Nuclear Engineering and Technology 54 (2022) 909–916

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original article

The game of safety behaviors among different departments of the nuclear power plants

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ARTICLE INFO

Article history:
Received 2 February 2021
Received in revised form
1 September 2021
Accepted 4 September 2021
Available online 7 September 2021

Keywords:
Evolutionary game
Nuclear power plants
Unsafe behavior
Safety investment

ABSTRACT

To study the developments and variations of unsafe behaviors in nuclear power plants thus reduce the possibility of human-related accidents, this paper, based on the Game Theory, focused on the changes in benefits of the Department of Management, Operational and Emergency in a nuclear power plant, and established the expected revenue functions of these departments. Additionally, the preventive measures of unsafe behaviors in nuclear power plants were also presented in terms of these 3 departments. Results showed that the violations of the Operation Department (OD) and the Emergency Department (ED) were not only relevant with the factors such as their own risks, costs, and the responsibility-sharing due to accidents, but also affected by the safety investments from the Management Department (MD). Furthermore, results also showed that the accident-induced responsibility-sharing of both the OD and the ED would rise, if the MD increased the investments in safety. As a result, the probability of violation behaviors of these 3 departments would be attenuated consciously, which would reduce the unsafe behaviors in the nuclear power plants significantly.

1. Introduction

Safety in the nuclear power plants(NPPs) is strongly related to people's health, property security, national economic developments and social stability. Nuclear safety is always the focus of all countries in the world. The Chernobyl nuclear accident occurred in 1986 is still affecting the local environment. Due to workers' unsafe behavior (such as misconducts), the containment vessel ruptured and fire was triggered, which brought the fission products and fallout into the atmosphere. Consequently, the radiation dispersed to most parts of eastern, northern and western of Europe. More than 335,000 people were forced to evacuate from the region. The immediate death resulted from the accident was 53, with thousands of people suffering from chronic radiation-related illnesses [1]. In 1999, similar unsafe behavior led to an accident in Japan's Tokamura uranium processing facility, where workers were poorly trained. The operators cut corners and ignored several safety issues when they were refining uranium fuel. Several steps of the refinery process were skipped to meet the deadline. As a result, two workers died from radiation exposure and dozens of people were exposed to higher-than-normal levels of radiation [2]. In recent years, the Chinese government has been paying more and more attention to the safety issues in nuclear industry. And a series of laws and regulations have been issued, which put the nuclear safe operations and safety procedures in nuclear plants in the form of laws to prevent accidents. The safety accident in NPPs have been reported in recent decades, although some accidents were caused by force majeure. For example, on 11 March 2011, the devastating Level 9.0 earthquake and tsunami that occurred in the north-eastern Japan, led to severe accidents in the No.I Nuclear Power Plant in Fukushima. However, most accidents were caused by unsafe behaviors of the staff of different departments in NPPs [3]. The Unsafe behavior is a human error that causes a high probability of accidents, and the misconduct is one type of the unsafe behaviors [4,5]. In this paper, unsafe behavior refers to the human errors of the MD, OD and ED in NPPs that may lead to accidents or increase accident losses. Therefore, it is of practical significance to investigate the unsafe behaviors in the NPPs and reduce the possibility of human-related accidents.

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https://doi.org/10.1016/j.net.2021.09.005
1738-5733/

There have been a few researchers studying the behaviors of different departments in some engineering by means of Evolutionary Game Theory in recent years, and they produced some interesting findings. These studies proved that the Evolution Game is an applicable method of the human behaviors. Consequently, we used some previous findings and the Evolutionary Game Theory to investigate the safety behavior in NPPs in this paper. The recent developments and progress in the studies on Evolutionary Game, the safety behaviors in general engineering, and the safety behaviors in NPPs have been reviewed as below.

The Evolutionary Game has been widely applied in various fields, such as economy, management and business operations [4–7]. Zhao [8] investigated the Game model between supervision departments and enterprises using the Evolutionary Game Theory and analyzed the factors affecting the safety behaviors of enterprises. Liu [9] applied the Prospect Theory and the Psychological Account Theory to the research of safety behaviors in coal mine engineering and combined the Evolutionary Game Theory to discuss the safety behaviors of miners, supervisors and managers under the equilibrium state. Gao [10] introduced the Prospect Theory and risk perception factors into the Evolutionary Game analysis, and modified the traditional payment matrix parameters through prospect value and weight function, and also analyzed the conditions that all departments reached a stability state in the major engineering.

On the other hand, a few researchers carried out some studies on safety behaviors in general engineering, in terms of the cooperative relationship, risks, profit distributions, reward and punishment mechanisms of all departments during the engineering. Tang et al. [11] believed that the cooperation among different departments in a project is one of the basic ways to enhance risk management abilities and reduce risks, by constructing the ‘project partner model’ and analyzing its mechanism. Bing et al. [12] hold the view that most macro and micro risks are shared by public or private sectors, while medium risks are shared by private sectors. Micheli et al. [13]and Martinus et al. [14] believed the basic criteria of risk sharing was constituted of several factors, including the cognition degree of risk, the ability of control, the risk willingness and the ability of participants. Tam [15] pointed out that the project risk management could usually reduce the uncertainty of risk occurrence to an acceptable level, and then allocates the responsibility to the most suitable party/department. Korytarova [16] found that public sectors needed to share all or part of the cost risks to prevent the moral hazard by establishing a risk-sharing proportion model that could affect the project costs. Lam et al. [17] used fuzzy mathematical methods to analyze the risk sharing between public and private sectors, and obtained some similar results as Korytarova [16]. Tang [18] analyzed the incompleteness of contracts and believed that risk-sharing was dynamic and should be adjusted constantly during the whole project.

Furthermore, studies concerning the safety behaviors in NPPs mainly focused on the factors that affected human-factorial reliability of the plants. For example, Reason [19] claimed that the reasons for human-related accidents should be investigated in terms of the management. In addition, Reason also tried to scrutinized into the reasons for the unsafe behavior of the staff in the MD and OD. Findings of Reference [20,21] also supported this conclusion. What's more, organizational factors were regarded as a key factor that affected the safety and management of the nuclear power plant. Based on that, Lee [22] tried to establish the 3-dimensional organizational equations. However, Rasmussen [23] declared that the departments in a nuclear power plant should be both centralized and decentralized, and it was necessary for the OD to adopt centralized activities. Meanwhile, Wagennar [24] and Ovale [25] made some further studies on the error-leading effects of the organizational factors.

In addition, in the studies on the human-related accidents caused by a crew (or a team) of the nuclear power plant, Rouse [26] established a psychological model and discussed the communication, collaboration and behaviors among different crews, which was regarded to be the crew model of the plant. There were still some researchers applying the computational methods to study the crew behaviors in NPPs. For example, Sasou [27,28] carried some system simulation to investigate the decision-making of the crew, and analyzed the decision-making ability of different crews in a plant under abnormal conditions. Shu [29] concentrated on the cognitive process of different crews through system analysis, and the reliability of the crews was also analyzed. Similar work was also carried out by researchers from the University of Maryland, who presented the IDA model to describe the cognitive development during work [30,31]. There were still some studies on human-related accidents in nuclear power plant in recent years [32–35], results of which were in accordance to the research above. In addition, a few Chinese researches have conducted some studies on the safety behaviors of the staff in NPPs since the 1990s, and they made a few interesting findings that have been already used in really NPPs [36–41]. All these studies in this field placed solid basis for this study. The literature review above indicated that the existing research mainly focused on the safety behaviors in different sectors or departments in general engineering projects and public projects, as well as the safety behaviors of the staff in NPPs, while the studies on safety behaviors issues of different bodies or departments in NPPs has been seldom reported. Meanwhile, the nuclear power plant consists of not only the common components like the MD and OD, but also include a special department of ED. This differences in the organization of the NPPs also enhance the necessity of this study. Therefore, we selected the Evolutionary Game Theory in this study to investigate the changes in profits of the MD, the OD and ED under different choices of strategies. Based on that, we presented the expected revenue function. In addition, the Evolutionary Game model between the OD and ED was also established, as well as the Game model among the MD, OD and ED. Finally, prevention measures of the unsafe behaviors in NPPs were put forward, in terms of the perspectives of these 3 departments, respectively.

The novelties of this study are as follows. First of all, safety issues of NPPs were investigated in terms of unsafe behaviors of the internal departments of NPPs, which has seldom been conducted in previous studies. We carried out this study in such a new method due to the fact that the unsafe behaviors of the departments in NPPs may give rise to the safety accidents/incidents significantly. The new method may produce a new research direction for future studies. Furthermore, the ED was introduced into the study of the unsafe behaviors. By introducing ED into the game, we established a 3- party game (among ED, MD, and OD) that is different from the traditional 2-party game (between MD and OD). Consequently, this study may contribute to the development of the evolutionary game theory in NPPs. The significance of this study lies in that it could provide some references for the decision-making on the everyday safety management of the MD, OD, and ED in NPPs. Additionally, it might also act as an important aspect of the safety culture development in nuclear power industries.

The paper is divided into four chapters. Following this introductory chapter that provides a background study and comprehensive literature review, Chapter 2 gives the method used for the evolutionary game model and basic assumptions. Chapter 3 provides the results and discussions that put forward the EG model among MD, OD, ED, and analyzes the evolutionary stability strategy. Chapter 4 draws some conclusive findings and implications for practical engineering.

2. Methods: The evolutionary game

The Evolutionary Game Theory (EGT) was adopted in this study to analyze the safety behaviors in NPPs. The EGT claims that all 'players' with bounded rationality cannot judge their own states accurately in the game [42]. And they usually need some strategies to evolve into a relative stable state gradually. A typical advantage of the EGT is that it is established based on the theories of biological evolution and genetic gene theory [43]. Consequently, it has a more systematic perspective. During the analysis of the safety behaviors in NPPs, it usually treats the adjustments of each department in NPPs as dynamic processes, so the behavior of each department, as well as the interplay among these departments, could be well described. As a result, the variety and complex of the behaviors of each department could be observed, and more sophisticated references and implications could be provided for the safety behaviors management in NPPs.

In this study, 4 assumptions were made. The reason why we took four assumptions was that the complexity of the environment, information asymmetry and the human factors were common in the working processes of the MD, OD and ED in NPPs. During the working process, these three departments were all regarded as the 'players' with bounded rationality because of these factors. (In this study, we incorporated the 'supervision department' into the MD, to simplify the calculation, although the 'supervision department' has sometimes been considered separately in some studies [44].). Consequently, each of three departments would have different options or measures to obtain its own relative stability, which however might bring safety risks to the NPPs. Therefore, these assumptions were presented to provide a better way for the analysis of the EG model.

The general processes that how we conducted four assumptions were given below. In EGT, the maximization of the revenue is an important criterion of the development of each department. All these three departments usually take some measures according to their own revenue states in order to realize a dynamic balance, which is the assumption of the EGT in this study. Based on the revenue states, the MD usually has 2 options, increasing or reducing the safety investments. And the OD also has 2 choices, conducting normally or misconducts. Besides, The ED can also choose to conduct regular emergency behaviors or to violate the standard emergency regulations. These assumptions were detailed below.

Assumption 1: provided that the probability of the MD to increase its safety investment is θ ($0 \leq \theta \leq 1$), the probability of the MD not to increase its safety investment is 1-θ. In the case that the safety investment remains unchanged, the profit of the MD is *I*, and the total wages paid to employees is *R*. While in the case of increasing the safety investment, additional cost of the MD on safety is *C*, and the total welfare benefits of the OD is *E*, and the additional profit obtained by the MD is I_1.

Assumption 2: provided that the probability of the OD running under normal procedures is x ($0 \leq x \leq 1$), then the total wages of the OD is *A*, and the labor cost and other costs are *D,* and the risk to undertake is *H*. Provided that the probability of safety accidents in the NPPs is ∂, and that the responsibility of the accidents g is undertaken by the MD, the probability of OD to conduct violations is 1-x. In this case, the labor cost of the OD decreases by D_1 and the risk to undertake increases by *H*. Provided that the probability of safety accident occurs in NPPs is β, obviously β is greater than ∂. In such case, the OD will have to undertake part of the responsibility of the accident *G*, with the proportion of λ. In addition, the OD will also be fined by *B,* as a penalty.

Assumption 3: provided that the probability of ED adopting standardized emergency behaviors is y ($0 \leq y \leq 1$), and that the wage income is *M*, the labor cost and other costs are *J*, and the risk assumed is H_2, the ED will not be required to undertake any responsibility when an accident occurs, and it may also reduce the loss of safety accidents with a proportion of γ. Meanwhile, the probability of ED to conduct violating emergency activities is 1-y. In this case, the labor cost of the ED decreases by J_1 and the risk may increase by H_3. Meanwhile, the loss of accidents is likely to be reduced, with a proportion of μ and $0 \leq \mu \leq \gamma$. However, the ED may also undertake part of the responsibilities, with a proportion of λ_1. In the meantime, it will also be fined by *F*, as a penalty.

Assumption 4: In the case of safety investment reduction, the additional profit obtained by the MD is I_2. Under this circumstance, the safety consciousness of the OD and ED would reduce due to the lack of safety training and the large psychological gap, etc., and the probability of the violation by OD increases by x_1, while the probability of the ED conducting the violating emergency activities increases by y_1.

The game tree among 3 bodies/parties (the MD, OD and ED) was shown in Fig. 1. Taking Node ⑧ as an example, Node ⑧ indicated that when the MD increased the safety investment, the ED will adopt standard emergency behaviors if the OD conducted violations.

1) From the perspective of the MD, its profit is $I + I_1$, and its employees' total salaries are *R*, its additional safety investment costs are *C*. In the meantime, the responsibility undertaken by MD is $\beta G(1\text{-}\gamma)(1\text{-}\lambda)$. As a result, the total profits of the MD will be $I + I_1\text{-}R\text{-}C\text{-}\beta G(1\text{-}\gamma)(1\text{-}\lambda)$.

2) From the perspective of the OD, its total welfare and profits are *E*, and the wage is *A*, the labor cost is $D\text{-}D_1$. Meanwhile, the risk to be undertaken by the OD is $H+H_1$, and the responsibility due to accidents is $\beta G\lambda(1\text{-}\gamma)$, with a penalty of βB. As a result, the total profits of the OD will be $E + A$ - $(D\text{-}D_1) - (H + H_1) - BB\text{-}\beta G\lambda(1\text{-}\gamma)$.

3) From the perspective of the ED, its total salary is *M*, and the total labor cost is *J*. In addition, the risk to be undertaken is H_2. Consequently, the total profits of the ED will be $M - J - H_2$. Similarly, profits of the MD, OD and ED of Node ⑨ to Node ⑮ could also be analyzed. The results were given in Table 1 and Table 2, in the form of the profit matrix.

3. Results and discussions

In this section, firstly we assumed that the MD chose to increase the investments on safety, due to the fact that all the MD always paid close attention to the safety in the NPPs. Based on the assumption, we analyzed the EG model between the OD and ED. Thereafter, we considered the real situation that the MD would not always increase the safety investment, so we put the MD into the 3-party game, and analyzed the EG model among these 3 departments in NPPs, which might be a real situation in practical applications.

3.1. Analysis of EG model between the OD and ED

3.1.1. The game model analysis under the circumstance that the MD increased the safety investment

Firstly, the EG model analysis between the OD and the ED was conducted when the MD increased the safety investments. According to the EGT, the expected revenue of the OD when adopting the normal procedures was defined in Equation (1).

$$E_{A1} = E + A - D\text{-}\ H \tag{1}$$

Meanwhile, the expected revenue of the OD when adopting abnormal procedures was defined in Equation (2).

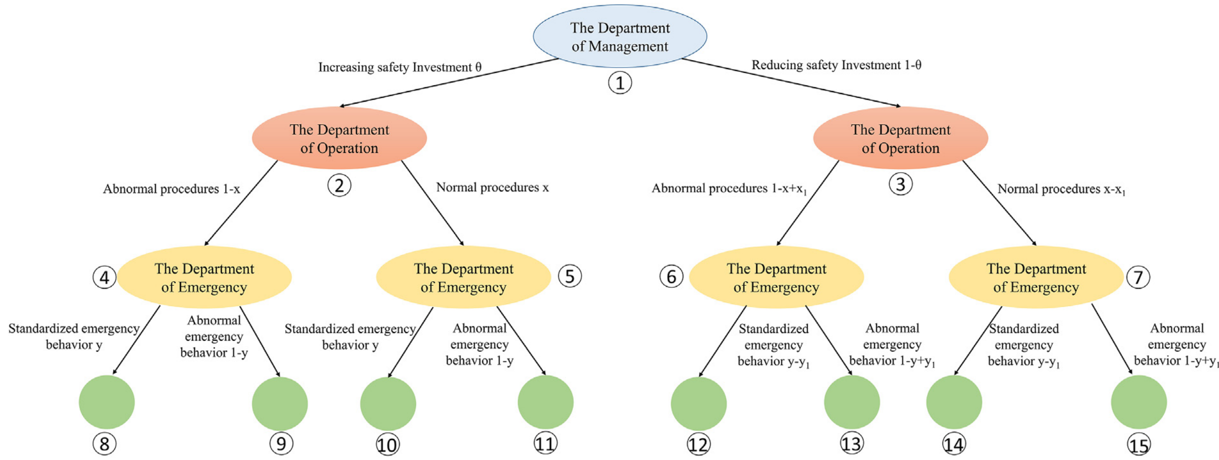

Fig. 1. The evolutionary game tree among the MD, OD and ED.

Table 1
The benefit matrices of the MD, OD and ED when the MD increased the safety investment.

The Department of Emergency	The Department of Management	
	Operations according to normal procedures x	Abnormal operations 1-x
Standard emergency behaviors y	Node ⑩ U_{A1}: $I+I_1-R-C-\partial g(1-y)$ U_{B1}: $E+A-D-H$ U_{C1}: $M-J-H_2$	Node ⑧ U_{A2}: $I+I_1-R-C-\beta G(1-y)(1-\lambda)$ U_{B2}: $E+A-(D-D_1)-(H+H_1)-\beta B-\beta G\lambda(1-y)$ U_{C2}: $M-J-H_2$
Abnormal emergency behaviors 1 - y	Node ⑪ U_{A3}: $I+I_1-R-C-\partial g(1-\mu)(1-\lambda_1)$ U_{B3}: $E+A-D-H$ U_{C3}: $M-(J-J_1)-(H_2+H_3)-\partial F-\partial g\lambda_1(1-\mu)$	Node ⑨ U_{A4}: $I+I_1-R-C-\beta G(1-\mu)(1-\lambda-\lambda_1)$ U_{B4}: $E+A-(D-D_1)-(H+H_1)-\beta B-\beta G\lambda(1-\mu)$ U_{C4}: $M-(J-J_1)-(H_2+H_3)-\beta F-\beta G\lambda_1(1-\mu)$

$$E_{A2}=E+A-(D-D_1)-(H+H_1)-\beta B-\beta G\lambda(1-\mu)+y\beta G\lambda(\gamma-\mu) \tag{2}$$

Consequently, the average expected revenue of the OD obtained in terms of Equation (1) and Equation (2) is given by Equation (3):

$$\bar{E}_A=xE_{A1}+(1-x)E_{A2} \tag{3}$$

As a result, the expected revenue of the ED based on Equation (4) and Equation (5) was acquired in Equation (6).

$$\bar{E}_B=yE_{B1}+(1-y)E_{B2} \tag{6}$$

Setting

$$F(x,y)=x(E_{A1}-\bar{E}_A)=x(1-x)(H_1-D_1+\beta B+\beta G\lambda(1-\mu)-y\beta G\lambda(\gamma-\mu)) \tag{7}$$

$$H(x,y)=y(E_{B1}-\bar{E}_B)=y(1-y)(H_3-J_1+\beta F+\beta G\lambda_1(1-\mu)-x(F(\beta-\partial)+\lambda_1(1-\mu)(\beta G-\partial g))) \tag{8}$$

In addition, the expected revenue of ED when adopting standardize emergency behaviors was defined in Equation (4).

$$E_{B1}=M-J-H_2 \tag{4}$$

and the expected revenue of ED when taking abnormal emergency behaviors was defined in Equation (5).

$$E_{B2}=M-(J-J_1)-(H_2+H_3)-\beta F-\beta G\lambda_1(1-\mu)+x(F(\beta-\partial)+\lambda_1(1-\mu)(\beta G-\partial g)) \tag{5}$$

Consequently, the dynamic differential equations based on the Evolutionary Game, under the circumstance that the OD chose to conduct normal procedures, and the ED adopted standardized emergency behaviors, could be obtained as Equations (9) and (10), respectively.

$$\frac{dx}{dt}=F(x,y) \tag{9}$$

Table 2
The benefit matrices of the MD, OD and ED when the MD reduced the safety investment.

The Department of Emergency	The Department of Management	
	Operations according to normal procedures x-x_1	Abnormal operations 1-x+x_1
Standard emergency behaviors $y - y_1$	Node ⑭ U_{A5}: I-R-∂g(1-y)+I_2 U_{B5}: A-D-H U_{C5}: M-J-H_2	Node ⑫ U_{A6}: I-R-βG(1-y)(1-λ)+I_2 U_{B6}: A-(D-D_1)-(H+H_1)-βB-$\beta G\lambda$(1-y) U_{C6}: M-J-H_2
Abnormal emergency behaviors $1 - y + y_1$	Node ⑮ UA7: I-R-∂g(1-μ)(1-λ_1)+I_2 U_{B7}: A-D-H U_{C7}: M-(J-J_1)-(H_2+H_3)-∂F-∂gλ_1(1-μ)	Node ⑬ U_{A8}: I-R-βG(1-μ)(1-λ-λ_1)+I_2 U_{B8}: A-(D-D_1)-(H+H_1)-βB-$\beta G\lambda$(1-μ) U_{C8}: M-(J-J_1)-(H_2+H_3)-βF-$\beta G\lambda_1$(1-μ)

$$\frac{dy}{dt} = H(x,y) \tag{10}$$

According to the stability theorem of the differential equation, the probability x or y to choose this strategy must be meet the criterion of Equation (11) respectively, so as to keep a certain strategy in a stable state.

$$F(x,y) = 0, \quad \frac{\partial F}{\partial x} < 0 \text{ or } H(x,y) = 0, \quad \frac{\partial H}{\partial y} < 0 \tag{11}$$

By solving Equation (11), solutions of the probability$x$and$y$ could be acquired as $(0,0)$ $(0,1)$ $(1,0)$ $(1,1)$, (x_o, y_o). Among them, $x_o = \frac{H_3 - J_1 + \beta F + \beta G\lambda_1(1-\mu)}{F(\beta - \partial) + \lambda_1(1-\mu)(\beta G - \partial g)}$, $y_o = \frac{H_1 - D_1 + \beta B + \beta G\lambda(1-\mu)}{\beta G\lambda(\gamma - \mu)}$.

Furthermore, the corresponding Jacobean matrix was given by Equation (12).

$$J = \begin{bmatrix} \frac{\partial F}{\partial x} & \frac{\partial F}{\partial y} \\ \frac{\partial H}{\partial x} & \frac{\partial H}{\partial y} \end{bmatrix} = \begin{bmatrix} (1-2x)(H_1 - D_1 + \beta B + \beta G\lambda(1-\mu) - y\beta G\lambda(\gamma - \mu)) & x(1-x)\beta G\lambda(\mu - \gamma) \\ -y(1-y)(F(\beta - \partial) + \lambda_1(1-\mu)(\beta G - \partial g)) & (1-2y)(H_3 - J_1 + \beta F + \beta G\lambda_1(1-\mu) - x(F(\beta - \partial) + \lambda_1(1-\mu)(\beta G - \partial g))) \end{bmatrix} \tag{12}$$

3.1.2. *Stability analysis of the evolutionary strategy of the OD*

If$F(x,y) = 0$, $\frac{\partial F}{\partial x} < 0$, x was the evolutionary stability strategy of the OD. Setting the solution of Equation (7) to be 0, we obtained x = 0, x = 1 and y = (H_1 − D_1 +βB +βGλ(1-μ)/βGλ(γ-μ).

When $y = (H_1 - D_1 + \beta B + \beta G\lambda(1-\mu))/\beta G\lambda(\gamma - \mu)$, $F(x) = 0$ was always true. It indicated that in this case, all levels were stable, and the probability of the OD conducting the normal procedures, x, would not change with the time.

However, when $y > (H_1 - D_1 + \beta B + \beta G\lambda(1-\mu))/\ \beta G\lambda(\gamma - \mu)$, $x = 0$and$x = 1$ were two strategies of x. Then we obtained $F'(0) > 0$ and $F'(1) < 0$, which meant that the probability of the OD conducting normal procedures, that was x = 1, was the equilibrium point. It indicated that conducting the normal procedures was the evolutionary stability strategy of the OD, when the OD's total profits were greater than its total costs through normal procedures. Finally, when $y < (H_1 - D_1 + \beta B + \beta G\lambda(1-\mu))/\beta G\lambda(\gamma - \mu)$, x = 0 and x = 1 were two strategies of x. Then we obtained $F'(0) < 0$ and $F(1) > 0$, which meant that the probability of the OD conducting normal procedures, that was x = 0, was the equilibrium point. It indicated that conducting the abnormal procedures was the evolutionary stability strategy of the OD, when the OD's total profits were less than its total costs through normal procedures.

3.1.3. *Stability analysis of the evolutionary strategy of the ED*

If $H(x,y) = 0$ and $\partial H/\partial y < 0$ were true, y would be the evolutionary stability strategy of the OD. Setting the solution of Equation (8) to be 0, we obtained y = 0, y = 1 and $x = \frac{H_3 - J_1 + \beta F + \beta G\lambda_1(1-\mu)}{F(\beta - \partial) + \lambda_1(1-\mu)(\beta G - \partial g)}$.

When$x = \frac{H_3 - J_1 + \beta F + \beta G\lambda_1(1-\mu)}{F(\beta - \partial) + \lambda_1(1-\mu)(\beta G - \partial g)}$, $H(y) = 0$ was always true. It indicated that in this case, all levels were stable, and the probability of the ED adopting standardized emergency behaviors, that was y, did not change with the time.

However, when$x > \frac{H_3 - J_1 + \beta F + \beta G\lambda_1(1-\mu)}{F(\beta - \partial) + \lambda_1(1-\mu)(\beta G - \partial g)}$, y = 0 and y = 1 were two strategies of y. Then we obtained $H'(0) > 0$ and $H'(1) < 0$, which meant that the probability of the ED adopting standardized emergency behaviors, that was y = 1, was the equilibrium point. It then indicated that when the total profits obtained by the ED through standardized emergency behaviors were greater than the total costs, adopting the standardized emergency behaviors was the evolutionary stability strategy of the ED.

Finally, when$x < \frac{H_3 - J_1 + \beta F + \beta G\lambda_1(1-\mu)}{F(\beta - \partial) + \lambda_1(1-\mu)(\beta G - \partial g)}$, y = 0 and y = 1 were two strategies of y. Then we obtained $H'(0) < 0$ and $H'(1) > 0$, which meant that the probability of the ED adopting standardized emergency behaviors, that was y = 0, was the equilibrium point. It indicated that when the total profits obtained by the ED through standardized emergency behaviors were less than its total costs, adopting the standardized emergency behaviors was the evolutionary stability strategy of the ED.

Similarly, the evolutionary stability strategies of the OD and ED could also be analyzed, respectively, in the case that the MD reduce the safety investment.

3.2. Analysis of EG model among the MD, OD and ED

3.2.1. Equilibrium solutions of the tripartite game model

The expected profit of the MD by increasing the safety investment was defined by Equation (13).

$$E_{A1} = xyU_{A1} + (1-x)yU_{A2} + x(1-y)U_{A3} + (1-x)(1-y)U_{A4} \tag{13}$$

Additionally, the expected profit of the MD by reducing the safety investment was defined by Equation (14).

$$\begin{aligned} E_{A2} &= (x-x_1)(y-y_1)U_{A5} + (1-x+x_1)(y-y_1)U_{A6} \\ &+(x-x_1)(1-y+y_1)U_{A7} + (1-x+x_1)(1-y+y_1)U_{A8} \end{aligned} \tag{14}$$

As a result, the expected profit of the MD based on Equation (13) and Equation (14) was given in Equation (15).

$$\bar{E_A} = \theta E_{A1} + (1-\theta)E_{A2} \tag{15}$$

And the dynamic replication equation describing the increase of safety investment by the MD was given in Equation (16).

$$F(\theta) = \frac{d\theta}{dt} = \theta(1-\theta)(E_{A1} - E_{A2}) \tag{16}$$

Similarly, the dynamic replication equation describing the application of the normal procedures by the OD was given in Equation (17).

$$F(x) = \frac{dx}{dt} = x(1-x)(E_{B1} - E_{B2}) \tag{17}$$

and the dynamic replication equation describing the application of standardized emergency behaviors by the ED was given in Equation (18).

$$F(y) = \frac{dy}{dt} = y(1-y)(E_{C1} - E_{C2}) \tag{18}$$

According to the stability theorem of differential equation, to keep a certain strategy in a stable state, the probabilities of choosing this strategy (θ, x and y) must meet the criterion in Equation (19), respectively.

$$F(\theta)=0, \quad \frac{\partial F(\theta)}{\partial \theta}<0 \text{ or } F(x)=0, \quad \frac{\partial F(x)}{\partial x}<0 \text{ or } F(y)=0, \quad \frac{\partial F(y)}{\partial y}<0 \tag{19}$$

Solving Equation (19), we obtained the solutions of probability θ, x and y, that was (0,0,0), (0,1,0), (0,0,1), (0,1,1), (1,0,0), (1,1,0), (1,0,1), (1,1,1), respectively.

Taking the equilibrium solution $(1,1,1)$ as an example to analyze whether the three-party Evolutionary Game model tended to be asymptotically stable or not. Firstly, the Jacobean Matrix of the three-party Evolutionary Game model at point $(1,1,1)$ was given in Equation (20).

$$J = \begin{bmatrix} -(I+I_1-R-C-\partial g(1-\gamma)) & & \\ & -(E+A-D-H) & \\ & & -(M-J-H_2) \end{bmatrix} \tag{20}$$

Therefore, the eigenvalue was given by Equation (21).

$$\lambda = \begin{bmatrix} -(I+I_1-R-C-\partial g(1-\gamma)) \\ -(E+A-D-H) \\ -(M-J-H_2) \end{bmatrix} \tag{21}$$

When $I+I_1>R+C+\partial G(1\text{-}\gamma)$, $E+A>D+H$, and $M>J+H_2$ were true, the eigenvalue was found to be negative, and the Evolutionary Game model tended to be asymptotically stable at the equilibrium point$(1,1,1)$. Similarly, the asymptotic stability of other equilibrium solutions could also be analyzed and acquired. The results were shown in Table 3.

3.2.2. Analysis on different equilibrium solutions of the tripartite evolutionary game model

Results above indicated that the equilibrium solutions (0,0,0), (1,1,0), (1,0,1) and (1,1,1) might be the asymptotic stability points of the tripartite Evolutionary Game model. An overall description of the equilibrium point (θ, x and y) was given below. $\theta=0$ indicated that the MD chose to reduce the safety investment, while $\theta=1$ meant that the MD's choice to increase the safety investment. The solution $x=0$ indicated that the OD tended to carry out abnormal procedures or violations, while $x=1$ suggested that the OD choose to conduct normal procedures. Additionally, the solution $y=0$ meant that the ED chosen to take the abnormal emergency behaviors, while $y=1$ described that fact that the ED chosen to take the normal emergency behaviors. The underlying means of different equilibrium solutions were discussed below, respectively.

Case 1. When $I+I_2>\beta G(1\text{-}\mu)(1\text{-}\lambda\text{-}\lambda_1)$, $A+D_1>D+(H+H_1)+\beta B+\beta G\lambda(1\text{-}\mu)$, and $M+J_1>J+(H_2+H_3)+\beta F+\beta G\lambda(1\text{-}\mu)$ were true, the equilibrium point of the EG model was (0,0,0). In this case, the MD chose to reduce the safety investment, and the OD tended to carry out abnormal procedures or violations, and the ED would also choose to take the abnormal emergency behaviors.

Case 1 showed that if the total profits (initial and additional profit) obtained by the MD were greater than the employees' total wages and the losses due to accidents when the MD chose to reduce the safety investment, it tended to reduce the safety investment. Under the circumstance that the OD conducted abnormal procedures, if the profits obtained by the OD were greater than its total costs, it would choose to violate the normal procedures consciously. In addition, under the circumstance that the ED conducted abnormal emergency behaviors, if the total profits (initial profit and additional profit) obtained by the ED were greater than its total costs and the losses because of accidents, it would tend to conduct

Table 3
The asymptotic stability of equilibrium solutions of tripartite Evolutionary Game model.

Equilibrium solution	Eigenvalue sign	Stability
(0,0,0)	When $I+I_2>R+\beta G(1\text{-}\mu)(1\text{-}\lambda\text{-}\lambda_1)$, $A+D_1>D+(H+H_1)+\beta F\lambda(1\text{-}\mu)$ and $M+J_1>J+(H_2+H_3)+\beta F+\beta G\lambda_1(1\text{-}\mu)$ were all negative	Asymptotic stability point
(0,1,0)	Positive	Instability point
(0,0,1)	Positive	Instability point
(0,1,1)	Positive	Instability point
(1,0,0)	Positive	Instability point
(1,1,0)	When $I+I_1>R+C+\partial g(1\text{-}\gamma)$, $E+A>D+H$ and $M+J_1>J+(H_2+H_3)+\partial F+\partial g\lambda_1(1\text{-}\mu)$ were all negative	Asymptotic stability point
(1,0,1)	When $I+I_1>R+C+\partial g(1\text{-}\gamma)$, $E+A+D_1>D+(H+H_1)+\beta B+\beta G\lambda(1\text{-}\gamma)$ and $M>J+H_2$ were all negative	Asymptotic stability point
(1,1,1)	When $I+I_1>R+C+\partial g(1\text{-}\gamma)$, $E+A>D+H$ and $M>J+H_2$ were all negative	Asymptotic stability point

abnormal emergency behaviors consciously.

The situation in Case 1 is more likely to lead to safety accidents. Under such situation, the actions taken by the MD, OD and ED increased the possibility of safety accidents. As a result, the internal rules and regulations of NPPs need to be re-established, and the reward/punishment measures should also be established. Besides, the behaviors of MD, OD and ED should be regulated.

Case2. When $M + J_1 > J + (H_2 + H_3) + \partial F + \partial g\lambda_1(1-\mu)$, $I + I_1 > R + C + \partial g(1-\gamma)$, and $E + A > D + H$ were true, the equilibrium point of this Evolutionary Game model was (1,1,0). Under this case, the MD chose to increase the safety investment, and the OD chose to conduct normal procedures, while the ED tended to carry out abnormal emergency actions.

Case 2 showed that if the total profits (initial and additional profit) obtained by the MD were greater than the employees' total wages and the losses due to accidents when the MD increased the safety investment, it tended to choose to increase the safety investment consciously. In addition, under the circumstance that the OD conducted normal procedures, if the total profits (initial profit and additional profit) obtained by the OD were greater than its total costs, it would tend to conduct abnormal procedures consciously. Finally, under the circumstance that the ED conducted abnormal emergency behaviors, if the total profits (initial profit and additional profit) obtained by the ED were greater than its total costs and the losses because of accidents, it would tend to conduct abnormal emergency behaviors consciously.

Consequently, in order to reduce the probability of a safety accident in case 2, it is necessary to increase the defrayment and the loss due to the accident of the ED appropriately.

Case 3. When $I + I_1 > R + C + \partial g(1-\gamma)$, $M > J + H_2$, and $E + A + D_1 > D + (H + H_1) + \beta B + \beta G\lambda(1-\gamma)$ were true, the equilibrium point of the EG model was (1,0,1). In this case, the MD would choose to increase the safety investment, and the OD would choose to carry out abnormal procedures, and the ED would choose to adopt standardized emergency behaviors.

Case 3 showed that if the total profits (initial and additional profit) obtained by the MD were greater than the employees' total wages and the losses due to accidents, when the MD chose to increase the safety investment, it tended to choose to increase the safety investment consciously. Additionally, under the circumstance that the OD conducted abnormal procedures, if its total profits were greater than the total costs, the OD might tend to conduct abnormal procedures consciously. Furthermore, under the circumstance that the ED conducted standardized emergency behaviors, if the total profits (initial profit and additional profit) obtained by the ED were greater than its total costs and the losses due to accidents, it would tend to conduct standardized emergency behaviors consciously.

As a result, in order to reduce the probability of the safety accidents in Case 3, it is necessary to increase the defrayment of the OD, as well as the defrayment and the loss due to the accident of the ED.

Case 4. When $I + I_1 > R + C + \partial g(1-\gamma)$, $M > J + H_2$, and $E + A > D + H$ were true, the equilibrium point of the EG model was (1,1,1). In such case, the MD might choose to increase the safety investment, and the OD would choose to obey all the normal procedures, meanwhile the ED would choose to adopt the standardized emergency behaviors.

Case 4 showed that if the total profits (initial and additional profits) obtained by the MD were more than the employees' total wages and the losses due to accidents when it chose to increase the safety investment, the MD might tend to increase the safety investment consciously. In addition, under the circumstance that the OD conducted normal procedures, if its total profits were greater than the total costs, the OD might tend to conduct normal procedures consciously. Furthermore, under the circumstance that the ED conducted standardized emergency behaviors, if the total profits (initial profit and additional profit) obtained by the ED were greater than its total costs and the losses due to accidents, it would also tend to conduct standardized emergency behaviors consciously.

Under the condition above, it is necessary to increase the defrayment of the OD, to reduce the probability of the safety accidents in Case 4.

4. Conclusions

Based on the EGT, this paper investigated the changes in benefits of the MD, OD and ED of the NPPs under different strategic choices, and established the evolutionary model. The main findings have been given below.

First of all, the violations of both the OD and ED were not only related to the responsibility-sharing, the probability of the accidents, labor cost reduction due to violations, the fine to be paid, but also significantly affected by the total safety investments from the MD.

Furthermore, the total profits of the MD were affected by the probability of accidents, the strategic choice of both the OD and ED, the consequences of accidents and the responsibility-sharing. Violations could be attenuated if the MD imposed more proportion of the responsibility on both the OD and ED.

Additionally, the reduction in abnormal procedures or violations should be encouraged during the on-site operations, which would reduce the probability of accidents significantly.

Finally, the ED should choose its working capacity based on the fact whether the OD conducted abnormal procedures or not. Meanwhile, it should reduce its own abnormal behaviors thus decrease the potential losses due to accidents.

Based on the findings of this study, a few suggestions could be summarized for the safety assessments in practical applications of NPPs. First of all, the findings that the unsafe behaviors in NPPs were affected by several factors required the MD to increase the safety investments in everyday management, such as the regular safety education, regular evaluation of the safety culture, and the establishment of a complete reward/punishment mechanism. Furthermore, the findings obligated 3 departments to improve the skills/professional levels of their staff by more training in safety culture, and to conduct the safety culture self-evaluation periodically.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors appreciate the financial support of the National Natural Science Foundation project (Grant number: U1867221), and of the Hunan Natural Science Foundation Project (Grant number: 2020JJ4078). Special thanks to Dr. Hui Zhu of Qingdao University of Technology, for his guidance and English proof reading of this paper.

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