Study on the Matching of Construction Subcontractor Based on Cooperative Game

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Abstract. China’s construction industry is the pillar industry of the national economy, but the market competition faced by construction enterprises is becoming increasingly fierce. The general contractor must carry out close business cooperation with other subcontractors and integrate the valuable resources of all parties to cope with the competition jointly. Based on this, this paper constructs the evolutionary game model between the general contractor and the subcontractor. The equilibrium point is calculated by copying the dynamic equation, and the influence of parameters on the evolution probability of both sides is explored. Finally, combined with the numerical simulation, some suggestions on the matching of construction subcontractor suppliers are put forward: improve the cognitive level of the supply chain and reduce the contract cost of the enterprise; adopt an efficient and transparent supervision mechanism to reduce the risk of cooperation; improve the information transmission network of the supply chain and reduce the cost of failure; clear project claims and reward and punishment measures to enhance the enthusiasm of enterprises. Keywords: General contractor, Subcontractor, Evolutionary game, Supply chains.

1 Introduction

In recent years, with the continuous promotion of economic globalization and China’s Belt and Road policy, China’s construction industry has developed rapidly [1]. However, the market competition of construction enterprises is becoming increasingly fierce. The general contractor usually has strong comprehensive strength [2], but also faces various challenges, such as accelerated technology iteration, personalized customer needs, short construction period, opaque information, and slow capital collection [3]. The general contractor cannot survive independently in this environment and must cooperate closely with other subcontractors. China has been vigorously promoting the construction of a general contracting management system with a reasonable structure. However, due to the complexity and dynamics of construction activities, there are still many risks in subcontracting [4]. Problems such as layer-upon-layer subcontracting, qualification affiliation, jerry-building, and construction delay frequently occur in reality [5]. Therefore, to maximize the project’s benefits, the general contractor should improve its governance capability and select appropriate subcontractors at the initial stage [6].

In many construction projects, 80%-90% of the tasks are performed by subcontractors, so the project’s success largely depends on the performance of subcontractors [7].
traditional way of cooperation, the general contractor and subcontractor take the realization of personal interests as the highest goal, resulting in a great waste of resources. Conflicts and distrust make the general contractor choose subcontractors to transfer risks and reduce costs [8]. The behaviors of both parties are completely constrained by the contract, instead of establishing a good and stable cooperative partnership. The general contractor and subcontractor should integrate superior resources, share information, and reasonably allocate risks, so as to achieve a win-win situation in the supply chain partnership. There have been evolutionary game studies on owner and contractor [9], government and contractor [10], and contractor and workers [11], but there is no relevant research in the field of construction subcontracting. Therefore, this study takes the general contractor and subcontractor as the research object and researches the construction subcontractor matching based on the evolutionary game method. The results of this study are intended to answer the following questions:

- What are the factors influencing the selection of subcontractors?
- How to promote supply chain partnership in the construction industry?

2 Literature Review

2.1 Selection of Subcontractors

After years of practice and exploration, there is much theoretical research in subcontracting construction management. Shi et al. [12] conducted a multiple regression analysis to test the impact of the general contractor’s ability on the subcontracting organization. Demirkesen and Bayhan [13] listed the advantages of three tunnel engineering subcontractors according to several determining factors and selected the best scheme using the Choosing-By-Advantages (CBA) method. Olanrewaju et al. [14] introduced the survey results on the pre-qualification criteria for Malaysian subcontractors. The study showed that the five main criteria for pre-qualification were the expected completion date, the subcontractor’s financial ability/stability, health and safety records, the subcontractor’s past performance, and the submitted bid price and quotation. Chen et al. [15] proposed a three-stage model for subcontractor selection based on Quality Function Deployment (QFD), Analytic Hierarchy Process (AHP), and Improved Grey Correlation Analysis (IGCA) to ensure the highest degree of consistency between selected subcontractors and general contractors. Lew et al. [16] analyzed the data obtained from 162 G7 contractors in Malaysia. A single model based on the structural equation modeling (SEM) method is used to study the relationship between subcontractor selection criteria and the impact of these criteria on project performance. Yousefi et al. [17] proposed a multi-objective approach to examine the impact of visibility on supplier selection issues, taking into account supply chain costs more broadly.

2.2 Evolutionary Game Theory

Game theory is a very important and useful analytical tool, but as time changes, it also gradually exposes some hidden problems, such as its rational basis. The traditional game theory requires people to have perfect rationality, but in practice, people’s decision-making is shown as rationality with certain restrictions. Evolutionary game theory is developed on this basis to study the dynamic process of a certain group over time [18]. There are two basic concepts in evolutionary game theory: the evolutionary stability strategy (ESS) proposed by Smith and Price and the replicator dynamics equation proposed by Taylor. Since its birth, evolutionary game theory has been widely used in different disciplines, from biology to psychology, politics, economics, sociology, and other fields. Through the equilibrium and stability analysis of
the game model, Huang et al. [19] obtained the evolutionary stability strategy of the cooperative consumption system. Zhang et al. [20] built an evolutionary game model of technological innovation behavior of the public sector and social organizations. They proposed that cooperation efficiency can be promoted by reducing the cost and risk of stakeholders and improving the transformation ability of cooperative technological innovation. Liu et al. [21] constructed an evolutionary game compensation model for construction waste disposal costs, in which the government, developers, and contractors are the participants. Considering the incentive and punishment mechanism, Zhu et al. [22] developed an evolutionary game model between the general contractor and workers to improve the effectiveness of safety management.

3 Evolutionary Game Model

Establishing friendly cooperation between construction enterprises will help both parties trust each other, exchange information, share resources, and ultimately achieve the collaborative optimization effect of the supply chain. It is significant to explore the establishment mode of their cooperation relationship. The general contractor and all subcontractors are limited rational roles; The strategic choice between the two sides is not individual behavior but group behavior; Over time, the proportion of strategies adopted by the subject will also change. Based on the above characteristics, this paper chooses evolutionary game theory as the theoretical model of building subcontract matching, which is applicable and scientific.

3.1 Basic Hypothesis

*Hypothesis 1.* The players in the game are the general contractor and subcontractor A. Both parties are limited rational when making strategic choices and will constantly optimize and adjust according to the other party’s strategy and market environment.

*Hypothesis 2.* For the general contractor and subcontractor A, there are only two strategic choices: cooperation and non-cooperation. The general contractor chooses cooperation, that is, to cooperate closely with subcontractor A and share resources; Select non-cooperation to contract the project to another subcontractor. Subcontractor A’s choice of cooperation means actively cooperating with the general contractor to improve various management measures and establish a supply chain partnership; Choosing not to cooperate means treating cooperation negatively or submitting a bid to other general contractors after rejection.

*Hypothesis 3.* Each party has a strategy selection ratio. The probability of the general contractor choosing to cooperate with subcontractor A is \( x \), and the probability of choosing not to cooperate is \( 1 - x \); The probability of the subcontractor A choosing to cooperate with the general contractor is \( y \), and the probability of choosing not to cooperate is \( 1 - y \), where \( 0 < x < 1, 0 < y < 1 \).

*Hypothesis 4.* For the general contractor, the net income obtained when choosing not to cooperate is \( R_0 \), and the organization and coordination cost paid when choosing cooperation is \( C_0 \); For Subcontractor A, the net income obtained when choosing not to cooperate is \( R_A \), and the improvement cost of various measures when choosing cooperation is \( C_A \). When both parties choose to cooperate, they will share resources, and the project will gain incremental payoffs. Among them, the general contractor gets \( \theta R \), and subcontractor A gets \( (1 - \theta)R \), where \( 0 < C_0 < R_0, 0 < C_A < R_A, 0 < \theta < 1 \).

*Hypothesis 5.* The general contractor has a greater right to choose. When the general contractor chooses not to cooperate, the two parties cannot enter into a contractual relationship, and the project has no incremental income; When the general contractor chooses to cooperate, and subcontractor A chooses not to cooperate, the general contractor can share resources unilaterally to make the project gain incremental payoffs \( R' \), of which \( 0 < R' < R, \theta R' < C_0 \).
### Table 1. Payoff matrix of evolutionary game

<table>
<thead>
<tr>
<th>Subcontractor A</th>
<th>Cooperation (y)</th>
<th>Non cooperation (1−y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooperation</td>
<td>[R_0 - C_0 + \theta R,]</td>
<td>[R_0, R_A - C_A]</td>
</tr>
<tr>
<td></td>
<td>[R_A - C_A + (1 - \theta)R]</td>
<td>[R_0, R_A]</td>
</tr>
<tr>
<td>Non cooperation</td>
<td>[R_0 - C_0 + \theta R']</td>
<td>[R_0, R_A]</td>
</tr>
<tr>
<td></td>
<td>[R_A + (1 - \theta)R']</td>
<td></td>
</tr>
</tbody>
</table>

#### 3.2 Evolutionary Game Model Establishment

According to the basic hypothesis put forward in 3.1, the evolutionary game income matrix of the general contractor and subcontractor A is obtained, as shown in table 1.

(1) Expected payoff of general contractor and subcontractor

Assuming that the expected payoff of the general contractor’s choice of cooperation strategy is \(E_{11}\), the expected payoff of non cooperation strategy is \(E_{12}\), and the average expected payoff of the general contractor is \(E_1\), then there are:

\[
E_{11} = y(R_0 - C_0 + \theta R) + (1 - y)(R_0 - C_0 + \theta R') = R_0 - C_0 + y\theta R + (1 - y)\theta R'.
\]   (1)

\[
E_{12} = yR_0 + (1 - y)R_0 = R_0.
\]   (2)

\[
E_1 = xE_{11} + (1 - x)E_{12} = x[R_0 - C_0 + y\theta R + (1 - y)\theta R'] + (1 - x)R_0 = R_0 + x[-C_0 + y\theta R + (1 - y)\theta R'].
\]   (3)

In the same way, suppose that the expected payoff of subcontractor A’s choice of cooperative strategy is \(E_{21}\), the expected payoff of non cooperative strategy is \(E_{22}\), and the average expected payoff of subcontractor A is \(E_2\), then there are:

\[
E_{21} = x[R_A] - C_A + (1 - \theta)R + (1 - x)(R_A - C_A) = R_A - C_A + (1 - \theta)R.
\]   (4)

\[
E_{22} = x[R_A] + (1 - \theta)R' + (1 - x)R_A = R_A + x(1 - \theta)R'.
\]   (5)

\[
E_2 = yE_{21} + (1 - y)E_{22} = y[R_A - C_A + (1 - \theta)R] + (1 - y)[R_A + x(1 - \theta)R'] = R_A + y[-C_A + x(1 - \theta)R] + (1 - y)x(1 - \theta)R'.
\]   (6)

(2) Replicator dynamic equation of general contractor and subcontractor

From \(E_{11}\) and \(E_1\), the replicator dynamic equation of the general contractor \(F(x)\) can be obtained

\[
F(x) = \frac{dx}{dt} = x(E_{11} - E_1) = x(1 - x)(E_{11} - E_{12}) = x(1 - x)[-C_0 + \theta R' + \theta y(R - R')].
\]   (7)
From $E_{21}$ and $E_2$, the replicator dynamic equation of subcontractor $A$ $F(y)$ can be obtained

$$F(y) = \frac{dy}{dt} = x(E_{21} - E_2) = y(1 - y)(E_{21} - E_{22})$$

$$= y(1 - y)[-C_A + x(1 - \theta)(R - R')]$$.

(8)

Formula 7 shows that if $E_{11}$ is higher than $E_1$, the probability of choosing a cooperation strategy will increase; Formula 8 shows that if $E_{21}$ is higher than $E_2$, the probability of choosing a cooperation strategy will increase.

However, it is the probability of the other party’s choice that determines the payoff of the cooperation strategy and the average expected payoff. Both parties conduct dynamic games and constantly adjust the selection probability of their own cooperation strategy until the change of the probability of the general contractor and subcontractor $A$ is zero, that is $\frac{dx}{dt} = \frac{dy}{dt} = 0$.

(3) Calculation of equilibrium point There are multiple equilibrium solutions to the replicator dynamic equation of general contractor and subcontractor $A$, and the equation set is as follows:

$$\begin{align*}
\left\{ \begin{array}{l}
\frac{dx}{dt} = x(1 - x)[-C_0 + \theta R' + \theta y(R - R')]
\frac{dy}{dt} = y(1 - y)[-C_A + x(1 - \theta)(R - R')] = 0
\end{array} \right. \\
x, y \in [0, 1]
\end{align*}$$

(9)

Obtain five equilibrium points: $O(0, 0)$, $C(0, 1)$, $D(1, 1)$, $E(1, 0)$, $F\left(\frac{C_A}{(1 - \theta)(R - R')}, \frac{C_A - \theta R'}{(R - R')}\right)$. In order to further study the stability of the five equilibrium points, the Jacobian matrix is introduced into the evolutionary game system. Let the Jacobian matrix be $T$. $det T$ is the value of matrix determinant, $trT$ is the trace of matrix. Where the point satisfying $det T > 0$ and $trT > 0$ is the unstable point; The point satisfying $det T > 0$ and $trT = 0$ is the saddle point; The point satisfying $det T > 0$ and $trT < 0$ is the evolutionary stable strategy (ESS) point [19].

$$T = \begin{bmatrix}
\frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\
\frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y}
\end{bmatrix} = \begin{bmatrix}
(1 - 2x)[-C_0 + \theta R' + \theta y(R - R')] & \theta x(1 - x)(R - R') \\
y(1 - y)(1 - \theta)(R - R') & (1 - 2y)[-C_A + x(1 - \theta)(R - R')]
\end{bmatrix}. \tag{10}
$$

$$det T = \frac{\partial F(x)}{\partial x} \cdot \frac{\partial F(y)}{\partial y} - \frac{\partial F(x)}{\partial y} \cdot \frac{\partial F(y)}{\partial x} = (1 - 2x)[-C_0 + \theta R' + \theta y(R - R')](1 - 2y)[-C_A + x(1 - \theta)(R - R')]$$

$$+ (1 - \theta)(R - R')] - \theta x(1 - x)y(1 - y)(R - R')^2. \tag{11}
$$

$$trT = \frac{\partial F(x)}{\partial x} + \frac{\partial F(y)}{\partial y} = (1 - 2x)[-C_0 + \theta R' + \theta y(R - R')] + (1 - 2y)[-C_A + x(1 - \theta)(R - R')]. \tag{12}
$$

Take $O(0, 0)$, $C(0, 1)$, $D(1, 1)$, $E(1, 0)$, $F\left(\frac{C_A}{(1 - \theta)(R - R')}, \frac{C_A - \theta R'}{(R - R')}\right)$ into Eq. 11 and Eq. 12 for calculation, as shown in table 2.

In table 2, the states of the two equilibrium points $D(1,1)$ and $E(1,0)$ are uncertain. If $R > C_0 + C_A + (1 - \theta)R'$ and $R' < C_0 - C_A + (1 - \theta)R$, then point $D(1,1)$ is the ESS, and point $E(1,0)$ is the unstable point, which is the situation that is expected to contribute. The results are shown in the following figure 1.

5
### Table 2. Local stability state of the equilibrium point

<table>
<thead>
<tr>
<th>Equilibrium point</th>
<th>$\text{det}T$</th>
<th>$\text{tr}T$</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0,0)</td>
<td>$C_A(\theta R - C_0)$</td>
<td>$\theta R - C_0 - C_A$</td>
<td>ESS</td>
</tr>
<tr>
<td>(0,1)</td>
<td>$C_A(\theta R - C_0)$</td>
<td>$C_A - C_0 + \theta R$</td>
<td>Unstable point</td>
</tr>
<tr>
<td>(1,1)</td>
<td>$(\theta R - C_0)((1 - \theta)(R - R') - C_A)$</td>
<td>$C_0 + C_A - R + (1 - \theta)R$</td>
<td>–</td>
</tr>
<tr>
<td>(1,0)</td>
<td>$(C_0 - \theta R)((1 - \theta)(R - R') - C_A)$</td>
<td>$C_0 - C_A - R + (1 - \theta)R$</td>
<td>–</td>
</tr>
<tr>
<td>$(\frac{C_A}{(1 - \theta)(R - R')}, \frac{C_0 - \theta R}{\theta(R - R')})$</td>
<td>+</td>
<td>0</td>
<td>Saddle point</td>
</tr>
</tbody>
</table>

![Phase diagram of dynamic evolution of cooperative game](image)

**Figure 1.** Phase diagram of dynamic evolution of cooperative game

### 3.3 Cooperation Strategy Analysis

The optimal evolutionary stable state of the general contractor and subcontractor A is (1,1). That is, the general contractor actively establishes a partnership with subcontractor A, and subcontractor A also takes various improvement measures to cooperate with the general contractor. Points (0,0) and (1,1) are both ESS points of the system. However, in order to finally converge to the (1,1) strategy, it is necessary to increase $S_{CDEF}$ and reduce $S_{COEF}$.

\[
S_{CDEF} = 1 - S_{COEF} \\
S_{COEF} = \frac{1}{2}(x_F + y_F) = \frac{1}{2}\left(\frac{C_A}{(1 - \theta)(R - R')} + \frac{C_0 - \theta R'}{\theta(R - R')}\right) = \frac{\theta C_A + (1 - \theta)(C_0 - \theta R')}{2\theta(1 - \theta)(R - R')} \tag{13}
\]

Method 1: Reducing $C_A$ means reducing the cost of improvement measures when subcontractor A chooses to cooperate. With the development of time, the two sides have established
a deeper and deeper partnership, and the cost of cooperation will be gradually reduced. This method is feasible.

Method 2: Reducing $C_0$ means reducing the general contractor’s time, energy, and organizational costs when choosing cooperation. With the increase in cooperation proficiency, the cost will inevitably decrease. This method is feasible.

Method 3: Increasing $R$ means increasing the benefits of cooperation between the two parties. At the same time, the gap between $R$ and $R'$ should be widened to reduce hitchhiking. Assume that when the general contractor cooperates unilaterally, the project income is almost the same as the cooperation between the two parties. In that case, Subcontractor A will tend not to cooperate, and the model will converge to $(1,0)$. Subcontractors are very important in the supply chains. The General Contractor shall give full play to the maximum value of subcontractors and promote cooperation between construction enterprises.

4 MATLAB Simulation

It can be seen from the above analysis that increasing $R$ can promote the convergence of cooperation between the two parties to $(1,1)$. In order to explain more intuitively, the evolutionary game of general contractor and subcontractor A is simulated through MATLAB software. To assign the data, the following inequality conditions must be met:

$$\begin{align*}
R &> C_0 + C_A + (1 - \theta)R' \\
R' &< C_0 - C_A + (1 - \theta)R \\
C_0 - \theta R' &> 0.
\end{align*}$$

Thus, let $C_0 = 1.2$, $C_A = 1$, $\theta = 0.6$, $R' = 1$, $R^1 = 4$, $R^2 = 5$. The first group of data points $(x_F, y_F) = (0.83, 0.33)$, and the second group of data points $(x_F, y_F) = (0.625, 0.25)$. To facilitate observation, the values of and are taken as $(0.6, 0.4)$, where and are the initial positions of $x$ and $y$. Let $y(1) = x, y(2) = y$. The data simulation analysis is as follows:

![MATLAB data simulation diagram when R is 4](image)

It can be seen from the figure that when $R$ is increased, the group evolution path of the general contractor and subcontractor will change. When $R = 4$, it moves toward the
Figure 3. MATLAB data simulation diagram when R is 5

equilibrium point of (0,0). When R is increased, it will move towards the equilibrium strategy state of (1,1). Based on this, it can be verified that increasing R can promote the convergence of both parties’ cooperation to (1,1).

In reality, to promote cooperation between the two sides, management measures can be optimized from the following aspects.

(1) Improve the cognition level of the supply chain and reduce the contracting cost of enterprises The General Contractor shall play the core role of the construction supply chain and improve the supply chain awareness of members. Clarify the rights and obligations of both parties, and quantify the potential additional benefits of cooperation between the General Contractor and subcontractors. Accordingly, the contract price shall be appropriately reduced, and a series of rewards and punishments such as subsidies, bonuses, and fines shall be used to promote a good cooperation environment.

(2) Adopt an efficient and transparent regulatory mechanism to reduce cooperation risks The general contractor is responsible for the supervision and management of the whole project. It is necessary to adopt fair, open, and just matching options. Make subcontracting behavior transparent through efficient and reasonable supervision and management means. Strengthen subcontractors’ credit management, maintain the construction market’s subcontracting order, and reduce cooperation risks.

(3) Improve the information transmission network of the supply chain and reduce the cost of mistakes Construction projects have a long cycle, many parties involved, and complex content. Information communication is the key to cooperation and sharing, which can significantly reduce the probability of participants making wrong decisions. The General Contractor and subcontractors shall hold regular meetings, establish online information databases and strengthen information security measures.

(4) Clarify project claims and reward and punishment measures to enhance enterprise enthusiasm All kinds of claims and disputes are inevitable in the construction of engineering projects. Clarifying claims can effectively protect the interests of participants. Implementing a series of reward and punishment measures can promote participants’ cooperation and avoid
“free riding”. Distribute benefits from the perspective of the supply chains to enhance the enthusiasm of enterprise cooperation.

5 Conclusions

This paper studies the matching problem of construction subcontracting suppliers. From the perspective of a group game and the bounded rationality of participants, an evolutionary game model of the general contractor and subcontractor is established. Based on the evolutionary stability strategy (ESS) and the replicator dynamic equation, the equilibrium point is calculated to explore the influencing factors of the cooperation probability of both parties. Finally, MATLAB simulation analysis is carried out to propose practical optimization management measures for the general contractor. The specific research conclusions are as follows:

(1) The optimal evolutionary stable state of the general contractor and subcontractor is (1,1). Both parties actively cooperate to achieve mutual benefit and win-win results. By studying the influence of parameter changes on the cooperation probability of both parties, $C_A$ and $C_0$ are determined to be negative correlation indicators, and $R$ is a positive correlation indicator. This requires reducing the cost of construction enterprises when choosing cooperation, increasing the cooperation revenue, and maximizing the value of the supply chains.

(2) The general contractor can optimize management measures through the following methods: Improve the level of supply chain awareness and reduce the cost of enterprise contracting; adopt an efficient and transparent regulatory mechanism to reduce cooperation risks; improve the information transmission network of the supply chain and reduce the error cost; clarify the project claims and reward and punishment measures to enhance the enthusiasm of the enterprise.

There are still some problems that have not been solved in the article and need to be further studied:

(1) In this paper, the evolutionary game model is used to study the matching problem of construction subcontractors. The process of the general contractor selecting subcontractor 1: n is simplified into a 1:1 game model. In terms of parameters, only cost, net income, and incremental income are set. The reality is more complicated, and many factors have yet to be considered.

(2) This paper only considers the cost-benefit situation of the general contractor and subcontractor. It does not consider the impact of the government, the owner, users, and other interested parties. Market factors are considered too little. It is hoped that future research can enrich the players in the game and explore the construction subcontracting problem more precisely and deeply. Use more empirical data to verify the effectiveness of the measures, so as to provide a systematic and scientific guidance plan for construction supply chain participants.

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References