

Evolutionary game and simulation of organizational information security investment

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Abstract

To investigate the evolution law of organizational information security investment, this paper analyses evolutionary stable strategies of organizational information security investments using evolutionary game theory and verifies the evolutionary stable strategies through the simulation based on Repast, a multi-agent simulation platform. First, according to the bounded rationality of actual organizations, this paper sets up the evolutionary game model of organizational information security investment. And then, we investigate the evolutionary stable strategies by replicator dynamics. Finally, we simulate the evolutionary game by Repast based on Java programming language, and the experimental results verify the evolutionary stable strategies obtained from the theoretical analysis. The research results can be used to predict the long-term stable trend of organizational information security investment, state that investment cost is the key for organizations to choose the strategy, and provide decision support for organizational information security investment.

Keywords: evolutionary game, information security investment, multi-agent simulation, evolutionary stable strategy

1 Introduction

Information security investment is an inevitable investment decision of organization in digital economy. As the result of global information security survey reveals [1], over half of enterprises spent more money on information security than before, but they do not feel safer. However, information security investment has the characteristics of concealment and confrontation and is different from other investments, which get effect instantly. In addition, the effect of information security investment is inconspicuous. Therefore, ordinary research method is not suitable for the study of information security investment.

The research of information security concentrates on technology field [2-3], however, the management study of information security is more important than technology study to some extent. In fact, the abstract characteristic of information security is the strategy interdependence, while strategy interdependence is just the focus of Game Theory. Thus, we can explore the information security investment by game theory. Samuel N.H. pointed out directly that applying game theory to information security study is a promising research direction.

Due to strategy dependency of inter-organizational information security investment, game theory can be used to research information security investment. Researches on information security game theory are currently still in the exploratory stage, only a few studies [3-7] are based

on the assumption of game party complete rationality, which is a great difference with game party bounded rationality in the real world.

Evolutionary game theory is the scientific method to study game party bounded rationality. Evolutionary game theory is based on Darwin's evolution theory and Lamarck's genetic theory, and takes game party bounded rationality as the study object. Therefore, Evolutionary game theory enhances the game analysis of scientific and credibility. John Nash's "herd behaviour explains" [8] can be thought as the earliest evolutionary game theory; Weibull summarized the evolutionary game theory [9] to form the systematic evolutionary game theory. Evolutionary game theory is a new field of game theory, but there are many gaps in the applications of economics, biology and other social science [10].

Considering information security investment entities in the real world have bounded rationality, the paper uses evolutionary game theory to analyse information security investments and simulates the theoretical result through the Repast, i.e. a multi-agent simulation platform.

The organization of the paper is as following. Section 2 establishes information security investments evolutionary game model. In section 3, we investigate the evolutionary stable strategy of information security investment by replicator dynamics. Section 4 simulates the evolutionary game by Repast simulation platform and verifies the evolutionary stable strategy of the third section by the experimental results. In addition, the results

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predict the long-term stability trends of information security investment and state that the investment cost is the key to organizational strategic choice. In the last section conclusions are given.

TABLE 1 Evolutionary game model of information security investment of two organizations

Organization 1	Organization 2	
	Investment	No investment
Investment	$E-C+I, E-C+I$	$E-C-qL+I, E-pL$
No investment	$E-pL, E-C-qL+I$	$E-pL-(1-p)qL, E-pL-(1-p)qL$

Game model, including the proceeds of a comprehensive information security function value of the investment benefits, not only to consider the prevention of information security incidents resulting direct value benefits, but also to consider the organization of information security investment brings enhance brand value, increased goodwill and other organizations the indirect value of intangible benefits.

2 Evolutionary game model of information security investment

In real world, information security investment entities have bounded rationality, and so investment decision often depends on instinctive intuition, or the simple imitation of the successful strategies. That means the strategic choice is rarely decided according to precise mathematical analysis, and thus rational level in investors decision-making is low. In view of this situation, this paper establishes information security investment evolutionary game model considering game party bounded rationality.

In the game model, the two players are assumed the same type of risk-neutral organization. The parameters in the model are defined as follows. E is the normal income of organization, which is independent of the cost-effectiveness of information security investment. C stands for costs of organization investing in information security. Since the information security investment can impact the intangible asset of the organization, we choose I to reflect the intangible asset from the investment of information security. L is the loss caused by information security failure. The disaster probability caused by the organization itself is p , and the disaster probability caused by other organizations is q , which represents negative externalities among the organizations.

Information security investments evolutionary game model is established with benefit matrix. The benefits of two organizations are $E-C+I$, when they are investing in information security. When one organization invests in information security but another organization doesn't invest, the benefit of organization investing is $E-C-qL+I$ because negative externalities cause the loss qL , and the benefit of organization not investing is $E-pL$ because its own information security incidents cause the loss pL .

When both two organizations are not investing in information security, each organization has its own security risks caused by p and negative externalities caused by other organizational impact q , and so the benefit of two organization are $E-pL-(1-p)qL$. Therefore, we establish information security investment evolutionary game model, as shown in Table 1.

3 Replicator dynamics of evolutionary game of information security investment

Replicator dynamics is the basic dynamics of evolutionary game theory, and can reasonably characterize the stability of bounded rationality game party in dynamic process of learning and adjustment, predict changing trends of game party groups [11]. Compared to other dynamic equations, replicator dynamics have a broader application prospects. The decision-making body of information security investment is less rational, and so it is suitable to investigate information security investments evolutionary game using replicator dynamics.

Replicator dynamics is the most valuable function in evolutionary game theory for application. Replicator dynamics can imitate the studying and regulating processes of the players with bounded rationality well, forecast the change trend of the colony behaviour, and provide the scientific reference for macro control. Compared with other dynamics function, replicator dynamics is the most widely used dynamics in evolutionary game theory.

In the analysis of Replicator Dynamics of information security evolutionary game, suppose x be the proportion of the organizations with the strategy of investing in information security, and the proportion of no investment strategy is $1-x$. Let $\frac{dx}{dt}$ represent the change ratio of the proportion of investment strategy. Then, replicator dynamics of information security evolutionary game is expressed:

$$\frac{dx}{dt} = x(u_i - \bar{u}). \tag{1}$$

In the above information security evolutionary game, u_i is the expectation benefit of game party adopting investment information security strategy:

$$u_i = x(E - C + I) + (1 - x)(E - C - qL + I). \tag{2}$$

u_n is the expectation benefit of game party not adopting investment information security strategy:

$$u_n = x(E - pL) + (1 - x)[E - pL - (1 - p)qL]. \tag{3}$$

Furthermore, the overall average expected benefit \bar{u} can be calculated:

$$\bar{u} = xu_i + (1-x)u_n. \tag{4}$$

Based on equations (2)–(4), we can obtain replicator dynamics of information security investment evolutionary game:

$$\frac{dx}{dt} = x(1-x)[pqLx + (pL + I - C - pqL)]. \tag{5}$$

Let replicator dynamics of information security investment evolutionary game equals to zero, and we can get three stable states as follows by solving equation (5):

$$x_a^* = \frac{C + pqL - pL - I}{pqL}, x_b^* = 0 \text{ and } x_c^* = 1. \tag{6}$$

According to the value of $x_a^* = \frac{C + pqL - pL - I}{pqL}$, we

investigate three evolutionary stable strategies of information security investment evolutionary game respectively and verify them based on the Repast simulation platform.

Evolutionary stable strategy (ESS) can be analysed on the basis of replicator dynamics. ESS is the equilibrium with the true stability and strong forecast ability, and can be reached by the regulation of the player. Also, ESS can resist the disturbance of wrong departure. Replicator dynamics and ESS are the two basic concepts in evolutionary game theory. The stable condition is the condition that the proportion of investment strategy and the proportion of no investment strategy are fixed.

4 Evolutionary stable strategy and simulation of evolutionary game of information security

In this paper, we use Repast simulation tools, JBuilder platform to verify the evolutionary stable strategy. Repast (Recursive Porous Agent Simulation Toolkit) is a multi-agent modelling and simulation toolset, which developed by the University of Chicago and Argonne National Laboratory [12]. Repast platform can control and reproduce simulation experiment, and the output results of the simulation experiment can be used to analyse the game's behaviour and trends well. Repast includes simulation scheduling Class, agent Class and space Class, and a series of input and output Class library, to provide the corresponding programming framework for the realization of the simulation model. Repast simulation modelling process and corresponding functions is shown in Figure 1.

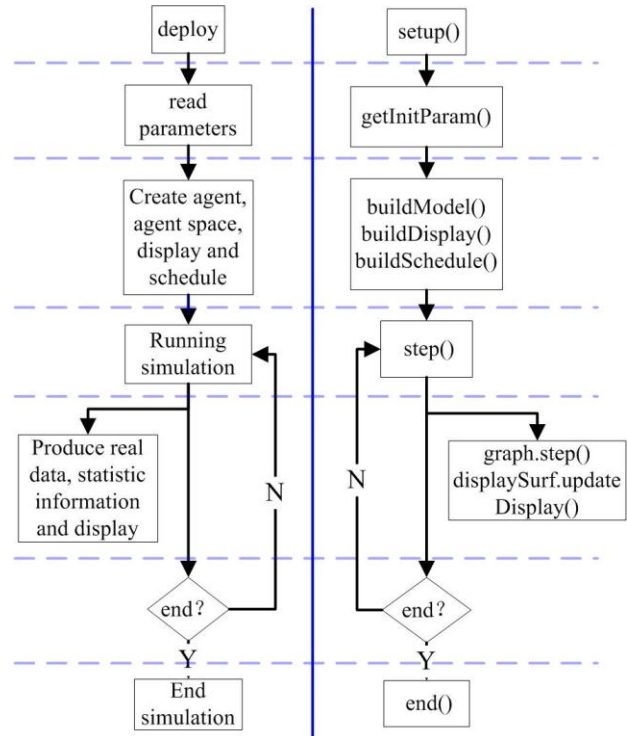


FIGURE 1 Repast simulation process and corresponding functions

4.1 EVOLUTIONARY STABLE STRATEGY AND SIMULATION WITH $x_a^* \leq 0$

Evolutionary stable strategy (ESS) is real equilibrium stability in evolutionary game theory, and can be used to predict long-term stable trend of game party group behaviour. $x_a^* \leq 0$ means $C \leq pL + I - pqL$, in addition x ranges from 0 to 1, so the replicator dynamics of information security investments evolutionary game have only two stable states, i.e. $x_b^* = 0$ and $x_c^* = 1$. In the two stable states, the evolutionary stable strategy equilibrium must be able to withstand a slight deviation from the disturbance. The explanation of mathematical analysis is as follows: when the disturbance makes x less than evolutionary stable strategy, $\frac{dx}{dt}$ must be greater than 0; when the disturbance makes x greater than evolutionary stable strategy, $\frac{dx}{dt}$ must be less than 0. In the phase diagram of replicator dynamics equation, the one with negative tangent slope in intersection points of replicator dynamics curve intersects and the horizontal axis is evolutionary stable strategy of evolutionary game replicator dynamics. Figure 2 shows the phase diagram of replicator dynamics equation of information security investment evolutionary game with $x_a^* \leq 0$. In Figure2, we can easily observe that when $x_a^* \leq 0$, $x_c^* = 1$ is the evolutionary stable strategy of the information security evolutionary game.

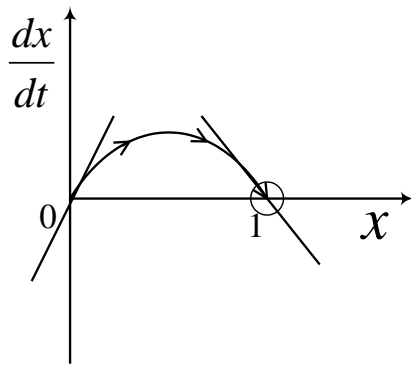


FIGURE 2 The phase diagram of replicator dynamics equation with $x_a^* \leq 0$

We use Java-based Repast simulation platform to verify the evolutionary stable strategy of information security investment with $x_a^* \leq 0$. The detailed simulation input parameters are shown in Table 2.

TABLE 2 The detailed simulation input parameters with $x_a^* \leq 0$

parameters	<i>E</i>	<i>I</i>	<i>L</i>	<i>p</i>	<i>q</i>	<i>C</i>	<i>x</i>
value	10	6	9	0.6	0.4	5	0.1

The overall strategy selection of the simulation initial stage is shown in Figure 3, where an agent represents an organization. The red means the investment strategy which the organization selected is information security, while the blue represents to not invest in information security. In initially stage, only 10% of organizations choose to invest in information security. With the simulation running of the evolution mechanism, the proportion of organization adopting investment in information security gradually raises. Figure 4 shows the phase diagram at which the proportion of organization adopting investment in information security is 50%. Figure 5 shows the final evolution result of the simulation, where all organizations choose to invest in information security.

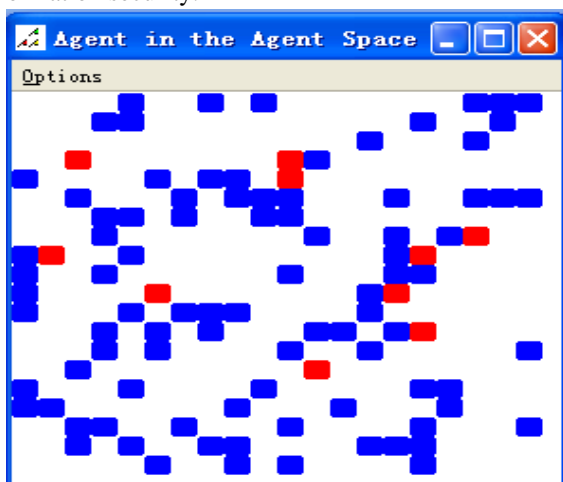


FIGURE 3 The overall strategy selection of the simulation initial stage with $x_a^* \leq 0$

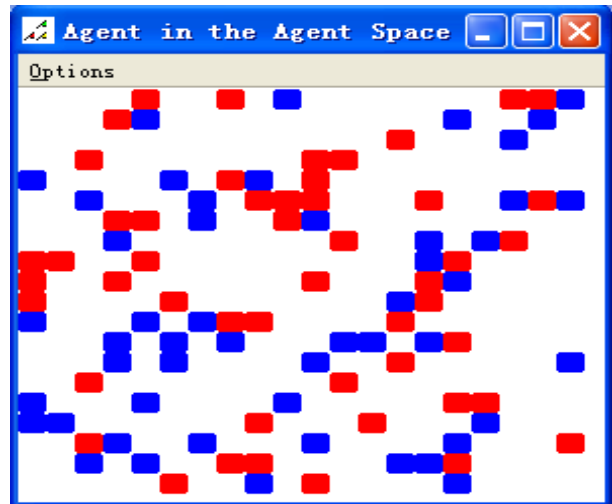


FIGURE 4 The overall strategy selection of the simulation phase diagram $x_a^* \leq 0$

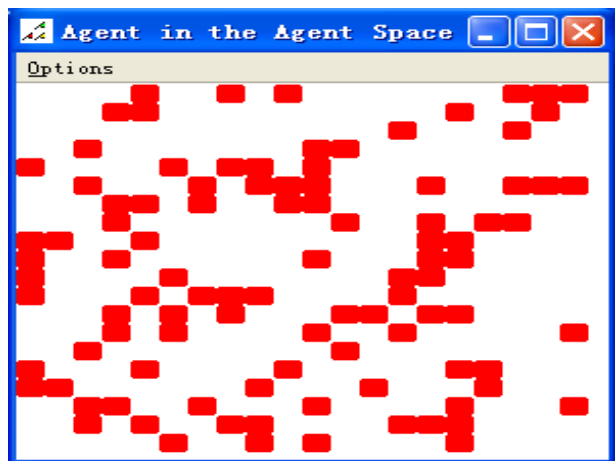


FIGURE 5 The overall strategy selection of stable trend with $x_a^* \leq 0$

Figure 6 shows the trend of the proportion of information security investment increasing from 10% to 50%. Figure 7 shows the whole trend, i.e., the proportion of information security investment increasing from 10% to 100%.

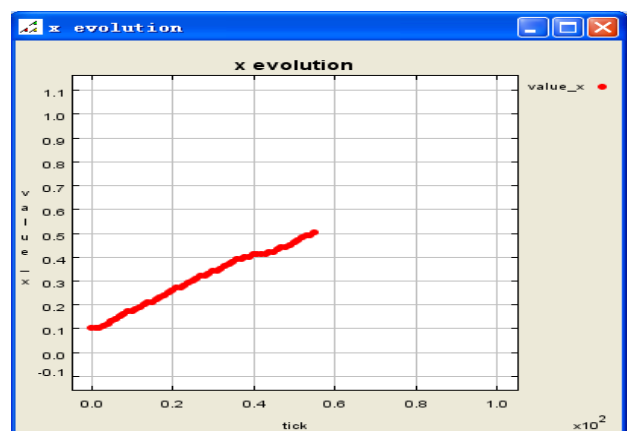


FIGURE 6 Trend of the proportion increasing from 10% to 50% under information security investment with $x_a^* \leq 0$

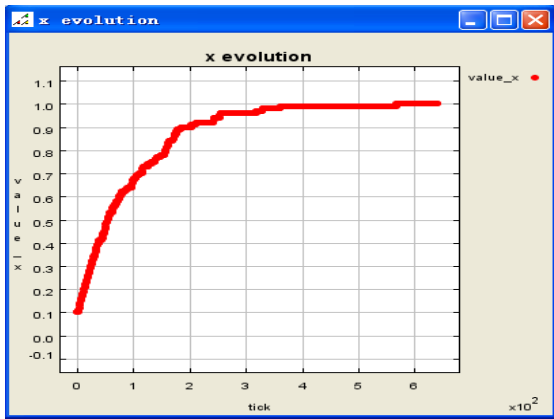


FIGURE 7 Whole trend of the proportion increasing from 10% to 100% under information security investment with $x_a^* \leq 0$

Therefore, the evolutionary game simulation results verify the replication dynamics evolutionary stable strategy with $x_a^* \leq 0$, i.e. when x is closing to 1, all organizations choose to invest in information security through long-term evolution. This evolutionary result interprets the actual situation well. $x_a^* \leq 0$ means $C \leq pL + I - pqL$, and so the cost of information security investment is lower, which prompts all organizations invest in information security. For the organizations choosing non-investment strategy, they will mimic the strategy of the successful enterprise to invest in information security when they find the benefit of information security investment, i.e. the expected revenue of investment is higher than that of no investment. Therefore, finally all organizations will adopt the strategy of investing information security.

4.2 EVOLUTIONARY STABLE STRATEGY AND SIMULATION WITH $x_a^* \geq 1$

$x_a^* \geq 1$ means $C \geq pL + I$, in addition x ranges from 0 to 1, so at the same time the replicator dynamics of information security investment evolutionary game also have only two stable states, i.e. $x_b^* = 0$ and $x_c^* = 1$.

Figure 8 is the phase diagram of replicator dynamics equation of information security investment evolutionary game with $x_a^* \geq 1$. From Figure 8, we can observe that $x_b^* = 0$ is the evolutionary stable strategy.

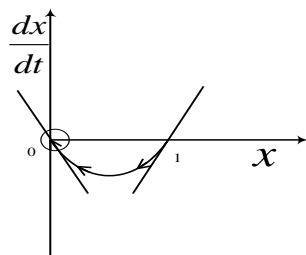


FIGURE 8 The phase diagram of replicator dynamics equation with $x_a^* \geq 1$

The evolutionary stable strategy of information security investment with $x_a^* \geq 1$ will be verified by simulation. The detailed simulation input parameters are shown in Table 3.

TABLE 3 The detailed simulation input parameters with $x_a^* \geq 1$

E	I	L	p	q	C	x
10	6	9	0.6	0.4	15	0.9

The simulation process is similar to Figures 4-6, and Figure 9 shows the completely evolutionary trend of the proportion of information security investment with $x_a^* \geq 1$ increasing from 90% to 0.

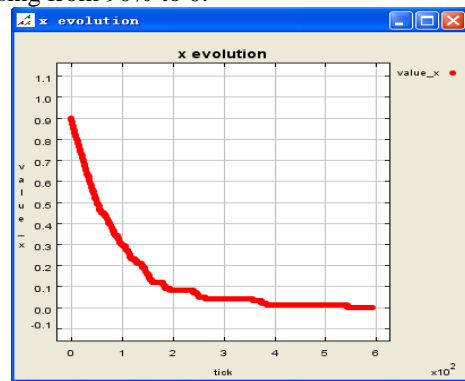


FIGURE 9 Whole evolutionary trend of the proportion decreasing from 90% to 0 under information security investment with $x_a^* \geq 1$

The simulation result proves that when $x_a^* \geq 1$, the evolutionary stable strategy is $x_b^* = 0$. The evolutionary result is consistent with the actual situation. $x_a^* \geq 1$ means $C \geq pL + I$, and so the cost of information security investment is higher, therefore, organizations will eventually not invest in information security in the long evolution process. To avoid this dangerous situation, information security technology must be improved to effectively reduce the cost of information security investment.

4.3 EVOLUTIONARY STABLE STRATEGY AND SIMULATION WITH $0 < x_a^* < 1$

$0 < x_a^* < 1$ means $pL + I - pqL < C < pL + I$. At this time, replicator dynamics includes three stable strategies, i.e. $x_a^* = \frac{C + pqL - pL - I}{pqL}$, $x_b^* = 0$, and $x_c^* = 1$. According to this phase diagram of replicator dynamics equation with $0 < x_a^* < 1$, as shown in Figure 10, we can get the evolutionary stable strategies under $0 < x_a^* < 1$ are $x_b^* = 0$ and $x_c^* = 1$.

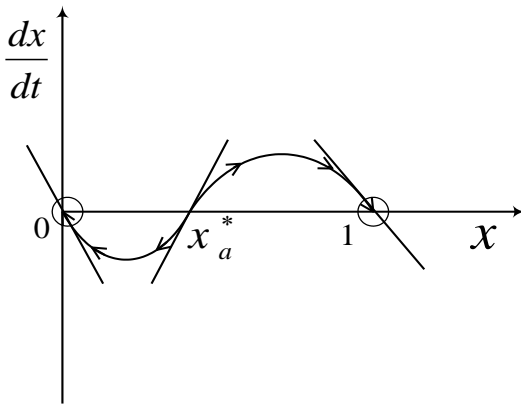


FIGURE 10 The phase diagram of replicator dynamics equation with $0 < x_a^* < 1$

According to the phase diagram of replicator dynamics, when the proportion of initial adoption information security investment (x) falls in interval $[0, x_a^*]$, the replicator dynamics will tend to evolutionary stable strategy of $x_b^* = 0$; when x falls in interval $[x_a^*, 1]$, the replicator dynamics will tend to be evolutionary stable strategy of $x_c^* = 1$.

The evolutionary stable strategy of information security investment with $0 < x_a^* < 1$ will be verified by simulation. For the situations with x in intervals $[0, x_a^*]$ and $[x_a^*, 1]$, the detailed simulation input parameters are shown in Table 4 and Table 5, respectively.

TABLE 4 The detailed simulation input parameters with $0 < x_a^* < 1$ and $0 < x < x_a^*$

E	I	L	p	q	C	x
10	6	9	0.6	0.4	10	0.3

TABLE 5 The detailed simulation input parameters with $0 < x_a^* < 1$ and $x_a^* < x < 1$

E	I	L	p	q	C	x
10	6	9	0.6	0.4	10	0.4

Figure 11 shows the whole evolutionary trend of the proportion decreasing from 30% to 0 under information security investment with $0 < x_a^* < 1$ and $0 < x < x_a^*$. Figure 12 shows the whole evolutionary trend of the proportion decreasing from 40% to 100% under information security investment with $0 < x_a^* < 1$ and $x_a^* < x < 1$.

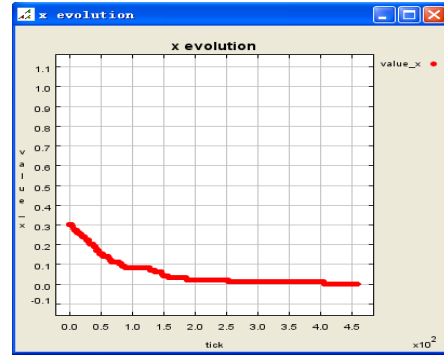


FIGURE 11 Whole evolutionary trend of the proportion decreasing from 30% to 0 under information security investment with $0 < x_a^* < 1$ and $0 < x < x_a^*$

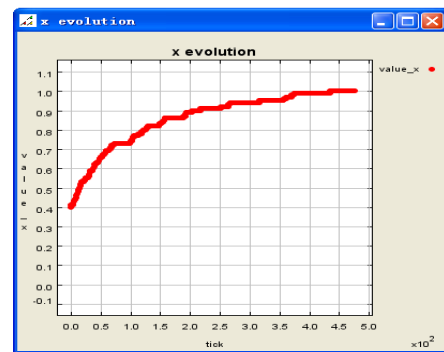


FIGURE 12 The whole evolutionary trend of the proportion decreasing from 40% to 100% under information security investment with $0 < x_a^* < 1$ and $x_a^* < x < 1$

The simulation results verify the evolutionary stable strategies under $0 < x_a^* < 1$, and explains the actual situation well. In practice, only when the proportional of organizations investing in information security is higher than x_a^* , the negative externality among organizations is relatively small. At this time, the organizations that have invested in information security will produce a positive demonstration effect in other organizations, which causes the number of organizations that will invest in information security increases. To achieve this ideal equilibrium result, x_a^* should close to the origin of the coordinate axes as possible, that is to say the information security investment cost C should close to $pL + I - pqL$ when $pL + I - pqL < C < pL + I$. Therefore, effectively reducing the cost of information security is the key to promote the organizations to invest in information security.

5 Conclusion

This paper analyses organizational information security investments with Evolutionary Game Theory and simulates the evolutionary game through Repast. Considering the bounded rationality of organizations in reality, we set up the evolutionary game model of information security investment. We investigate the evolutionary stable strategy by replicator dynamics and simulate the evolutionary game by Repast based on Java,

and the experimental results verify the evolutionary stable strategy obtained from the theoretical analysis. The research result reveals that investment cost is the key for organizations to choose the strategy, predicts the long-term stable trend of organizational information security investment, and provides good direction for organizational information security investment.

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