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Historical dynamics of construction business systems: an institutional evolution perspective

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As a kind of basic institutional environment, the construction business system provides an underlying platform of the interactions for stakeholders of construction projects and hence exerts a great influence on the building sector. Taking the view of 'the construction business system as a complex adaptive system', a research framework is developed with the aim of understanding how and why construction business systems emerge and evolve over time. The principles of evolutionarily stable strategy and replicator dynamic are briefly introduced. A three-strategy evolutionary game model is developed on the basis of a set of assumptions, with the distinctiveness of the construction industry fully taken into consideration. The model illustrates some characteristic outcomes: multiple equilibria, path dependence, original-state-sensitiveness, the long-term persistence of Pareto-inferior outcomes as well as proneness to the stable equilibrium characterized by more efficient negotiation and higher average payoff. It is expected that introducing 'revolutionary' events that are not explicitly modelled, such as non-best responses and exogenous changes, could break the existing equilibrium and bring about new equilibrium outcomes.

Keywords: Complexity, construction business system, equilibrium, evolution, game theory, modelling.

Introduction

According to the new institutional economics, social, political, legal and economic institutions could be divided into four categories or levels: (1) social or cultural foundations, or embeddedness, (2) basic institutional environment, (3) institutions of governance and (4) short-term resource allocation (Williamson, 2000). In the construction project/the construction market settings, the construction business system, or 'contracting system' for short in the UK (Winch, 2000a), belongs to the second level where the focus is to get the institutional environment right. The tectonic approach to managing construction projects takes the construction business system as a 'highly structured set of relationships', 'institutionalized sets of interests' and the building sector-specific national business system with the functions of allocating roles, defining responsibilities and specifying liabilities for various actors in the construction market (Winch, 2000a, pp. 89–90). This approach is characterized by a three-level analysis framework: the institutional-level shapes, and is shaped by decisions made at the governance level, which in turn have a great influence on the process level as well as the performance of construction projects (Winch, 2010, p. 13). Thus, the construction business system provides an underlying platform of the interactions for stakeholders of construction projects and hence exerts a great influence on the building sector.

Notice that the construction business system and the construction industry are two different but interrelated concepts. The latter is a sector of national economy engaged in preparation of land and construction, alteration and repair of buildings, structures and other real property, while the former is an 'institutional system that regulates the relations between the actors in the construction industry' (Campagnac, 2000, p. 131) and shapes the strategy and performance of construction firms in nationally distinctive ways (Winch, 2010, p. 24). In addition, the construction business system is different from other non-institutional systems with

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the construction industry, such as information system, logistic system and so on.

In recent years, we have seen a steady growth of research in the construction business system. The relevant literature involves various countries, such as the UK (Winch, 2000b), France (Campagnac, 2000), Germany (Syben, 2000), Italy (Bologna and Del Nord, 2000), the Netherlands (Brener and Kok, 2000), Sweden (Bröchner *et al.*, 2002), the USA (Pietroforte and Miller, 2002), Japan (Reeves, 2002), Singapore (Dulaimi *et al.*, 2002) and China (Sha, 2004), from which the following arguments can be drawn:

- Diversity is an essential feature of the construction business system. In the European Union, for instance, there are Anglo-Saxon-type systems represented by the UK, corporatist-type system represented by Germany and the Netherlands, and *étatique*-type system represented by France and Italy. These countries are geographically close to each other, while the above-mentioned construction business systems are different in various aspects, each having its advantages and disadvantages (Winch, 2000a).
- Path dependence is at the heart of the evolution of the construction business system (Winch, 2010, p. 34). Any construction business system, whether 'good' or 'bad', is invariably branded with its own social, cultural and historical stamp. Take Japan for instance; it is the unique cultural and historical background that created a distinctive construction business system characterized by encouraged collaboration and restricted competition, with large general contractors being predominant in the construction market (Reeves, 2002).
- Although planned change is difficult, the system provides more or less space for innovation, in which 'revolutionary' events such as major disasters, wars and big economic and social reforms acted as a trigger. For example, the great fire of London in 1666 provided Britain with its first building regulations, and made separate trades contracting become the norm. More than 100 years later, under the pressures generated by the French wars in particular, and the industrial revolution more generally, the trade system began to break down and was gradually replaced by general contracting during the first half of the nineteenth century (Loosemore, 2000, pp. 2–3; Winch, 2000b). The two-century development of the US infrastructure procurement can be described as a three-phase change in two-dimensional space (direct vs. indirect funding in vertical direction, and segmented vs. combined procurement in horizontal direction), with the Depression, the Second World War and the information revolution acting as dividing lines (Pietroforte and Miller, 2002). More recently, it is the fundamental reform from a planned economy to a market economy that spurred the emergence of China's construction business system (Sha, 2004).

Despite these achievements, however, there is still room for improvement. In the literature mentioned above, what hampers a thorough analysis is that the construction business system is taken as an exogenously given one. As Winch (2010, p. 21) argued,

> In this perspective, … [p]atterns of behavior become institutionalized so that they act back upon the actors through the process of *structuration*—the rules of the game come to be seen as given, normal, the only way to do things.

This makes the research work remain at a level where one can understand the hows but not the whys of the system. More attention has been given to the dynamic balance between various actors in a given construction business system, leaving the following questions untouched:

- Why is the construction business system present in varied forms?
- Why does the construction business system evolve in a path-dependent manner?
- What is the situation under which the construction business system is more likely to reach a stable equilibrium?
- Why can some Pareto-inferior construction business systems persist over long periods?

Here we have two terms, path dependence and Pareto-inferior outcomes, that need to be explained. Path dependency theory was originally developed by economists to explain technology adoption processes and industry evolution, and has had a strong influence on evolutionary economics. Most generally, path dependence means that where we go next depends not only on where we are now but also upon where we have been (Liebowitz and Margolis, 2000, p. 981). So-called Pareto inferior is opposite to Pareto optimal. Pareto optimality, or Pareto efficiency, is a concept in economics which is named after an Italian economist Vilfredo Pareto. By Pareto optimality, we mean a situation in which no feasible change can rise anybody's welfare without lowering that of somebody else (Black, 2002, p. 343).

In order to explain these questions, it is essential to make a shift from the assumption of an exogenously given system to that of an endogenous one. Using the evolutionary game theory as the main analysis tool, this paper attempts to make a modest contribution by examining the system from the perspective of institutional evolution. Starting from the requirement analysis, a complex system perspective and an evolutionary game theory-based approach are determined. Subsequently, the principles of evolutionarily stable strategy (ESS) and replicator dynamic are briefly introduced. Then, in light of the nature of the construction business system, a set of assumptions are proposed and a three-strategy game model is developed. Finally, the conclusion is drawn on the basis of a discussion about the outcomes of the game, including multiple equilibria, path dependence, self-sustainability of Pareto-inferior outcomes and the probabilities of different equilibria.

Research perspective and approach

The term 'institution' is multifaceted and has different meanings in different contexts. For example, there is a dichotomy in conceptualizations of institutions: institutions as 'rules of a game' vs. institutions as 'endogenous equilibrium outcomes of a game' (Aoki, 2001). From the first perspective, evolutions occur simply because of changes of exogenous parameters; while in the second case, institutional change results from destabilization of a prevailing equilibrium as well as a subsequent process of convergence towards a new set of shared beliefs (Brousseau and Raynaud, 2011). To take the left fork or the right, this is a purpose-dependent problem. If one wants to examine how the construction business system influences the relations between various actors in the construction market, it is reasonable to regard the system as the given rules of the game, as argued in the first perspective. However, the purpose of this paper is to explore the inherent mechanism of historical dynamics of the system, so we should adopt the second approach, taking the system as an endogenous one and examining it from a holistic perspective. In this connection, achievements in the study of complex systems may provide some conceptual insights.

By complex systems, we refer to systems that have a large number of components, often called agents, which interact locally, resulting in a system globally changing over time. A complex system is adaptive if it evolves through some evolutionary process of hereditary reproduction, mutation and selection. Complex adaptive systems generally have following properties: non-linearity, inter-relationships, self-organization, sensitivity to initial conditions, adaptability using feedback from the environment and from themselves, and emergence, or as Goldstein (1999) defined, 'the arising of novel and coherent structures, patterns and properties during the process of self-organization in complex systems'.

A prominent characteristic of a complex adaptive system is that its behaviour emerges from the interactions of its components and so the complex system theory always develops a holistic or ecological perspective rather than a reductionist or atomistic one (Seedhouse, 2010). It is the holistic perspective that fits in perfectly with our study. In addition, examining institutional changes through a lens of the complex system theory may also provide a platform for new approaches and techniques such as the evolutionary game theory and agent-based models. In fact, there are elements of overlap between the complex system theory and the evolutionary game theory. In consideration of the suitability of the complex system theory and the practicability of the evolutionary game theory, we conceptualize the construction business system as a complex adaptive one and adopt an evolutionary game theory-based approach.

In order to enhance the credibility of this paper and position the research properly, the game theory and its application to the construction industry should be addressed in a few words. Concisely, game theory is a study of strategic decision-making. So-called strategic interaction refers to the situation in which the consequences of individual actions depend on the actions taken by others (Bowles, 2004, p. 31). The audience for game theory has grown dramatically in recent years and now spans disciplines as diverse as economics, political science, sociology, psychology and biology, among others (Shoham and Leyton-Brown, 2008). In the construction project/the construction market settings, there is an extensive literature on the application of game theory, involving many aspects such as collaborative negotiation methodology to facilitate or mediate the negotiation of conflicts in large-scale civil engineering projects (Pena-Mora and Wang, 1998; Pena-Mora and Tamaki, 2001), analytical model to understand the dynamic nature between construction claims and opportunistic bidding (Ho and Liu, 2004), game model to understand the behaviour of subcontractors in allocating resources to projects (Sacks and Harel, 2006), empirical application of the prisoner's dilemma (PD) game to explain a lack of cooperation in buyer−supplier relationships within construction and facilities management (Eriksson, 2007), the governance strategies in public−private partnerships (Ho, 2005, 2006), the vertical governance, or transaction relationships between the client and its first-tier suppliers of construction projects (Sha, 2011), agent-based simulation to examine the hold-up problem in project networks (Unsal and Taylor, 2011), the strategies concerning investment decisions for knowledge management programmes (Ho *et al.*, 2011) and knowledge sharing between individual employees in engineering firms (Levitt *et al.*, 2013). However, these applications are largely limited to the category of classical game theory in which players are treated as 'intelligent rational' decision-makers with very strong forward-looking cognitive powers, making their strategic choice on a wholly rationally determined evaluation of probable outcomes. Since we are trying to examine the historical dynamics of construction business systems, it seems appropriate to take the Darwinian approach, giving up the assumption of intelligent rational players, and focusing on the dynamics of strategy change more than the properties of strategy equilibria. That is why we adopt the evolutionary game theory as the main analysis tool. Compared with the existing research on applications of the game theory to the construction industry, the contribution of this paper can be summarized in the following aspects: (1) new perspective: the dynamics of strategy change; (2) new assumption about decision-makers' rationality and (3) new analysis tool: the evolutionary game theory.

A brief review of the evolutionary game theory

The evolutionary game theory is derived partly from biological evolution models and partly from the classical game theory. There are two approaches to the evolutionary game theory. The first approach employs the concept of ESS as the principal tool, and can be thought of as providing a 'static' conceptual analysis of evolutionary stability (McKenzie, 2009). The second approach constructs an explicit model of replicator dynamic to explain changes in fitness of individuals forming a population.

Evolutionarily stable strategy

The concept of ESS was first introduced in a 1973 *Nature* paper about the 'limited war' between animals of the same species: 'an ESS is a strategy such that, if most of the members of a population adopt it, there is no "mutant" strategy that would give higher reproductive fitness' (Maynard Smith and Price, 1973, p. 15). In other words, a population all playing an ESS will repel an invasion of individuals playing other strategies.

In essence, an ESS is a refined or modified form of Nash equilibrium. In Nash equilibrium, if all players adopt their respective parts, no player can benefit by switching to any alternative strategy, that is to say, all players have no reason to change the status quo. Consider a two-person game, let $E(x, y)$ represent the payoff for playing strategy x against strategy y. The strategy profile (x, x) is Nash equilibrium if and only if this is true for both players and for all $x \neq y$: $E(x, x) \geq E(y, x)$. If Nash equilibrium is a strategy profile in which all players' strategies are best responses to other strategies in the profile, then an ESS is a best response to itself. Maynard Smith and Price (1973) specified two conditions for a strategy x to be an ESS: either (1) $E(x, x) > E(y, x)$, or (2) $E(x, x) = E(y, x)$ and $E(x, y) > E(y, y)$ for all $y \neq x$.

Replicator dynamic

The replicator dynamic approach uses Darwinian fitness of individuals forming a population to measure their ability to reproduce: if an individual is fitter than another, then that individual is more likely to reproduce than the other. In other words, strategies with above-average payoffs will be adopted by others and thus increase their share of the population (Bowles, 2004, p. 70).

Consider a large (strictly, infinite) population in which individuals are randomly paired to interact in a symmetrical two-person game. For clarity, we normalize the size of the population to unity. Suppose that there are two strategies dictated by traits, x and y, with the population frequency of $p \in [0, 1]$ and $1 - p$, respectively. The following reduced replicator dynamics equation specifies the change of population frequency from one period to the next (Taylor and Jonker, 1978; Bowles, 2004, p. 73):

$$\Delta p = p' - p = p(1 - p)(\pi_x - \pi_y) = p(\pi_x - \bar{\pi}) \qquad (1)$$

where $p' \in [0, 1]$ is the population frequency of x-persons in the next period, π_x and π_y are expected payoffs of strategy x and y, respectively, and $\bar{\pi} = p\pi_x + (1 - p)\pi_y$ is the population average payoff.

Evolutionarily stable state

The concepts of an evolutionarily stable state and an ESS are closely linked but describe different situations. As Maynard Smith (1982, p. 204) argued,

> [A] population is said to be in an 'evolutionarily stable state' if its genetic composition is restored by selection after a disturbance, provided the disturbance is not too large.

It can be shown that for the replicator dynamics equation, Equation 1, if a state is evolutionarily stable then it is an asymptotically stable rest point. The converse is true if the game matrix is symmetric. That is why evolutionarily stable states are often taken as solutions of the replicator dynamics equation.

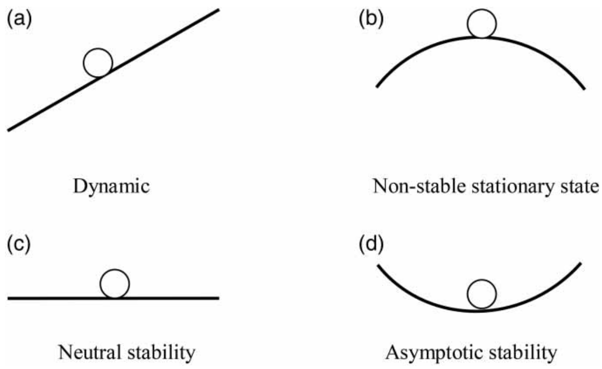

Figure 1 Understanding stationary state and stability: a mechanics perspective

The concepts of stationary state and stability are prone to be confused with each other. So it is helpful to understand these concepts by means of a mechanics analogy. Consider a ball and a sustain plane; as shown in Figure 1, the ball may be in various states depending on the conditions of the forces on it. (a) Being on an inclined plane, the ball is in the dynamic—since the gravity and the plane's supporting force are not in equilibrium, the ball will roll down with constant acceleration. (b) Being on the top of a convex arch, the ball is in the non-stably stationary state—if there is no horizontal force acting on the ball, it will remain static; otherwise, it will roll down rapidly. (c) Being on a horizontal plane, the ball is in the neutral stability—all sufficiently small horizontal forces will make it move but not result in further movement away from its original position. (d) Being on the bottom of a concave arch, the ball is in asymptotic stability—all sufficiently small horizontal forces acting on it will result in changes leading back to its original position.

In the evolutionary game context mentioned above, the stationary state refers to the status where the population frequency remains constant as time elapses. This demands that $\mathrm{d}p/\mathrm{d}t = 0$ in the continuous case, and $\Delta p = 0$, or $\pi_x = \bar{\pi}$ in the discrete case. Obviously, the stability belongs to the stationary state, while the asymptotic stability demands that an additional condition, $\mathrm{d}\Delta p/\mathrm{d}p < 0$, is satisfied, so that all sufficiently small perturbations will not displace the population frequency away from the original stationary state. Note that when the weaker condition, $\mathrm{d}\Delta p/\mathrm{d}p = 0$, is satisfied, the stability is neutral.

A three-strategy evolutionary game model

Any model, in essence, is an assumption-based abstraction of the reality. In order to develop a model to meet the requirements of our study, the following assumptions are made according to the evolutionary approach chosen above and the nature of the construction industry:

- *Procedurally rationality assumption*. In the evolutionary approach, we have a basic assumption that people act like adaptive agents who are neither zero-intelligence agents in biological evolution models nor completely rational players in classical game theory, but rather procedurally rational players who make their decisions according to evolved rules of thumb (Hendrikse, 2003, p. 18). In addition, members of this population are randomly paired.
- *Getting-nothing-without-project assumption*. It is well known that the construction industry is a typically project-based one. This means that production activities in the building sector must be organized in the form of the construction project. So we have the second assumption that various actors in the construction market, however strong they are, could get nothing without reaching an agreement with others to form a temporary coalition.
- *Three-strategy assumption*. The construction market distinguishes itself by one-off project-oriented transactions and its derivative—imbalanced demand−supply relationships. The status difference between actors in the market has resulted in various attitudes. Although the majority of actors are in favour of fair play, there are always some actors, like clients in China's public sector (Sha, 2004) and large general contractors in Japan (Reeves, 2002), who are predominant in the market and trend to bully the weak consciously or unconsciously. So we have the third assumption that the actors may adopt three strategies in their interactions: grabbing (G), sharing (S) and bourgeois (B). Grabbers, by definition, tend to claim the greater part of the surplus of the construction project. Sharers advocate equally distributing the surplus. While Bourgeois' strategy is: 'if occupant, play Grabber; if intruder, play Sharer.'

On the basis of these assumptions, we can develop a model to examine the evolutionary process of the construction business system. Consider a population of individuals who make a living by devoting themselves to construction projects. For clarity, we normalize both the size of the population and the surplus of the construction project to unity. Grabbers' offer is set as $z \in (1/2,\ 1)$. The payoff matrix of row players is shown in Table 1.

The following is a description of the payoff matrix. (1) When two Grabbers meet, the fact that the sum of both

Table 1 Grabber–Sharer–Bourgeois game (row player's payoffs)

	Grabbing (G)	Sharing (S)	Bourgeois (B)
Grabbing (G)	0	z	$z/2$
Sharing (S)	$1 - z$	1/2	$(3 - 2z)/4$
Bourgeois (B)	$(1 - z)/2$	$(1 + 2z)/4$	1/2

sides' offers exceeds the surplus implies that they cannot reach an agreement on a project, making the payoffs of both sides zero. (2) When a Grabber meets a Sharer, assuming that the latter can accept the former's offer, their payoffs are z and $1 - z$, respectively. (3) When two Sharers meet, they divide the surplus equally, each getting a payoff of 1/2. (4) When a Bourgeois meets a Grabber or a Sharer, suppose the members of the pair have an equal probability of being an occupant. For example, when a Bourgeois meets a Grabber, half of the time the Bourgeois is not the occupant and so acts like a Sharer, granting z to the opponent, while the other half of the time the Bourgeois, as occupant, acts like a Grabber, yielding a payoff of zero, as a result, the expected payoff is $(1 - z)/2$. (5) When two Bourgeois meet, it is always the case that one is the occupant and the other the intruder. With the probability that one-half of the time the first one is an occupant, playing Grabber, facing the second one who, as an intruder, plays Sharer, while the other half of the time the first one, as intruder, playing Sharer, facing the second one who, as an occupant, plays Grabber, yielding an expected payoff of 1/2.

Although the model is developed specially for the construction business system at first glance, it seems it is suitable for all types of companies. So it is necessary to say a few more words to explain its nature of construction industry-specific customization. The main difference between the construction industry and general industries lies in two aspects: one is the project-based property of the construction industry; the other is one-off project-oriented transactions in the construction market. These aspects were taken into consideration when 'getting-nothing-without-project assumption' and 'three-strategy assumption' were made. So it is valid that the three-strategy model developed here is a customized analysis tool for the evolutionary process of the construction business system.

Note that this model does draw inspiration from existing models, and from the Grabber–Sharer–Punisher game model in particular (Bowles, 2004, pp. 282–288), so the structure format of these models is more or less the same. However, our model is developed on the basis of substantially different assumptions, which make it distinct from the others. For example, in Bowles' model the prize to be divided is given *ex ante* regardless of the cooperation between the players; and the player with payoff 0 is weak (Sharer). By contrast, in our model the object to be divided is the surplus of a construction project which is cooperation dependent; and the player with payoff 0 is strong (Grabber). As shown below, the different payoff matrixes will inevitably bring out different equilibrium outcomes.

Let α, β and $\gamma = 1 - \alpha - \beta$ represent the population frequency of Grabbers, Sharers and Bourgeois, respectively; the simplex in Figure 2 can be used to illustrate the state space for distribution of strategies. Note that at any point in the simplex, D, the length of the line segment perpendicular to each edge indicates the frequency of the strategy indicated at the vertex opposite the edge. Since the simplex is a regular triangle with a height of 1, by comparing the simplex's area and the sum of areas of $\triangle$SDG, $\triangle$GDB and $\triangle$BDS, it is clear that the three line segments sum to 1. In addition, it is necessary to identify conversion relations between the simplex and rectangular coordinate system: $x = \gamma$ cot 60° + β csc 60° and $y = \gamma$, which gives facilities for subsequent arithmetic operations.

Let π^{G}, π^{S} and π^{B} be the expected payoff to being a Grabber, a Sharer and a Bourgeois, respectively. The expected payoff of a given strategy, e.g. π^{G}, is the weighted average of three payoffs on the corresponding row, e.g. the first row, in the payoff matrix presented in Table 1, with three frequencies, α, β and γ, acting as weight coefficients. Obviously, it is the function of population frequencies of the three strategies, α, β and γ.

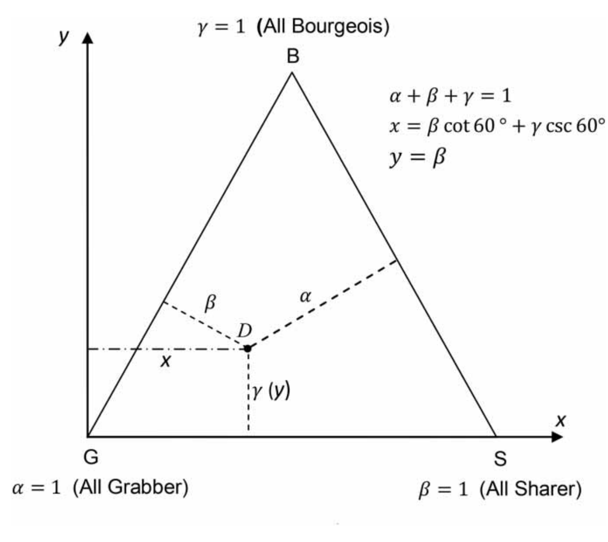

Figure 2 The state space for distribution of strategies: simplex vs. rectangular coordinate system

Given the payoff matrix and the population frequencies of the three strategies, α, β and γ, it is easy to calculate the expected payoffs to each strategy and the average payoff, as follows:

$$\pi^{\mathrm{G}} = z\beta + \frac{z}{2}\gamma \tag{2}$$

$$\pi^{\mathrm{S}} = (1-z)\alpha + \frac{1}{2}\beta + \frac{3-2z}{4}\gamma \tag{3}$$

$$\pi^{\mathrm{B}} = \frac{1-z}{2}\alpha + \frac{1+2z}{4}\beta + \frac{1}{2}\gamma \tag{4}$$

$$\begin{aligned}\bar{\pi} &= \alpha\pi^{\mathrm{G}} + \beta\pi^{\mathrm{S}} + \gamma\pi^{\mathrm{B}} \\ &= \alpha\beta + \frac{\alpha\gamma}{2} + \frac{\beta^2}{2} + \beta\gamma + \frac{\gamma^2}{2}\end{aligned} \tag{5}$$

In the following sections we will commence solving the Grabber–Sharer–Bourgeois model to find out the stable equilibrium points. The job can be divided into two steps. The first step is to draw the stationary loci corresponding to Grabber, Sharer and Bourgeois in the state space by examining the time rate of change of the three strategies, and then determine stationary points. The second step is to single out the stable equilibrium points from all stationary points by checking their response to a sufficient small disturbance.

Determining stationary points

The distributions of individual strategies in a population and their evolution over time depend on which strategies are copied and which are abandoned. As presented in the replicator dynamics equation, Equation 1, the process of copying is frequency dependent: strategies with above-average payoffs are adopted by others and thus increase their share of the population, and vice versa.

Since the replicator dynamics equation is derived from two-strategy games, it is natural to pose the question: is the equation applicable for a three-strategy problem? The answer is positive because the concern here is the change of the frequency of a given strategy rather than that of other strategies. Take the Grabber's frequency, α, for example. An increment in α, e.g. 0.3, implies a corresponding decrement in β and γ. However, it is unimportant for α whether β is reduced by 0.2 or 0.1, with γ reduced by 0.1 or 0.2 correspondingly—in either case, α is increased by 0.3. Therefore, by conceiving of a set of non-Grabber's frequency, $\bar{A} = \{\beta, \gamma\}$, we can transform the three-status problem into a two-status one, and use Equation 1 to determine the time rate of change of α: $\Delta\alpha = \alpha(\pi^{\mathrm{G}} - \bar{\pi})$. The same is true of β and γ. By the way, the discrete-time replicator dynamics equation, Equation 1, is applicable to the evolutionary games that have any number of strategies (Bowles, 2004, p. 73).

In the state space illustrated in Figure 2, the replicator equation provides a kind of mapping for every value of the strategy frequency. Take Grabber's frequency, α, for example. The mapping $\Delta\alpha = A(\alpha)$ where the function A, termed a vector field, defines for each point in the state space the direction and velocity of the change of Grabber's frequency, α, at the point. If $\Delta\alpha > 0$, the fraction of Grabbers is increasing and the vector arrow is pointing in the positive G direction, or rather pointing away from the edge opposite point G (All Grabber, $\alpha = 1$). To the contrary, if $\Delta\alpha < 0$, the fraction of Grabbers is decreasing, the vector arrow is pointing in the negative G direction, or rather pointing to the edge opposite point G. Turning now to the issue of stationary states in which we are really interested, if $\Delta\alpha = 0$, the fraction of Grabbers will remain constant as time elapses. Thus, we have the Grabbers' stationary state (also called rest point or critical point of the dynamic). All states satisfying this condition are points on the Grabber's stationary loci. The same is true of β and γ.

Now we can roughly imagine the configuration in the state space. First, we can determine that the three edges of the simplex, BS, BG and GS, are stationary loci corresponding to Grabber, Sharer and Bourgeois, respectively. For example, edge BS is a Grabber's stationary locus, because for all points on this edge we have $\alpha = 0$, and then $\Delta\alpha = \alpha(\pi^{\mathrm{G}} - \bar{\pi}) = 0$. Second, we can find out some stationary points. What has been discussed above is the stationary state for a given strategy. For a point in the state space, it is at the stationary state if and only if $\Delta\alpha = \Delta\beta = \Delta\gamma = 0$. The three vertices of the simplex, G, S and B, are stationary points since the stationary conditions for each strategy are simultaneously satisfied at these points. For example, at the vertex G where all members of the population are Grabber, we have $\alpha = 1$, $\beta = \gamma = 0$. According to the formula $\bar{\pi} = \alpha\pi^{\mathrm{G}} + \beta\pi^{\mathrm{S}} + \gamma\pi^{\mathrm{B}}$, we have $\bar{\pi} = \pi^{\mathrm{G}}$, and then $\Delta\alpha = \alpha(\pi^{\mathrm{G}} - \bar{\pi}) = 0$. From $\beta = 0$, we have $\Delta\beta = \beta(\pi^{\mathrm{S}} - \bar{\pi}) = 0$. In the same way, we have $\Delta\gamma = \gamma(\pi^{\mathrm{B}} - \bar{\pi}) = 0$. Furthermore, if there are other stationary points beside vertices G, S and B in the state space, they must be the intersection point of stationary loci of the three strategies. They, if existing, will be calculated in the next section.

According to the replicator dynamics equation, Equation 1, we set the change rates of the population frequencies with respect to time equal to zero to arrive at the stationary conditions for each strategy, α, β and γ:

$$\Delta\alpha = \alpha(\pi^{G} - \bar{\pi}) = \alpha\left(z\beta + \frac{z}{2}\gamma - \bar{\pi}\right) = 0$$

yielding

$$\alpha = 0 \tag{6}$$

and

$$z\beta + \frac{z}{2}\gamma - \bar{\pi} = 0 \tag{7}$$

$$\Delta\beta = \beta(\pi^{S} - \bar{\pi}) = \beta\left\{(1-z)\alpha + \frac{1}{2}\beta + \frac{3-2z}{4}\gamma - \bar{\pi}\right\} = 0$$

yielding

$$\beta = 0 \tag{8}$$

and

$$(1-z)\alpha + \frac{1}{2}\beta + \frac{3-2z}{4}\gamma - \bar{\pi} = 0 \tag{9}$$

$$\Delta\gamma = \gamma(\pi^{B} - \bar{\pi}) = \gamma\left\{\frac{1-z}{2}\alpha + \frac{1+2z}{4}\beta + \frac{1}{2}\gamma - \bar{\pi}\right\} = 0$$

yielding

$$\gamma = 0 \tag{10}$$

and

$$\frac{1-z}{2}\alpha + \frac{1+2z}{4}\beta + \frac{1}{2}\gamma - \bar{\pi} = 0 \tag{11}$$

As mentioned above, from Equations 6, 8 and 10, we have obtained three stationary loci, edge BS, BG and GS, corresponding to Grabber, Sharer and Bourgeois, respectively. The job now is to find out the other stationary loci determined by Equations 7, 9 and 11. Because of the complexity of calculation and plotting, we have recourse to MathCAD, a computer software programme that allows users to enter and manipulate mathematical equations, perform calculations and plot data. With MathCAD's user-friendly interface, we can enter equations and graph data as well as mathematic formulas without changing their format in the workspace. MathCAD is capable of generating several different types of plots (*x*–*y* plots, bar graphs, 3D plots and so on). According to formulas $x = \gamma \cot 60° + \beta \csc 60°$ and $y = \gamma$, the simplex-oriented problems described by Equations 7, 9 and 11 can be converted to those in rectangular coordinate system so that the '*x*–*y* plot' method can be applied to create the stationary loci. As illustrated in Figure 3 that is plotted by means of '*x*–*y* plot' type-specific *Graph* function of MathCAD, Equations 7, 9 and 11 depict stationary loci, marked by $\Delta\alpha = 0$, $\Delta\beta = 0$ and $\Delta\gamma = 0$, respectively. Note that on the two sides of a given stationary locus, the population frequency corresponding to this locus changes in opposite directions. For example, as illustrated in Figure 3(a), in regions I, II and IV that are on the left side of the stationary locos defined by $\Delta\alpha = 0$, the population frequency α is decreasing (the arrows are pointing to the edge

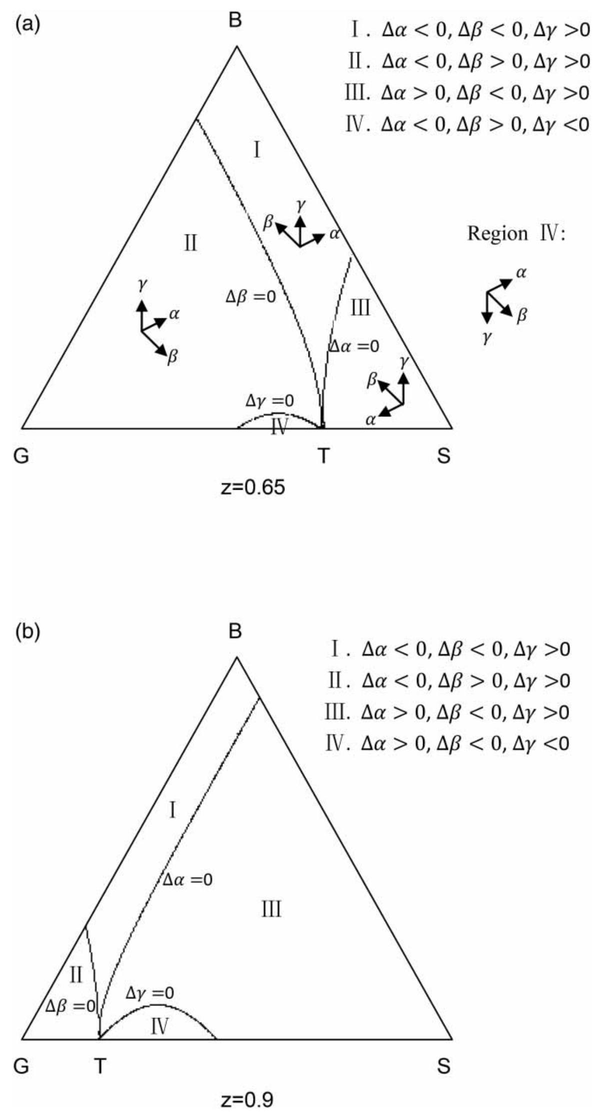

Figure 3 Replicator dynamics for the Grabber–Sharer–Bourgeois game

opposite to vertex G), while in region III that is on the right side of the stationary locus, α is increasing (the arrow is pointing away from this edge). Intuitively, the point T on the bottom edge of the simplex should be the fourth stationary point because it is the intersection point of stationary loci of the three strategies at which Equations 7, 9 and 11 are satisfied simultaneously. By using the *Find*(x, y) function of MathCAD to solve the simultaneous equations composed of Equations 7, 9, 11 and $\alpha+\beta+\gamma=1$, we can work out each frequency of the three strategies at point T: $\alpha=2z-1$, $\beta=2(1-z)$ and $\gamma=0$.

As a parameter of the model, the Grabber's offer, z, has a greater influence on the layout of stationary curves, and ultimately on the location of the stationary point T. By comparing Figure 3(a) where $z=0.65$ and Figure 3(b) where $z=0.9$, it is clear that a larger value of z makes the position of point T closer to point G.

Checking the stability of stationary points

In the above-mentioned two-strategy game (x vs. y), for strategy x with the population frequency of $p\in[0,1]$, the precondition of being asymptotic stability is that the inequality $\mathrm{d}\Delta p/\mathrm{d}p<0$ holds. This expresses the nature that stable equilibria must be characterized by negative feedbacks: increases in the frequency of x's reducing the relative advantage of the x's. In other words, a chance increase in p will benefit y's more than x's and thereby displace p close to the stationary point, $p*$. As regards the strategy G, S and B, in the same way, we have the following criteria for stability:

$$\frac{\mathrm{d}\Delta\alpha}{\mathrm{d}\alpha}=\pi^{\mathrm{G}}-\bar{\pi}-\alpha\left(\beta+\frac{\gamma}{2}\right)<0$$

$$\frac{\mathrm{d}\Delta\beta}{\mathrm{d}\beta}=\pi^{\mathrm{S}}-\bar{\pi}+\beta\left(\frac{1}{2}-\alpha-\beta-\gamma\right)<0$$

$$\frac{\mathrm{d}\Delta\gamma}{\mathrm{d}\gamma}=\pi^{\mathrm{B}}-\bar{\pi}+\gamma\left(\frac{1}{2}-\frac{\alpha}{2}-\beta-\gamma\right)<0$$

According to these criteria, together with Equations 2–5, we can check the stability of the four stationary points determined in the last section, G, S, B and T. For example, at point B where $\gamma=1$, $\alpha=\beta=0$, we have

$$\frac{\mathrm{d}\Delta\alpha}{\mathrm{d}\alpha}=\pi^{\mathrm{G}}-\bar{\pi}=\frac{z}{2}-\frac{1}{2}<0$$

$$\frac{\mathrm{d}\Delta\beta}{\mathrm{d}\beta}=\pi^{\mathrm{S}}-\bar{\pi}=\frac{1-2z}{4}<0$$

and

$$\frac{\mathrm{d}\Delta\gamma}{\mathrm{d}\gamma}=\pi^{\mathrm{B}}-\bar{\pi}-\frac{1}{2}=-\frac{1}{2}<0$$

Thus it can be concluded that point B is in asymptotic stability.

While at point T where $\alpha=2z-1$, $\beta=2(1-z)$ and $\gamma=0$, we have

$$\frac{\mathrm{d}\Delta\alpha}{\mathrm{d}\alpha}=\pi^{\mathrm{G}}-\bar{\pi}-\alpha\beta=-\alpha\beta<0$$

$$\frac{\mathrm{d}\Delta\beta}{\mathrm{d}\beta}=\pi^{\mathrm{S}}-\bar{\pi}+\beta\left(\frac{1}{2}-\alpha-\beta\right)=-\frac{1}{2}\beta<0$$

and

$$\frac{\mathrm{d}\Delta\gamma}{\mathrm{d}\gamma}=\pi^{\mathrm{B}}-\bar{\pi}=0$$

So it is clear that point T is in asymptotic stability for the strategies of Grabbers and Sharers, and in neutral stability for Bourgeois' strategy. In the same way, it can be determined that point G and S are in a static but not stable state.

Discussion

It is neither rational nor practical to bank on so simple a model developed here to fully explain so complicated a problem like institutional changes. Nevertheless, this model can provide us with some insight about the way in which a construction business system emerges, develops and withers away.

First, the coexistence of two stable points, B and T, indicates that the evolution of the construction business system has the property of multiple equilibria. This can explain the reason for institutional diversity, since (1) binary is the simplest way to present the concept of 'many', so, the step from one to two does not simply imply one unit increase in number but rather the substantial change from 'few' to 'many' and (2) as mentioned above, the location of the stationary point T is variable with the change of the Grabber's offer, z, so it is prospected that there will be different stationary points on the bottom edge of the simplex in different scenarios. At point B, all individuals adopt strategy B; and the payoff of strategy profile (B, B) is equal to that of strategy profile (S, S) at point S. If equilibrium S represents the scenario of free market competition, equilibrium B may be thought of as a quasi-free competition condition. As shown in Figure 4, both the equilibria have the same average payoff, $\bar{\pi}$, that reaches the maximum value of 0.5. So we may say that strategy profile (B, B) is a conditional (if occupant, play Grabber; if intruder, play Sharer) sharing. Equilibrium B is 'welcome' since its average payoff reaches the highest level. It is Pareto optimal since there is no possibility of making Pareto improvement (a change to a different allocation that makes at least one individual better off without making any other individual worse off, given an initial allocation of goods among a set of individuals). In contrast, equilibrium T is a portrayal of market failure, characterized by inefficient negotiation and a lower level of average payoff. As illustrated in Figure 4, at point T, we have lower average payoff $\bar{\pi} = 2z(1 - z) < 0.5$. Equilibrium T is 'unwanted' since its average payoff does not reach the highest level. It is Pareto inferior since there exists the possibility for Pareto improvement.

Second, the model can be used to reveal the reason why the system's evolution is path-dependent and original-state-sensitive. Given that there are more than one stable point, which of these equilibria would we expect to obtain? In the absence of non-best response play (opposite to best response play, or the idiosyncratic play that represents actions whose reasons are not explicitly modelled, and is often deliberate rather than accidental action by members of a group disadvantaged under the status quo equilibrium (Bowles, 2004, p. 371)), the answer can only be that the outcome depends on initial conditions. As illustrated in Figure 3, the vectors indicate the direction of movement for a population composed by frequencies given by the point at the base of the arrows; and the unperturbed dynamical system will move either towards point B or point T, depending on the original state of the system. For example, if the original state is on the bottom edge of the simplex, then we can predict that the equilibrium outcome is point T. In contrast, if the original state is on the right or left edge, the system can be expected to reach equilibrium at point B.

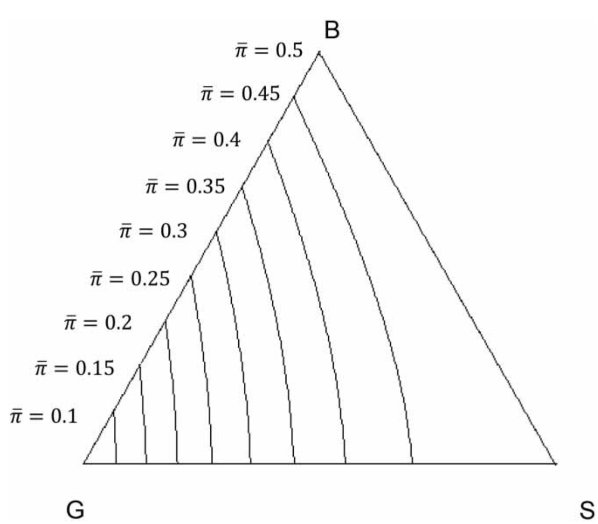

Figure 4 Average payoff contours of the Grabber–Sharer–Bourgeois game

Third, the model can be used to predict where the system is more likely to reach a stable equilibrium. Simulations using the 'relative payoff sum' learning rule (Maynard Smith, 1982, pp. 60–67) and agent-based simulations (Bowles, 2004, pp. 392–399) can give insight into evolutionary processes that are so complicated that mathematical models cannot yield illuminating analytical solutions. However, it seems to us that theoretical analysis can yet be regarded as a simple but effective approach. For the following two reasons, it can be intuitively expected that the system is much more likely to reach the stable equilibrium at point B than at point T. (1) As illustrated in Figure 3(a), in region I, II and III, the population frequency γ is increasing (the arrows corresponding to γ are pointing away from the edge opposite to vertex B), while in region IV, γ is decreasing (the arrow corresponding to γ is pointing to this edge). Since the area of region IV is much smaller than the sum of areas of regions I, II and III, it can be expected that there is much less probability of the system reaching stable equilibrium on this edge where point T is located. (2) As mentioned above, point T is in asymptotic stability for strategy G and S, and in neutral stability for strategy B, while point B is in asymptotic stability for all three strategies. This implies that the stability of equilibrium B is stronger than that of equilibrium T. This argument could be verified by empirical cases. For example, investigations have revealed that the 50–50 sharecropping is a widely accepted institutional arrangement, irrespective of whether the country is developed (US) or underdeveloped (West Bengal) (Bowles, 2004, p. 94). In fact, the longstanding terms for sharecropping in different languages, such as *mezzadria* (in Italian), *metayage* (in French) and *ardhika* (in ancient Sanskrit), all have the same meaning, one-half, as if by prior agreement (Bowles, 2004, p. 200). Furthermore, it could be confirmed, to a certain extent, by the market-oriented reform of China's building sector that the construction business system is more likely to reach a stable equilibrium where market values are admired.

Finally, stable equilibria, whether they are 'welcome' or not, once formed, are bound to be difficult to change in the absence of 'revolutionary' events. That is why some Pareto-inferior systems, however they are unwanted, may persist over a long period of time. Take equilibrium T for example, as mentioned above, point T is in asymptotic stability for strategy G and S, and in neutral stability for strategy B. This implies that for strategy G and S, all sufficiently small perturbations will not displace the population frequency away from the original state; and for strategy B, all sufficiently small perturbations will make it move but not result in further movement away from its original position. So it is expected that equilibrium T will maintain stable unless the payoff matrix is changed, even if there exists the possibility for Pareto improvement.

In order to break the existing equilibria, it is essential to change the payoff matrix by incorporating some 'revolutionary' events into the model. There are two kinds of 'revolutionary' events: one is the above-mentioned non-best response, and the other is the change or subversion of the cultural and social foundations that underpin the system. As regards the first situation, the emergence within a system of a lot of individuals who act in ways that violate the existing rules will initiate a revolution. The second situation relates to exogenous changes that can be attributed either to competition among groups governed by different institutions, e.g. capitalist vs. socialist system, or to advances in technology such as Watt's steam engine, electrification and automation which are the impetus for the first and the second industrial revolution (Bowles, 2004, p. 400). Including 'revolutionary' events into the model implies the change of the payoff matrix, which would break the existing equilibrium and bring about new equilibrium outcomes.

This model can also be used to explain the origin of the construction business system that emerged in the early nineteenth century in the UK. As mentioned above, emergence implies the arising of novel and coherent structures, patterns and properties. One of the origins of the radically novel order seen in emergent phenomena is the manner in which far-from-equilibrium conditions allow for the amplification of random events Goldstein, 1999). The Grabber–Sharer–Bourgeois model is developed on the basis that there has existed construction-project-oriented relationships in the construction market, characterized by

> insulation of activities facing the highest uncertainty in the design stages from market forces altogether through the development of the professionally organized consultant architect or engineer reimbursed on a fee basis, and the evolution of control actors responsible for regulating those activities that remained subject to market forces—principally construction—on behalf of the client and the wider community. (Winch, 2000b, p. 142)

From the perspective of the Grabber–Sharer–Bourgeois game, the construction business system emerges because a stable equilibrium condition is reached; the system evolves because a stable equilibrium condition is replaced by another one.

Conclusion

As the institutional environment of construction projects, the construction business system has a great influence on the practice of project governance and project management, and ultimately on the performance of the building sector. The system, in turn, is also shaped by activities at the project governance level, and deeply affected by its social and cultural foundations.

Some factors, including the project dependence of the construction industry, one-off project-oriented transactions and imbalanced demand−supply relationships in the construction market, make the construction business system different from the rest. By conceptualizing the system as a complex adaptive one, a three-level evolutionary game model is developed on the basis of a set of assumptions, with the distinctiveness of the construction industry fully taken into consideration. The model illustrates some characteristic outcomes: multiple equilibria, path dependence, original-state-sensitiveness, the long-term persistence of Pareto-inferior outcomes as well as proneness to the stable equilibrium characterized by more efficient negotiation and higher average payoff. They are fairly consistent with what happened in the progress of construction business systems around the world, the above-proposed assumptions thus being checked. As discussed above, the model could not only describe the way in which the system evolutes over time, but also explain the questions proposed in the introduction section.

No doubt the Grabber–Sharer–Bourgeois game model could not explain all the minor details, but it is really capable of providing some clues for studying the historical dynamics of the construction business system. It can be seen that each system has its own reason for existence, with the original endowment playing a decisive role; and that there is no optimal system but the most suitable one, so the practice of copying a 'good' system mechanically and applying it slavishly, just like cutting the feet to fit the shoes, is invalid. Once stable equilibrium is reached, whether favourable or not, it could sustain for a considerably long duration of time like 10–100 years. That is why it is often difficult for some well-designed plans to destabilize an existing system. From a holistic and long-term perspective, however, change is absolute. A prevailing stable equilibrium will be broken sooner and later, with 'revolutionary' events acting as an impetus, and replaced by a new one. Further research is required to explore the influence of 'revolutionary' events on the historical dynamics of the construction business system systematically, which implies developing a new model.

We are trying to understand the historical dynamics of construction business systems by an evolutionary game model. This model may be unrealistically simple in many aspects, but it is this simplicity that may make the fundamental issues of the evolutionary process easier to see in this model than in the vastly more complicated situations of real life. To a great extent, the power of economic models just lies in their abstraction from the reality. For example, the PD model, a simplest two-person game model, does challenge the fundamental proposition of welfare economics (individual utility-maximizing behaviour will definitely lead to socially optimal outcomes) by revealing the fact that individual rationality may lead collective non-rationality. Similarly, regardless of its simplicity, the Grabber–Sharer–Bourgeois game model may shed light on the basic characteristics of the historical dynamics of construction business systems.

However, in order to learn more about the evolutionary process of the construction business system, it is helpful to take some elements, such as the conformist cultural transmission and between-group as well as within-group selection processes, into consideration. When these elements are involved, the complexity of the model will be so exacerbated that mathematical models could not yield analytical solutions. In such a case, we should have recourse to agent-based simulation that can give insights into the evolutionary process in a lifelike way.

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