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Research Article

Complexity Analysis of Prefabrication Contractors' Dynamic Price Competition in Mega Projects with Different Competition Strategies

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This paper considers a repeated duopoly game of prefabrication contractors in mega infrastructure projects and assumes the contractors exhibit bounded rationality. Based on the theory of bifurcation of dynamical systems, a dynamic price competition model is constructed considering different competition strategies. Accordingly, the stability of the equilibrium point of the system is discussed considering different initial market capacities, and numerical simulation is performed. The results show the system has a unique equilibrium solution when initial capacity is high and the parameters meet certain conditions. The contractors' price adjustment strategy has an important influence on system stability. However, an overly aggressive competition strategy is not conducive to system stability. Moreover, the system is sensitive to initial parameter values.

1. Introduction

Recently, the development of urbanization, technology, and economy, as well as the demand for convenience, have triggered enthusiasm worldwide towards building mega infrastructure projects, such as high-speed railways, the Hong Kong-Zhuhai-Macao Bridge in China, or the Land transport distance between New Lamu Port and Break-Even Point in Africa [1, 2]. Mega projects often have a high degree of complexity, use large amounts of resources, require a complex construction environment, and have high technical difficulty [3]. The interaction with the surrounding environment during the construction process results in new complexities. Therefore, the owners of mega infrastructure projects have to pay attention to the selection of suppliers as well as adhere to strict requirements on project quality, duration, environmental protection, and so on [4]. Traditional on-site open construction has increasingly failed to meet current requirements of the owners, and prefabricated production has gradually become a popular trend [5]. For example, the demand of steel in Hong Kong-Zhuhai-Macao Bridge is 420,000 tons, and most of them need to be processed and prefabricated in the factory to meet the requirements of the owner. Compared with traditional on-site construction, on one hand, prefabrication has the advantage of meeting the owner's requirement; on the other hand, prefabrication also can meet the sustainability requirement. Prefabrication allows some of the on-site processes to move to a stable factory, thus reducing the pollution, as well as saving energy, water, and human resources. For example, the Hong Kong-Zhuhai-Macao Bridge realized the splicing of large sections of the steel box girder at the construction site. One of the large block steel box girders used in the navigable span bridge reached 134.45 meters. Splicing of the small blocks was carried out inside the factory, thus greatly reducing the amount of work on site. The less amount of offshore construction, there will be lower risks and will be more environmentally friendly.

Different from the traditional on-site production, prefabrication is an off-site construction method that produces key components of the project in a professional factory using a standardized manufacturing process and then transports them to the project construction site to assemble and further construct [6–8]. As such, prefabrication production affects product reliability and allows for a more accurate prediction of the construction period. As a result, it is of great help to mega infrastructure projects, which are sensitive to the large number of products used, tight duration, and environment friendly requirements [9, 10]. Some scholars have discussed these issues from various perspectives such as techniques, environment influence, and risk of prefabrication. For instance, Li et al. [11] used social network analysis to identify and investigate potential networks of stakeholder-related risk factors in house prefabrication cases, and they [12] also proposed a prefabrication quantitative evaluation technology that can minimize the impact of construction waste and subsequent waste disposal activities in an empirical study on China. Jaillon and Poon [13] studied the design of the life cycles of deconstruction and industrialization through literature review and case study analysis. However, there are still some barriers to use prefabrication techniques [14]. As such, Mao et al. [15] pointed out that the cost of prefabrication would be higher than on-site production by 27% to 109%. Additionally, high transportation cost, R&D complexity, and design changes are obstacles for prefabrication [16]. To solve these obstacles, there is a need for R&D work in the production process, which will likely prompt suppliers to cooperate for innovation and gain higher profits when they produce the same key components. Further, Shi et al. [17] explored the multisuppliers' cooperation tendency in mega construction projects based on evolutionary game model. Cheung et al. [18] identified the cooperative and aggressive drivers that facilitate cooperative contracting in construction projects. Saad et al. [19] found that supply chain management methods had been adopted increasingly to establish long-term strategic cooperation relationships in construction. However, spillover effects will occur in the cooperation process. Dussauge et al. [20] pointed out it is difficult for participants to control the boundary of knowledge investment. Hsuan and Mahnke [21] found knowledge and reputation spillovers can generally bring benefits to the suppliers.

In many developing countries, there are many mega projects under construction, and the prefabrication technology of key components is monopolized by a few companies, which makes it possible and meaningful to study the price competition of contractors. For oligopolistic competition, the most well-known models are the Cournot and Bertrand models [22, 23]. The Cournot model was first proposed in 1838 to study the output competition of two companies. In 1883, Bertrand proposed a price competition model. For dynamic price competition under bounded rationality, the Cournot model had been researched extensively [24–28]. Recently, the dynamics of the Bertrand model have drawn increasing attention [29, 30]. Researchers have adopted a variety of adjustment mechanisms, including horizontal product differentiation [31], a gradient adjustment mechanism [32], among others. Tu and Wang [33] proposed a dynamic competition triopoly game considering two-stage R&D input.

As mentioned before, prefabricated production of key components in mega projects has a great advantage and has become a trend. Due to the characteristics of mega projects, only a limited number of contractors in the market have the qualifications and capabilities, resulting in a monopoly. For example, there are only two contractors for the prefabricated production of the steel box girder of the Hong Kong-Zhuhai-Macao Bridge: the China Railway Shanhaiguan Bridge Group Co., Ltd. and the Wuhan Heavy Engineering Co., Ltd. Due to the long-term nature of mega project construction, especially for developing countries, enterprise competition under monopolistic conditions will exist for a long time. Therefore, it is meaningful to deal with this problem with a long-term evolutionary perspective. The motivation of this paper is to provide the analysis method to investigate the impact of the pricing strategies on the competition equilibrium and evolution path of market for prefabrication contractors under different circumstances. The conclusions can provide advice and suggestions for contractors' pricing strategies under long-term scales and uncertain conditions.

In this paper, we focus on the competition among mega project contractors and establish a price competition model considering the limited rationality of the contractor. Meanwhile, we also consider the influence of the spillover effect on cost reduction and use nonlinear dynamics to study the price competition model. The rest of this paper is organized as follows. Section 2 establishes a duopoly monopoly price competition model to describe the decision characteristics of contractors. In Section 3, we solve the model and analyze the stability of equilibrium points. In Section 4, system evolution is given in the form of diagram through numerical simulation. Finally, the conclusions of the paper are presented in Section 5.

2. Model

In the supply chain of mega projects, the prefabrication contractors who have the ability to provide key components on the market are often limited. As Mao et al. [34] indicated, technological monopoly is an important factor in prefabricated production. As a matter of fact, there is a technical monopoly in the steel box girder of the Hong Kong-Zhuhai-Macao Bridge. There are very few contractors in the market that can meet the high requirements of the owners. In this case, there are only two contractors for steel box girder, namely, the China Railway Shanhaiguan Bridge Group Co., Ltd. and the Wuhan Heavy Engineering Co., Ltd. Among them, the Wuhan Heavy Engineering Co., Ltd. also needs technical cultivation to meet the requirements. Based on this realistic background, we assume that the market is a monopoly and is a duopoly. Specifically, there are only two prefabrication contractors on the market. One is the leader and the other the competitor, and they adopt different price competition strategies. That is, contractor 1 is pursuing profit maximization and contractor 2 expanding the market as much as possible. The two contractors carry out repeated price competition on the market, assuming contractor i is priced at $p_i(t)$ during period t and the prefabricated part is sold for $q_i(t)$. Therefore, the sales function of two contractors are

$$\begin{aligned} q_1(t) &= a_1 - b_1(p_1(t) + p_2(t)) + \theta_1(p_2(t) - p_1(t)), \\ q_2(t) &= a_2 - b_2(p_1(t) + p_2(t)) + \theta_2(p_1(t) - p_2(t)), \end{aligned} \tag{1}$$

where a_i is the basic sales volume, which reflects the market's demand for contractor i; b_i the average price impact factor, which reflects the impact of substitutes, and $b_i = 0$ indicates there are no other alternative products. The larger b_i is, the easier it is for the contractor to be replaced. The higher the average price on the monopoly market, the lower the sales volume will be. θ_i is the differential coefficient, which reflects the sensitivity of sales to price differences. Considering the difference and not losing generality, we assume basic sales volumes are equal, that is, $a_1 = a_2 = a$, and the average price impact factors are equal, that is, $b_1 = b_2 = b$, meaning the sales function can be simplified as

$$\begin{aligned} q_1(t) &= a - b(p_1(t) + p_2(t)) + \theta_1(p_2(t) - p_1(t)), \\ q_2(t) &= a - b(p_1(t) + p_2(t)) + \theta_2(p_1(t) - p_2(t)). \end{aligned} \tag{2}$$

Assume the two contractors carry out R&D strategies that can reduce costs to a certain extent. However, the market scope of prefabrication production is relatively concentrated; due to the flow of human resources and technical cooperation between contractors, the spillover effect of knowledge is prone to occur. Because of this spillover effect, R&D strategies will also reduce the counterparty's costs when the contractor is reducing its own costs. The cost function is

$$\begin{aligned} c_1(t) &= c_L - r_1 - \beta_1 r_2, \\ c_2(t) &= c_F - r_2 - \beta_2 r_1. \end{aligned} \tag{3}$$

Here, c_L represents the cost of contractor 1; c_F the cost of contractor 2; r_i the cost of contractor i through R&D strategies, and β_i the cost coefficient of contractor i through spillover effect, which reflects the contractor i acquiring the ability of the counterparty. This paper further assumes that neither of the two contractors has a cost advantage, that is, $c_L = c_F = c_0$, their own R&D strategies have the same impact on cost, that is, $r_1 = r_2 = r$. To focus more on the study of spillover effects, we consider $c = c_0 - r$, so the cost function can be simplified as

$$\begin{aligned} c_1(t) &= c - \beta_1 r, \\ c_2(t) &= c - \beta_2 r. \end{aligned} \tag{4}$$

Therefore, we can obtain the profit function of contractor i

$$\begin{aligned} \Pi_1(p_1(t), p_2(t)) &= (p_1(t) - c + \beta_1 r)\big(a - b(p_1(t) \\ &\quad + p_2(t)) + \theta_1(p_2(t) - p_1(t))\big), \\ \Pi_2(p_1(t), p_2(t)) &= (p_2(t) - c + \beta_2 r)\big(a - b(p_1(t) \\ &\quad + p_2(t)) + \theta_2(p_1(t) - p_2(t))\big). \end{aligned} \tag{5}$$

According to the hypothesis of this paper, the strategy adopted by contractor 1 for profit maximization is requiring marginal profit to be 0. Therefore, for the contractor 1's profit function for the current price derivative, current marginal profit can be

$$\begin{aligned} \frac{\partial \Pi_1(p_1(t), p_2(t))}{\partial p_1(t)} &= (a + (b + \theta_1)(c - \beta_1 r)) \\ &\quad - 2(b + \theta_1)p_1(t) + (\theta_1 - b)p_2(t). \end{aligned} \tag{6}$$

Contractor 2 is pursuing the highest market share, so it only needs to meet $\Pi_2(p_1(t), p_2(t)) = 0$. According to the nature of contractor 2's profit function, its optimal pricing strategy can be divided into two situations:

$$\begin{aligned} &\text{When } a + (\theta_2 - b)p_1(t) - (\theta_2 + b)(c - \beta_2 r) \\ &\quad \geq 0, p_2^*(t) = c - \beta_2 r; \\ &\text{When } a + (\theta_2 - b)p_1(t) - (\theta_2 + b)(c - \beta_2 r) \\ &\quad < 0, p_2^*(t) = \frac{a + (\theta_2 - b)p_1(t)}{\theta_2 + b}. \end{aligned} \tag{7}$$

According to the initial hypothesis, the two contractors exhibit bounded rationality. As such, it is difficult for them to obtain complete market information, meaning they adjust their price strategies according to certain rules and gradually reach a state of equilibrium. It is assumed contractor 1 is adopting a "near-sightedness" strategy, while contractor 2 adopts a "self-adaption" strategy; that is, contractor 1 dynamically adjusts the price for the next period based on the profitability of the previous period, and contractor 2 uses a linear adjustment mechanism based on the previous and optimal prices. That is,

$$\begin{aligned} p_1(t+1) &= p_1(t) + \gamma_1 p_1(t) \frac{\partial \Pi_1(p_1(t), p_2(t))}{\partial p_1(t)}, \\ p_2(t+1) &= (1 - \delta)p_2(t) + \delta p_2^*(t). \end{aligned} \tag{8}$$

3. Equilibrium Points and Stability in a Dynamic Price Competition System

The above adjustment mechanism uses "near-sightedness" and "self-adaption" adjustment methods and combines them into a dynamic adjustment system. In this system, let $p_i(t+1) = p_i(t)$. The nonlinear algebra system can be obtained as follows:

$$\begin{aligned} \gamma_1 p_1(t) \frac{\partial \Pi_1(p_1(t), p_2(t))}{\partial p_1(t)} &= 0, \\ \delta p_2(t) - \delta p_2^*(t) &= 0. \end{aligned} \tag{9}$$

According to the range of parameters, the system is divided into the following two situations.

(1) $a + (\theta_2 - b)p_1(t) - (\theta_2 + b)(c - \beta_2 r) < 0$, where the system has two equilibrium points: $E_0 = (0, a/(\theta_2 + b))$ and $E_1 = (p_1^*, p_2^*)$, where $p_1^* = a(\theta_1 + \theta_2) + (b + \theta_1)(b + \theta_2)(c - \beta_1 r)/\theta_1\theta_2 + 3b(\theta_1 + \theta_2) + b^2$, $p_2^* = ab + a(2\theta_1 + \theta_2) + (b + \theta_1)(\theta_2 - b)(c - \beta_1 r)/\theta_1\theta_2 + 3b(\theta_1 + \theta_2) + b^2$.

The Jacobian matrix of the system at any point is given by

$$J(p_1, p_2) = \begin{bmatrix} 1 + \gamma_1((a + (b + \theta_1)(c - \beta_1 r)) - 4(b + \theta_1)p_1 + (\theta_1 - b)p_2) & \gamma_1(\theta_1 - b)p_1 \\ \dfrac{\delta(\theta_2 - b)}{\theta_2 + b} & 1 - \delta \end{bmatrix}. \tag{10}$$

Proposition 1. $E_0 = (0, a/(\theta_2 + b))$ *is the unstable equilibrium point of the dynamic price competition system between contractors.*

Proof 1. The Jacobian matrix at E_0 takes the form

$$J(E_0) = \begin{bmatrix} 1 + \gamma_1\left((a + (b + \theta_1)(c - \beta_1 r)) + (\theta_1 - b)\dfrac{a}{\theta_2 + b}\right) & 0 \\ \dfrac{\delta(\theta_2 - b)}{\theta_2 + b} & 1 - \delta \end{bmatrix}. \tag{11}$$

It gives two eigenvalues, $\lambda_1 = 1 + \gamma_1((a + (b + \theta_1)(c - \beta_1 r)) + (\theta_1 - b)(a/(\theta_2 + b)))$ and $\lambda_2 = 1 - \delta$, obviously satisfying $|\lambda_1| > 1$ and $|\lambda_2| < 1$. Therefore, from the stability criterion of the fixed-point theorem, we obtain that E_0 is the unstable equilibrium point of dynamic price competition between contractors. On the other hand, it is clear $p_1^* = 0 < c - \beta_1 r$. Contractor 1 is unlikely to sell at price 0, which is lower than the cost and therefore unsustainable, so E_0 is the unstable equilibrium point of the system.

Proposition 2. $E_1 = (p_1^*, p_2^*)$ *is the unstable equilibrium point of the dynamic price competition system between contractors.*

Proof 2. The Jacobian matrix at E_1 takes the form

$$J(E_1) = \begin{bmatrix} 1 - 2\gamma_1(\theta_1 + b)p_1^* & \gamma_1(\theta_1 - b)p_1^* \\ \dfrac{\delta(\theta_2 - b)}{\theta_2 + b} & 1 - \delta \end{bmatrix}. \tag{12}$$

From the stability criterion of the fixed-point theorem, we can obtain that E_1 is locally stable if the eigenvalues of the equilibrium point are inside the unit circle of the complex plane. According to the Jury stability criterion, the necessary and sufficient conditions of the local stability of E_1 satisfy

$$\begin{aligned} &4 - 2\delta + 2\gamma_1(\theta_1 + b)p_1^*(\delta - 2) - \frac{\gamma_1\delta(\theta_2 - b)(\theta_1 - b)p_1^*}{(\theta_2 + b)} > 0, \\ &2 - \delta + 2\gamma_1(\theta_1 + b)p_1^*(\delta - 1) - \frac{\gamma_1\delta(\theta_2 - b)(\theta_1 - b)p_1^*}{(\theta_2 + b)}. \end{aligned} \tag{13}$$

In the plane formed by the price adjustment coefficients (γ_1, δ) of the two contractors, E_1 is locally stable if γ_1 and δ satisfy the upper constraints. However, when the values of γ_1 and δ exceed the above range, E_1 is no longer locally stable. In the above equilibrium state, submitting p_1^* into constraint $a + (\theta_2 - b)p_1(t) - (\theta_2 + b)(c - \beta_2 r) < 0$, we can obtain $p_2^*(t) < c - \beta_2 r$, at which point contractor 2 is unprofitable. Therefore, from the perspective of contractor's individual rationality, this point is not the stable equilibrium point of the system.

(2) $a + (\theta_2 - b)p_1(t) - (\theta_2 + b)(c - \beta_2 r) \geq 0$.

We can introduce $p_2^*(t) = c - \beta_2 r$ into the dynamical system:

$$\begin{aligned} &\gamma_1 p_1(t)((a + (b + \theta_1)(c - \beta_1 r)) \\ &\quad - 2(b + \theta_1)p_1(t) + (\theta_1 - b)p_2(t)) = 0, \\ &\delta p_2(t) - \delta(c - \beta_2 r) = 0. \end{aligned} \tag{14}$$

There are two equilibrium points, $E_0 = (0, p_2^*)$ and $E_1 = (p_1^*, p_2^*)$, where $p_1^* = a + 2\theta_1 c - (b + \theta_1)\beta_1 r - (\theta_1 - b)\beta_2 r/2(b + \theta_1)$, $p_2^* = c - \beta_2 r$.

$$J(p_1, p_2) = \begin{bmatrix} 1 + \gamma_1((a + (b + \theta_1)(c - \beta_1 r)) - 4(b + \theta_1)p_1 + (\theta_1 - b)p_2) & \gamma_1(\theta_1 - b)p_1 \\ 0 & 1 - \delta \end{bmatrix} \tag{15}$$

Proposition 3. *$E_0 = (0, c - \beta_2 r)$ is the unstable equilibrium point of the dynamic price competition system between contractors.*

Proof 3. The Jacobian matrix at E_0 takes the form

$$J(E_0) = \begin{bmatrix} 1 + \gamma_1 (a + 2\theta_1 c - (b + \theta_1)\beta_1 r - (\theta_1 - b)\beta_2 r) & 0 \\ 0 & 1 - \delta \end{bmatrix}. \tag{16}$$

It gives two eigenvalues, $\lambda_1 = 1 + \gamma_1 (a + 2\theta_1 c - (b + \theta_1)\beta_1 r - (\theta_1 - b)\beta_2 r)$ and $\lambda_2 = 1 - \delta$, obviously satisfying $|\lambda_1| > 1$ and $|\lambda_2| < 1$. Therefore, from the stability criterion of the fixed-point theorem, we obtain E_0 is the unstable equilibrium point of the dynamic price competition system between contractors. On the other hand, $p_1^* = 0 < c - \beta_1 r$. As contractor 1 is unlikely to sell at price 0, E_0 is the unstable equilibrium point of the system.

Proposition 4. *In case $r_1 < 2/a + 2\theta_1 c - \beta_1 r(b + \theta_1) - (\theta_1 - b)\beta_2 r$, $E_1 = (p_1^*, p_2^*)$ is the stable equilibrium point of the dynamic price competition system between contractors.*

Proof 4. The Jacobian matrix at E_1 takes the form

$$J(E_1) = \begin{bmatrix} 1 - 2\gamma_1 (\theta_1 + b) p_1^* & \gamma_1 (\theta_1 - b) p_1^* \\ 0 & 1 - \delta \end{bmatrix}. \tag{17}$$

Its eigenvalues are $\lambda_1 = 1 - 2\gamma_1 (\theta_1 + b) p_1^*$ and $\lambda_2 = 1 - \delta$. According to the local stability criterion of the fixed-point theorem, this point is locally stable when conditions $|\lambda_1| < 1$ and $|\lambda_2| < 1$ are satisfied. According to the assumptions, $|\lambda_2| < 1$ is true.

Moreover, by calculating $|\lambda_1| < 1$, we get $r_1 < 2/a + 2\theta_1 c - \beta_1 r(b + \theta_1) - (\theta_1 - b)\beta_2 r$. This completes the proof of Proposition 4.

4. Numerical Simulations

In the above analysis, we discuss the equilibrium stability of a price competition system composed of two contractors in two situations.

To reflect the influence of different parameters on the system more intuitively, numerical simulations are used to simulate this system based on different price competition strategies of the two contractors.

(1) For $a + (\theta_2 - b)p_1(t) - (\theta_2 + b)(c - \beta_2 r) < 0$, to meet constraints, we respectively set the initial prices of contractors as $p_1(0) = 1.32$ and $p_2(0) = 1.15$, initial market sales as $a = 3.45$, average market price coefficient as $b = 1.2$, differential price sensitivity coefficient of the two contractors as $\theta_1 = 1.55$ and $\theta_2 = 1.35$, contractor's cost as $c = 1.8$, contractor's profit on cost control as $r = 0.5$, spillover utility coefficients of R&D cost as $\beta_1 = 0.2$ and $\beta_2 = 0.5$, and price adjustment coefficient of contractor 2 as $\delta = 0.8$.

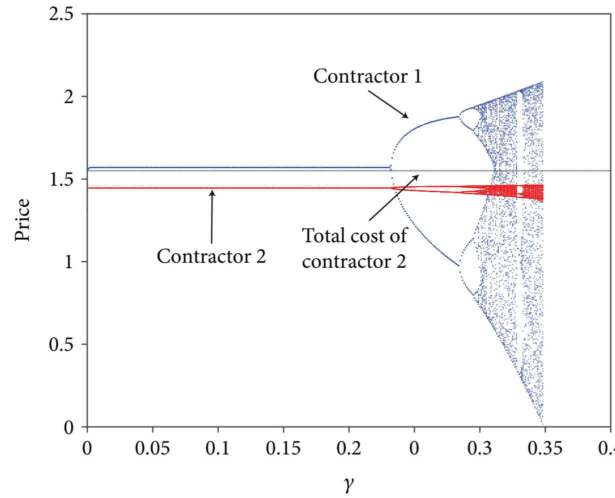

Figure 1: Price bifurcation diagram in situation 1.

With the above parameter settings, Figure 1 shows the price dynamical evolution diagram with respect to the price adjustment coefficient of contractor 1. From Figure 1, both contractors have entered a state of the period-doubling bifurcation from a stable state and then a chaotic state with the increase of price adjustment coefficient γ. This shows price adjustment coefficient γ has an important influence on system stability. The price change for contractor 1 is larger than that of contractor 2 in the state of bifurcation and chaos, given the change in γ. Further, in this situation, the price of contractor 2 is always lower than its total cost under different conditions. Therefore, in this situation, the equilibrium point is not the stable equilibrium point of the system according to the rational agent assumption. Further, Proposition 2 is also verified.

In Figure 2, we present a strange attractor diagram with $\gamma = 0.347$ and $N = 20000$, which shows the track of price changes in the chaotic state. That is, with the change of γ, the shape of strange attractor also changes.

(2) $a + (\theta_2 - b)p_1(t) - (\theta_2 + b)(c - \beta_2 r) \geq 0$.

We set the initial prices of contractors as $p_1(0) = 1.32$ and $p_2(0) = 1.15$, initial market sales as $a = 4.8$, average market price coefficient as $b = 0.4$, differential price sensitivity coefficient of the two contractors as $\theta_1 = 1.25$ and $\theta_2 = 0.75$, contractor's cost as $c = 1$, contractor's profit on cost control as $r = 0.5$, spillover utility coefficients of R&D cost as $\beta_1 = 0.2$ and $\beta_2 = 0.5$, and price adjustment coefficient of contractor 2 as $\delta = 0.5$.

Under the above parameter settings, Figure 3 shows the price dynamical evolution diagram with respect to the price adjustment coefficient of contractor 1. From Figure 3,

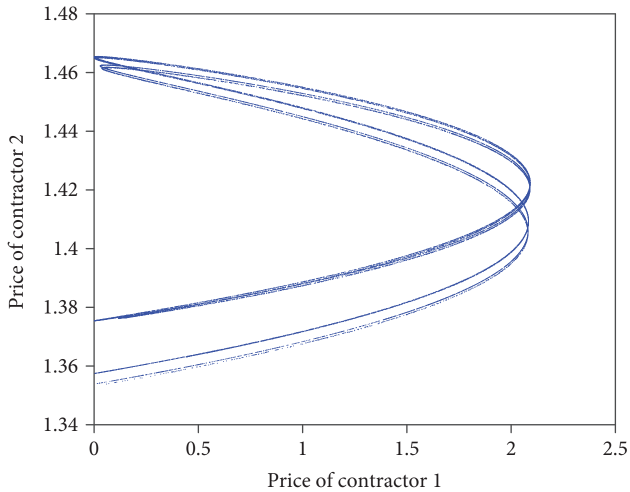

Figure 2: Price strange attractor in situation 1.

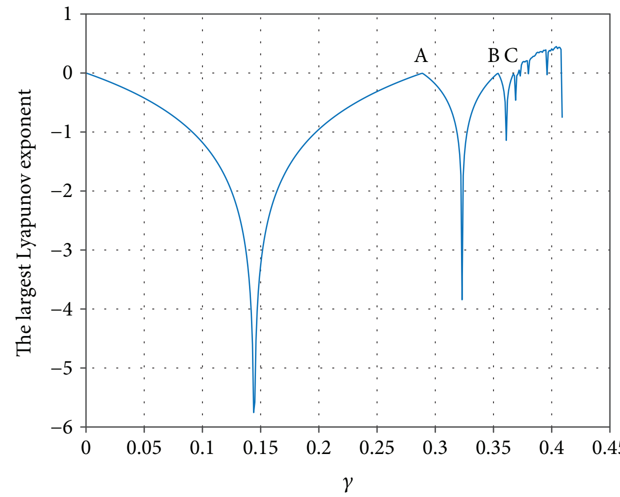

Figure 4: Largest Lyapunov exponent in situation 2.

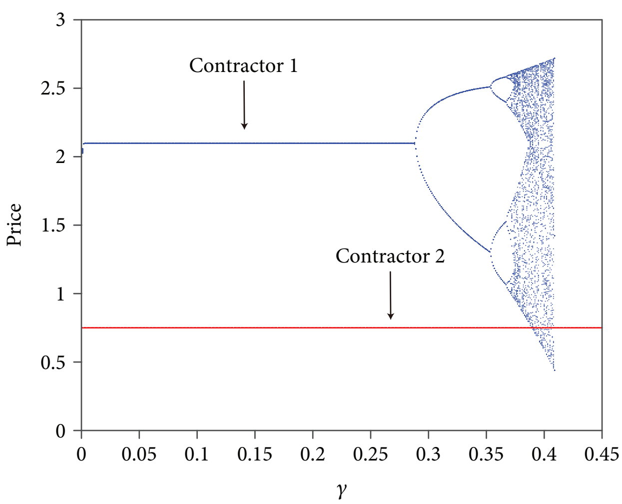

Figure 3: Price bifurcation diagram in situation 2.

contractor 1 entered the state of the period-doubling bifurcation from a stable state and then the chaotic state with the increase of price adjustment coefficient γ, while contractor 2 remains stable. In this situation, contractor 2 adopts a strategy whereby pricing is always consistent with cost, while the pricing of contractor 1 varies considerably with γ. This shows that, although contractor 1 holds a leading position on the market, excessive price adjustment changes will still make it difficult for it to make business decisions.

In Figure 4, we use the largest Lyapunov exponent, which can help us identify the bifurcation point of profit. Comparing Figure 3 with 4, the point where the largest Lyapunov exponent in Figure 4 is 0 corresponds to the bifurcation point in Figure 3. At point A in Figure 4, the system produces the first bifurcation; at point B, it produces the second bifurcation; and at point C, it produces the third bifurcation. Further, when γ is greater than a certain degree, the largest Lyapunov exponent will be above 0. At this time, the system will enter a chaotic state.

Figures 5 and 6 show a sequence diagram of the price competition between contractors 1 and 2 when the system is under stability, bifurcation, and chaos, respectively. If we set $\gamma = 0.25$ in Figure 5(a), contractor 1 moves rapidly from the initial value to the equilibrium solution then surpasses the latter. Subsequently, it fluctuates up and down around the equilibrium solution and amplitude decreases gradually. Finally, it remains in a stable state. If we set $\gamma = 0.35$ in Figure 5(b), contractor 1 presents a stable cyclical track of the price after experiencing initial unstable fluctuations. If we set $\gamma = 0.4$ and $\gamma = 0.405$, respectively, the blue line can be observed. Further, the price change of contractor 1 presents a more complicated chaotic situation that is more difficult to describe.

In Figure 6(a), the parameters we set up for contractor 1 are $\gamma = 0.4$, $\beta_1 = 0.2$ and $\gamma = 0.4$, $\beta_1 = 0.201$, respectively. In Figure 6(b), the parameters are $\gamma = 0.405$, $\beta_1 = 0.2$ and $\gamma = 0.405$, $\beta_1 = 0.201$, respectively. That is, the spillover effect coefficient of contractor 1 has changed slightly in the same diagram. At period $T < 12$, the changes of pricing of contractor 1 are not significant at the different initial values. However, over the period, there is a significant difference in the trends of price changes for contractor 1 in two situations. Even if the difference of the initial value is only 0.001, the difference in these tracks is still significant. Therefore, the system is sensitive to the initial value under chaos.

Figure 7 shows a dynamic change diagram of the average profit of the two contractors where the period is set to 500. Corresponding to the first bifurcation point in Figure 3 and the value of γ at point A in Figure 4, the system enters the first bifurcation. At this time, the profit of contractor 1 experienced a rapid decline. At the second bifurcation, the profit of contractor 1 continues to fall after a brief fluctuation. When the system enters bifurcation and chaos, the profit of contractor 1 is lower than that under stability state. Therefore, if contractor 1 adopts an overly rapid model of price adjustment, bifurcation and chaos occur. As a result, this has a negative effect on the profit of contractor 1, and the effect is considerable.

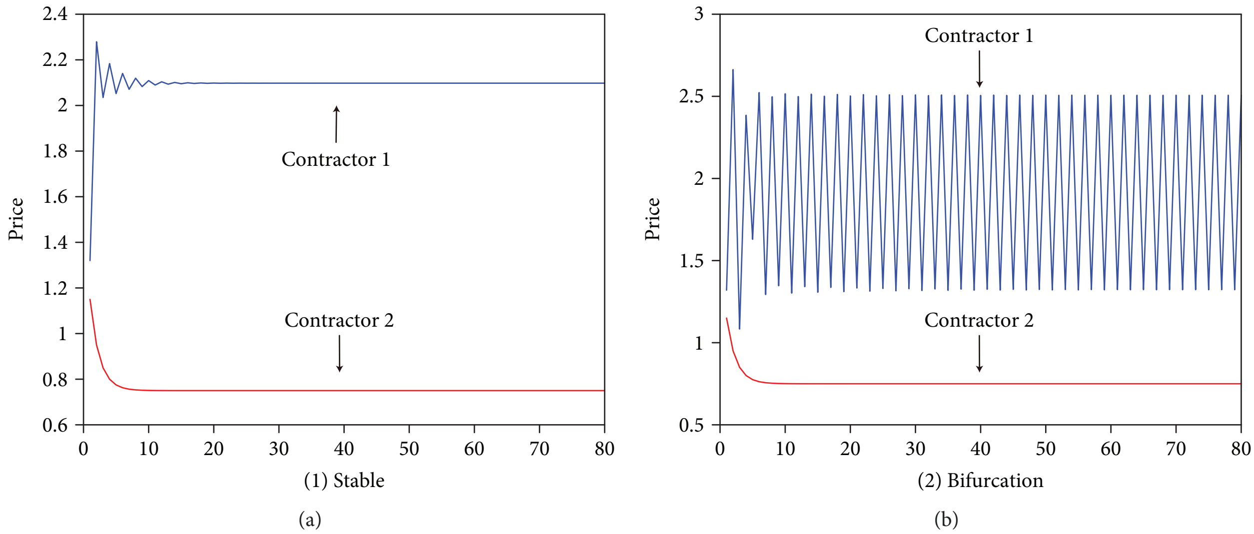

FIGURE 5: Sequence diagram for stability and bifurcation in situation 2.

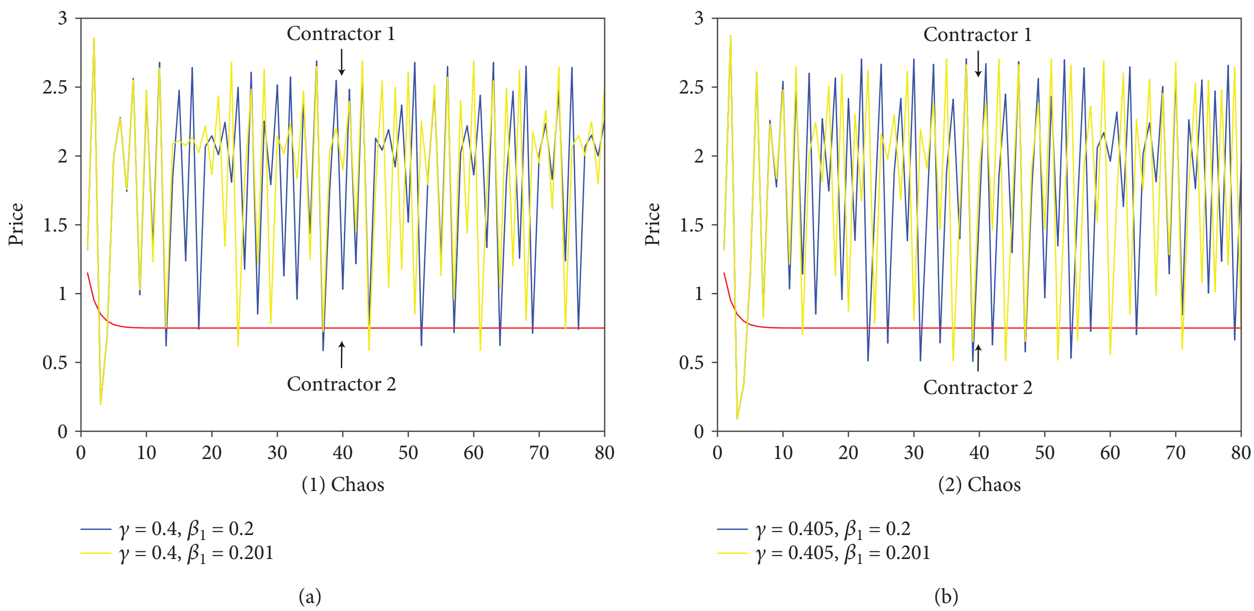

FIGURE 6: Sequence diagram in chaos in situation 2.

5. Conclusion

In the construction of mega projects, some key components in certain areas are often supplied by a limited number of contractors with set production capacities, making it objectively easy to form an oligopoly situation, such as the manufacturing of steel structures for the Hong Kong-Zhuhai-Macao Bridge in China. Therefore, this paper proposes a duopoly market structure, which is closer to the realistic background of mega projects, and considers the spillover effects of both parties' R&D activities on the market. The traditional oligopoly model requires complete information and participant's complete rationality, which is difficult to realize in the actual competition. Recently, scholars have introduced limited rationality to simulate the real decision-making situations of participants. We consider one contractor follows a "near-sightedness" strategy and the other "self-adaption" and construct a dynamic price competition model between the two contractors. We then analyze the equilibrium point of the competition model and perform stability analysis. Additionally, through numerical simulation, we study the complexity of price competition between the two contractors and profit changes due to price competition.

The results show that (1) when the initial capacity of the market is not high, both parties fall under bifurcation and chaos in price competition, which makes the price of the follower lower than the cost and, according to the rational agent assumption, the follower will withdraw from competition; (2) when the initial capacity of the market is high, the pricing of the market leader will fall under bifurcation and chaos with

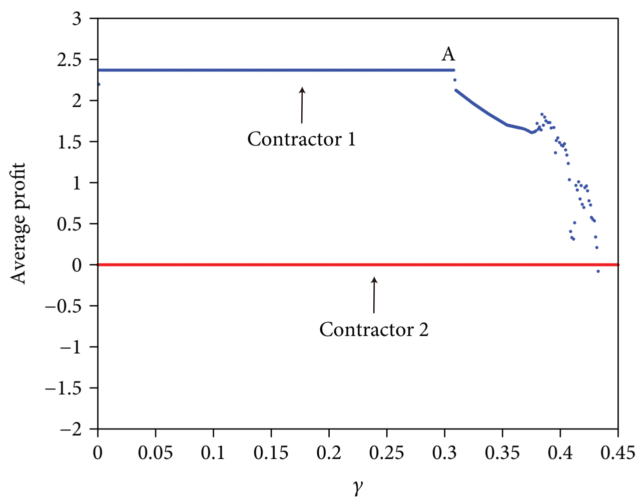

Figure 7: Average profit in situation 2.

the increase in the price adjustment speed, while the follower maintains its price constant; (3) under chaos, the system is extremely sensitive to the initial value, and the small initial disturbance will have a significant impact on the market as a whole; and (4) for the market leader that adopts the "near-sightedness" strategy, an aggressive price adjustment strategy will make the market unpredictable and have a significant negative impact on the market leader's profits. That is, we should avoid adopting too aggressive price adjustment strategies to avoid price competition under chaos.

For the followers in the market, the initial capacity of the market is a key factor to consider. Under low-capacity market conditions, followers should quit competition quickly, otherwise, they will suffer from long-term losses. While in high-capacity market conditions, followers choose a stable strategy. When price competition falls into chaos, market initial conditions, such as spillover effects, differentiation, and average price, would have a great impact on the equilibrium of price competition. For the leaders in the market, the price adjustment speed needs to be treated cautiously. An overly aggressive strategy will make the market enter chaos and result in the losses of the contractors. Contractors need to balance the advantages and disadvantages in the efficiency and revenue. This paper provides analytical tools and ideas for decision makers in the evolution of long-term price competition.

As this study considers the duopoly monopoly price competition of prefabricated parts for mega projects, we can further study the price competition model by considering the incentives of the owner, government subsidies, and other factors.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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