Three-party evolutionary game theory analysis of the development of Chinese professional construction micro enterprises

Changming Hu[1], Shasha Huang[1*], Zhanxue Zhang[2] and Ping Li[2]

[1]School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an, 710055, China
[2]Management of the Housing and Urban-Rural Construction Department of Shaanxi Province, Xi′an, 710004, China

Abstract. With construction employment system reform, labor enterprise qualifications elimination and professional construction micro-enterprises development have become the general trends. In this case, this article builds a three-party evolutionary game model between local governments, contractor teams and construction enterprises to discusses evolutionary paths and stability strategies. And Matlab is used for numerical simulation to demonstrate the influence of different initial states on results. The research results show that increase initial probabilities, local governments' reputations, rewards and punishments, contractor teams' transformation profits, construction enterprises' employment profits, and reduce local governments' costs, contractor teams' operational costs, construction enterprises' subcontracting and management costs, which will help the dynamic system to evolve toward an ideal state, which is conducive to the development of micro-enterprises.

1 Introduction

With the rapid development of Chinese construction industry, present employment system quickly exposes defects, which are non-standard employments, "empty shell" labor subcontractors and few construction teams owned by construction enterprises [1]. These cause labor subcontracting market become disorder, multi-tier subcontracting became general and contractor teams become actual work organizations [2-3]. However, the contractor team is a backward organizational form. not only is it not conducive to protect workers' rights because of ambiguous labor relations, but also leads to frequent safety and quality accidents and damage to market order because of pursuing maximum benefits [4-5]. It has become a "bottleneck" to constrain the improvement of Chinese construction level.

In 2016, in order to break through the bottleneck, the Central People's Government of the People's Republic of China began to promote construction employment system reform, and encouraged contractor teams to transform into professional construction micro-enterprises (hereafter called micro-enterprises). It opens a new employment mode. However, its development situation is not optimistic. Xi'an as one of the initial pilot cities has only established four micro-enterprises at yet. Therefore, it is urgent to study how to attract and guide the transformation.

In recent years, evolutionary game theory has been widely used to research construction industry sustainable development. Fu et al. analyze cooperation and competition between general contractors and owners [6]. Sun et al. explore factors that affect Chinese construction workers' mobility and skills training [7-8]. Liu et al. analyzes the issue of strategic choice for opportunistic behavior by governments and private investors [9]. Li et al. analyze the conditions that prevent investors' opportunism behaviors [10]. Chen et al. explore the stability and feasibility of government policy in promoting prefabricated construction [11]. Huang explores the influencing factors of the game behaviors of developers and owners [12]. Dong explore the conditions for eliminating the construction teams' opportunistic behaviour [5].

However, there is no literature using the evolutionary game theory to analyze micro-enterprises development. Consequently, in order to fill this research gap, an incomplete information evolutionary game model is used to explore evolutionary paths and stability strategies of local governments, contractor teams and construction enterprises. It can provide a theoretical basis for governments to promote the development of micro-enterprises.

2 Evolutionary game model

2.1 Assumptions

In order to establish the three-party evolutionary game model conveniently, the following basic assumptions are made.

Assumption1 Local governments have two strategies: "support" and "non-support". When adopt "support"

*Corresponding author's e-mail: 1208258055@qq.com

strategy, local governments punish illegal contractor teams and construction enterprises that hire teams, and adopt positive incentives for micro-enterprises. Nowadays, most construction workers are in contractor teams. These lawless relationships make it difficult to protect workers' rights, improve projects qualities, promote employment and entrepreneurship, achieve social harmonies [13-14]. Consequently, local governments can solve them by supporting micro-enterprises development to improve their reputations. Conversely, reputations decline.

Assumption2 Constructor teams have two strategies: "transformation" and "non-transformation". When adopt "transformation" strategy, it can effectively improve labor productivity and increase competitiveness [15-17]. It is more conducive to sign subcontracts, but it also bring additional operation and management costs. When adopt "non-transformation" strategy, they gain more potential benefits, but face fines from local governments supervision.

Assumption3 Construction enterprises have two strategies: "employment" and "non-employment". When adopt "employment" strategy, they can avoid labor subcontractors to extract benefits [4]. Moreover, they can bid item by item and flexibly arrange work teams to enter and leave construction sites. It is effective to save subcontracting costs. However, without intermediate levels, they will take more responsibility for coordination and management. And employing contractor teams not only seriously affects reputations [5], but also faces punishments. When adopt "non-employment" strategy, subcontracting costs is higher, but by this way can reduce management stress and workload.

Assumption4 The probability that local governments adopt "support" strategy is $x(0 \le x \le 1)$, then the probability of selecting "non-support" strategy is $1 - x$; the probability that contractor teams adopt "transformation" strategy is $y(0 \le y \le 1)$, then the probability of selecting "non-transformation" strategy is 1-y; and the probability that the construction enterprises adopt "employment" strategy is $z(0 \leqslant z \leqslant 1)$, then the probability of selecting " non-employment" strategy is 1-z.

2.2 Parameters

Based on assumptions above, parameters and variable descriptions of the model are listed in Table 1.

Table 1. Model parameters and variable descriptions.

Description	Parameter
Local governments' reputation promotion by supporting micro-enterprises development	U
Local governments' benefit from micro-enterprises' formation	R_l
Local governments' punishment for construction enterprises that employ contractor teams	P

Table 2. Cont.

Description	Parameter
Local governments' reward or punishment for contractor teams' transformation or non-transformation	S / M
Local governments' guiding cost of implement support policies	C_l
Social benefit increasing or decreasing for construction enterprises' employment or non-employment micro-enterprises	W / K
Construction enterprises' basic profit	R_c
Construction enterprises' subcontracting cost by employing micro-enterprises or contractor teams	r
Construction enterprises' subcontracting cost increasing by employing subcontractors	ΔC
Construction enterprises' management costs by employing micro-enterprises or contractor teams	C_m
Contractor teams' profit increasing by transforming into micro-enterprises	T_1
Contractor teams' operational cost increasing by transforming into micro-enterprises	C_t
Contractor teams' basic labor cost	C_1

Based on assumptions and parameters setting above, it can be obtained that the payoff matrix of the three-party evolutionary game is shown in Table 3.

Table 3. The payoff matrix of the three-party evolutionary game.

Contractor teams		Transform		Do not transform	
Construction enterprises		Employ	Do not employ	Employ	Do not employ
Local governments	Support	$\begin{bmatrix} R_l - C_l + U - S + W \\ r + T_1 + S - C_1 - C_t \\ R_c - r - C_m + T_1 \end{bmatrix}$	$\begin{bmatrix} R_l - C_l + U - S - K \\ S + T_1 - C_1 - C_t \\ R_c - r - \Delta C \end{bmatrix}$	$\begin{bmatrix} U - C_l + M + P - K \\ r - C_1 - M \\ R_c - r - C_m - P \end{bmatrix}$	$\begin{bmatrix} W - C_l + M - K \\ -M \\ R_c - r - \Delta C \end{bmatrix}$
	Do not support	$\begin{bmatrix} R_l + W \\ r + T_1 - C_t - C_1 \\ R_c - r - C_m + T_1 \end{bmatrix}$	$\begin{bmatrix} R_l - K \\ T_1 - C_1 - C_t \\ R_c - r - \Delta C \end{bmatrix}$	$\begin{bmatrix} -K \\ r - C_1 \\ R_c - r - C_m \end{bmatrix}$	$\begin{bmatrix} -K \\ 0 \\ R_c - r - \Delta C \end{bmatrix}$

2.3 The Expected Payoff and Replicator Dynamics Equation of the Three Game Players

2.3.1 The replicator dynamics equation of local governments.

Let U_x represent the expected payoff of local governments if they pursue "support" strategy, and U_{1-x} represent the expected payoff of local governments if they pursue "non-support" strategy. $\bar{U}_x$ represents the average expected payoff of local governments. U_x, U_{1-x} and $\bar{U}_x$ can be expressed as:

$$\begin{cases} U_x = yz\left(R_l - C_l + U - S + W\right) + y\left(1-z\right)\left(R_l - C_l + U - S - K\right) + \left(1-y\right)z\left(-C_l + U + M + P - K\right) + \\ \qquad \left(1-y\right)\left(1-z\right)\left(-C_l + M - K + W\right) \\ U_{1-x} = yz(R_l + W) + y\left(1-z\right)\left(R_l - K\right) + \left(1-y\right)z(-K) + \left(1-y\right)\left(1-z\right)\left(-K\right) \\ \bar{U}_x = xU_x + \left(1-x\right)U_{1-x} \end{cases} \tag{1}$$

According to the replication dynamics proposed by Taylor and Jonker [18], the replicator dynamics equation of local governments can be written as:

$$F(x) = \frac{dx}{dt} = x\left(1-x\right)U - C_l - yS + \left(1-y\right)\left(M + zP\right) + \left(1-y\right)\left(1-z\right)\left(W - U\right) \tag{2}$$

2.3.2 The replicator dynamics equation of contractor teams.

Let U_y represent the expected payoff of contractor teams if they pursue "transformation" strategy, and U_{1-y} represent the payoff of contractor teams if they pursue "non-transformation" strategy. $\bar{U}_y$ represents the average expected payoff of contractor teams. Then U_y, U_{1-y} and $\bar{U}_y$ can be expressed as:

$$\begin{cases} U_y = xz\left(r + S + T_1 - C_1 - C_t\right) + x\left(1-z\right)\left(S + T_1 - C_1 - C_t\right) + \left(1-x\right)z\left(r + T_1 - C_1 - C_t\right) + \\ \qquad \left(1-x\right)\left(1-z\right)\left(T_1 - C_1 - C_t\right) \\ U_{1-y} = xz\left(r - C_1 - M\right) + x\left(1-z\right)\left(-M\right) + \left(1-x\right)z\left(r - C_1\right) \\ \bar{U}_y = yU_y + \left(1-y\right)U_{1-y} \end{cases} \tag{3}$$

The replicator dynamics equation of contractor teams can be written as:

$$F\left(y\right) = \frac{dy}{dt} = y\left(U_y - \bar{U}_y\right) = y\left(1-y\right)\left(T_1 - C_1 - C_t\right) + x\left(S + M\right) + zC_1 \tag{4}$$

2.3.3 The replicator dynamics equation of construction enterprises.

Let U_z represent the expected payoff of construction enterprises if they decide to employ, and U_{1-z} represent the expected payoff of construction enterprises if they decide not to employ. $\bar{U}_z$ represents their average expected payoff. Then U_z, U_{1-z} and $\bar{U}_z$ can be expressed as:

$$\begin{cases} U_z = xy\left(R_c - r - C_m + T_1\right) + x\left(1-y\right)\left(R_c - r - C_m - P\right) + \left(1-x\right)y\left(R_c - r - C_m + T_1\right) + \\ \qquad \left(1-x\right)\left(1-y\right)\left(R_c - r - C_m\right) \\ U_{1-z} = xy\left(R_c - r - \Delta C\right) + x(1-y)(R_c - r - \Delta C) + \left(1-x\right)y\left(R_c - r - \Delta C\right) + \\ \qquad \left(1-x\right)\left(1-y\right)\left(R_c - r - \Delta C\right) \\ \bar{U}_z = zU_z + \left(1-z\right)U_{1-z} \end{cases} \tag{5}$$

The replicator dynamics equation of construction enterprises can be written as:

$$F\left(z\right) = \frac{dz}{dt} = z\left(U_z - \bar{U}_z\right) = z\left(1-z\right)\left[-C_m + yT_1 + \Delta C - x\left(1-y\right)P\right] \tag{6}$$

3 Stability Analysis of the Evolutionary Game

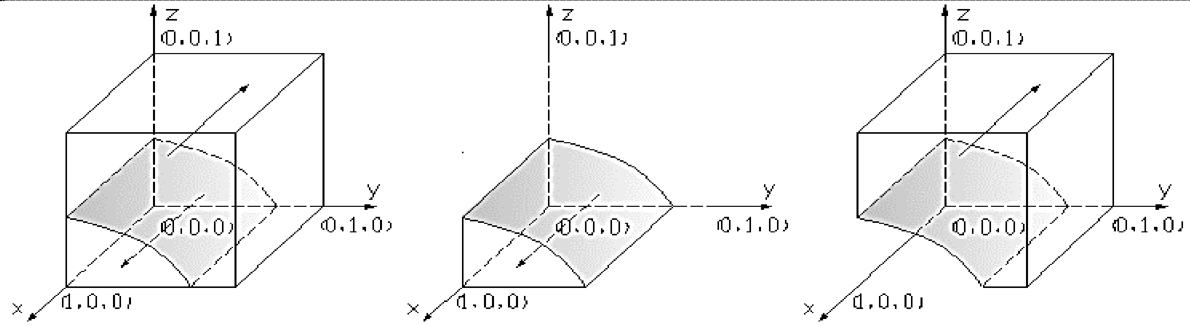
According to the stability theory of differential equations, if satisfies $F(i) = 0, \frac{\partial F(i)}{\partial i} < 0$ $(i = x, y, z)$, it means the equilibrium strategies x, y and z respectively represent the stable strategy adopted by the three players in the evolution process.

3.1 Analysis of the asymptotic stability of local governments.

If $U - C_l - yS + 1 - y(M + zP) + (1-y)(1-z)(W - U) = 0$, then $F(x) \equiv 0$, indicating the boundary of the stable state, as shown in Figure 1a. If $U - C_l - yS + (1-y)(M + zP) + (1-y)(1-z)(W - U) \neq 0$, let $F(x) = 0$, and we can get two stable points of $x = 0$ and $x = 1$. If $U - C_l - yS + (1-y)(M + zP) + (1-$

$y)(1-z)(W-U)<0$, then $\frac{\partial F(x)}{\partial x}|_{x=0}<0$ and $\frac{\partial F(x)}{\partial x}|_{x=1}>0$. Therefore, $x=0$ is the stable strategy, and local governments will decide not to support, as shown in Figure 1c. On the contrary, if $U-C_l-yS+(1-y)(M+zP)+(1-y)(1-z)(W-U)>0$, then $\frac{\partial Fx}{\partial x}|_{x=0}>0$ and $\frac{\partial Fx}{\partial x}|_{x=1}<0$. Therefore, $x=1$ is the stable strategy and local governments will decide to support, as shown in Figure 1b.

Figure 1 shows when the proportion of construction enterprises employment is greater than a critical value, local governments tend to select "non-support" strategy. But with reputations promotion and costs saving of local governments support, social benefits growing of construction enterprises employment, preferential demand reduction of contractor teams transformation, and proportional reduction of contractor teams transformation and construction enterprises employment, the proportion of construction enterprises employment will be less than the critical value, then local governments will turn to select "non-support" strategy.



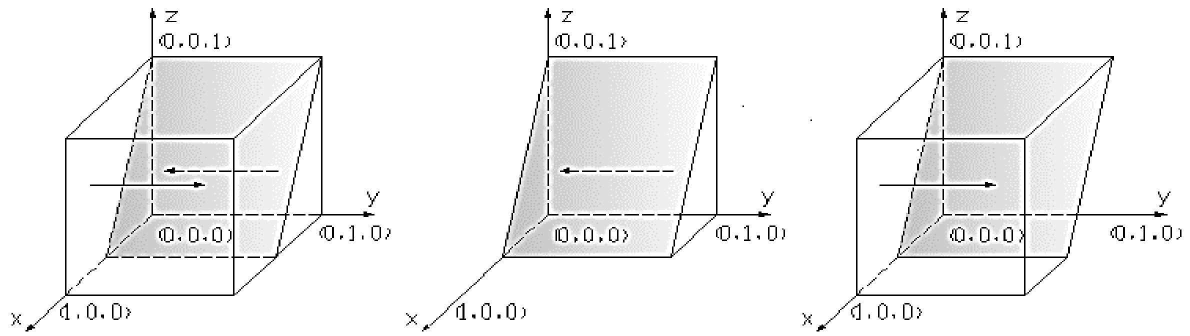
$(a)z=\frac{U-C_l-yS+(1-y)(W-U+M)}{(1-y)(W-U-P)}$ $(b)z<\frac{U-C_l-yS+(1-y)(W-U+M)}{(1-y)(W-U-P)}$ $(c)z>\frac{U-C_l-yS+(1-y)(W-U+M)}{(1-y)(W-U-P)}$

Figure 1. Evolutionary diagram of local governments' strategy.

3.2 Analysis of the asymptotic stability of contractor teams.

If $(T_1-C_1-C_t)+x(S+M)+zC_1=0$, then $F(y)\equiv 0$, indicating the boundary of the stable state, as shown in Figure 2a. If $(T_1-C_1-C_t)+x(S+M)+zC_1\neq 0$, let $F(y)=0$, and we can get two stable points of $y=0$ and y=1. If $(T_1-C_1-C_t)+x(S+M)+zC_1<0$, then $\frac{\partial F(y)}{\partial y}|_{y=0}<0$ and $\frac{\partial F(y)}{\partial y}|_{y=1}>0$. Therefore, $y=0$ is the stable strategy, and contractor teams will decide not to transform, as shown in Figure 2b. On the contrary, if $(T_1-C_1-C_t)+x(S+M)+zC_1>0$, then $\frac{\partial F(y)}{\partial y}|_{y=0}>0$ and $\frac{\partial F(y)}{\partial y}|_{y=1}<0$. Therefore, y=1 is the stable strategy and contractor teams will decide to transform, as shown in Figure 2c.

Figure 2 shows when the proportion of local governments support is less than a critical value, contractor teams tend to select "non-transform" strategy. But with profits promotion and operational costs reduction of contractor teams transformation, rewards and punishments enhancement of local governments support, and proportional increasement of local governments support and construction enterprises employment, the proportion of local governments support will be greater than the critical value, and contractor teams will turn to select "transformation" strategy.



$(a)\ x=\frac{C_t+(1-z)C_1-T_1}{S+M}$ $(b)\ x<\frac{C_t+(1-z)C_1-T_1}{S+M}$ $(c)x>\frac{C_t+(1-z)C_1-T_1}{S+M}$

Figure 2. Evolutionary diagram of contractor teams' strategy.

3.3 Analysis of the asymptotic stability of construction enterprises.

If $C_m + yT_1 + \Delta C - x(1-y)P = 0$, then $F(z) \equiv 0$, indicating the boundary of the stable state, as shown in Figure 3a. If $C_m + yT_1 + \Delta C - x(1-y)P \neq 0$, let $F(z) = 0$, and we can get two stable points of $\mathrm{z} = 0$ and $\mathrm{z} = 1$. If $C_m + yT_1 + \Delta C - x(1-y)P < 0$, then $\frac{\partial F(z)}{\partial z}|_{z=0} < 0$ and $\frac{\partial F(z)}{\partial z}|_{z=1} > 0$. Therefore, $\mathrm{z} = 0$ is the stable strategy, and construction enterprises will decide not to employ, as shown in Figure 3b. On the contrary, if $C_m + yT_1 + \Delta C - x(1-y)P > 0$, then $\frac{\partial F(z)}{\partial z}|_{z=0} > 0$ and $\frac{\partial F(z)}{\partial z}|_{z=1} < 0$. Therefore, $\mathrm{z} = 1$ is the stable strategy and construction enterprises will decide to employ, as shown in Figure 3c.

Figure 3 shows when the proportion of construction enterprises employment is less than the critical value, contractor teams tend to select “no employment” strategy. But with management costs reduction of construction enterprises employment, subcontracting costs increase of construction enterprises non-employment, profits promotion of construction enterprises which employ micro-enterprises, and proportional increasement of local governments support and construction enterprises employment, the proportion of contractor teams transformation will be greater than the critical value, and construction enterprises will turn to select “employment” strategy.

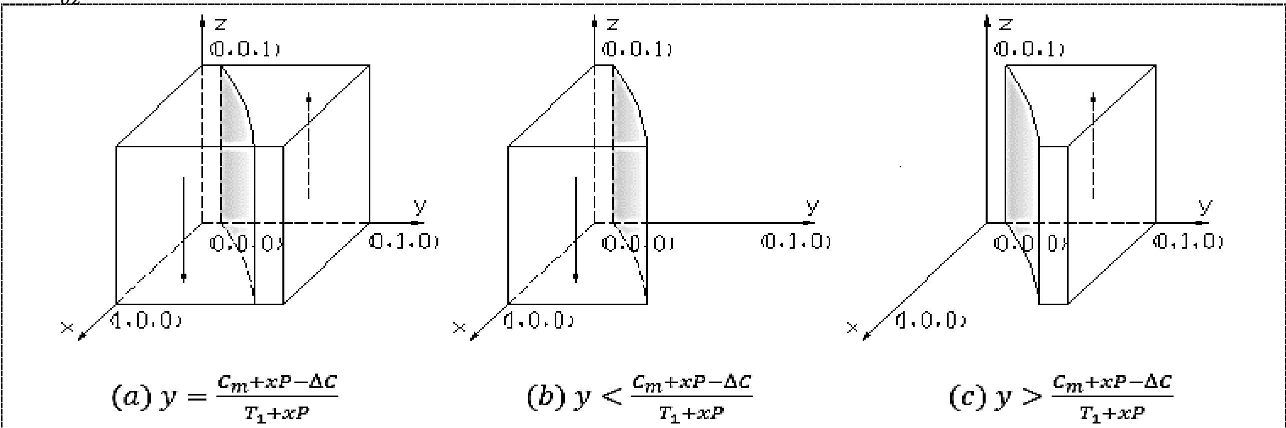


Figure 3. Evolutionary diagram of construction enterprises’ strategy.

3.4 Analysis of the three-party game hybrid strategy.

According to the conclusion proposed by Ritzberger and Weibull, the three-party game hybrid strategy can only analyze the asymptotic stability of points $Q_1(0,0,0)$, $Q_2(1,0,0)$, $Q_3(0,1,0)$, $Q_4(0,0,1)$, $Q_5(1,1,0)$, $Q_6(1,0,1)$, $Q_7(0,1,1)$, $Q_8(1,1,1)$ [19]. And this paper focuses on promoting micro-enterprises development. Therefore, only the stability of Q_8 is analyzed. According to the dynamic replication equations system of the three players and the method of evolutionary equilibrium stability analysis proposed by Friedman [20], the Jacobian matrix corresponding to Q_8 can be obtained as:

$$\begin{bmatrix} -(U - C_l - S) & 0 & 0 \\ 0 & -(T_1 - C_t + S + M) & 0 \\ 0 & 0 & -(T_1 + \Delta C - C_m) \end{bmatrix} \quad (7)$$

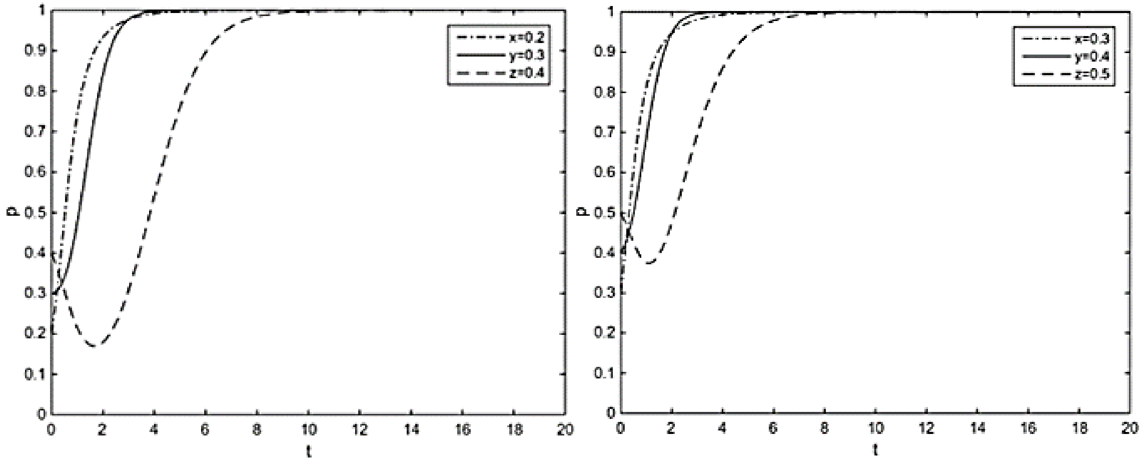
The characteristic roots of Q_8 are $-(U - C_l - S)$, $-(T_1 - C_t + S + M)$ and $-(T_1 + \Delta C - C_m)$. Then according to the first method of Lyapunov, when three characteristic roots are negative, Q_8 is an evolutionary stability strategy [21]. It means the three-party game evolves to the ideal condition in which local governments adopt “support” strategy, contractor teams adopt “transformation” strategy and construction enterprises adopt “employment” strategy.

3.5 Simulations and Conclusion

In order to be able to more intuitively reflect the evolutionary direction of the system under the ideal condition, MATLAB programming is used to realize the numerical simulation of the three-party game’s evolutionary process. The specific parameters are set as follows: $U = 6$, $R_l = 5$, $P = 2$, $S = 2$, $M = 1$, $C_l = 3$, $W = 1$, $K = 1$, $R_c = 6$, $r = 3$, $\Delta C = 2$, $C_m = 3$, $T_1 = 2$, $C_t = 2$, $C_1 = 1$.

Study the dynamic evolution of three players under the different initial states. The different initial probabilities of two groups are shown in Figure 4. It is obvious that when $x = 0.2$, $y = 0.3$, $z = 0.4$, the system reaches evolutionary stable state at around $\mathrm{t} = 10$. When $x = 0.3$, $y = 0.4$, $z = 0.5$. the system reaches at around $\mathrm{t} = 8$. It suggests when initial probabilities increase, the time to an ideal state will be shortened.

In conclusion, increase initial probabilities, local governments’ reputations, rewards and punishments, contractor teams’ transformation profits, construction enterprises’ employment profits, and reduce local governments’ costs, contractor teams’ operational costs, construction enterprises’ subcontracting and management costs, which will help the dynamic system to evolve toward an ideal state, which is conducive to the development of micro-enterprises.



$(a) x = 0.2,\ y = 0.3,\ z = 0.4$ $(b) x = 0.3,\ y = 0.4,\ z = 0.5$

Figure 4. Evolutionary process of the system under different initial conditions.

Acknowledgments

We are very grateful for the foundation support of the Ministry of Housing and Urban-Rural Construction of the People's Republic of China.

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