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Evolutionary Gaming Analysis of Path Dependence in Green Construction Technology Change

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ABSTRACT

In the context of instigating green construction technology by changing current technology practices, evolutionary game theory is used to solve path dependence problems that yield stable equilibrium. Replicating dynamic gaming shows that in inducing technological change some problems concerning multiple equilibrium definitely exist and that profit is the prime motivation to use or supply new technology. The model also shows that a lock-in of a current technology can be broken as a consequence of players' studies.

Keywords: Green Construction Technology; Path Dependent; Evolutionary Game

1. Introduction

1.1. Green Construction Technology

Construction is a process of building in which materials are transformed into products, such as buildings, airports and highways, which unfortunately by its nature leads inevitably to some level of environmental pollution, extravagant energy consumption and resource depletion. The process is outlined in **Figure 1**. Because construction is a necessary activity, the question arises as to how to minimize its detrimental effects; green construction technology (GCT) incorporates the right choices to achieve this goal. GCT refers to a kind of sustainable development technology enabling consumption of less resource, less energy and to bring lighter environmental pollution during the entire construction cycle [1]. Despite its green credentials, GCT promotion has not however been satisfactory. It has been rejected by many builders simply because giving up old technologies is not to their liking, perhaps due to the expense, inconvenience or disruption to business. In this paper, the problem confronting construction builders given their technology options is investigated using evolutionary game theory to analyze the path dependence to stable equilibrium.

1.2. Brief View of Path Dependence Research

Research using path dependence analysis covers a rich variety of fields. In 1975, Paul A. David of Stanford University developed the concept of path dependence within the context of technological change [2]. David, along with colleague W. Brian Arthur [3-6], systematized this idea of path dependence, establishing it as one of the more valuable theories finding a rapid development within modern economics. They considered that technological change was a system which was influenced by a "positive feedback mechanism", and that change has several characteristics, which are itemized as follows: 1) Multiple equilibrium—that is to say, the result of a developing system is not singular but has more than one outcome; 2) Close-down—this refers to one technology which, once adopted, employs income-increasing mechanisms preventing it from being displaced by other technologies; 3) Non-efficient possibility—those locked-in technologies having a strangle-hold within the market are no longer the best choices; and 4) Path dependence—the path of an evolutionary system is dependent on the system's original state and trajectory. Leibowitz and Margolis (1990,1994) [7,8] thought that there were two methods which can break this path dependence: either by predicting the results from the different choices present or by provided more communication on options before choices are made. Unless the subject of economics is unwilling to change, path dependence is inevitable.

2. The Asymmetric Replication Dynamic Game Model of Technological Change on GCT

Evolutionary gaming is based on several hypotheses summarized as follows: 1) Players who adopted higher revenue strategies will repeat their strategy more readily, and therefore in the long run, the fraction of players who adopt lower revenue strategies will decrease; 2) Players

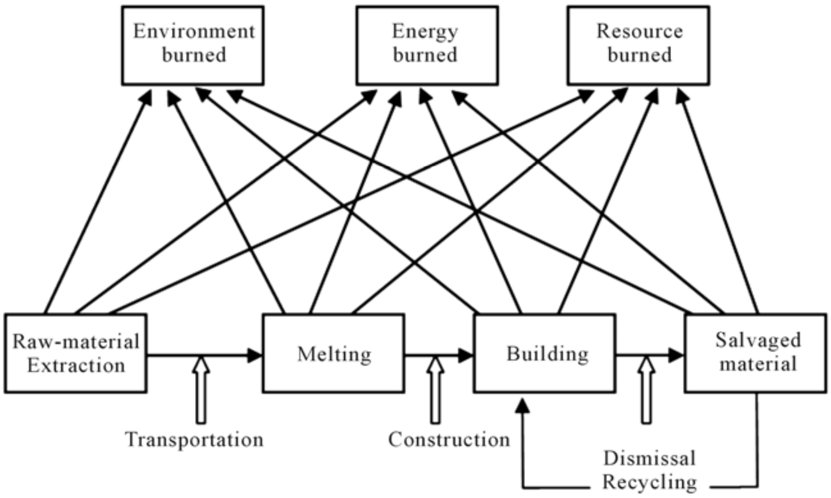

Figure 1. The impact of construction on environment, resources and energy.

may usually imitate other players' behaviors, and positive correlations may ensue between their revenues and their imitative tendencies; and 3) When one player changes strategy, they always treat the present situation as a known condition, and then change to a kind of corresponding best strategy.

Given the above hypotheses, an asymmetric replication dynamic game model is considered to analyze the process of instigating change to GCT. Assuming there are two groups of players: one group comprising the GCT (GCTs, for instance manufacturers, which we here denote by F (we do not know *a priori* whether the technology used is GCT or not); the other group comprising the technology users, for instance consumers which we here denote by C. We assume two techniques can be chosen in the market. The strategies of GCTs are SF = $\{S_1, S_2\}$, where S_1, and S_2 mean those GCTs choosing technique 1 and technique 2, respectively. The strategy space of the technology users is SC = $\{S_1, S_2\}$, where the S_i denote the same as above. For this situation we can form a matrix game by establishing pay-offs between random pairings of GCTs and users (see **Figure 2**).

Here we let A, C denote profits to be gained when suppliers choose technique 1 while E, G denote the same when technique 2 is chosen. The benefits to users are denoted as B, D, F and H as above. In addition, we assume technique 2 can gain more profit than technique 1, that is to say, $A < B$, $C < D$.

At the start of the Game, the fraction of suppliers adopting technique 1 is p while the difference $1 - p$ represents those adopting technique 2. Similarly, the fraction of technology users adopting technique 1 is q, while $1 - q$ corresponds to those adopting technique 2. Let u_{f1} be the expected revenue when the GCTS choose technique 1 and u_{f2} the expected revenue of those choosing technique 2. The average revenue is denoted by $\bar{u}_f$.

		User	
		S_1	S_2
GCTs	S_1	***A, B***	***C, D***
	S_2	***E, F***	***G, H***

Figure 2. Pay-off matrix of user-supplier.

We then have the following set of consistency relations:

$$u_{f1} = q^* A + (1-q)^* C \tag{1}$$

$$u_{f2} = q^* E + (1-q)^* G \tag{2}$$

$$\begin{aligned} \bar{u}_f &= p^* u_{f1} + (1-p)^* u_{f2} \\ &= (A+E)pq + (C+G)(1-p)(1-q) \end{aligned} \tag{3}$$

Similarly, revenues for the technology users satisfy a set of like relations:

$$u_{c1} = p^* B + (1-p)^* D$$

$$u_{c2} = p^* F + (1-p)^* H$$

$$\begin{aligned} \bar{u}_c &= q^* u_{c1} + (1-q)^* u_{c2} \\ &= (B+F)pq + (D+H)(1-p)(1-q) \end{aligned}$$

From evolutionary gaming theory, we can develop the replicated dynamic equation for both groups associated with the two positions. This leads to the GCTS' replicated dynamic equation:

$$\begin{aligned} \frac{\mathrm{d}p}{\mathrm{d}t} &= p\left(u_{f1} - u_{f2}\right) \\ &= p(1-p)\left[(A-E)q - (G-C)(1-q)\right] = F(y) \end{aligned} \tag{4}$$

If $q = B/(A+B)$, then $\mathrm{d}p/\mathrm{d}t$ will always be 0, that is to say, all the p are stable. If $q > B/(A+B)$, then

$q^* = 0$ and $p^* = 1$ are two stable states of p, for which $p = 1$ is an evolutionary stable strategy. If $q < B/(A+B)$, then $p^* = 0$ and $p^* = 1$ are still the two stable states of p, but for which $p^* = 0$ now becomes the evolutionary stable strategy.

Likewise, the replicated dynamic equation of the technology users group is:

$$\frac{\mathrm{d}q}{\mathrm{d}t} = q(u_{c1} - u_c) = q(1-q)\left[(C+D)p - D\right] \quad (5)$$

If $p = D/(C+D)$, then $\mathrm{d}p/\mathrm{d}t = 0$; that is to say, all values of p are stable. If $p > p = D/(C+D)$, then $q^* = 0$ and $q^* = 1$ are two stable states of q, with $q = 1$ being the evolutionary stable strategy. If $p < p = D/(C+D)$, then $q^* = 0$ and $q^* = 1$ are again two stable states of p, with $q^* = 0$ the evolutionary stable strategy. The proportional change and replicator dynamics are shown in **Figure 3**.

From **Figure 3**, we find that this game will converge to points (0, 0) and (1, 1). These two points correspond to two equilibrium points: respectively, one is $p^* = 0$ and $q^* = 0$, the other $p^* = 1$ and $q^* = 1$. In **Figure 3**, the graph is divided into four regions by lines L_1 and L_2. The analysis is as follows: 1) When the initial state falls within the left inferior region, that is to say, the fraction of GCTs less than $D/(C+D)$ and the fraction of technology users less than $B/(A+B)$ that have changed choice to technique 1. In this situation the Game will eventually converge to the evolutionary stable strategy $p^* = 0$ and $q^* = 0$, and technique 1 will eventually not be totally adopted; 2) When the initial state falls within the right superior region, the fraction of GCTs is greater than $D/(C+D)$ and the fraction of technology users is greater than $B/(A+B)$, and both groups begin to choose technique 1. As a consequence the Game will eventually converge to the evolutionary stable strategy $p^* = 1$ and $q^* = 1$, and technique 1 will eventually be adopted in total; 3) When the initial state falls within either the left superior region or the right inferior region, the Game will converge to point (0, 0) or (1, 1). The final equilibrium state is dependent on the speed that the groups learn and adjust. When the state falls within the left superior region and the evolution dynamics passes through line L_1 arriving at the right superior region first, the final equilibrium will be $p^* = 0$ and $q^* = 0$; in contradistinction, if the evolution dynamics passes through line L_1 and arrives at the left inferior region first, the final equilibrium will be $p^* = 1$ and $q^* = 1$; in regard to the right inferior and left superior regions, the evolution dynamics are just mirror opposites.

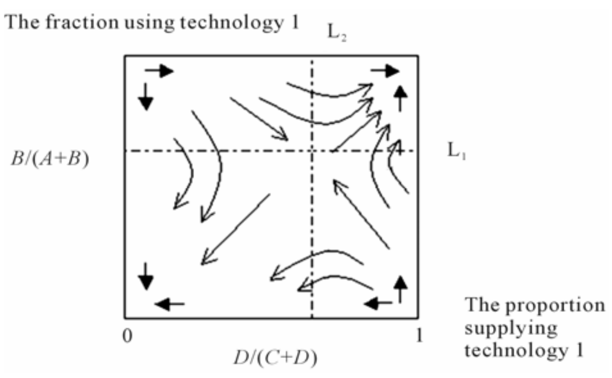

Figure 3. The connection between proportional change and replicator dynamics of the two types of groups.

By the above model analysis, we can see clearly that different initial states will lead to different equilibrium. At the initial stage, the probability bias in adopting one of several techniques compels the process of technological change or locks the process of GCT changes towards an equilibrium point of game. Evolution has several potential outcomes based on multiple equilibriums.

3. Game Analyses on Breaking Technology Lock-In

Although the asymmetric replication dynamic game model above explains the reason of multiple equilibrium and tells us why subdominant option technology can be used during technological changes, however, the model needs to be modified to pay more attention to several real world issues which we now present.

3.1. The Situation of New Players Joining

When a new player adopting technique 2 is added to the original technology users group, the total population will increase. The addition may make the proportion adopting technique 2 exceed $B/(A+B)$, which in turn makes the group that had adopted technique 1 opt for technique 2. Likewise, when a new exotic player opting for technique 2 is added to the original technology supplier group, and the fraction adopting technique 2 now exceeds $D/(C+D)$, the technology suppliers group that had adopted technique 1 will also convert to technique 2 with similar consequences.

3.2. The Result on Technology Compatibility

If some compatibility between techniques 1 and 2 exists, the revenues for both GCTs and technology users will no longer be zero when they both choose technique 2. We need to modify the pay-off matrix in **Figure 1** to that shown in **Figure 4**. Here both U_{I} and U_{II} are less than A, and both U_{III} and U_{IV} are less than C. We had supposed $A < B$ and $C < D$ previously, so we can conclude that $U_{\mathrm{I}} < A < B$, $U_{\mathrm{II}} < A < B$, $U_{\mathrm{III}} < C < D$ and $U_{\mathrm{IV}} < C < D$.

Here, the expected revenues when the GCTs choose either technique 1 or technique 2 are u_{f1} and u_{f2} respectively. The average revenue is denoted as $\bar{u}_f$. The consistency relations become:

		User	
		S_1	S_2
Supplier	S_1	***A*, *B***	**U_I, U_{III}**
	S_2	**U_{II}, U_{IV}**	***G*, *H***

Figure 4. Pay-off matrix of user-supplier.

$$u_{f1} = q^* A + (1-q)^* U_{\mathrm{I}} = Aq + (1-q)U_{\mathrm{I}}$$

$$u_{f2} = q^* U_{\mathrm{II}} + (1-q)^* B = qU_{\mathrm{II}} + B(1-q)$$

$$\begin{aligned} u_f &= p^* u_{f1} + (1-p)^* u_{f2} \\ &= Apq + p(1-q)U_{\mathrm{I}} + (1-p)\left[qU_{\mathrm{II}} + B(1-q)\right] \end{aligned}$$

The replicated dynamic equation of the GCTS group is:

$$\begin{aligned} \frac{\mathrm{d}p}{\mathrm{d}t} &= p\left(u_{f1} - \bar{u}_f\right) \\ &= p(1-p)\left[\left(A+B-U_{\mathrm{I}}-U_{\mathrm{II}}\right)q + U_{\mathrm{I}} - B\right]. \end{aligned}$$

The horizontal boundary line L_1 is fixed by its q-value (seeing as **Figure 3**):

$$\begin{aligned} q &= \left(B-U_{\mathrm{I}}\right) \big/ \left[\left(A-U_{\mathrm{II}}\right)+\left(B-U_{\mathrm{I}}\right)\right] \\ &= 1-\left(A-U_{\mathrm{II}}\right) \big/ \left[\left(A-U_{\mathrm{II}}\right)+\left(B-U_{\mathrm{I}}\right)\right] \end{aligned}$$

The technology users' expected revenues are respectively:

$$u_{c1} = p^* C + (1-p)^* U_{\mathrm{IV}} = Cp + (1-p)U_{\mathrm{IV}}$$

$$u_{c2} = p^* U_{\mathrm{III}} + (1-q)^* Dd = pU_{\mathrm{III}} + D(1-p)$$

$$\begin{aligned} \overline{U}_f &= q^* u_{c1} + (1-q)^* u_{c2} \\ &= Cpq + q(1-p)U_{\mathrm{IV}} + (1-q)\left[pU_{\mathrm{III}} + D(1-p)\right] \end{aligned}$$

The replicated dynamic equation of technology users group is:

$$\begin{aligned} \frac{\mathrm{d}q}{\mathrm{d}t} &= q\left(u_{c1} - \bar{u}_c\right) \\ &= q(1-q)\left[\left(C+D-U_{\mathrm{III}}-U_{\mathrm{IV}}\right)p + U_{\mathrm{IV}} - D\right], \end{aligned}$$

While the vertical boundary line L_2 is determined by the p-value (seeing as **Figure 3**):

$$\begin{aligned} p &= \left(D-U_{\mathrm{IV}}\right) \big/ \left[\left(C-U_{\mathrm{III}}\right)+\left(D-U_{\mathrm{IV}}\right)\right] \\ &= 1-\left(C-U_{\mathrm{III}}\right) \big/ \left[\left(C-U_{\mathrm{III}}\right)+\left(D-U_{\mathrm{IV}}\right)\right]. \end{aligned}$$

Clearly the more incompatible techniques 1 and 2 are, the closer the GCTs' profit U_{II} is to A when suppliers choose technique 2, and the closer the technology users' profit U_{III} is to C when technique 2 is chosen.

3.3. The Breaking Mechanism

In a real world environment, every player will be gaming with neighbors or with a correlative group. We build a local interactive game model to examine this behavior (as indicated in **Figure 5**). This model represents an application of iterative game theory and the evolution strategies of a few rational players. In this model, we suppose there are five players, and in every period players will game with neighbors or with a correlative group. This can be represented graphically by placing identifying marks say numbered stars, one for each player (see **Figure 5**) on a circle with each player gaming repeatedly only with their neighbors.

Because players are assumed to be "bounded rational", each player in the first game will either adopt technique 1 or 2. Assume at time t, players' strategies are (T_1, T_1, T_1, T_1, T_2). That is to say, players 1 through 4 will choose technique 1 while player 5 will choose technique 2. All single players will adjust their strategy simply, and this decision is based on the strategy distribution which is given by the players' neighbors. If both neighbors choose technique T_1 (or T_2), it is to the advantage of player i to follow suit in the next period. If the neighbors' strategy distribution is (1/2, 1/2) from the previous period, player i will choose T_2 in the next period because the average revenue of T_1 is $A/2$, which is lower than the T_2 average revenue of $B/2$. Obviously, in period (t + 1), the players' strategy distribution from period t becomes (T_2, T_1, T_1, T_2, T_1). Similarly, we learn that the players' strategy distribution becomes (T_1, T_2, T_2, T_1, T_2) in period (t + 2), and (T_1, T_2, T_2, T_1, T_2) in periods (t + 3) and (t + 4). This shows that although almost all players have chosen a non-superior technology at period t, a better technology will finally obtain advantaged status among all players interacting with each other via nearest neighbors (as indicated in **Figure 6**).

Combinatorially, we see in **Figure 5** that players have two options of either T_1 or T_2, so there are $2^5 = 32$ configurations possible in total for the first Game. It is easy to prove that if, in **Figure 5**, there is at least player choosing technique 2, the Game evolves to the final state where all players will ultimately have chosen technique 2. When the initial game distribution is (T_1, T_1, T_1, T_1, T_1), this situation is not always stable. Once one player has chosen another technique and in a sense betrayed the others in seeking more profit, players will within a finite

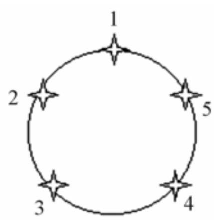

Figure 5. The game of player with neighbors or with correlative group.

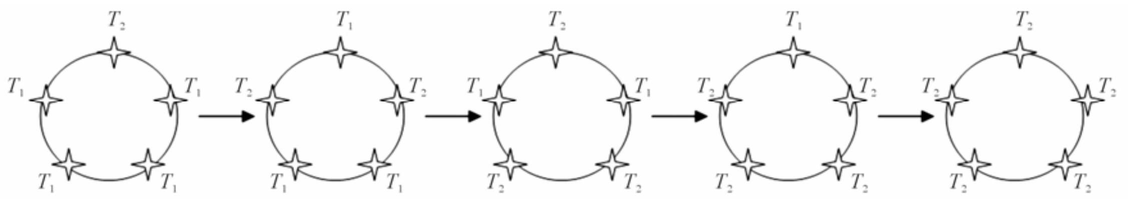

Figure 6. GCT strategic distributions.

period draw closer to the state (T_2, T_2, T_2, T_2, T_2) employing the better technology. According to this theoretical analysis, all non-superior technologies will ultimately be replaced by the more efficient technologies.

4. Conclusions

1) The model presented shows that, in instigating a process of technological change, several problems in regarding to multiple equilibriums definitely exist. In competition, the final result of the dynamic evolution is that one of several techniques either occupied the market totally or has no market share. Which of the techniques will dominate is however hard to predict as the results of the Game are affected directly by its initial states. This model has though explained the path dependence in instigating technological change.

2) On questions of whether lock-in of subdominant optional technology can be broken, three principle situations have been discussed: the addition of new players, technology compatibility and several learning players. All of these situations indicated that the close-down state of subdominant optional technology is unstable under certain environments, and that more efficient techniques will eventually replace subdominant option technology.

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