [78], $\theta=14.55$ yuan/ton CO_2. The specific data simulation parameter settings are shown in Table 6.

In order to facilitate calculation and discussion, when the product has differentiation, the substitution coefficients of the products between enterprises are the same; that is, $l_{ji}=l$. The values of l are 0.95, 0.90, 0.85, 0.80, 0.75, respectively, and the other parameters are consistent with the production of the same product.

4.2. Empirical Analysis

4.2.1. $l=1$. When the steel oligopoly enterprises in each region produce only one identical product, in the case of only the carbon tax policy, after calculation, when the industry emission reduction target is 15%, the equilibrium output of

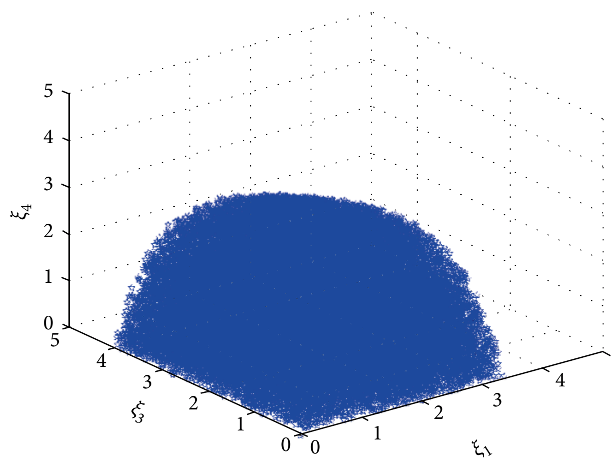

Figure 2: The market stability domain $(\xi_2=\xi_5=\xi_6=0, l=1)$.

enterprises in various regions is $E^*=(2.5789\times10^8, 0.3823\times10^8, 2.1623\times10^8, 1.7354\times10^8, 1.1672\times10^8, 0.4867\times10^8)$, and the unit is the ton. In order to facilitate the discussion of the change range of ξ, this section has adjusted α, β, q, etc., and has changed the cost and output units to 10,000 yuan and 100 million tons. At this time, there are:

$$\begin{aligned}
&J_{11}=1-0.5828\xi_1, J_{12}=J_{13}=J_{14}=J_{15}=J_{16}=-0.2914\xi_1,\\
&J_{22}=1-0.0864\xi_2, J_{21}=J_{23}=J_{24}=J_{25}=J_{26}=-0.0432\xi_2,\\
&J_{33}=1-0.4887\xi_3, J_{31}=J_{32}=J_{34}=J_{35}=J_{36}=-0.2443\xi_3,\\
&J_{44}=1-0.3922\xi_4, J_{41}=J_{42}=J_{43}=J_{45}=J_{46}=-0.1961\xi_4,\\
&J_{55}=1-0.2638\xi_5, J_{51}=J_{52}=J_{53}=J_{54}=J_{56}=-0.1319\xi_5,\\
&J_{66}=1-0.1099\xi_6, J_{61}=J_{62}=J_{63}=J_{64}=J_{65}=-0.0550\xi_6.
\end{aligned} \quad (15)$$

Based on the results of balanced production, the six regional enterprises are clearly divided into two groups. North China, East China, and South Central China have always occupied the top three places in the six regions; the outputs of the other three regions are lower. In order to explore the impact of production adjustment speed (ξ_i) on system stability, this section examines the two cases below: (1) the changes in production adjustment speed and market stability in North China, East China, and South Central China under the conditions of constant production adjustment rates in Northeast, Southwest, and Northwest China; and (2) the changes in production adjustment speed and market stability in Northeast, Southwest, and Northwest China under the conditions of constant production adjustment in North China, East China, and South Central China.

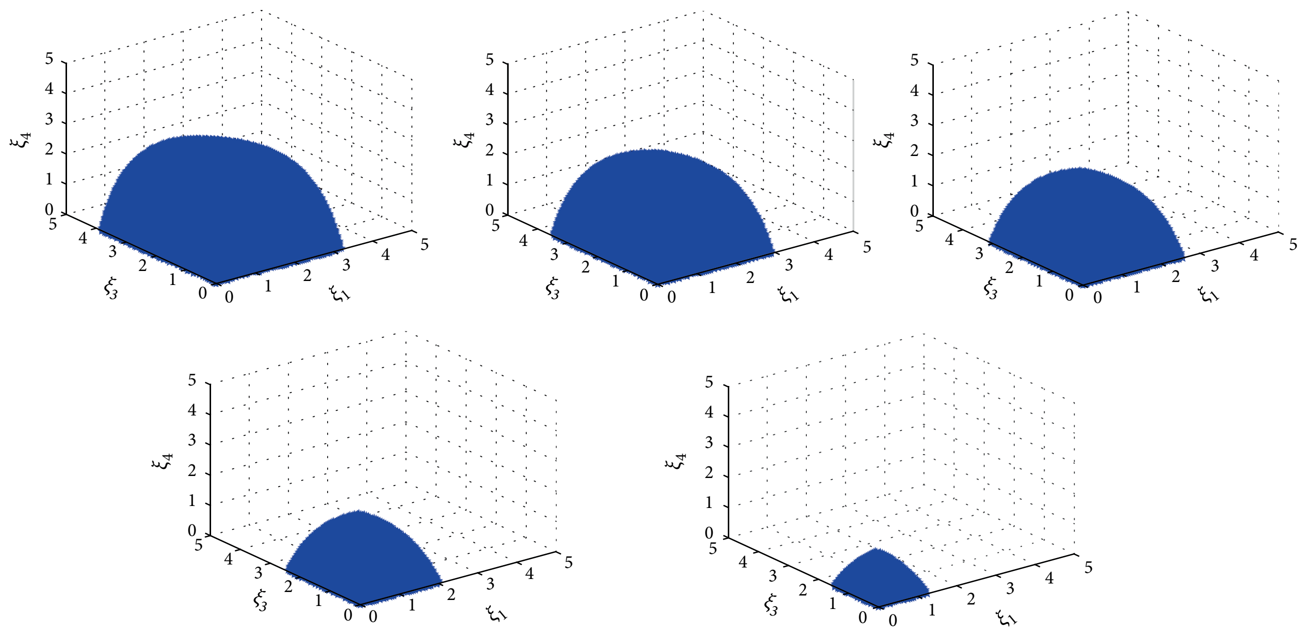

Figure 3: The market stability domain ($\xi_2 = \xi_5 = \xi_6 = 1 \sim 5$, $l = 1$).

(1) The Output Adjustment Rate in Northeast, Southwest, and Northwest China Remains Unchanged. When ξ_2, ξ_5, ξ_6 are 0 at the same time, that is, these three regions do not adopt any expected strategy, and the marginal profit changes in period K will not affect the output change in period $K+1$. The stable market of the steel market composed of ξ_1, ξ_3, ξ_4 is shown in Figure 2. It can be seen from the figure that in order to maintain the stability, the range of adjustment coefficient ξ_1 is [0, 3.40], ξ_3 is [0, 4.00], ξ_4 is [0, 5.00], and the entire stable domain presents a hemispherical shape. When ξ_i is negative, it means that the change in marginal profit of the base period will cause the enterprise to make reverse production decisions in the next period. In the vast majority of cases, this does not meet the actual decisions of the enterprise. This section will focus on the analysis of $\xi_i \geq 0$.

When ξ_2, ξ_5, ξ_6 simultaneously increase from 1.00 to 5.00, the stability domain is shown in Figure 3. This shows that when Northeast China, Southwest China, and Northwest China take a positive production adjustment coefficient at the same time, the stability of the entire market is gradually shrinking. However, when ξ_2, ξ_5, ξ_6 are 5, ξ_1, ξ_3, ξ_4 can still remain in the interval of [0,1.25], [0,1.45], and [0,1.80]. It indicates that when Northeast, Southwest, and Northwest regions adopt a very large positive production adjustment policy, the other three regions can still adopt a more liberal production strategy. That is to say, for enterprises with large output, the production adjustment policies of enterprises with small output cannot strongly influence their production strategies, and they still have a lot of adjustment space and other strategies to choose from. Of course, if an enterprise with small production loses its rationality, or if it misjudges the market situation and adjusts its production strategy at will, regardless of the consequences, it may still cause market imbalance.

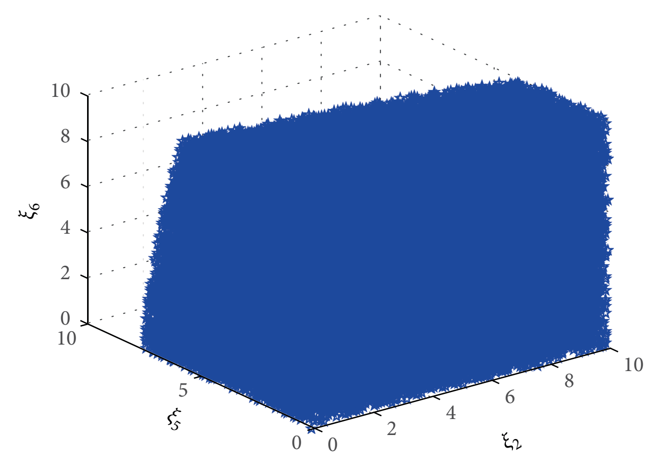

Figure 4: The market stability domain ($\xi_1 = \xi_3 = \xi_4 = 0$, $l = 1$).

(2) The Output Adjustment Rate in North China, East China, and South Central China Remains Unchanged. When ξ_1, ξ_3, ξ_4 are 0 at the same time, that is, these three regions do not adopt any expected strategy, and the marginal profit changes in period K will not affect the output change in period $K+1$. The stable market of the steel market composed of ξ_2, ξ_5, ξ_6 is shown in Figure 4. It can be seen from the figure that in order to maintain the stability, the range of adjustment coefficient ξ_2 is [0,10.00], ξ_5 is [0,7.50], ξ_6 is [0,10.00], or even more. This shows that when North China, Northeast China, and Central South China do not adopt any production adjustment measures, the other three regions can have considerable decision-making power for production.

When ξ_1, ξ_3, ξ_4 simultaneously increase, the stability domain is shown in Figure 5. This shows that when North China, Northeast China, and South Central China take a positive production coefficient at the same time, the stability of the entire market is gradually shrinking, which is similar to the conclusion of (1). However, unlike the

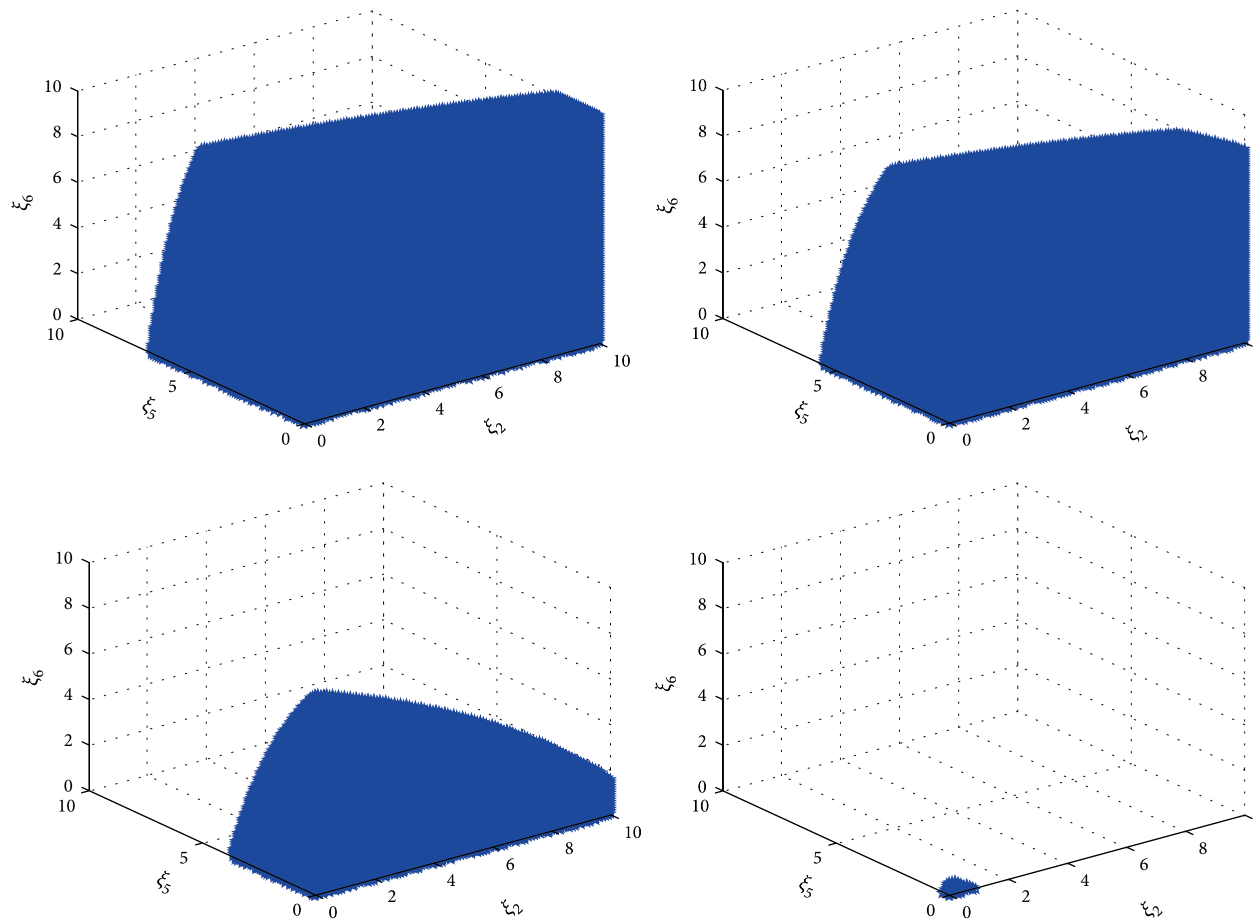

Figure 5: The market stability domain $(\xi_1 = \xi_3 = \xi_4 = 0.5 \sim 2,\ l = 1)$.

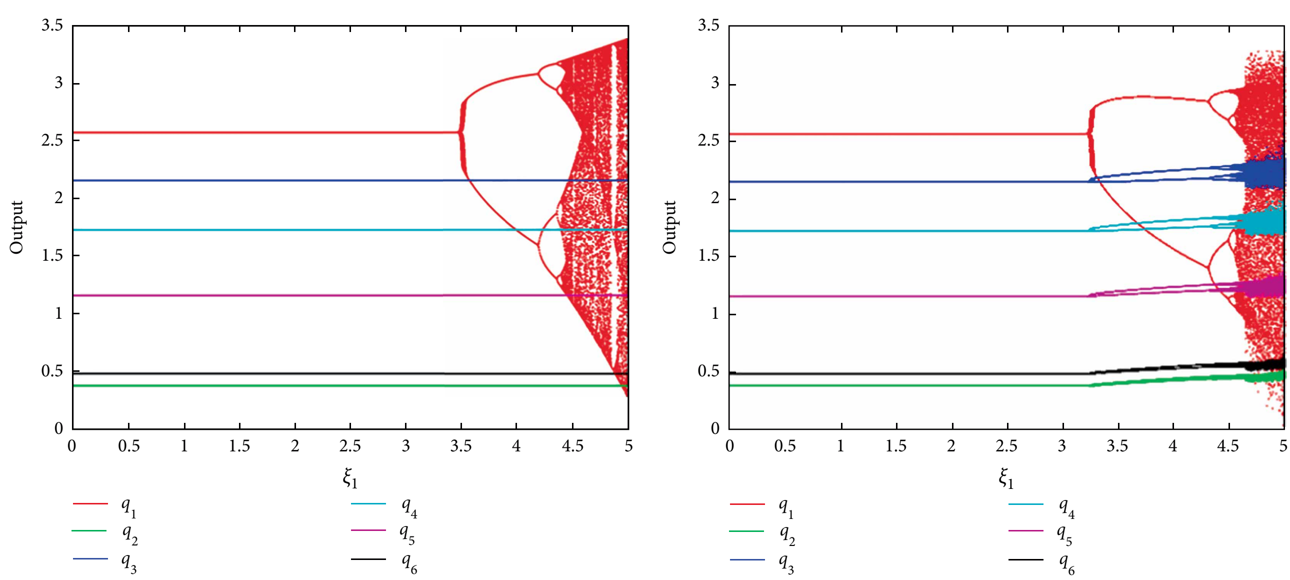

Figure 6: The bifurcation diagram of ξ_1 ($l_{ji} = 1$, left: $\xi_2 \sim \xi_6 = 0$, right: $\xi_2 \sim \xi_6 = 0.4$).

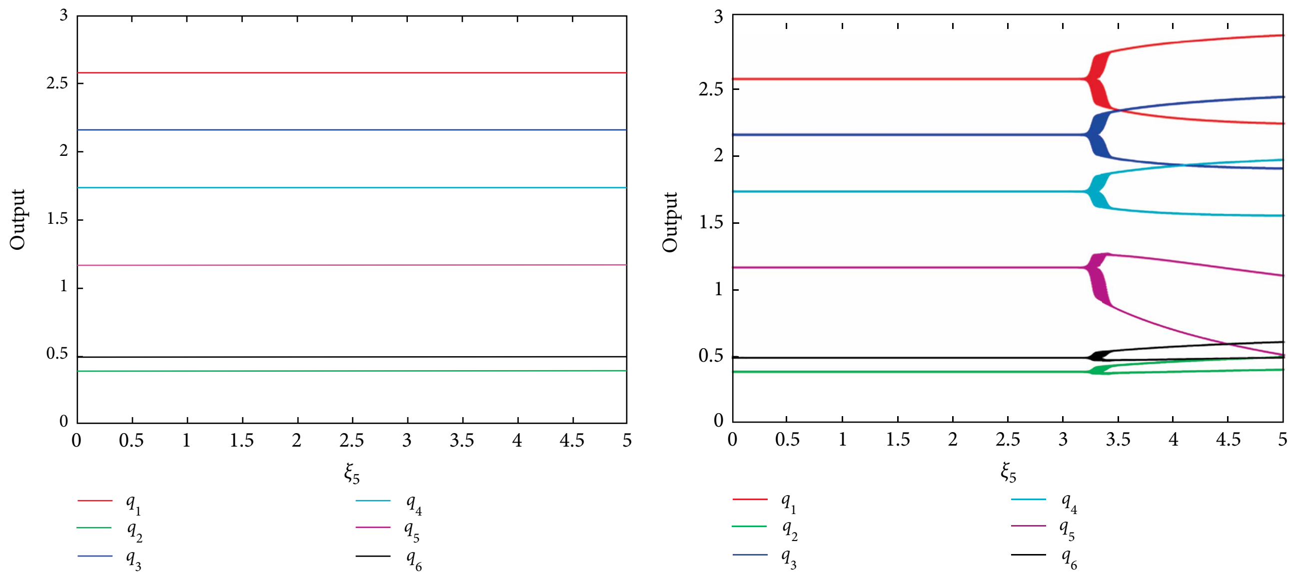

Figure 7: The bifurcation diagram of ξ_5 ($l_{ji} = 1$, left: $\xi_1, \xi_2, \xi_3, \xi_4, \xi_6 = 0$, right: $\xi_1, \xi_2, \xi_3, \xi_4, \xi_6 = 1.5$).

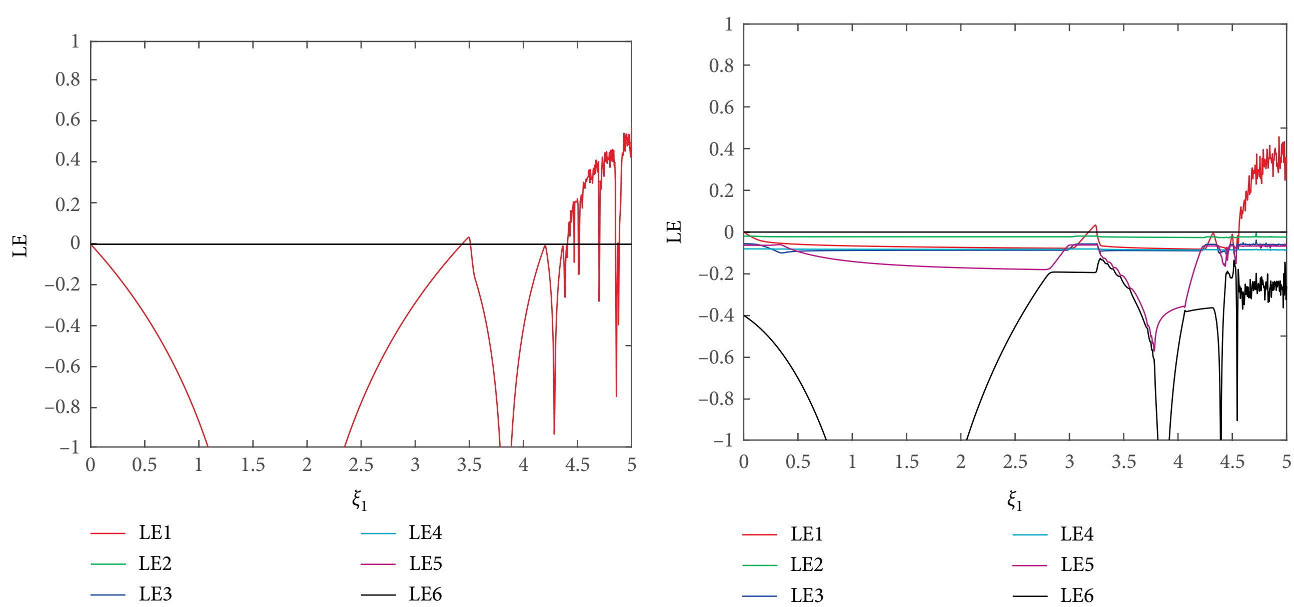

Figure 8: The Lyapunov exponent diagram ($l_{ji} = 1$, left: $\xi_2 \sim \xi_6 = 0$, right: $\xi_2 \sim \xi_6 = 0.4$).

previous conclusions, it can be clearly found that when ξ_1, ξ_3, ξ_4 take a small positive value, Northeast China, Southwest China, and Northwest China still have relatively large independent decision-making power. But when ξ_1, ξ_3, ξ_4 gradually increase, the market stability domain shrinks drastically. As ξ_1, ξ_3, ξ_4 are 2, ξ_2, ξ_5, ξ_6 only have a small range of values. Obviously, when ξ_1, ξ_3, ξ_4 increase continuously, the market will easily lose balance. Once the market is in an unbalanced state and product output fluctuates drastically, it will be difficult for steel oligarchy companies in all regions to obtain accurate information, make long-term plans, and obtain stable profits.

That is to say, for enterprises with small output, when enterprises with large output adopt weak positive adjustment policies, they can still have relatively free production autonomy. However, when the enterprises with large output adopt a larger output adjustment policy, the enterprises with small output will be strongly impacted, and the adjustment space will be sharply compressed.

(3) Analysis of System Dynamic Characteristics. Since the equilibrium yield results of the six regions show a polarized distribution, the stable region also shows two different results. Therefore, this section takes two representative enterprises in two groups, enterprise in North China (companies with large output) and in Southwest China (enterprises with smaller output). This section discusses production adjustment coefficient factors ξ_1 and ξ_5 and the impacts of changes in the stability of the system. The results are shown in the bifurcation diagrams and Lyapunov exponent below.

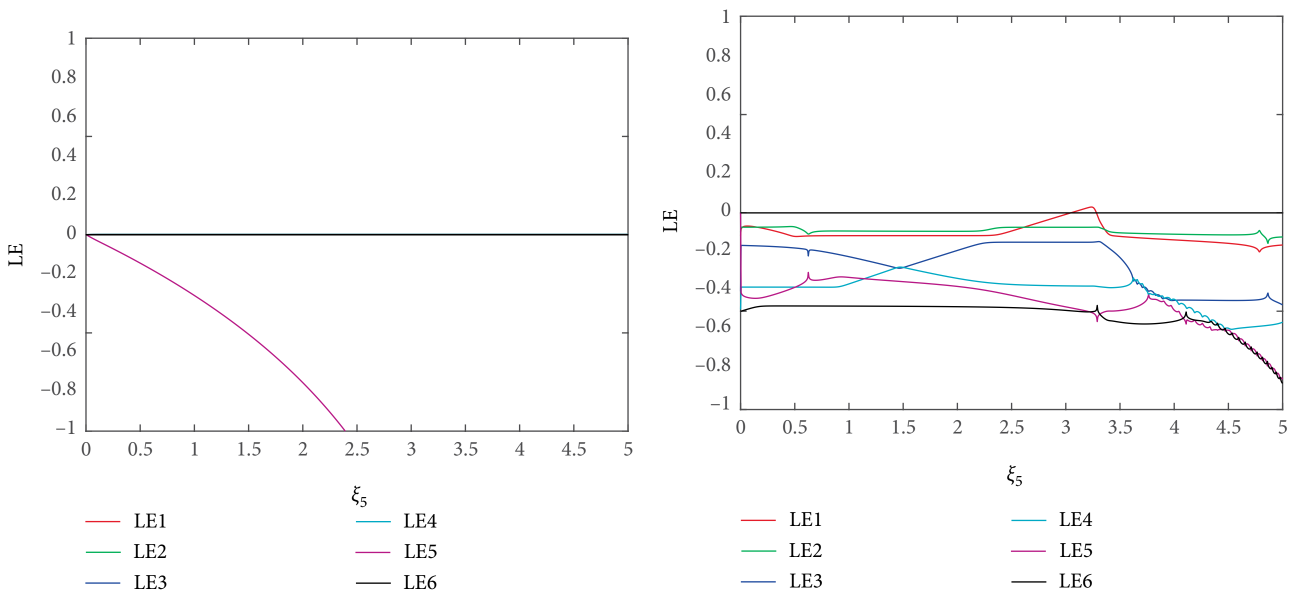

Figure 9: The Lyapunov exponent diagram ($l_{ji} = 1$, left: ξ_1, ξ_2, ξ_3, ξ_4, $\xi_6 = 0$, right: ξ_1, ξ_2, ξ_3, ξ_4, $\xi_6 = 1.5$).

The left graph of Figure 6 shows that when $\xi_2 \sim \xi_6 = 0$, with the change of ξ_1 (the abscissa values range from 0 to 5, the same below), the bifurcation diagram. It can be seen that when other areas do not take any adjustment measures, the system is stable when ξ_1 is between 0 and 3.485. Then, there is a small interval where q_1 production is unstable. When ξ_1 is gradually increased from about 3.500, the system transitions change from stable, to double-cycle, to chaos. However, at that time, only the output of North China is out of balance. The right graph in Figure 6 shows that when $\xi_2 \sim \xi_6 = 0.4$, and ξ_1 is from 0 to 3.230, the system is stable. Then, there is a small interval where q_1 production is unstable. When ξ_1 gradually increased from 3.250, the system transitions change from stable, to double-cycle, to chaos. However, unlike the left graph, as ξ_1 gradually increases, the output of other regions experiences an imbalance.

This shows that the system is more likely to fall into an unbalanced state when multiple enterprises adopt a policy of dynamic output adjustment at the same time rather than when a single enterprise adopts the measure of output adjustment.

The left graph of Figure 7 shows that when $\xi_1, \xi_2, \xi_3, \xi_4, \xi_6$ equal 0, and the change of ξ_5, the bifurcation diagram. It can be seen that the system is always in balance regardless of ξ_5. The right graph in Figure 7 shows that when $\xi_1, \xi_2, \xi_3, \xi_4, \xi_6$ are at 1.5, and ξ_5 ranges from 0 to about 3.100, the system is stable. Then, there is a small interval where all enterprises' production is unstable. When the ξ_5 value is gradually increased from about 3.250, the system transitions change from stable, to double-cycle, to chaos.

From the results of Figures 6 and 7, it can be seen that the enterprises with larger output have far more influence on the system balance than the enterprises with smaller output and improper production adjustment by these larger producers will easily cause market imbalance.

Figures 8 and 9 show the Lyapunov exponents for Figures 5 and 6. In the left graph of Figure 8, when $\xi_2 \sim \xi_6 = 0$ and $\xi_1 = 3.500$, the system first shows bifurcation. When $\xi_1 > 4.465$, the maximum Lyapunov exponent starts to go positive, and the system appears chaotic. In the right graph of Figure 8, when $\xi_2 \sim \xi_6$ are 0.4 and $\xi_1 = 3.250$, bifurcation of the system first appears, and then, all companies bifurcate. When $\xi_1 > 4.560$, the maximum Lyapunov exponent starts to go positive, and the system turns chaotic.

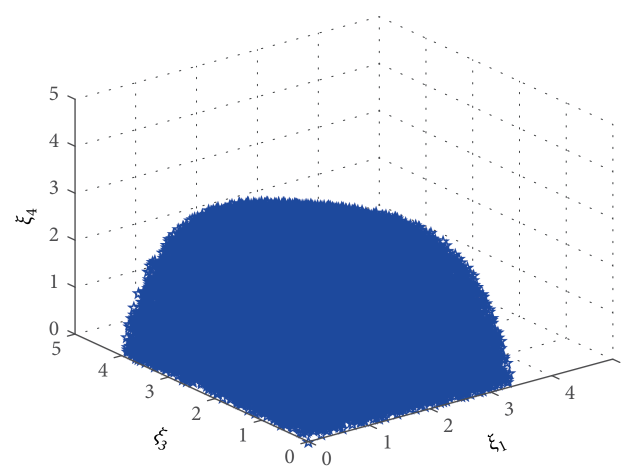

Figure 10: The market stability domain ($\xi_2 = \xi_5 = \xi_6 = 0$, $l = 0.95$).

In the left graph of Figure 9, when $\xi_1, \xi_2, \xi_3, \xi_4, \xi_6$ are 0, the maximum Lyapunov exponent is no more than 0. In the right graph of Figure 9, when $\xi_1, \xi_2, \xi_3, \xi_4, \xi_6$ equal 1.5 and ξ_5 ranges from 3.100 to 3.250, the maximum Lyapunov exponent began to appear positive and the bifurcation phenomenon occurs in each area. When $\xi_5 > 3.250$, the maximum Lyapunov exponent is less than 0, and the system transitions change to double-cycle.

4.2.2. $l \neq 1$, the Market Stability Research under Product Differentiation Conditions. When the steel oligopoly

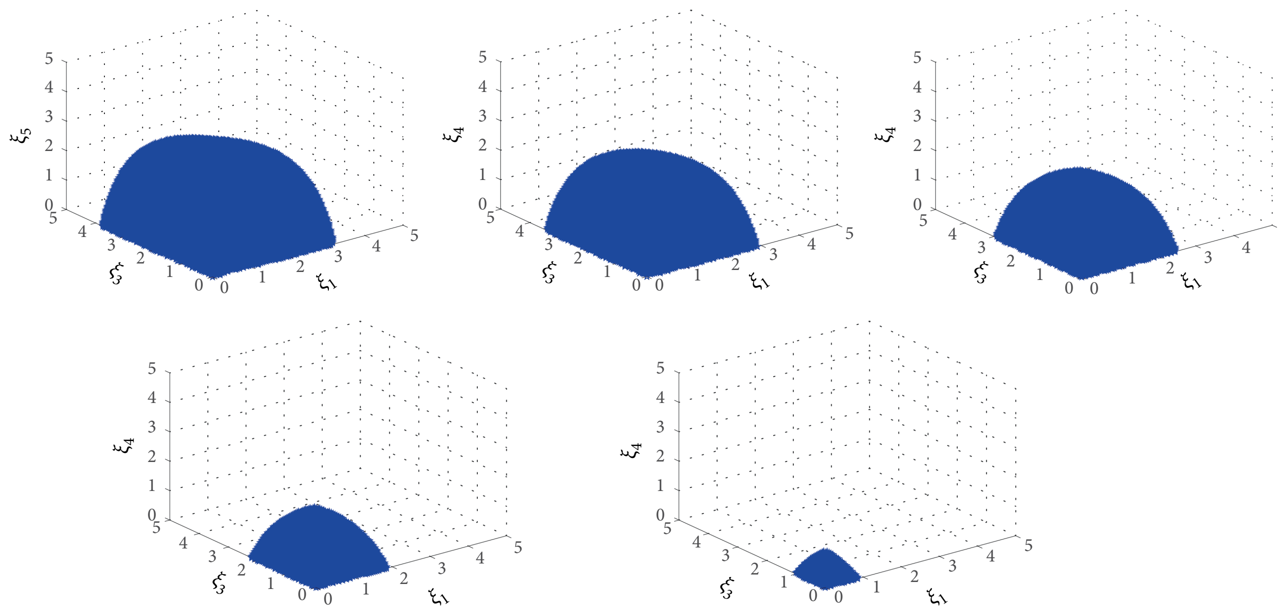

Figure 11: The market stability domain $(\xi_2 = \xi_5 = \xi_6 = 1 \sim 5,\ l = 0.95)$.

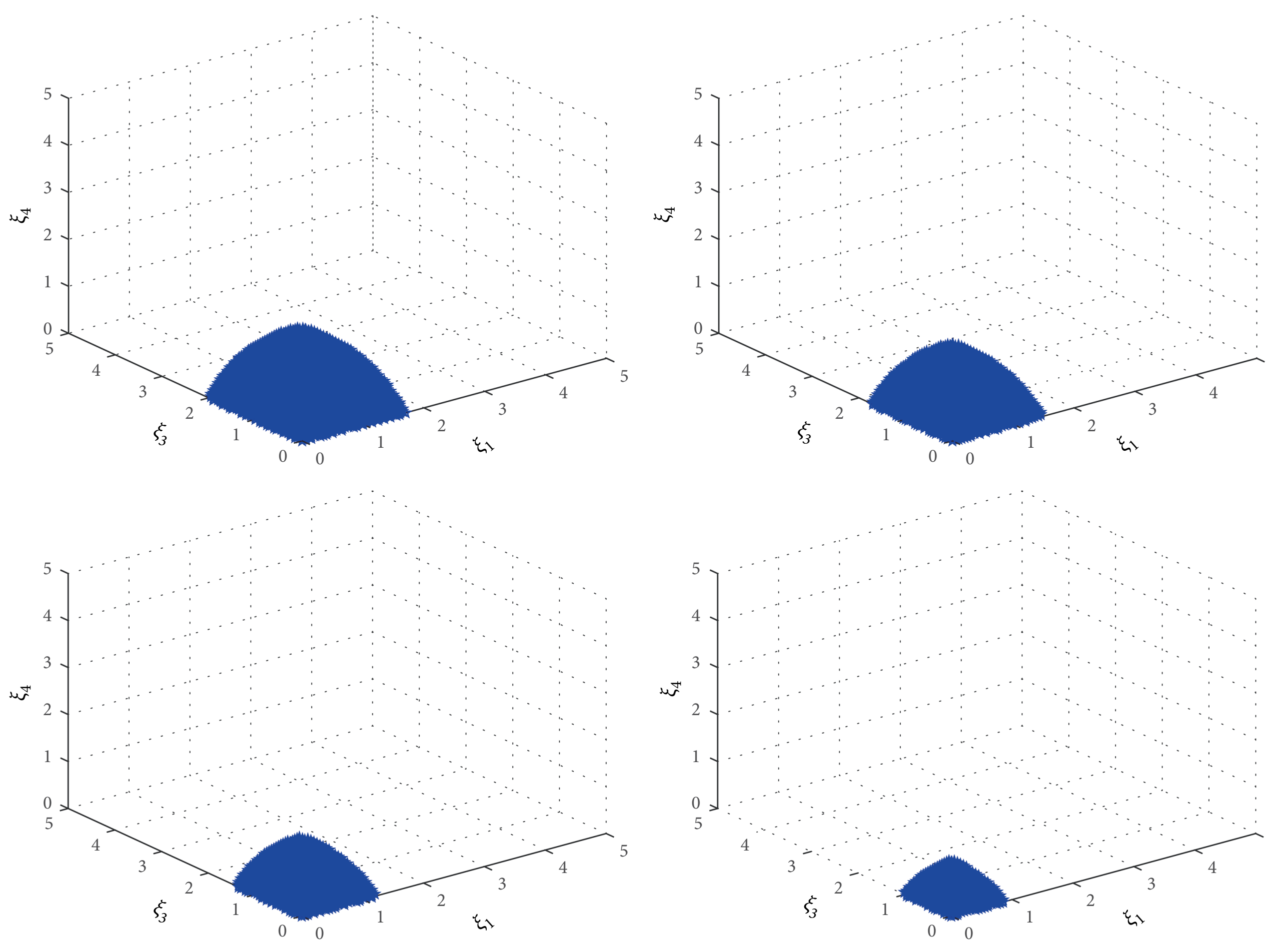

Figure 12: The market stability domain $(\xi_2 = \xi_5 = \xi_6 = 4,\ l = 0.90,\ 0.85,\ 0.80,\ 0.75)$.

enterprises in each region produce only one product that can replace each other's product, after calculation, $E^* = (2.5772 \times 10^8,\ 0.4818 \times 10^8,\ 2.1790 \times 10^8,\ 1.7723 \times 10^8,\ 1.2307 \times 10^8,\ 0.5802 \times 10^8)$, and the unit is the ton. In order to facilitate calculation and discussion, when the product has differentiation, the substitution coefficient of the products between enterprises is the same; that is, $l_{ji} = l$. When $R = 15\%$ and the substitution coefficient is 0.95, there are:

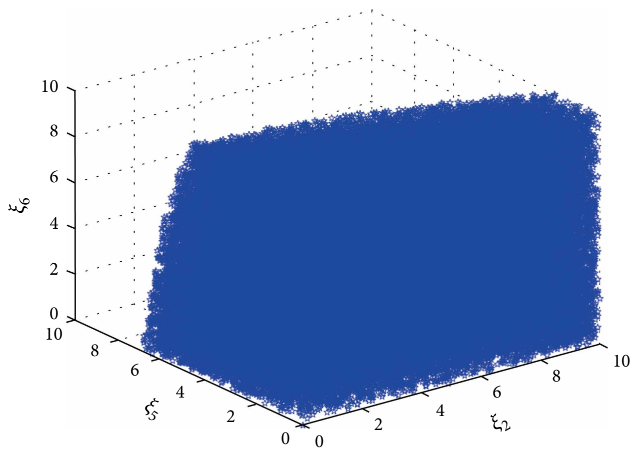

FIGURE 13: The market stability domain ($\xi_1 = \xi_3 = \xi_4 = 0$, $l = 0.95$).

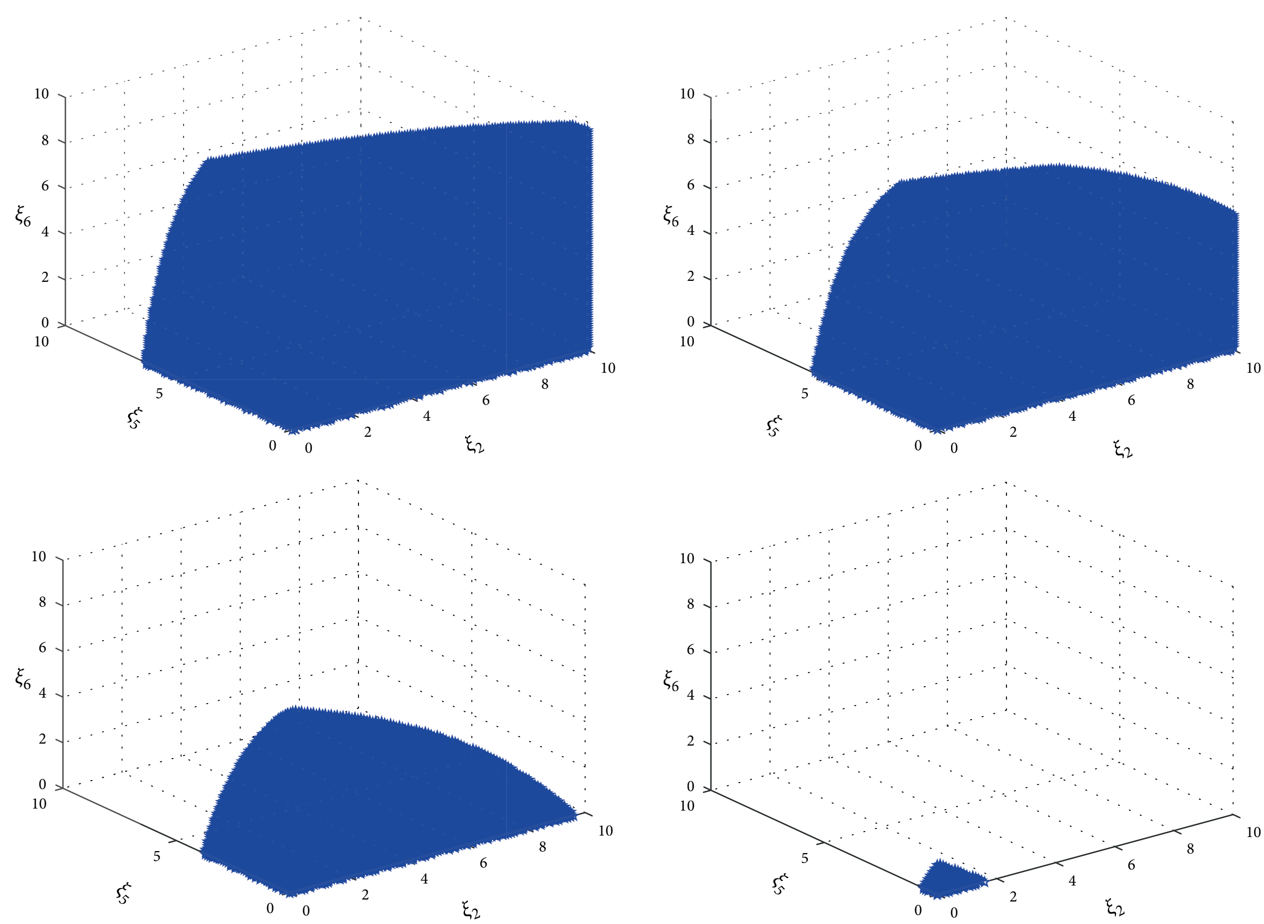

FIGURE 14: The market stability domain ($\xi_1 = \xi_3 = \xi_4 = 0.5 \sim 2$, $l = 0.95$).

$$\begin{aligned}
J_{11} &= 1 - 0.5242\xi_1, J_{12} = J_{13} = J_{14} = J_{15} = J_{16} = -0.2767\xi_1,\\
J_{22} &= 1 - 0.0980\xi_2, J_{21} = J_{23} = J_{24} = J_{25} = J_{26} = -0.0518\xi_2,\\
J_{33} &= 1 - 0.4432\xi_3, J_{31} = J_{32} = J_{34} = J_{35} = J_{36} = -0.2339\xi_3,\\
J_{44} &= 1 - 0.3605\xi_4, J_{41} = J_{42} = J_{43} = J_{45} = J_{46} = -0.1903\xi_4,\\
J_{55} &= 1 - 0.2503\xi_5, J_{51} = J_{52} = J_{53} = J_{54} = J_{56} = -0.1321\xi_5,\\
J_{66} &= 1 - 0.1180\xi_6, J_{61} = J_{62} = J_{63} = J_{64} = J_{65} = -0.0623\xi_6.
\end{aligned} \tag{16}$$

Similarly, this section examines two cases:

(1) The Output Adjustment Rate in Northeast, Southwest, and Northwest China Remains Unchanged. When the substitution coefficients are all 0.95, ξ_2, ξ_5, ξ_6 are 0 at the same time; that is, these three regions do not adopt any expected strategy, and the marginal profit changes in period K will not affect the

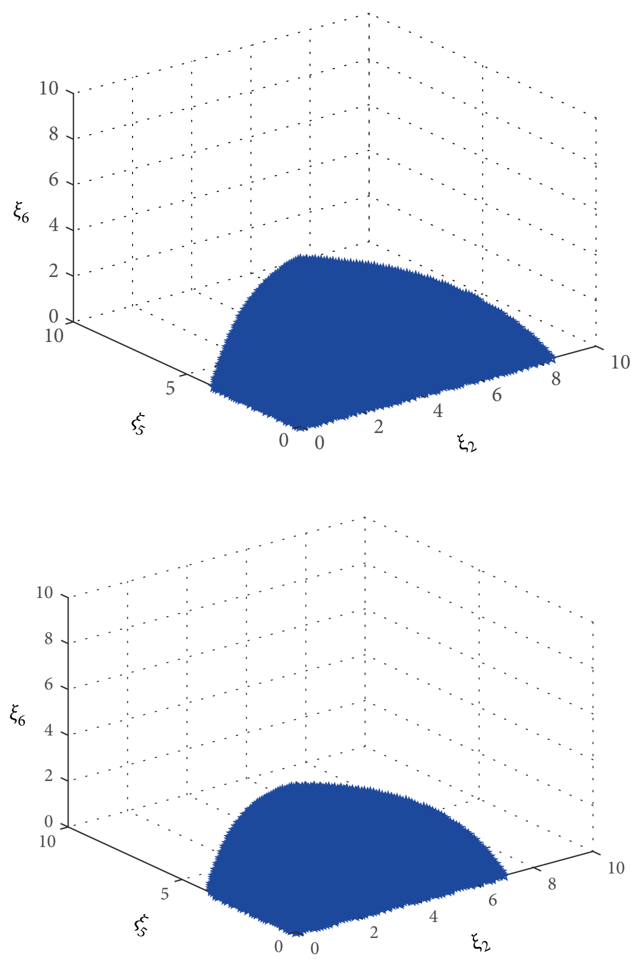

Figure 15: The market stability domain ($\xi_1 = \xi_3 = \xi_4 = 1.5$, $l = 0.90, 0.85, 0.80, 0.75$).

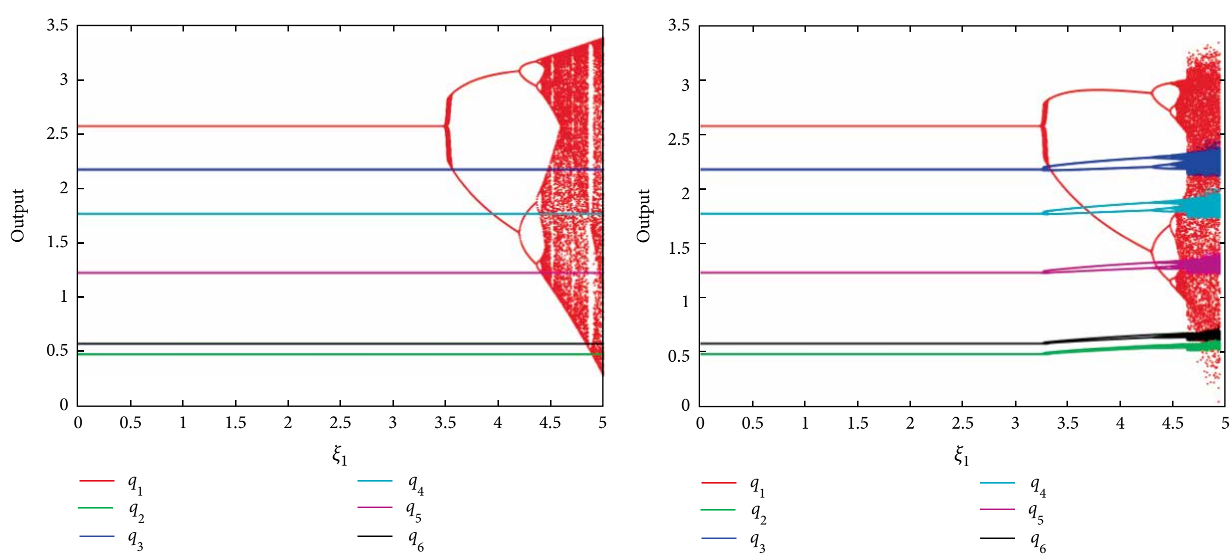

Figure 16: The bifurcation diagram of ξ_1 ($l_{ji} = 0.95$, left: $\xi_2 \sim \xi_6 = 0$, right: $\xi_2 \sim \xi_6 = 0.4$).

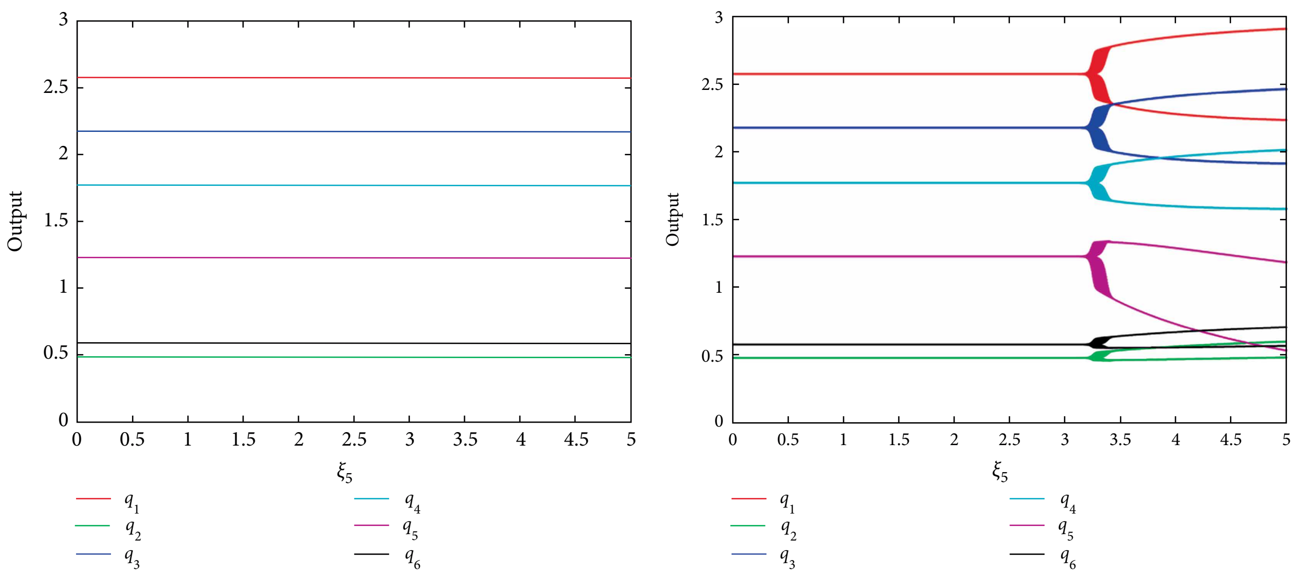

Figure 17: The bifurcation diagram of ξ_5 ($l_{ji} = 0.95$, left: $\xi_1, \xi_2, \xi_3, \xi_4, \xi_6 = 0$, right: $\xi_1, \xi_2, \xi_3, \xi_4, \xi_6 = 1.5$).

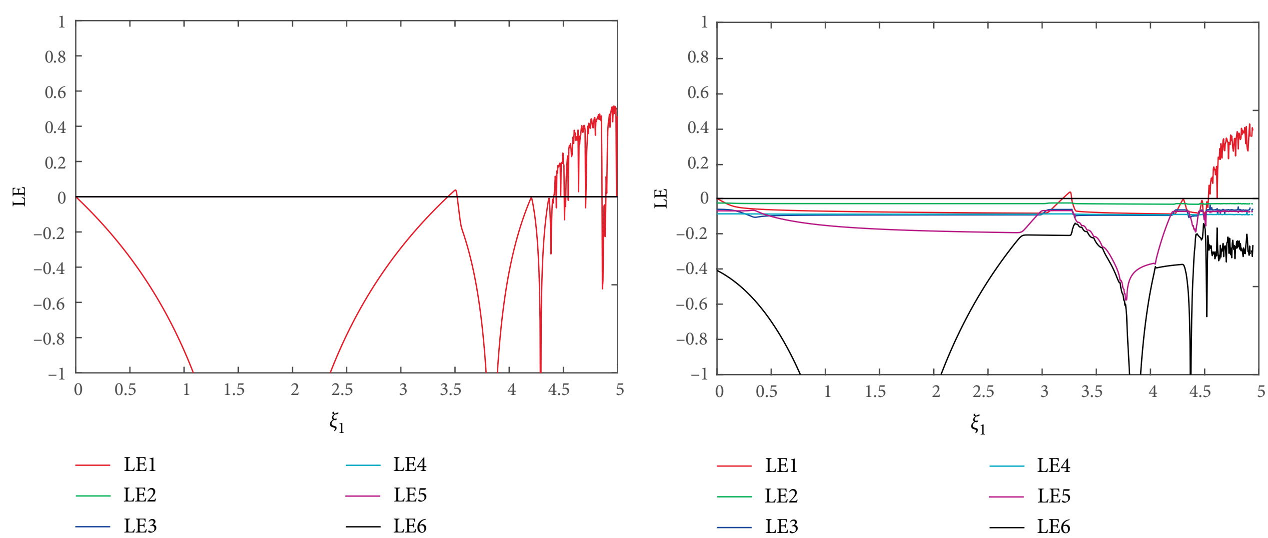

Figure 18: The Lyapunov exponent diagram ($l_{ji} = 0.95$, left: $\xi_2 \sim \xi_6 = 0$, right: $\xi_2 \sim \xi_6 = 0.4$).

output change in period $K + 1$. The stable market of the steel market composed of ξ_1, ξ_3, ξ_4 is shown in Figure 10. It can be seen from the figure that in order to maintain the stability, the range of adjustment coefficient ξ_1 is [0,3.35], ξ_3 is [0,4.00], ξ_4 is [0,4.90], and the entire stable domain presents a hemispherical shape. It can be seen that when the degree of product differentiation is not obvious, the stability domain of the market is slightly smaller than that of the same product, but the change is little.

When the substitution coefficients are all 0.95 and ξ_2, ξ_5, ξ_6 simultaneously increase from 1 to 5, the stability domain is shown in Figure 11. The conclusion is basically consistent with Figure 3. It shows that product differentiation affects the area of the market stability domain, but does not affect the trend of stability domain changes caused by production adjustment.

When the substitution coefficients are 0.90, 0.85, 0.80, 0.75 and ξ_2, ξ_5, $\xi_6$equal 4, the stability domain is shown in Figure 12. As can be seen from the figure, when ξ_i gradually decreases, the market stability area will shrink gradually. Obviously, when ξ_i decreases further, the market will easily lose balance.

(2) The Output Adjustment Rate in North China, East China, and South Central China Remains Unchanged. When the substitution coefficients are all 0.95, ξ_1, ξ_3, ξ_4 are 0 at the same time; that is, these three regions do not adopt any expected

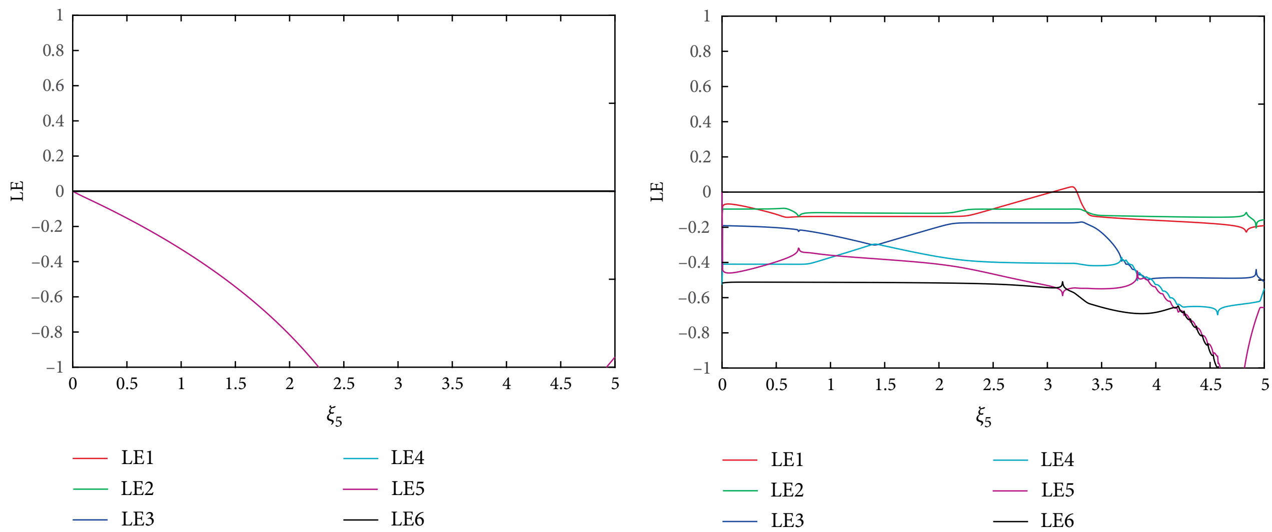

Figure 19: The Lyapunov exponent diagram ($l_{ji} = 0.95$, left: ξ_1, ξ_2, ξ_3, ξ_4, $\xi_6 = 0$, right: ξ_1, ξ_2, ξ_3, ξ_4, $\xi_6 = 1.5$).

strategy, and the marginal profit changes in period K will not affect the output change in period $K + 1$. The stable market of the steel market composed of ξ_2, ξ_5, ξ_6 is shown in Figure 13. It can be seen from the figure that in order to maintain the stability, the range of adjustment coefficient ξ_2 is [0,10.00], ξ_5 is [0,7.10], ξ_6 is [0,10.00], or even more. This shows that when North China, Northeast China, and South Central China do not take any production adjustment measures, the other three regions can have considerable decision-making power for production. This is basically consistent with the conclusion in Figure 4.

When the substitution coefficients are all 0.95 and ξ_2, ξ_5, ξ_6 simultaneously increase, the stability domain is shown in Figure 14. The conclusion is basically consistent with Figure 5. It shows that product differentiation affects the area of the market stability domain, but does not affect the trend of stability domain changes caused by production adjustment.

When the substitution coefficients are 0.90, 0.85, 0.80, 0.75 and ξ_1, ξ_3, ξ_4 equal 1.5, the stability domain is shown in Figure 15. As can be seen from the figure, when ξ_i gradually decreases, the market stability area will shrink gradually. Obviously, when ξ_i decreases further, the market will easily lose balance. This is the same as the conclusion of Figure 12.

Combined with the above conclusions, it can be seen that the appropriate product differentiation strategy can reduce the fluctuation in output adjustment for a manufacturer by causing fluctuations in the output adjustment of competitors. Also, this can cause the social welfare and other indicators to show an increasing trend. However, excessively increasing the degree of product differentiation and large adjustment coefficient will gradually shrink the market stability domain or even cause it to disappear leaving the steel market in an unbalanced state. Therefore, product differentiation strategies and decision-making based on bounded rationality have their own advantages and disadvantages which the steel enterprise and the industry department need to weigh carefully.

(3) Analysis of System Dynamic Characteristics. Similarly, this paper also studies the dynamic characteristics of the system when $l_{ji} = 0.95$ and obtains the same conclusion when $l_{ji} = 1$. The left graph of Figure 16 shows that when ξ_2–$\xi_6 = 0$, with the change of ξ_1, the bifurcation diagram. It can be seen that when other areas do not take any adjustment measures, the system is stable when ξ_1 is between 0 and 3.495. Then, there is a small interval where q_1 production is unstable. When ξ_1 is gradually increased above 3.510, the system transitions change from stable, to double-cycle, to chaos. Only the output of North China is out of balance. The right graph in Figure 16 shows that when ξ_2–$\xi_6 = 0.4$, and ξ_1 ranges from 0 to 3.200, the system is stable. Then, there is a small interval where q_1 production is unstable. When ξ_1 is gradually increased from 3.270, the system transitions change from stable, to double-cycle, to chaos. As the ξ_1 gradually increases, the output of other regions is also imbalanced.

The left graph of Figure 17 shows that when $\xi_1, \xi_2, \xi_3, \xi_4, \xi_6$ equal 0, the system is always in balance regardless of ξ_5. The right graph in Figure 17 shows that when $\xi_1, \xi_2, \xi_3, \xi_4, \xi_6$ are 1.5, and when ξ_5 ranges from 0 to 3.080, the system is stable. Then, there is a small interval where all enterprises' production is unstable. When ξ_5 gradually increases over about 3.270, the system transitions change from stable, to double-cycle, to chaos.

Figures 18 and 19 are the Lyapunov exponents for ξ_1 and ξ_5. In the left graph of Figure 18, when $\xi_2 \sim \xi_6 = 0$ and $\xi_1 = 3.510$, bifurcation first appears in the system. When $\xi_1 > 4.405$, the maximum Lyapunov exponent starts to become positive, and the system turns chaotic. In the right graph of Figure 18, when $\xi_2 \sim \xi_6$ are 0.4 and $\xi_1 = 3.270$, bifurcation appears in the system for the first time, and then, all companies bifurcate as well. When $\xi_1 > 4.530$, the maximum Lyapunov exponent begins to be positive, and the system goes chaotic.

In the left graph of Figure 19, when $\xi_1, \xi_2, \xi_3, \xi_4, \xi_6$ are 0, the maximum Lyapunov exponent is no more than 0. In the right graph of Figure 19, when $\xi_1, \xi_2, \xi_3, \xi_4, \xi_6$ take 1.5, and when ξ_5 ranges from 3.080 to 3.270, the maximum Lyapunov exponent began to be positive and the output imbalance phenomenon occurs in each area. When $\xi_5 > 3.270$, the maximum Lyapunov exponent is less than 0, and the system transitions change to double-cycle.

5. Conclusions

Based on the carbon tax mechanism, this paper introduces the product differentiation and bounded rational expectation strategy and establishes the production selection model of steel oligopoly enterprises under dynamic conditions. It also analyses the output dynamic adjustment of each steel oligopoly enterprise, market imbalance conditions, and system dynamic characteristics. The main conclusions are as follows:

Compared with the output adjustment of a single enterprise, the system is more likely to fall into an unbalanced state when multiple enterprises adopt the policy of dynamic output adjustment simultaneously. The influence of large production enterprises on the system balance is much stronger than that of small production enterprises. When enterprises produce the same product, and when the enterprises with large output (North China, Northeast China, and Central South China) adopt a weak positive adjustment policy, enterprises with small output (Northeast, Southwest, and Northwest) can have more free production autonomy. However, when large-scale enterprises adopt a bit larger production adjustment policy, enterprises with small output will be strongly impacted, and the available adjustment space will be sharply compressed. Conversely, for enterprises with large-scale production, the production adjustment policies of small-scale companies do not strongly influence their production strategies. They still have a lot of space for adjustment and other strategies to choose from.

When product differentiation and bounded rationality strategies coexist, market stability research will be more complicated. When the products produced by different enterprises have some differences, the conclusion of the changing trend of the stable domain is basically consistent with that of the same products. But as the product substitution coefficient gradually decreases, that is, the difference between products gradually increases, the market stability domain shows a trend of continuous reduction. On this basis, if the degree of product differentiation is increased excessively, the steel market will be in an unbalanced state when an enterprise adopts a more severe production adjustment policy.

Based on the conclusions and related analysis of this paper, the following suggestions are made for the transformation and upgrading of China's steel industry:

The production adjustment policy is an active change strategy adopted by various production enterprises in response to changes in the future situation. When each enterprise adjusts its output according to the marginal profit of the previous period, in order to maintain the stability, each enterprise may have certain right of independent choice, but there are obvious regional differences. If the production adjustment policies are implemented in North China, Northeast China, and South Central China, the market stability will be better than having the other three regions adopt output adjustment policies. Therefore, when each steel oligopoly enterprise formulates its production plan, it needs to comprehensively consider the changes in output of other enterprises. Steel enterprises with relatively small output should not adjust their production plans drastically. It is necessary for them to observe the changes of large steel enterprises and make decisions. Of course, the government also needs to pay attention to the small production enterprises' adjustments of at any time and needs to prevent them from losing their minds, arbitrarily adjusting and maliciously destroying the market competition order.

For each steel enterprise, the appropriate product differentiation strategy can reduce its output adjustment fluctuation through the impact of the competitor's adjustments, and it can also increase economic indicators such as output and social welfare. But if one were to excessively increase the degree of product differentiation and production adjustment factors, the steel market may enter an unbalanced state. Therefore, product differentiation strategies and bounded rationality adjustment strategies have advantages and disadvantages. The enterprises and the industry should carefully weigh these strategic issues.

Data Availability

The statistics in this paper are from China Statistical Yearbook, China Industrial Statistical Yearbook, China Energy Statistical Yearbook, China Steel Yearbook, and the statistical yearbooks of various provinces. The time span is from 2005 to 2016. All data are publicly available on the website of the National Bureau of Statistics of China and the statistical office of every province. Also, these statistical yearbooks can also be purchased. Therefore, these data are public. The relevant results of this paper are calculated on the basis of these public data, and these statistical data and books have been marked and quoted in the paper (references [68–71]).

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Authors' Contributions

The authors gratefully acknowledge the financial support and all authors. Both authors contributed equally to this work. In particular, Hailin Mu and Ye Duan had the original idea for the study, and both coauthors conceived of and designed the methodology. Ye Duan drafted the manuscript, which was revised by Zenglin Han, Jun Yang, and Yonghua Li. All authors have read and approved the final manuscript.

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