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Analysis on the Selection of Technological Innovation Mode in Enterprises under Government Subsidy Mechanism Based on Evolutionary Game Theory

Yuanyuan Li*, Yuchen Chai
School of Business Administration, Shanxi University of Finance and Economics, Taiyuan, Shanxi, China
*Corresponding Author: Yuanyuan Li

Abstract:

Under the conditions of information asymmetry and limited rationality, with the help of the theory of evolutionary economics, an evolutionary game-based mode for selection of innovation pattern in enterprises under government subsidy mechanism is constructed to study the problem of selecting innovation pattern in enterprises under the influence of government policy, and the evolutionary equilibrium strategy of the mode when different parameters change is simulated with MATLAB software. The results indicate that government subsidy, open innovation cost and open innovation revenue are the relational factors affecting the evolutionary game system among enterprises. Therefore, increasing government subsidies for open innovation modes, reducing subsidies for closed innovation, lowering the cost of open innovation and increasing the benefits of open innovation can help guide enterprises to evolve towards open innovation modes.

Keywords: *Government subsidies, Technological innovation mode, Evolutionary game.*

I. INTRODUCTION

Due to the acceleration of global economic integration, the international market competition pattern has changed a lot, which makes the advantage of low-cost cannot meet the needs of new development, so it is imperative to shift from low-cost advantage to innovative advantage. As a result, the competition focus of enterprises as the main body of technological innovation has changed from low cost to knowledge-based technology competition, which means that enterprises will integrate internal and external innovation resources, formulate innovation incentive policies, organize and implement technological innovation activities, undertake innovation risks to obtain innovation benefits. Practice has shown that successful technological innovation can bring excess profits and significant competitive advantages to enterprises, and

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the failure of technological innovation not only causes a waste of enterprise resources, but also brings survival crisis to enterprises. However, technological innovation mode is not universal. Different innovation modes reflect the different risk preference, expected investment amount and intrinsic motivation of enterprises [1]. Thus, it is clear the selection of technological innovation mode is a key factor in determining the success of technological innovation activities and an important strategic decision of enterprises. Consequently, it has important theoretical value and practical significance to enhance the innovation ability of enterprises, accelerate the implementation of the national innovation-driven strategy, and develop the entire industrial chain to a mid-to-high level.

According to different innovative connotations, most domestic and foreign scholars classify innovation modes as imitative, independent and cooperative. The rise of knowledge economy and the increase of technology complexity have brought new changes to the innovation concept. In essence, the mode of technological innovation has changed to enhance the technological innovation ability of enterprises through the effective allocation and integration of many innovative resource elements inside and outside the enterprise [2].

Closed innovation is a closed, highly centralized mode with high costs and inefficiencies. Open innovation emphasizes the use of both commercialized resources within the Enterprise and innovative resources outside the enterprise from the perspective of resources [3], mainly manifested by the blurred boundaries of the enterprise. Innovative ideas can come from both inside and outside the enterprise, so as to realize complementary advantages, reduce the risk of technological innovation and accelerate the pace of innovation through effective integration of internal and external knowledge. Today, open innovation has become a hot topic in the field of innovation. With the improvement of technology development, it is difficult for closed innovation to meet the technical and financial requirements required in the process of innovation. In order to compete for the leading technology position, enterprises need to cooperate with universities, research institutes and enterprises with technical advantages. Therefore, the open innovation mode is the direction of the development of Chinese enterprises. However, at present, the main mode of technological innovation in China is closed innovation, only focusing on the use of its own existing resources, and limited use of external resources, which is manifested in the disassociation of consumers from the product innovation, imposed responsibility of technological innovation on the R&D departments, unhooked relationship between R&D projects of universities or scientific research institution and enterprises, the lack of awareness of cooperative innovation, risk sharing and benefit sharing among companies in the supply chain, leading to the difficulty of improving the overall technical level of Chinese enterprises. Therefore, as the main part of technological innovation, how to rationally use internal and external resources for innovation is particularly important.

Although innovation management theory has become a hot topic of academic research, there are few literatures on the choice of technological innovation mode, and scholars consider more from a single aspect [4]. Aylen qualitatively analyzed the influence of selection of technological innovation mode guided by different competitive strategies on the development of GISE continuous rolling mill in the United States. Herzog studied the influence of selection of technological innovation mode on enterprise development from the perspective of innovation culture [5]. Chinese scholars have also made a lot of valuable theoretical research. Li Ming and others discussed the internal mechanism of enterprises with different strengths in choosing technological innovation mode by establishing game model and profit function of independent and imitative innovation, pointing out that the selection of innovation mode is a dynamic process [6]. Wan Junkang and others discussed the selection mechanism of technological innovation mode in enterprises by establishing game model and put forward suggestions to promote technology innovation of Chinese science and technology enterprises [7]. Although existing research has provided important theoretical basis for the choice of enterprise innovation mode, they are limited to the characteristics of innovation mode itself and their impact on enterprises, while ignoring the interactive evolution between closely related social environments.

In the process of global economic integration, it is the unshirkable responsibility of the government to effectively promote the continuous technological innovation of enterprises, increase the scientific and technological content of products, optimize and upgrade industries, and create wealth for society. Meng-Jie pointed out that only government intervention and promotion can drive innovation successfully, because the role of the government is not only reflected in financial allocations, but also in the guidance and integration of innovation [8]. However, there are few relevant studies on the selection of technological innovation modes under the influence of government policies. Gu Qun's research using panel data of listed companies shows that government subsidies can promote exploratory innovation of enterprises but hinder development innovation [9]. Ke Zhongyi and others believed that government subsidies can change the mode of cooperative innovation among enterprises, at the same time of maximizing their profits and social welfare [10]. The existing literature only discusses the role of government policies, but rarely studies the government subsidy mechanism in depth. In order to achieve the desired effect, government policy intervention needs to be designed according to the change of participant's policy behavior and the threshold value of sudden decision change. As an exogenous variable, government subsidies may cause chaos in the original system, so it is necessary to avoid the chaotic period reasonably, which is more rarely studied. Therefore, the selection of technological innovation mode in enterprises is studied in this paper based on the government subsidy mechanism in order to provide decision-making reference for the government to formulate a reasonable subsidy policy.

The selection of technological innovation mode in enterprise is its natural choice behavior to participate in the dynamic response of market competition. Therefore, it is not enough for an enterprise to consider only its own innovation cost and innovation ability when choosing technological innovation mode. As a branch of evolutionary economic theory, evolutionary game theory originates from the idea of biological evolution. It is a model based on the continuous dynamic system of differential equations. It has natural advantages in describing the dynamic evolution process of strategies. Therefore, it has advantages in analyzing the selection

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behavior of enterprise technological innovation mode. At present, scholars have done a lot of research in the fields of travel mode selection, supply chain enterprise cooperation, power bidding market and so on [11-13], while few scholars have studied the selection of enterprise technology innovation mode under the government subsidy mechanism. Therefore, in this paper, firstly, an evolutionary game model of enterprise technology innovation mode selection based on government subsidy mechanism is constructed; then, a two-dimensional dynamic system is built and its evolutionary stable equilibrium solution (ESS) is analyzed to study the selection of stable strategies in enterprise innovation mode selection; next, the model established is simulated by using Matlab software, which more intuitively reflects the evolutionary trend of innovation mode selection process; finally, several policy suggestions are put forward for the government and enterprise.

II. BASIC HYPOTHESES AND MODELING

Enterprises will show open closed innovation in the process of innovation. The whole enterprise group is divided into two distinct game players with bounded rationality: enterprise group A and B. During the game, one player is randomly selected for a pairing game.

Hypothesis 1: In the natural environment regardless of other constraints, enterprise group A and group B are treated as a complete system. Both parties in the system are bounded rational individuals with certain learning ability and have their corresponding selection strategies and powers. x, y represent the selection probability of corresponding strategies of enterprises A and B respectively, and $x, y \in [0,1]$, both of which are functions of time t.

Hypothesis 2: The total investment of a technology innovation project is R with the total benefit of S. Two enterprises from different groups are making innovative decisions, and each enterprise has two alternative strategies: open innovation or closed innovation.

The following is a detailed analysis of the game revenue of Enterprise A and Enterprise B: (1) When both enterprises A and B choose open innovation strategy, they get higher innovation benefit because cooperation improves innovation efficiency and reduces innovation cost. For the convenience of analysis, the differences in other aspects between the two players are ignored, and then they share equally the profits from innovation. At this time, the government subsidies for both enterprises are G_1, while the profits for enterprises A and B are 1/2 (S-R) $+G_1$. (2) When Enterprise A adopts open innovation and Enterprise B closed innovation, the benefit to Enterprise A is W. However, its input also needs certain cost C, where W is the incremental function of C. At this time, the government subsidies for Enterprise A are G_1 and for Enterprise B are G_2 ($G_1 > G_2$).In this game, the benefit to Enterprise A is $W - C + G_1$ and that to Enterprise B is $S - W - R + G_2$. (3) When Enterprise A adopts the closed innovation and Enterprise B the open innovation, the government subsidies for Enterprise A are G_2 and for Enterprise B are G_1.Similar to the second scenario, the benefit to Enterprise A is $S - W - R + G_2$ and that to Enterprise B is $W - C + G_1$. (4) When both enterprises A and B adopt the closed innovation, the benefits to both players are less than in the case of open cooperation. The government subsidies for both parties are G_2, and both enterprises A and B get a benefit of

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$\frac{1}{2}S-R+G_2$.

According to the above assumptions and analysis, the evolutionary game payoff matrix of Enterprise A and B is constructed on the principle that the profit of the participants equals the difference between profit and cost [12] (TABLE I).

TABLE I. Payoff matrix of both game players

Game players and behavioral strategies		**Enterprise B**	
		Open innovation (y)	**Closed innovation (1-y)**
Enterprise A	Open innovation (x)	$\frac{1}{2}(S-R)+G_1$ $\quad$ $\frac{1}{2}(S-R)+G_1$	$W-C+G_1$ $\quad$ $S-W-R+G_2$
	Closed innovation (1-x)	$S-W-R+G_2$ $\quad$ $W-C+G_1$	$\frac{1}{2}S-R+G_2$ $\quad$ $\frac{1}{2}S-R+G_2$

III. EVOLUTIONARY GAME MODEL ANALYSIS

3.1 Equilibrium Point of Evolution Process

The expected revenues E_0^1, E_0^2 and average earnings $\overline{E}_0$ of Enterprise A for open innovation and closed innovation are respectively:

$$E_0^1=\frac{1}{2}y(S-R)+yG_1+(1-y)(W-C-G_1)=\frac{1}{2}y(S-R)+W-C+G_1-Wy+yC$$

$$E_0^2=y(S-W-R+G_2)+(1-y)(\frac{1}{2}S-R+G_2)=\frac{1}{2}yS-yW+\frac{1}{2}S-R+G_2$$

$$\overline{E}_0=xE_0^1+(1-x)E_0^2=-\frac{1}{2}xyR+Wx-Cx+G_1x+xyC+\frac{1}{2}yS-yW+\frac{1}{2}S-R+G_2-\frac{1}{2}xS+xR-xG_2$$

According to Malthusian dynamic equation [13], the replicator dynamics equation of Enterprise A is:

$$F(x)=\frac{dx}{dt}=x(E_0^1-\overline{E}_0)=x(1-x)(-\frac{1}{2}yR+W-C+G_1-G_2+yC-\frac{1}{2}S+R)$$

Similarly, the expected revenues E_1^1, E_1^2 and average earnings $\overline{E}_1$ of Enterprise B for open innovation and closed innovation are respectively:

$$E_1^1=\frac{1}{2}x(S-R)+xG_1+(1-x)(W-C-G_1)=\frac{1}{2}x(S-R)+W-C+G_1-Wx+xC$$

$$E_1^2=x(S-W-R+G_2)+(1-x)(\frac{1}{2}S-R+G_2)=\frac{1}{2}xS-xW+\frac{1}{2}S-R+G_2$$

The replicator dynamics equation of Enterprise B is:

$$F(x)=\frac{dx}{dt}=x(E_0^1-\overline{E}_0)=\mathrm{y}(1-y)(-\frac{1}{2}xR+W-C+G_1-G_2+xC-\frac{1}{2}S+R)$$

On the basis of the above two formulas, a two-dimensional discrete dynamic system is obtained, i.e.,

$$\begin{cases}\dfrac{dx}{dt}=x(1-x)(-\dfrac{1}{2}yR+W-C+G_1-G_2+yC-\dfrac{1}{2}S+R)\\ \dfrac{dy}{dt}=y(1-y)(-\dfrac{1}{2}xR+W-C+G_1-G_2+xC-\dfrac{1}{2}S+R)\end{cases}$$

In order to facilitate the analysis of the equilibrium point and stability of the system, let $A=\dfrac{W-C+G_1-G_2-\frac{1}{2}S+R}{\frac{1}{2}R-C}$, $B=\dfrac{W-C+G_1-G_2-\frac{1}{2}S+R}{\frac{1}{2}R-C}$.

Proposition 1 The equilibrium points of the system are (0, 0), (0, 1), (1, 0), (1, 1), (A, B).

It is proved that (0,0), (0,1), (1,0), (1,1) are the equilibrium points of the two-dimensional discrete dynamical system, when $\frac{dx}{dt}=0$ and $\frac{dy}{dt}=0$. Substituting (A, B) into the two-dimensional discrete dynamic system, and also when $\frac{dx}{dt}=0$, $\frac{dy}{dt}=0$, five local equilibrium points are obtained.

3.2 Equilibrium Point and Stability Analysis

The equilibrium point obtained by the replicator dynamics equation is not necessarily the evolutionary stability strategy (ESS) of the system. According to Friedman's method [13], the stability of the evolutionary equilibrium can be derived from the local stability analysis of Jacobian matrix (denoted as J).

$$J=\begin{bmatrix}\dfrac{\partial F(x)}{\partial x} & \dfrac{\partial F(x)}{\partial y}\\ \dfrac{\partial F(y)}{\partial x} & \dfrac{\partial F(y)}{\partial y}\end{bmatrix}=\begin{bmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{bmatrix}$$

Where,

$$a_{11}=(1-2x)(-\frac{1}{2}yR+W-C+G1-G2+yC-\frac{1}{2}S+R)$$

$$a_{12}=x(1-x)(C-\frac{1}{2}R)$$

$$a_{21}=y(1-y)(C-\frac{1}{2}R)$$

$$a_{22}=(1-2y)(-\frac{1}{2}xR+W-C+G1-G2+xC-\frac{1}{2}S+R)$$

If the following two conditions can be met at the same time, the equilibrium point of the above replicator dynamics equation is the Evolutionary Stability Strategy (ESS).

$$trJ=a_{11}+a_{22}<0(tracecondition)$$

$$\det J=\begin{vmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{vmatrix}=a_{11}a_{22}-a_{12}a_{21}>0$$

(Jacobian determinant condition)

Therefore, the specific values of a_{11}, a_{12}, a_{21} and a_{22} at 5 local equilibrium points (as

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shown in TABLE II) can be obtained.

TABLE II. The specific values of a_{11}, a_{12}, a_{21} and a_{22} at 5 local equilibrium points

Equilibrium points	a_{11}	a_{12}	a_{21}	a_{22}
(0,0)	$W-C+G1-G2-\frac{1}{2}S+R$	0	0	$W-C+G1-G2-\frac{1}{2}S+R$
(0,1)	$W-C+G_1-G2-\frac{1}{2}S+\frac{1}{2}R$	0	0	$-(W-C+G1-G2-\frac{1}{2}S+R)$
(1,0)	$-(W-C+G1-G2+-\frac{1}{2}S+R)$	0	0	$W-C+G_1-G2-\frac{1}{2}S+\frac{1}{2}R$
(1,1)	$-(W-C+G_1-G2-\frac{1}{2}S+\frac{1}{2}R)$	0	0	$-(W-C+G_1-G2-\frac{1}{2}S+\frac{1}{2}R)$
(A,B)	0	M	N	0

Where,

$$M=\frac{W-C+G_1-G_2-\frac{1}{2}S+R}{\frac{1}{2}R-C}\left(1-\frac{W-C+G_1-G_2-\frac{1}{2}S+R}{\frac{1}{2}R-C}\right)\left(C-\frac{1}{2}R\right)$$

$$N=\frac{W-C+G_1-G_2-\frac{1}{2}S+R}{\frac{1}{2}R-C}\left(1-\frac{W-C+G_1-G_2-\frac{1}{2}S+R}{\frac{1}{2}R-C}\right)\left(C-\frac{1}{2}R\right)$$

Obviously, there is $a_{11}+a_{22}=0$ at the local equilibrium point (A, B), which does not meet condition (1), so (A, B) the local equilibrium point is not an evolutionary stabilization strategy (ESS), as only those meeting both trace conditions and Jacobian determinant conditions are the evolutionary stabilization strategies of the system. Therefore, only the other four equilibrium points need to be considered. Based on the previously mentioned judgment methods, the determinant and trace values of the Jacobian matrix J at each equilibrium point can be obtained, and the local stability can be determined. To get closer to reality, restriction $W-C>\frac{1}{2}(S-R)$ is added.

Local stability can be determined by analyzing the trace and determinant symbols of the four local equilibrium points of the Jacobian matrix J. Therefore, the system stability of the above models can be divided into the following four scenarios.

Scenario 1: The evolutionary analysis when $W+G_1-G_2-\frac{1}{2}S+\frac{1}{2}R>0$

Equilibrium point	Trace symbol	Determinant symbol	Equilibrium result
(0,0)	+	+	Unstable point
(0,1)	-	-	Saddle point
(1,0)	-	-	Saddle point
(1,1)	-	+	ESS

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Scenario 2: The evolutionary analysis when $W-C+G1-G2-\frac{1}{2}S+R>0$ and $\frac{1}{2}R-C<0$

Equilibrium point	Trace symbol	Determinant symbol	Equilibrium result
(0,0)	+	+	Unstable point
(0,1)	-	-	Saddle point
(1,0)	-	-	Saddle point
(1,1)	-	+	ESS

Scenario 3: The evolutionary analysis when $W-C+G_1-G_2-\frac{1}{2}S+R<0$ and $\frac{1}{2}R-C>0$

Equilibrium point	Trace symbol	Determinant symbol	Equilibrium result
(0,0)	-	+	ESS
(0,1)	-	-	Saddle point
(1,0)	-	-	Saddle point
(1,1)	+	+	Unstable point

Scenario 4: The evolutionary analysis when $W-C+G1-G2-\frac{1}{2}S+R<0$ $\frac{1}{2}R-C<0$ and $W+G_1-G_2-\frac{1}{2}S+\frac{1}{2}R<0$

Equilibrium point	Trace symbol	Determinant symbol	Equilibrium result
(0,0)	-	+	ESS
(0,1)	-	-	Saddle point
(1,0)	-	-	Saddle point
(1,1)	+	+	Unstable point

IV. RESEARCH ON EVOLUTIONARY SIMULATION

Evolutionary simulation analysis using Matlab software can be used to more intuitively describe how enterprises choose the closed and open innovation modes under the mechanism of government subsidies. Suppose Enterprise A chooses probability B of open technological innovation at the beginning of the game.

(1) When $W+G_1-G_2-\frac{1}{2}S+\frac{1}{2}R>0$, assume W=8, G_1=3, C=4, G_2=1, S=12, R=7. As shown in Fig. 1 of Matlab simulation results, when the evolutionary iteration steps are superimposed, the proportion of Enterprise A and Enterprise B choosing open innovation mode increases continuously. Finally, the stable point of their interactive behavior evolution is (1, 1).When Enterprise A adopts the open innovation mode and Enterprise B the closed innovation mode, the total revenue of Enterprise A is greater than that of both players when they adopt the closed innovation mode, that is, both Enterprise A and Enterprise B choose the open innovation mode (Fig. 1).

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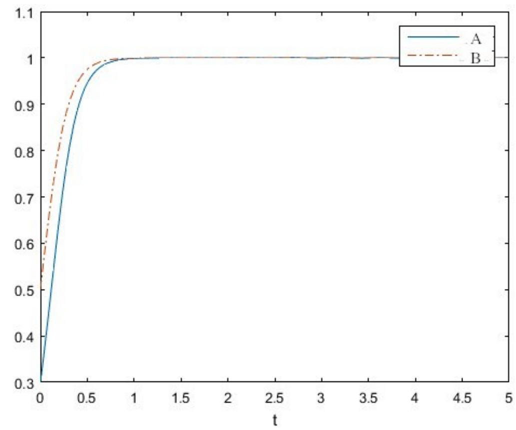

Fig 1: Simulation results of stable point (1,1)

(2) When $W-C+G1-G2-\frac{1}{2}S+R>0$ and $\frac{1}{2}R-C<0$, assume W=8, C=3, G_1=3, G_2=1, S=14, R=4. When Enterprise A adopts the open innovation mode and Enterprise B adopts the closed innovation mode, the total revenue of Enterprise A is greater than that of both players. When Enterprise A adopts the open innovation mode and Enterprise B the closed innovation mode, the cost of Enterprise A is more than half of the total investment of the project, Enterprise A and Enterprise B both choose the open innovation mode. The Matlab simulation result program are shown in Fig. 2.

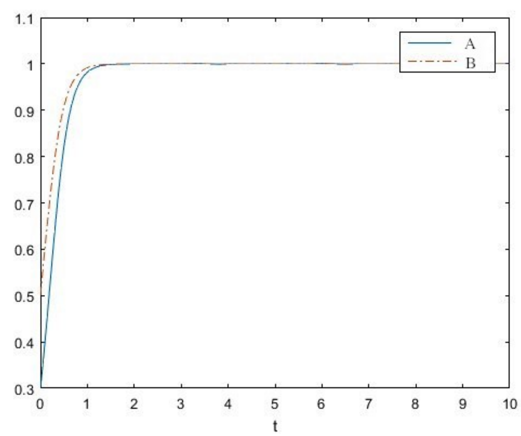

Fig 2: Simulation results of stable point (1,1)

(3) When W-C+G_1-G_2-$1/2S$+R < 0 and 1/2R-C > 0, assume W=4, C=2, G_1=3, G_2=2, S=20, R=6. When Enterprise A adopts the open innovation mode and Enterprise B the closed innovation mode, the total revenue obtained by Enterprise A is less than that obtained when both of them adopt the closed innovation mode. When Enterprise A adopts the open innovation mode and Enterprise B the closed innovation mode, and the cost paid by Enterprise A is less than half of the total investment of the project, Enterprise A and Enterprise B both choose the closed innovation mode. At this time, the evolution stabile point is (0,0). The results of Matlab

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simulation are shown in Fig. 3.

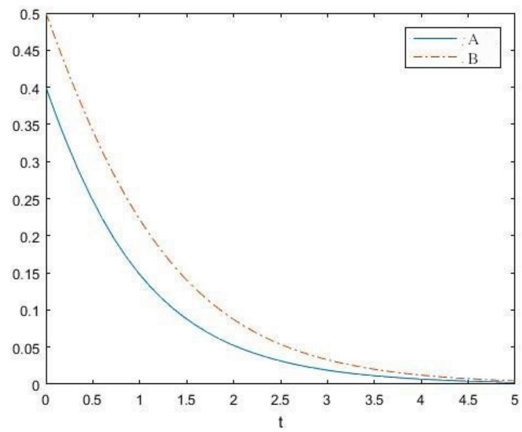

Fig 3: Simulation results of stable point (0,0)

(4) When $W-C+G1-G2-\frac{1}{2}S+R<0$ $\frac{1}{2}R-C<0$ and $W+G1-G2-\frac{1}{2}S+\frac{1}{2}R<0$, assume W=6, C=5, G_1=3, G_2=2, S=22, R=6. Matlab simulation results are shown in Fig. 4 that as the evolution iteration steps increase, the proportion of Enterprises A and B choosing open innovation mode decreases continuously. Finally, the stable point of their interactive behavior evolution is (0, 0). When Enterprise A adopts the open innovation mode and Enterprise B the closed innovation mode, the total revenue obtained by Enterprise A is less than that obtained by both of them when adopting the closed innovation mode. When Enterprise A adopts the open innovation mode and Enterprise B the closed innovation mode, the cost paid by Enterprise A is more than half of the total investment of the project. When Enterprise A adopts the open innovation mode and Enterprise B the closed innovation mode, and the sum of gross income of Enterprise A, government subsidy and half of total project investment is less than the sum of government subsidy and project total income when Enterprise A adopts closed innovation, both Enterprise A and Enterprise B choose closed innovation mode.

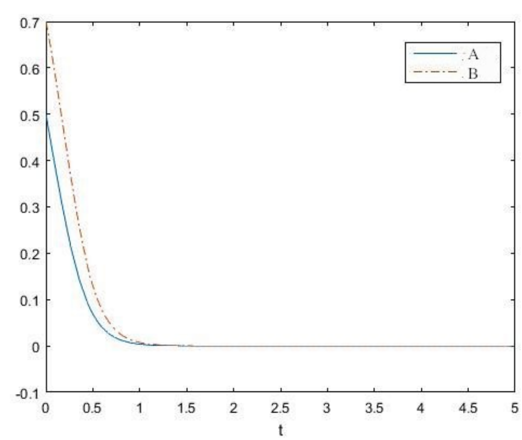

Fig 4: Simulation results of stable point (0,0)

V. CONCLUSIONS

Under the conditions of limited rationality and information asymmetry, using evolutionary game theory in the process of selecting enterprise technological innovation mode, an evolutionary game model of enterprise technology innovation mode selection based on government subsidy mechanism is established. The simulation analysis is carried out by obtaining five local equilibrium points of replicator dynamic equation and evolutionary stabilization strategy (ESS). The analysis results show that the equilibrium state of the system converges to two modes, one is ideal state, i.e., Enterprise A and Enterprise B both choose open innovation mode, the other is bad state, i.e., both choose closed innovation mode, which is not only detrimental to creating benefits for the social and industrial chains, but also hinders the sustainable development of enterprises. Therefore, in order to get out of the bad state, enterprises urgently need to optimize the path of innovation mode. Under the above analysis, the following suggestions are put forward: (1) The subsidy G_1 of the open innovation mode should be increased, while the subsidy G_2 of the closed innovation should be reduced, and enterprises should be encouraged to choose the open innovation mode from the perspective of government policy to reduce the risk of open innovation. (2) The open innovation cost C should be reduced. Enterprises can use external innovation resources such as customers, suppliers, universities, scientific research institutes and other effective resources by industry-university-research cooperation. They can also flexibly use cooperation or joint R&D, technology transfer, authorization, merger and acquisition to improve R&D efficiency and ultimately obtain R&D returns. (3) The government should increase subsidies for enterprises that adopt open innovation, improve relevant laws and policies on intellectual property protection, and speed up the transformation of social achievements, so as to speed up the expected benefits of technological innovation activities of enterprises.

In the future, the research will focus on the following aspects: (1) Since only the evolutionary game model between two enterprises is discussed in this study, that of more than three enterprises can be expanded in the future, which will be closer to reality because of the complexity of economic environment. (2) The two-dimensional dynamic differential equation established in this study is static, and it can be attempted in the future to establish differential equations that are continuously adjusted with time.

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