Research on Game Evolution of Safety Culture

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Abstract. In order to clarify the effectiveness of different measures taken by enterprises to build a safety culture, this paper constructs a tripartite game evolution model consisting of executive, management, and decision-making layers. A logical relationship is established based on the three strategic spaces of employee safety behavior, management behavior, and decision-making layer regulatory behavior. The results show that whether the executive level implements safety behavior is the key to the construction of enterprise safety culture. Increasing fines and rewards can improve the efficiency of enterprise safety culture construction, but increasing fines will reduce the maximum expected value. With the increase in regulatory costs, enterprise safety culture construction efficiency is higher, but excessive regulation will reduce the maximum expected value. The simulation results have certain guiding significance for enterprises to clarify the laws of safety culture construction.

Keywords: safety culture, tripartite game, evolution, strategy, simulation.

1 Introduction

The evolution of safety culture is influenced by several factors and is dependent on the interaction of multiple factors such as the organization, industry, and society. Research on safety culture focuses mainly on defining, measuring, evaluating, and constructing safety culture [1]. Researchers primarily explore the construction of safety culture from the industries' perspective [2-6]. Those research focuses mainly on industries such as mining, construction, power, and medical industries and provides constructive opinions on management systems, equipment, and facilities.

Safety culture evaluation is an important way to identify and correct problems in the process of building a company's safety culture. In order to evaluate the construction status of enterprise safety culture, the evaluation indicators should be clearly defined first, and then the evaluation levels of each indicator should be given. Combined with the evaluation indicators and the current situation of the enterprise, the current state and

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development stage of enterprise safety culture should be determined. According to the characteristics and needs of different organizations, researchers have proposed 2 to 19 evaluation indicators for measuring and evaluating safety culture in foreign countries [7-11], but there is currently no consensus. Summarizing these evaluation indicators, their commonalities are reflected in six indicators: basic characteristics, safety commitment, safety system and environment, safety training and learning, incentive system, and overall participation. However, based on the analysis of the construction content, there is no clear correspondence between the evaluation indicator system and the construction content, which is cross and not independent of each other. There may also be certain difficulties in the specific analysis and evaluation process. On the basis of analyzing a large number of evaluation systems, Wiegmann et al [12] summarized that safety culture has at least five common characteristics, namely organizational commitment, management participation level, employee authorization, reward and punishment system, and reporting system. Compared with the above construction evaluation criteria and guidance opinions in China, these common characteristics have similarities and differences with each other. Therefore, there is currently no unified standard for the evaluation indicators of safety culture construction in China, and it is necessary to clarify the development pattern.

Different organizations and fields have distinct characteristics that affect the construction of safety culture indicators. These indicators influence the practicality of safety measures. For example, in the manufacturing industry [13], safety culture may focus on the operation and maintenance of mechanical equipment, whereas in the medical industry, the focus may be on patient safety and the behavior of medical staff [14]. The different focuses result in various safety culture construction indicators.

In terms of determining safety culture construction indicators and proposing policy opinions, different scholars have conducted relevant research using game theory methods. For a specific industry, Qin Guojun et al [15] proved that a safety culture evaluation model based on game theory can not only make the weight of indicators more in line with the actual situation, but also overcome the uncertainty of safety culture evaluation, and finally make an objective and reasonable evaluation of safety culture; Zhang Yu et al [16] combined the individual perception of workers with evolutionary game theory to construct a subjective game model, providing targeted suggestions for the rapid formation of safety culture; Zhou Jiangtao et al [17] demonstrated through constructing a game model that the good development of enterprises cannot be separated from the construction of safety culture. The government and safety supervision departments should encourage and assist enterprises in building safety culture; Liu Yongliang et al [18] analyzed coal mine safety management and miner violation behavior based on evolutionary game theory, and proposed targeted behavioral countermeasures. The research results of the above scholars have demonstrated the practicality of game theory methods in the process of building a safety culture.

In order to understand the various factors and laws that influence the effectiveness of building a safety culture in a company, this paper aims to employ game theory techniques. This will involve using the execution layer, management layer, and decision-making layer as the key players in a simulation to calculate the development patterns of safety culture. The purpose of this research is to provide theoretical backing for the construction of a safety culture in an enterprise.

2 Method

2.1 Making Hypotheses

To construct a game model, analyze the stability of various strategies and equilibrium points, as well as the impact relationships of various factors, the following assumptions are made:

Assumption 1: Typically, a company can be divided into three levels: decision-making, management, and execution, expressed as senior, middle, and grassroots [19-20]. The three parties of execution, management, and decision-making [21-22] are all participants of bounded rationality, and strategy selection gradually stabilizes and becomes the optimal strategy over time.

Assumption 2: Strategy space of the execution layer $\alpha=\{\alpha1,\alpha2\}$=[Safe behavior, Unsafe behavior], The employee chooses $\alpha1$ with probability x and $\alpha2$ with probability 1-x, $x\in[0,1]$; Management's policy space $\beta=\{\beta1, \beta2\}$=[Implementation inspection, Non-implementation inspection], The management chooses $\beta1$ with probability y and $\beta2$ with probability 1-y, $y\in[0,1]$;The policy space of the decision level $y=\{\xi1, \xi2\}$=[Strict regulation, Loose regulation], The enterprise decision level chooses $\xi1$ with the probability of z, and chooses $\xi2$ with the probability of 1-z, $z\in[0,1]$.

Assumption 3: When a company establishes a good safety culture, its revenue is Rp, the cost of building safe behaviors is Cph, and the cost of building unsafe behaviors is Cpl, with Cph>Cpl. When employees take safety actions, the accident rate of the enterprise is very low, and the employee's income is M1, while the management is G1; The management conducts safety behavior inspections at a cost of Bt, which is less than (Cph-Cpl). When the management team implements inspections and discovers unsafe behaviors of employees, they will be fined Fp; When the inspection is not implemented, the behavior information of employees is unknown.

Assumption 4: When the decision-making level strictly supervises, if it is found that the management does not implement inspections, the management will be fined Ft; If the management implements inspections, employees will receive a reward of Mp if they take safety actions; The management will also receive a reward of Mt. When decision-makers loosen regulation, management's inspection information cannot be obtained. The cost of strict supervision by the decision-making level is Cg.

Assumption 5: The safety behavior of enterprise employees not only helps the company complete projects faster and reduce accidents and casualties, but also plays a good publicity role for the company's long-term development and social reputation, and the company will gain potential benefits. When employees engage in unsafe behavior, accidents occur frequently, and companies begin various types of training and rectification activities, which will increase additional costs. The decision-making level has relaxed supervision, and in the event of an accident, they will be punished by the superior supervisory department, with a penalty amount of Tg and Tg>Cg.

2.2 Building Model

Based on the above assumptions, the strategy game matrices of the executive, management, and decision-making levels are shown in Table 1.

Table 1. Tripartite game model between staff, management and decision maker

Management layer			Decision-maker	
			Strict regulation z	Loose regulation 1-z
Execution layer	safety behavior x	Implement inspection y	M_1+M_p, G_1+M_t, $R_p-C_{ph}-B_t-C_g+A_g$	M_1, G_1, $R_p-C_{ph}-B_t+A_g$
		Non-implementation inspection 1-y	M_1, G_1-F_t, $R_p-C_{ph}-C_g+A_g$	M_1, G_1, $R_p-C_{ph}+A_g$
	Unsafe behavior 1-x	Implement inspection y	M_1-F_p, G_1+M_t, $R_p-C_{pl}-B_t-C_g-D_g$	M_1, G_1, $R_p-C_{pl}-B_t-D_g-T_g$
		Non-implementation inspection 1-y	M_1, G_1-F_t, $R_p-C_{pl}-C_g-D_g$	M_1, G_1, $R_p-C_{pl}-D_g-T_g$

3 Model Analysis

3.1 Analysis of Policy Stability at the Executive Level

The expected benefits and average expected benefits (E11, E12, $\overline{E_1}$) of enterprise employees engaging in safe or unsafe behavior are:

$$E_{11} = yz(M_1 + M_p) + y(1-z)M_1 + (1-y)zM_1 + (1-y)(1-z)M_1 \quad (1)$$

$$E_{12} = yz(M_1 - F_p) + y(1-z)M_1 + (1-y)zM_1 + (1-y)(1-z)M_1 \quad (2)$$

$$\overline{E_1} = xE_{11} + (1-x)E_{12} \quad (3)$$

The replication dynamic equation for enterprise employee strategy selection is:

$$F(x) = \frac{dx}{dt} = x(E_{11} - \overline{E_1}) = -x(x-1)yz(F_p + M_p) \quad (4)$$

The first derivative of x and G(y) are:

$$\frac{d(F(x))}{dx} = (1-2x)yz(F_p + M_P) \quad (5)$$

$$G(y) = yz(F_p + M_p) \quad (6)$$

According to the stability principle of differential equations, the probability of employees choosing safety behavior strategies in a stable state must meet the following conditions: F(x)=0 and d(F(x))/dx<0. Due to $\frac{\delta G(y)}{\delta y} > 0$, G(y) is an increasing function with respect to y.

y,z∈[0,1], when z=0, G(z)=0,here$\frac{d(F(x))}{dx}=0$, Employees can not determine the stability strategy; when y>0, G(y)>0, here$\left.\frac{d(F(x))}{dx}\right|_{x=1}<0$,, Then x∈(0.5,1) are evolutionarily Stable Strategies(ESS) of employees.

3.2 Management Strategy Stability Analysis

The expected benefits and average expected benefits (E21, E22, $\overline{E_2}$) of implementing or not implementing safety inspections by enterprise management are:

$$E_{21}=xz(G_1+M_t)+x(1-z)G_1+(1-x)z(G_1+M_t)+(1-x)(1-z)G_1 \quad (7)$$

$$E_{22}=xz(G_1-F_t)+x(1-z)G_1+(1-x)z(G_1-F_t)+(1-x)(1-z)G_1 \quad (8)$$

$$\overline{E_2}=yE_{22}+(1-y)E_{22} \quad (9)$$

The replication dynamic equation for the strategic selection of enterprise management is:

$$F(y)=\frac{dy}{dt}=y(E_{21}-\overline{E_2})=-y(y-1)z(F_t+M_t) \quad (10)$$

The first derivative of *y* and *J*(*z*) are:

$$\frac{d(F(y))}{dy}=(1-2y)z(F_p+M_p) \quad (11)$$

$$J(z)=z(F_p+M_p) \quad (12)$$

According to the stability principle of differential equations, the probability of employees choosing safety behavior strategies in a stable state must meet the following conditions: F(y)=0 and d(F(y))/dy<0. Due to $\frac{\delta J(z)}{\delta z}>0$, J(z) is an increasing function with respect to z.

z∈[0,1], when z=0, J(z)=0, then$\frac{d(F(y))}{dy}=0$, the enterprise employees cannot determine the stability strategy; when z>0, J(z)>0, then$\left.\frac{d(F(y))}{dy}\right|_{y=1}<0$, y∈(0.5,1) is the ESS of the management level.

3.3 Analysis of Strategy Stability of Decision-maker

The expected benefits and average expected benefits (E31, E32, $\overline{E_3}$)of implementing strict supervision or not implementing strict supervision by the decision-maker level of enterprises are:

$$E_{31}=xy\left(R_p-C_{ph}-B_t-C_g+A_g\right)+x(1-y)\left(R_p-C_{ph}-C_g+A_g\right)+(1-x)y\left(R_p-C_{pl}-B_t-C_g-D_g\right)+(1-x)(1-y)\left(R_p-C_{pl}-C_g-D_g\right) \quad (13)$$

$$E_{32} = xy(R_p - C_{ph} - B_t + A_g) + x(1-y)(R_p - C_{ph} + A_g) + (1-x)y(R_p - C_{pl} - B_t - D_g - T_g) + (1-x)(1-y)(R_p - C_{pl} - D_g - T_g) \quad (14)$$

$$\overline{E_3} = zE_{31} + (1-z)E_{32} \quad (15)$$

The replication dynamic equation for the strategy selection of enterprise decision-makers is:

$$F(z) = \frac{dz}{dt} = z(E_{31} - \overline{E_3}) = z(z-1)(C_g - T_g + xT_g) \quad (16)$$

The first derivative of z and H(x) are:

$$\frac{d(F(z))}{dz} = (2z-1)(C_g - T_g + xT_g) \quad (17)$$

$$H(x) = C_g - T_g + xT_g \quad (18)$$

According to the stability principle of differential equations, the probability of employees choosing safety behavior strategies in a stable state must meet the following conditions: F(z)=0 and d(F(z))/dz<0. Due to $\frac{\delta H(x)}{\delta x} > 0$, H(x) is an increasing function with respect to x.

x ∈ [0,1], when $x = 1 - \frac{C_g}{T_g}$, H(x)=0, then $\frac{d(F(y))}{dy} = 0$, the enterprise decision-maker level cannot determine the stability strategy; when x>$(1 - \frac{C_g}{T_g})$, H(x)>0, then $\left.\frac{d(F(z))}{dz}\right|_{z=0} < 0$, y∈(0.5,1) is the ESS of the management level.

3.4 Stability Analysis of Equilibrium Points in Tripartite Evolutionary Game Systems

From F(x)=0, F(y)=0, F(z)=0, Obtaining system equilibrium point E1(0, 0, 0), E2(0, 1, 0), E3(0, 0, 1), E4(1, 0, 0), E5(1, 1, 0), E6(1, 1, 1), E7(0,1,1), E8(1,0,1), E9(Tg-Cg/Tg,0,1), E10(Tg-Cg/Tg, 1, 0), Since Tg>Cg, all points are meaningful. The Jacobian matrix for constructing a three-way evolutionary game is:

$$J = \begin{vmatrix} \frac{\delta F(x)}{\delta x} & \frac{\delta F(x)}{\delta y} & \frac{\delta F(x)}{\delta z} \\ \frac{\delta F(y)}{\delta x} & \frac{\delta F(y)}{\delta y} & \frac{\delta F(y)}{\delta z} \\ \frac{\delta F(z)}{\delta x} & \frac{\delta F(z)}{\delta y} & \frac{\delta F(z)}{\delta z} \end{vmatrix} = \begin{vmatrix} (1-2x)yz(F_p + M_p) & -x(x-1)z(F_p + M_p) & -x(x-1)y(F_p + M_p) \\ 0 & (1-2y)z(F_p + M_p) & -y(y-1)(F_p + M_p) \\ z(z-1)T_g & 0 & (2z-1)(C_g + T_g + xT_g) \end{vmatrix} \quad (19)$$

The eigenvalues obtained by solving the matrix are shown in Table 2.

Table 2. Jacobian matrix eigenvalues

Equilibrium point	*Jacobian* matrix eigenvalues
$E_1(0, 0, 0)$	$0, 0, -C_g-T_g$
$E_2(0, 1, 0)$	$0, 0, -C_g-T_g$
$E_3(0, 0, 1)$	$0, F_p+M_p, C_g+T_g$
$E_4(1, 0, 0)$	$0, 0, -C_g-2*T_g$
$E_5(1, 1, 0)$	$0, 0, -C_g-2*T_g$
$E_6(1, 1, 1)$	$C_g+2*T_g, -F_p-M_p, -F_p-M_p$
$E_7(0, 1, 1)$	$-F_p-M_p, F_p+M_p, C_g+T_g$
$E_8(1, 0, 1)$	$0, C_g+2*T_g, F_p+M_p$
$E_9(x_1, 0, 1)$	$0, F_p+M_p, C_g+T_g+T_g*x_1$
$E_{10}(x_1, 1, 0)$	$0, 0, -C_g-T_g-T_g*x_1$

4 Results

Referring to the actual situation of the enterprise, assign array 1 as employee penalty amount Fp=100, employee reward amount Mp=150, management penalty amount Ft=200, management reward amount Mt=250, regulatory cost Cg=50, and superior penalty Tg=300; Array 2 is assigned the values of employee fine Fp=150, employee reward Mp=200, management penalty Ft=250, management reward Mt=300, regulatory cost Cg=70, and superior penalty Tg=350. Simulate using Matlab r2022b software.

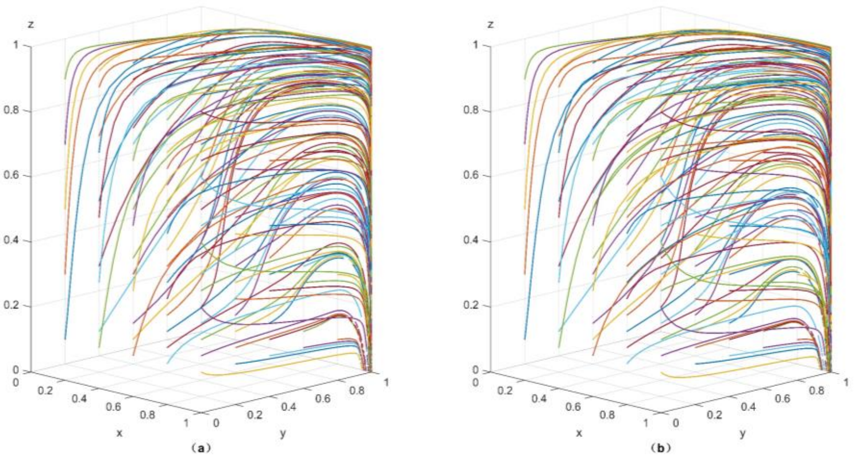

Fig. 1. Results of 50 evolutions of arrays (a) indicates the result of 50 evolutions of array 1; (b) indicates the result of 50 evolutions of array 2)

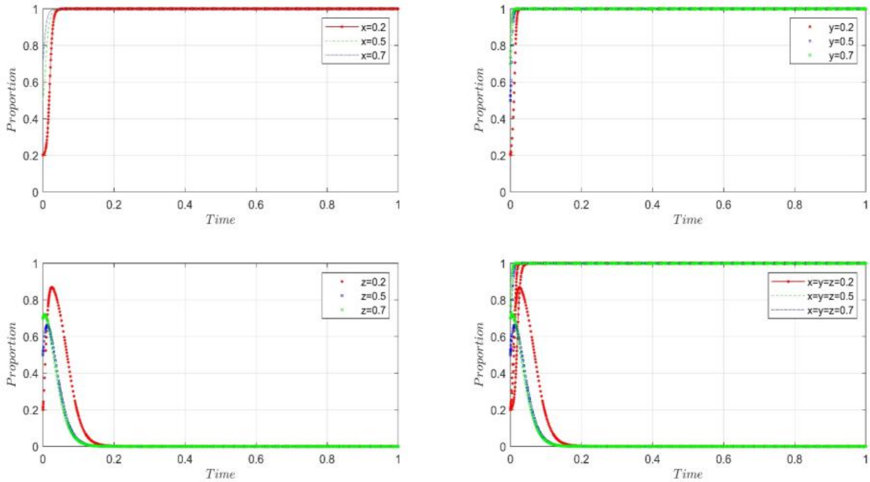

Fig. 2. Simulation of the evolution of a three-party subject

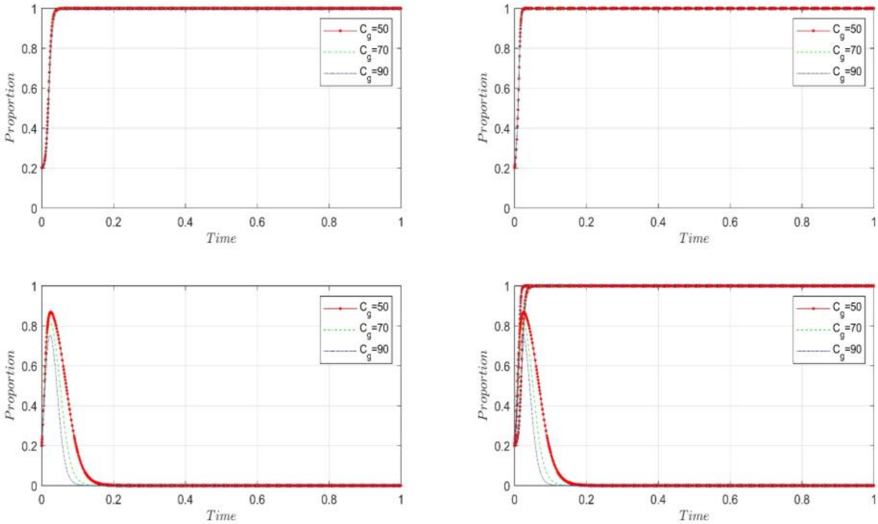

Fig. 3. Simulation of the evolution of the game subject with different C_g

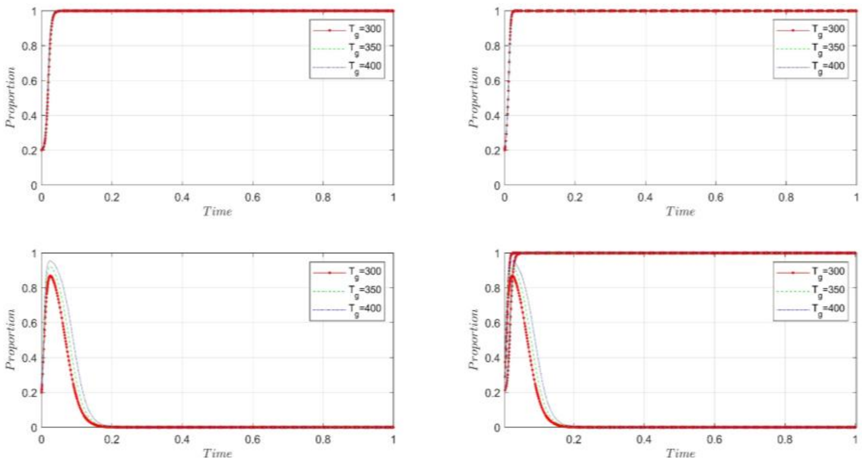

Fig. 4. Simulation of the evolution of the game subject with different T_g

As shown in Figure 1, after evolving arrays 1 and 2 50 times, the results show that E(1, 1, 0) is an unstable equilibrium point, and the system only has one evolutionary stable policy combination (safe behavior, implementation checks, and loose supervision).

As shown in Figure 2, it can be seen that the evolution of the three main entities, namely employees, management, and decision-making, varies. It can be seen that whether employees implement safety behavior is the key to building a company's safety culture. The implementation of safety behavior by employees can achieve the best results in the construction of corporate safety culture. Relying on management inspections and strict supervision by decision-making can quickly complete the construction of corporate safety culture, but the effect is limited.

In the short term, increasing fines for employees can speed up the construction of a safety culture, but it can lower the expected value of such construction.

Figure 3 shows that increasing regulatory costs lead to a faster rate of corporate safety culture construction. However, excessive regulation reduces the maximum expected value of corporate safety culture construction.

As shown in Figure 4, it is evident that enhancing the punishment imposed by the higher-level government on enterprises can enhance the effectiveness of constructing a safety culture within the enterprise. However, this measure can also impede the pace of building the safety culture within the enterprise.

5 Discussion

The simulation results indicate the effectiveness pattern of enterprise safety culture construction. Whether the execution team implements safety behaviors is the key to building a company's safety culture, which is consistent with the views of Ding Maoting

[23], Hu Yu [24]et al. Currently, a problem in China's safety production work is that the individual role of employees has not been fully utilized, and the safety culture atmosphere is not strong.

Increasing fines and rewards can improve the efficiency of enterprise safety culture construction, but increasing fines will lower the maximum expected value of enterprise safety culture construction. As the amount of administrative penalties imposed by higher authorities increases, the probability of strict supervision by enterprise management increases. Scholz J T et al. [25-26] also pointed out that fines imposed by regulatory agencies are an important factor affecting safety, and a reduction in fines can lead to a 22% increase in personal injury accidents. However the efficiency of reaching the stable point of the system decreases.

For decision-makers, with the increase in regulatory costs, the efficiency of building a corporate safety culture is higher. However, excessive regulation will lower the maximum expected value, and the increase in regulatory costs will reduce the enthusiasm of decision-makers to engage in regulatory behavior [27].

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