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Research article

Game analysis of enterprise safety investment and employee safety behavior strategy evolution in high-risk industries

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A R T I C L E I N F O

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A B S T R A C T

This paper aims to explore the influential relationship between the decision-making of investment of enterprise safety and employee safety behavior strategy selection, thus improve the effectiveness of decision-making. Based on traditional game theory, this paper establishes an evolutionary game model of enterprise safety investment and employee safety behavior strategy selection, and conducts numerical simulation analysis. The result shows:when the security investment cost is greater than the security investment benefit, the employee's security behavior strategy choice is significant for the enterprise security investment strategy decision; when the security investment benefit is greater than the security investment cost, the enterprise security investment decision is not affected by the employee safety behavior strategy; the choice of employee safety behavior strategy is not affected by the choice of enterprise safety investment strategy. The conclusion can provide a reference basis for enterprise safety production decision-making, which has certain theoretical and practical significance.

1. Introduction

Safety in production is the top priority in the production, operation and management of enterprises, especially for high-risk industries such as coal mines and buildings. As the country and enterprises pay more attention to safety in production, and actively take various measures to ensure safety in production, the incidence of safety accidents has been significantly reduced. However, many safety accidents still occur in China every year, causing significant property losses and casualties. Therefore, how to further reduce the incidence of safety accidents, ensure the safety of employees, and promote safe and efficient production of enterprises is an important issue faced by the country and enterprises.

According to relevant statistics and analysis of the causes of safety accidents, more than 87% of accidents are caused by personnel, so personnel are one of the main factors causing safety accidents [1,2]. Therefore, it has become an important research direction to prevent safety accidents.

In addition, whether there is a relationship between the safety input, which is one of the basic elements of safety production, and the unsafe behavior of personnel, which is one of the main causes of safety accidents. Whether increasing safety investment can promote the improvement of unsafe behaviors of employees, and thus achieve the purpose of improving safety benefits, is the focus of further research for enterprises. However, at present, there is little research on the relationship between enterprise safety investment

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and employees' unsafe behaviors. The focus of this study is to develop a dynamic evolutionary game model for the investigation of the relationship between enterprise safety investment and employees' unsafe behaviors.

2. Literature review

Unsafe behavior of personnel generally refers to accidents caused by human error, mainly including illegal operation, use of unsafe equipment, violation of labor discipline, etc. Many scholars have conducted a lot of research on unsafe behavior of personnel. It mainly includes safety training, safety attitude, organizational environment and improvement strategy.

In terms of safety training, Wang et al. [3] through the questionnaire survey on the coal mine front line and the data analysis using PCA, BLR and PR methods, it is concluded that strengthening the safety education and training of miners, establishing a safe climate and a reasonable management system have a positive effect on improving the safety behavior of employees. At the same time, Della et al. [4] found in the research on the safety behavior of ferry transport employees that strengthening safety training has an important positive impact on the safety behavior of employees. In addition, BAYRAM [5] found that safety training, safety knowledge, safety motivation and safety compliance have an impact on improving the safety productivity of employees through the investigation of employees participating in OHS basic training.

In terms of safety attitude, Li et al. [6] explored the impact of safety attitude on employees' safety behavior by issuing questionnaires to four coal mines in China, and the results showed that safety attitude has a positive effect on safety behavior, safety participation and safety compliance. Basahel, A. M [7] discussed the causal effect of leadership and attitude regulated by safety motivation and knowledge on safety compliance and safety participation. The results show that safety leadership, safety attitude and their interaction can predict safety motivation and safety knowledge. Deng et al. [8] constructed a cognitive failure model including five aspects: cognitive vigilance, hazard identification, safety knowledge, safety attitude and professional skills. Through the questionnaire analysis, it is found that the safety attitude is the main factor in the reaction selection process. Niu and Zhao [9] found that safety attitude can effectively reduce human errors in the study of human errors in coal mines.

About organizational environment, Liu et al. [10] designed a questionnaire to identify and model unsafe behaviors based on HFACS theory and characteristics of coal mine safety activities. Through SEM analysis, it is concluded that the external environment has direct and indirect effects on unsafe behaviors. Chen et al. [11] studied the influence of leadership behavior on employees' safety behavior by issuing questionnaires, and the results showed that leadership incentive behavior had an important positive impact on employees' work safety behavior. Johnston et al. [12] carried out exploratory case studies in 10 manufacturing plants of 9 companies, and the results showed that a good safety culture and organizational climate had lower injury rates. Wang et al. [13] analyzed the unsafe behavior factors of miners by using the New Hybrid MCDM Model, and concluded that the organizational safety culture is the core of the organizational environment factors.

As for the part of improvement strategy, Brian H.W et al. [14] analyzed the safety behaviors of construction workers by establishing an integrated model. The results showed that the strategy of combining safety organizations, safety groups and safety workers could effectively reduce unsafe behaviors of employees. Zaira and Hadikusumo [15], through random distribution of questionnaires to construction workers and exploratory factor analysis, concluded that technical intervention of management and personnel has a positive effect on improving the safety behavior of construction workers. Tong et al. [16] proposed a target intervention theory to solve the problem of untimely intervention of unsafe behaviors of coal miners, and constructed the target intervention node positioning process. Tian et al. [17] made a quantitative analysis of unsafe behaviors of miners based on the grey theory, and concluded that unsafe behaviors violating labor discipline have the highest risk value, which is an important direction to improve the safety production of coal mines. In addition, Yang et al. [18] analyzed the unsafe behaviors of deep mining miners through the comprehensive use of HFACS-CM, SD, SEM mathematical methods, and found that the physiological state, psychological state, business ability, resource management, and organizational climate are the five major factors affecting the unsafe behaviors of miners.

It can be seen from the research of the above scholars that the research on unsafe behaviors of personnel mainly focuses on the occurrence mechanism of unsafe behaviors, the identification of factors affecting unsafe behaviors, and the correlation between unsafe behaviors of personnel, which provides theoretical reference and basis for improving unsafe behaviors of employees and preventing the occurrence of safety accidents.

In the way of preventing safety accidents, it is not enough to rely only on improving the unsafe behaviors of employees, because there are many factors that cause safety production accidents. It is generally believed that the factors affecting safety production mainly include safety culture, safety science and technology, safety legal system, safety investment and safety responsibility, and these five factors are often independent of each other, but complement each other as prerequisites. As one of the five elements of safety production, safety investment is the basic guarantee of safety production and plays an important role in ensuring the safety production of enterprises. Safety input refers to the sum of various human, material, financial and other resources invested for safety activities, mainly including safety facilities and equipment, safety science and technology, safety professionals, etc. Some scholars have conducted relevant research. Chen [19] analyzed the logical relationship between the five elements of safety production, and concluded through research and analysis that strengthening safety investment can improve the intrinsic safety level of enterprises. Li et al. [20] proposed a safety investment model integrating support vector machine and continuous ant colony algorithm to solve the problem of insufficient and unreasonable safety investment of coal mining enterprises, so as to seek the optimal safety investment. Cao et al. [21] verified the impact of different safety input methods and directions on workers' safety performance by building a structural equation model, and revealed an effective path to improve the safety performance of construction workers. Yang et al. [22] put forward a shipping safety optimization model based on GA-SVR-PSO in order to seek the method of optimizing safety investment, which provides a reference for enterprises to make decisions on safety investment. It can be seen from the research of the above scholars that most of the research covers the relevant research from the role of safety investment in safety production, to how to optimize the safety investment method, and then to optimize the safety investment path. Relevant optimization and improvement methods and measures are proposed, which basically clarifies the role mechanism of safety investment in enterprise safety production, and lays a theoretical and methodological foundation for enterprises to prevent safety accidents.

For enterprises, increasing security investment means increasing their operating costs; For employees, improving unsafe behaviors means increasing work load. Therefore, for enterprises and employees, no matter which strategy they adopt, they will weigh the gains and losses of the selected strategy. Evolutionary game theory is based on the bounded rationality of players. When both players cannot accurately judge their own state in the game process, the process of combining game theory analysis and dynamic evolution process analysis to finally achieve stable change [23] is an effective method to study the evolution of multi actor strategies. Evolutionary game theory has been applied in coal mines, buildings, urban construction and many other aspects [24–26], but less in personnel safety behavior.

Therefore, this paper introduces evolutionary game theory into the field of safety production from the interests of both enterprises and employees in choosing strategies. According to the evolutionary game theory, a dynamic evolutionary game model of strategy selection is constructed, which takes enterprises and employees as the main body, analyzes the evolution law of enterprise security investment and employee unsafe behavior, and conducts numerical simulation analysis, further analyzes the impact of changes in employee unsafe behavior strategies on enterprise security investment, and puts forward corresponding improvement suggestions, which provide reference for enterprises to make reasonable decisions.

3. Material and methods

3.1. Construction of game model of enterprise safety investment and employee safety behavior evolution in high-risk industries

3.1.1. Model assumptions

According to the characteristics of enterprises in high-risk industries and the particularity of the operating environment of operators in high-risk industries, the following assumptions are made when building a game model for the evolution of enterprise safety investment and employee safety behavior in high-risk industries:

(1) There are only two strategies adopted by the enterprise: increasing security investment and not increasing security investment;
(2) There are only two kinds of strategies for employees: taking safe behaviors and taking unsafe behaviors.
(3) There is no other situation for the strategies of the two game players.

The meanings of notations in the model are listed as follows:

R: When the enterprise does not increase safety input, the fixed income.

C:The cost of the enterprise to increase safety input.

R_1:The additional income brought by the enterprise to increase safety input.

R_3:The fixed income of employees.

R_2:When the enterprise increases safety input, the employees take safety actions to obtain additional benefits.

q:The probability of safety accidents caused by employees' unsafe behaviors. D:the losses brought to the enterprise by safety accidents.

The proportion of the enterprise and its employees to bear the loss of safety accidents is f_1,f_2.

I_1:The enterprise is fined by the superior department for safety accidents.

I_2:The employee is fined by the enterprise for safety accidents caused by unsafe behaviors.

The enterprise does not increase the safety investment, and the enterprise needs to invest foreign capital R_4 to repair safety accidents caused by unsafe behaviors of employees.

3.1.2. Establishment of game subject income matrix

According to the above assumptions, calculate the benefits when each game player adopts different strategies.

(1) When an enterprise increases its safety investment, according to the different strategies adopted by employees, the profits of the enterprise and employees are also different: a) When employees take safety actions, the enterprise's income is f_3, and the employee's income is f_4 ; b) When employees take unsafe behaviors, the enterprise income is f_5, and the employee income is f_6.

$$f_3 = R + R_1 - C, f_4 = R_2 + R_3,$$

$$f_5 = R + R_1 - C - q \times (f_1 \times D + I_1), f_6 = R_3 - q \times (f_2 \times D + I_2)$$

(2) The enterprise does not increase safety investment: c) When employees take safety actions, the enterprise benefits is R, and the employee benefits are R_3; d) When employees take unsafe behaviors, the enterprise income is f_7,and the employee income is f_8. Therefore, the income matrix of enterprises and employees is shown in Table 1.

$$f_7 = R - q \times (f_1 \times D + I_1 + R_4), f_8 = R_3 - q \times (f_1 \times D + I_2)$$

3.1.3. Solution and analysis of evolutionary game model

According to the income matrix of enterprises and employees in Table 1, the evolutionary game replication dynamic equation of each game subject is constructed. It is assumed that enterprises and employees are independent of each other in the process of selecting strategies. The probability value that the enterprise chooses to increase safety input is x, then the probability value that the enterprise chooses not to increase safety input is $1 - x$. If the probability value of the employee's choice of safe behavior is y, the probability value of the employee's choice of unsafe behavior is $1 - y$. The expected income of the enterprise when it chooses to increase safety investment is E_{qi}.The expected income when it does not increase safety investment is E_{qui}, and the average expected income of the enterprise is E_q.

$$\begin{aligned} E_{qi} &= y(R + R_1 - C) + (1 - y)[(R + R_1 - C) - q \times (f_1 \times D + I_1)] \\ &= q(y - 1)(f_1 \times D + I_1) + (R + R_1 - C) \end{aligned}$$

$$\begin{aligned} E_{qui} &= y \times R + (1 - y) \times [R - q \times (f_1 \times D + I_1 + R_4)] \\ &= q(y - 1)(f_1 \times D + I_1 + R_4) + R \end{aligned}$$

$$\begin{aligned} E_q &= x \times E_{qi} + (1 - x) \times E_{qui} \\ &= (y - 1)(f_1 \times D + I_1 + R_4) - xq(y - 1)R_4 + x(R_1 - C) + R \end{aligned}$$

In the same way, we can get the expected benefits of employees' choosing safe behaviors is E_{ks}.The expected benefits of choosing unsafe behaviors is E_{kus}, and the average expected benefits of employees is E_k.

$$E_{ks} = x(R_2 + R_3) + (1 - x)R_3 = xR_2 + R_3 \quad E_{kus} = x \times [R_3 - q \times (f_2 \times D + I_2)] + (1 - x)[R_3 - q \times (f_2 \times D + I_2)] = R_3 - q(f_2 \times D + I_2) \quad E_k = y \times E_{ks} + (1 - y) \times E_{kus} = xyR_2 + q(y - 1)(f_1 \times D + I_2) + R_3$$

Since the game player will adjust the selected strategy at any time according to the change of environment and conditions when selecting the strategy, it will generate a continuous overall dynamic in time, which is called dynamic replication equation [27]. According to the expected benefits of each strategy of the game players, the dynamic replication equation of each game player can be obtained. The dynamic replication equation for enterprises to choose the strategy of increasing safety investment is recorded as $F(x)$, and the dynamic replication equation for employees to choose the strategy of safety behavior is recorded as $F(y)$. Then:

$$F(x) = \frac{dx}{dt} = x\left(E_{qi} - E_q\right) = x(1 - x)\left(E_{qi} - E_{qui}\right) = x(1 - x)[R_1 - C + (1 - y)qR_4]$$

$$F(y) = \frac{dy}{dt} = y(E_{ks} - E_k) = y(1 - y)(E_{ks} - E_{kus}) = y(1 - y)[xR_2 + q(f_2 \times D + I_2)]$$

Let $F(x) = 0, F(y) = 0$, form a set of differential equations to solve, and we can get five equilibrium points of the evolution system of the game subject's strategy selection, respectively:

$$Q_1(0,0)\ ,\ Q_2(0,1)\ ,\ Q_3(1,0)\ ,\ Q_4(1,1)\ ,\ Q_5\left(-\frac{q}{R}(f_2 \times D + I_2), \frac{R_1 - C + q \times R_4}{q \times R_4}\right)$$

According to Friedman's theory, when a group state is described by a set of differential equations, the stability of the system's equilibrium point can be analyzed using the local stability description of the system's Jacobian matrix [28]. Therefore, $F(x)$ and $F(y)$ respectively calculate the partial derivatives of x and y to obtain the Jacobian matrix J of the enterprise and employee strategy evolution game system, as follows.

$$J = \begin{bmatrix} \dfrac{\partial F(x)}{\partial x}, \dfrac{\partial F(x)}{\partial y} \\ \dfrac{\partial F(y)}{\partial x}, \dfrac{\partial F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} (1 - 2x)[R1 - C - q(1 - y)R_4], x(1 - x)qR_4 \\ y(1 - y)R_2, [xR_2 + q(f_2 \times D + I_2)](1 - 2y) \end{bmatrix}$$

When the equilibrium point of the evolutionary game system satisfies the determinant $DetJ = |J| > 0$ of the Jacobian matrix and the trace time $trJ < 0$, the equilibrium point is in a locally stable state, otherwise it is not in a locally stable state [29]. The calculation formula of $DetJ$ and trJ is as follows:

$$\begin{aligned} DetJ = &(1 - 2x)(1 - 2y)[R_1 - C + (1 - y)qR_4] \times [xR_2 + q(f_2 \times D + I_2)] \\ &+ xyq(x - 1)(1 - y)R_2R_4 \end{aligned}$$

Table 1
Income matrix of enterprises and employees.

	Enterprise increase safety investment	Enterprise not increase in safety investment
Employee safety behavior	$(R + R_1 - C,\ R_2 + R_3)$	$(R,\ R_3)$
Employee unsafety behavior	$(R + R_1 - C - q \times (f_1 \times D + I_1),\ R_3 - q \times (f_2 \times D + I_2))$	$(R - q \times (f_1 \times D + I_1 + R_4),\ R_3 - q \times (f_2 \times D + I_2))$

$$trJ = (1-2x)[R_1 - C + (1-y)qR_4] + (1-2y)[xR_2 + q(f_2 \times D + I_2)]$$

Substitute the five equilibrium points of the game system of enterprise and employee strategy evolution into the *DetJ*, *trJ* formula for calculation, and judge whether it is in the local stable point ESS according to its result symbol. The results are shown in Table 2.

It can be seen from Table 2 that the evolutionary game system of enterprise and employee strategy selection has three local stability points, and the stable evolutionary strategy of enterprise and employee is as follows:

(1) When the system is stable at $Q_2(0,1)$, that is the enterprise chooses not to increase the safety investment, and the employees take safety behaviors. This is a low safety investment cost, low safety behavior cost mode.
(2) When the system is stable at $Q_3(1,0)$, that is the enterprise chooses to increase safety investment, and the employees take unsafe behaviors, this is a mode of high safety investment cost and high safety behavior cost.
(3) When the system is stable at $Q_4(1,1)$, that is the enterprise chooses to increase safety investment, and the employees take safety behaviors. At this time, it is a mode of high safety investment income and low safety behavior cost.

4. Model application

4.1. Numerical simulation of game model of enterprise safety investment and employee safety behavior evolution

In order to further analyze the influence of the selection process of both sides of the game, the evolution process of enterprise and employee strategy selection is numerically simulated according to the dynamic replication equation of enterprise and employee strategy selection, and the influence of the probability value of both sides of the game when choosing a strategy on the evolution process of both sides of the game is analyzed.

4.1.1. Numerical simulation of evolution game of enterprise strategy choice

Among the three equilibrium points in Table 2, the conditions of $Q_2(0,1)$ and $Q_3(1,0)$ equilibrium points are approximately the same, so only $Q_3(1,0)$ and $Q_4(1,1)$ equilibrium points are selected for numerical simulation. Assume $R_2 = 4, q = 0.3, f_2 = 0.4, f_1 = 0.6, D = 10, I_2 = 8, t = 30, R_4 = 11$.

(1) When it is at equilibrium point $Q_3(1,0)$, take $C = 6, R_1 = 5$, and select $y = 0.3, y = 0.7$ as the probability value of employees' choice of safety behavior strategy for numerical simulation. The results are shown in Fig. 1.
(2) When it is at the $Q_4(1,1)$ equilibrium point, take $C = 5, R_1 = 6$ and conduct numerical simulation of $y = 0.3, y = 0.7$ respectively. The results are shown in Fig. 2.

4.1.2. Numerical simulation analysis of employee strategy choice evolution game

It can be seen from the three equilibrium points of the evolutionary game of enterprise and employee strategy selection that the conditions involved in employee strategy selection at each equilibrium point are consistent, so equilibrium point $Q_3(1,0)$ is selected for numerical simulation of evolutionary game of employee strategy selection. According to the value of each variable in 2.1 and the dynamic replication equation of employee strategy selection, the probability value $x = 0.3, x = 0.7$ of enterprises' choice to increase safety investment is selected for numerical simulation, and the simulation results are shown in Fig. 3.

5. Results and discussion

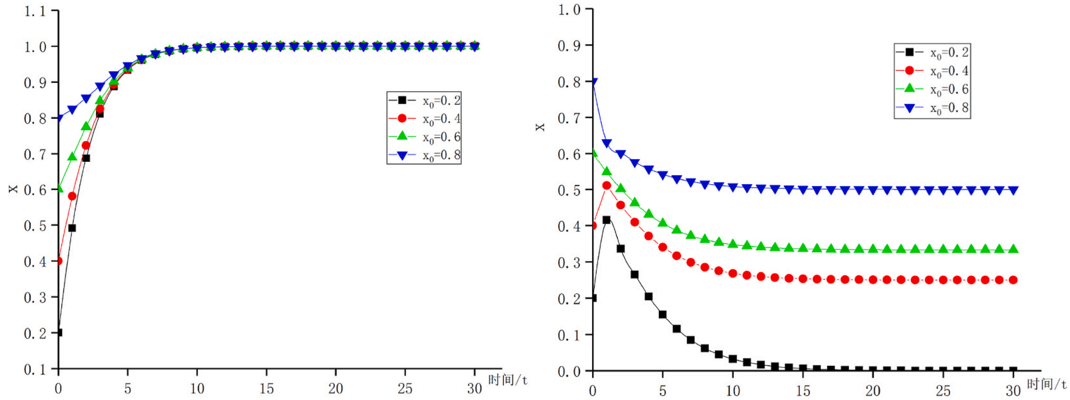
5.1. Results

It can be seen from Fig. 1 (*a*) that when the probability value of employees choosing the safety behavior strategy is low, the enterprise will finally make a decision to increase the safety investment strategy, even if the benefit of safety investment is less than the cost of safety investment at this time.

It can be seen from Fig. 1 (*b*) that when the probability value of employees choosing safety behavior strategy is high, the probability value of enterprises choosing to increase safety investment will gradually decrease over time. Therefore, it can be concluded that the probability value of employees' choice of safety behavior strategy will significantly affect the decision of enterprises' choice of

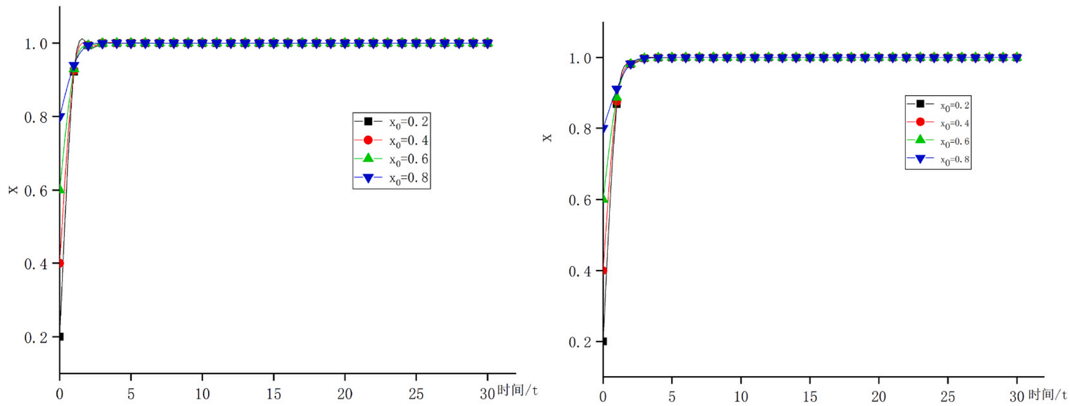
Table 2
Local stability analysis.

Equilibrium point	condition	DetJ Symbol	trJ Symbol	Stability
$Q_1(0,0)$	–	Uncertain	Uncertain	Saddle point
$Q_2(0,1)$	$C > R_1$	+	–	Stability Equilibrium
$Q_3(1,0)$	$C > R_1$, $R_4 < f_2 \times D + I_2$	+	–	Stability Equilibrium
$Q_4(1,1)$	$R_1 > C$	+	–	Stability Equilibrium
Q_5	$C > R_1$, $qR_4 > C - R_1$	+	0	Saddle point



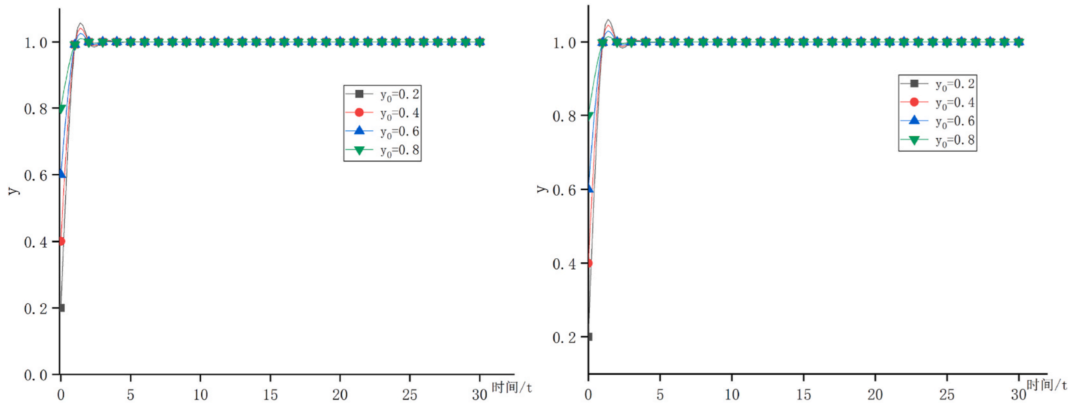
（a） $y = 0.3$ （b） $y = 0.7$

Fig. 1. Numerical simulation of the evolutionary game of corporate strategy at $Q_3(1,0)$ equilibrium.



（a） $y = 0.3$ （b） $y = 0.7$

Fig. 2. Numerical simulation of the evolutionary game of corporate strategy at $Q_4(1,1)$ equilibrium.



（a） $x = 0.3$ （b） $x = 0.7$

Fig. 3. Numerical simulation of evolutionary game of employee strategy selection.

increasing safety investment strategy.

The results are shown in Fig. 2 (a) and (b). It can be seen from the figure that the probability value of employees' choice of safety behavior strategy has no impact on the probability value of enterprises' choice of increasing safety investment. Enterprises will choose to increase safety investment, because at this time, for enterprises, the benefits from increasing safety investment are greater than the costs of increasing safety investment. Therefore, when it is profitable for the enterprise to increase safety investment, the probability value of employees' choice of safety behavior has no impact on the enterprise's strategy choice.

It can be seen from Fig. 3 (a) and (b) that the change of the probability value of the enterprise's increasing safety investment has no impact on the employees' choice of safety behavior strategies. That is, no matter whether the enterprise increases the safety investment or not, the employees all choose the safety behavior strategy.

5.2. Discussion

According to the numerical simulation results of employee strategy selection in Fig. 3, the choice of employee safety behavior strategy is not directly related to the enterprise's safety investment, which shows that employees prefer to choose safety behavior in essence, because safety behavior has an important impact on their own safety protection. However, in the actual operation process, because the selection of their own safety behavior is affected by their own physical state, natural environment and other factors, leading to their inability to make correct safety behavior in emergency or dangerous situations, which leads to the occurrence of safety accidents. Therefore, from the physical state of employees, the physiological mechanism of the occurrence of employees' safety behavior is studied by measuring various physiological parameters of employees, It is a direction for further research in the future to put forward early warning and monitoring on whether employees' physical conditions meet the operation requirements, and then take targeted measures to reduce the rate of safety accidents.

6. Conclusion

Safety investment is the basis of enterprise safety production, and personnel safety behavior is an important way to reduce safety accidents. In order to further explore the relationship between enterprise safety investment decision and employee safety behavior, this paper establishes an evolutionary game model of enterprise safety investment and employee safety behavior from the perspective of traditional game theory, and conducts numerical simulation analysis, which provides a reference for enterprises and employees to choose strategies. The conclusions and recommendations are as follows:

(1) When the profit from increasing safety investment is less than the cost of safety investment, the probability value of employees' adopting safety behavior strategy will significantly affect the decision of enterprise strategy selection. At this time, the enterprise should increase the safety education and training for employees, or take necessary measures to urge employees to take actions that conform to the operation safety specifications, so as to reduce the cost of the enterprise and reduce the occurrence of safety accidents.

(2) When the benefit of increasing safety investment is greater than the cost of safety investment, the strategy adopted by employees will not affect the choice of enterprises to increase safety investment. At this time, the enterprise can appropriately give employees safety rewards, improve employee welfare and other measures to encourage employees to work safely and reduce the occurrence of safety accidents.

Production notes

Author contribution statement

Youcai Xie: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.
Gang Lu: Contributed reagents, materials, analysis tools or data.
Desheng Lai: Performed the experiments.
Meng Tao: Analyzed and interpreted the data.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

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