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Application of game theory in risk management of urban natural gas pipelines

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ABSTRACT

This paper presents a game theory methodology for risk management of urban natural gas pipelines, which is a collaborative participation mechanism of the stakeholders, including government, pipeline companies, and the public. Firstly, the involvement proportion of stakeholders in risk management under rational conditions is estimated by the static game theory. Subsequently, the system dynamics (SD) simulation is used to establish an evolution game model of stakeholders in risk management under the irrational conditions, in which the stability of the evolution game process is analyzed. The stakeholders' involvement proportions from the static game model are utilized as the inputs for the evolution game model to simulate the dynamic evolution behavior of risk management strategies with different involvement proportions of stakeholders. Eventually, the dynamic evaluation game can extract an optimal strategy for risk management of urban natural gas pipelines. A case study is used to illustrate the methodology. In essence, this methodology can be extended for implementing risk management of urban infrastructure.

1. Introduction

The safety of urban natural gas pipelines is challenged by a series of adverse factors, particularly, third-party activities. Because urban natural gas pipelines are close to the public living area, natural gas release and explosion resulting from urban gas pipeline leak may pose catastrophic consequences, e.g., human casualties and assets loss, as reported in the recent urban natural gas pipeline accidents (Li et al., 2021). Thus, implementing the reasonable risk management strategy is helpful to prevent urban natural gas pipeline accidents.

Currently, risk management of natural gas pipelines attracted many attentions due to the frequent occurrence of accidents. Monte Carlo simulation, visualization tools and graphical techniques were used for risk identification, and vulnerability assessment of natural gas pipelines (Viana et al., 2021, 2022; Fakhravar et al., 2017; Wang et al., 2022). The previous studies focused on finding risk factors and estimating the potential consequences in the daily operation of natural gas pipelines. Nevertheless, they are only a part of risk management of natural gas pipeline. Multi-interest issues are generally included in risk management of urban natural gas pipelines. This issue were not considered in the previous studies. The responsibility for risk management needs to be assigned to each stakeholder of urban natural gas pipelines, and the stakeholders should collaboratively participate in the risk management of urban natural gas pipelines.

During the daily operation of urban natural gas pipelines, the government is supervised by the public, and pipeline operators are supervised by the public and government. The government sometimes may collude with the operator to benefit by lowering security regulatory requirements on operators. This action by the government can increase the complexity of risk management in the daily operation of natural gas pipelines. Risk management of urban natural gas pipelines is a complex task involving multiple stakeholders. Game theory was widely used in the conflict prevention and control involving various parties. The application of game theory to addressing risk management is relative a new topic. The game theory was used for explaining the conflicting aspects of building an offshore wind farm to choose the best location to install (Golestani et al., 2021), scheduling safety inspection of pipeline system (Rezazadeh et al., 2017), and estimating third-party intrusion of pipeline (Cui et al., 2020). Zarreh et al. (2019) used game theory to model the competition between the attacker and the system as a game to determine the possibility of the attacker's actions. The traditional static game theory assumes that players in the game are in a perfectly rational

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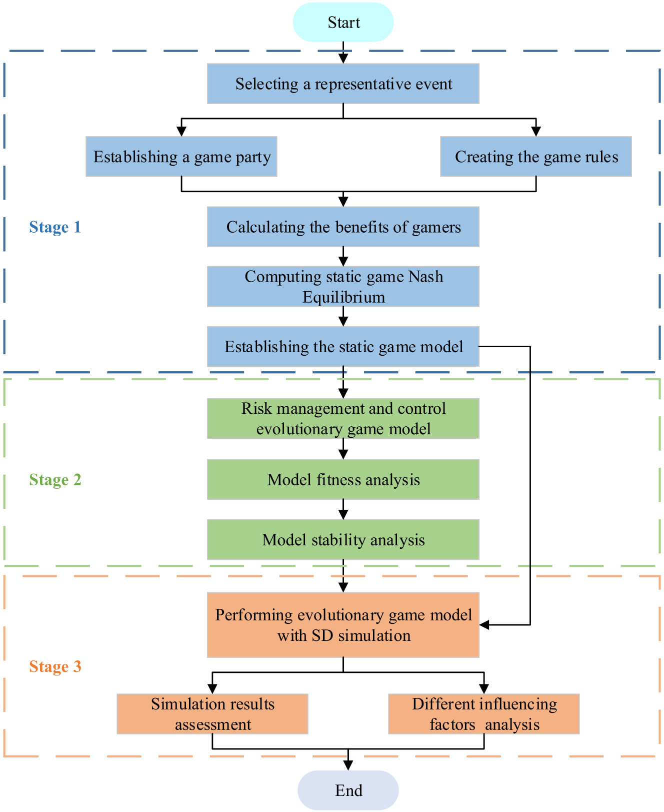


Fig. 1. Flowchart of the methodology.

state and that there is information equivalence among the players. In practice, the players will randomly choose their strategies at the beginning of the game since the information is not completely equivalent. The strategy selection of the players in the game will be constantly adjusted and changed according to the observed information. Based on the static game model, the evolutionary game model is selected to simulate the complex dynamic game process of natural gas pipeline operation participants.

The decision-making of risk management involving multiple stakeholders is an adjustable process that depends on the actual situation over time. SD is an auxiliary method for decision design that can solve decision problems of complex dynamic systems. It is suitable for analyzing the dynamic problems that arise in complex policymaking (Norouzian-Maleki et al., 2022), management (Bajomo et al., 2022), economic (Wu et al., 2022), or ecological systems (Dai et al., 2022). The game model can be combined with SD to perform a dynamic simulation of the game system. You et al. (2020) used SD method to simulate the multiplayer evolutionary game of the internal safety inspection system of Chinese coal enterprises. Jin and Zheng (2022) used SD and game model to analyze the strategic choice of core enterprises subsidizing small and medium-sized enterprises to achieve pollution control under government regulation. The problem of evolutionary game model with many parameters can be solved by combining SD model and evolutionary game model.

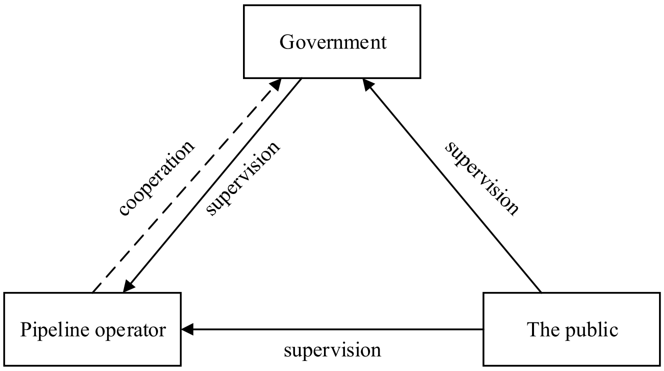


Fig. 2. "Government - pipeline operator - the public" collaborative management relationship.

This paper aims to present a game theory methodology for risk management of urban natural gas pipelines. It can generate the collaborative participation of government, pipeline operator, and the public in risk management of urban natural gas pipelines. Based on game theory, the cooperative participation ratio of multiple stakeholders can be obtained, which is then used as the input of SD model to perform a dynamic simulation of the evolution behavior of risk management strategy. The methodological contribution of this study is the integration of static game model and evolutionary game model, which can overcome the limitation of static game model to search for the adaptive strategy of risk management of urban natural gas pipelines. Essentially, the methodology can support more efficient risk management of urban natural gas pipelines.

The rest of this study is organized as follows: Section 2 presents the methodology for risk management of urban natural gas pipelines. A case study is conducted in Section 3 to illustrate the methodology. Section 4 summarized the present work and presented the conclusions of this study.

2. Methodology

The game theory-based methodology for risk management of urban natural gas pipelines is presented in Fig. 1. The main steps of the methodology are shown as follows:

- Establishing the static game model;
- Developing the evolutionary game model using the outputs of static game;
- Dynamic evaluation of risk management strategy with SD simulation.

The first step is to establish a static game model for risk management of urban gas pipelines. In this step, the game parties involved in the model are determined, and the game relationship among these game parties is analyzed. To facilitate the analysis, the rules of the game model are set to create the game tree. Then, the cost and benefits of the game parties are calculated, and the Nash equilibrium state of the model is obtained.

In practice, it is difficult for game players to be completely rational. Therefore, based on the results of static game analysis, evolutionary game theory is used to analyze the dynamic process of strategy evolution of game players. The adaptability analysis of the players and the stability analysis of the strategy selection of the players are included in the evolutionary game model analysis.

Since there are many parameters in the evolutionary game analysis and the calculation is complicated, it is difficult to judge the positive and negative relationship of matrix determinant and trace. SD model is built based on the evolutionary game. The stability of equilibrium points and the dynamic game feedback structure of the game players in the evolutionary game system are studied by establishing SD model.

3. Case study

3.1. A static game model of pipeline risk management

3.1.1. Game tree of risk management

Currently, risk management parties of urban natural gas pipelines usually include the government and pipeline companies (Liu et al., 2020). The pipeline companies are responsible for safety investment

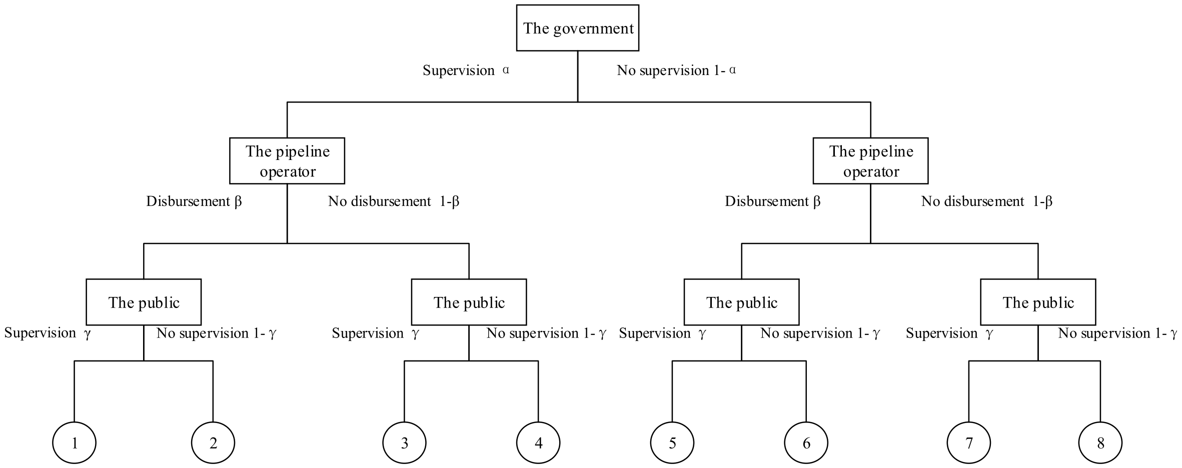


Fig. 3. Game tree for risk management of urban natural gas pipelines.

during the entire life of pipelines, whereas the government should conduct safety supervision on the operation of pipelines. In the case of a pipeline leak, fire, and explosion, the government and pipeline companies should jointly participate in the emergency rescue and post-mortem repairs (Xing et al., 2020). However, the operational safety of pipelines is easily affected by public activities, and some risks facing are often challenging to be identified. In practice, pipeline incidents due to third-party activities are usually reported by the public to the relevant safety department or enterprise. Once the pipeline accident occurs, the public is the direct victim of accident. Therefore, risk management of urban natural gas pipelines involves the government, the pipeline operator, and the public.

Fig. 2 presents the cooperative relationship among the government, the pipeline operator, and the public in risk management of urban natural gas pipelines (Liu et al., 2022). The government supervises the safe operation of pipeline operator, and pipeline operator makes safety investments in accordance with the laws promulgated by the government. However, the pipeline operator often sacrifices safety investment in pipeline design, construction, and operation to maximize their interests and even generate the rent-seeking behavior toward government. Meanwhile, the government conspired with the pipeline operator to save the costs for safety supervision and seek benefits from the pipeline operator, resulting in the poor effect of safety supervision. In addition, the public may neglect the safety supervision of pipelines due to the poor management performance of government and pipeline operator. Therefore, the public can serve as the supervisory party of government and pipeline operator and report pipeline failure incidents to pipeline operator or government, as shown in Fig. 3.

3.1.2. *Strategy set for each player*

- In the static game model, the game parties are treated to be completely rational, and the goals pursued are the maximization of their interests. The game parties do not know the strategy choices of other participants when they choose their strategies.
- The government, pipeline companies, and the public have two strategies in the game. The strategy set of government includes supervision and no supervision; the strategy set of pipeline operator involves implementing safety investment and not implementing safety investment; the strategy set of the public includes supervision and no supervision. The game tree is formed based on the strategy set of game parties.
- The government supervision rate (supervision intensity) is set as α, the safety investment rate (investment level) of pipeline operator is set as β, and the public supervision rate (supervision intensity) is set as γ. Consequently, the government's non-supervision intensity is $(1-\alpha)$, the No-safety investment rate of pipeline operator is set as $(1-\beta)$, and the non-supervision intensity of the public is set as $(1-\gamma)$.
- Urban natural gas pipeline leak accidents will occur when the government does not supervise pipeline, and the pipeline operator does not make safety investments for pipeline.
- It is assumed that the regular operation of the pipeline will benefit government and pipeline operator, which can be reached only when government and pipeline operator strictly supervise and implement safety investments.
- The government and pipeline operator will shoulder the losses caused by pipeline accidents only when the government, pipeline operator, and the public does not fulfill their respective responsibilities in the supervision and investment for pipeline safety.
- It is assumed that the total accident loss is L, and the ratio that government, pipeline operator, and the public respectively bear the accident loss is 3: 5: 2.

3.1.3. *Estimating cost and income of game parties*

The government, pipeline operator, and the public have different costs and benefits in the case of various risk management strategies. The government supervises the safe operation of pipelines, which requires human and material costs C_1. The safety operation of pipelines will bring the social reputation T_1 to the government. At this time, if pipeline operator does not make any safety investment, the government will give a monetary penalty F to pipeline operator. On the contrary, if pipeline operator makes a safety investment, the government will allocate funds T_5 to the pipeline operator. Suppose the government does not supervise the safe operation of pipelines. In that case, the government will suffer from accident loss of 0.3 PL (P is accident probability) after the accident, and the government of higher levels will impose an administrative penalty C_2 on the local government.

The pipeline operator implements the required safety investment, and the safety input cost is C_3. At this time, the regular operation of pipeline will bring revenue T_3 for pipeline operator, and the pipeline operator will collect pipeline maintenance cost T_9 from the public. If pipeline operator does not make the required safety investment, the accident loss is 0.5 PL, and it is assumed that there is rent-seeking behavior between government and pipeline operator. When pipeline operator and government fail to perform their responsibilities at the same time, it is assumed that the government will seek rent from pipeline operator for a cost of T_2.

If the public takes supervision measures, the public needs to pay the supervision cost C_5. Under the condition that the government carefully supervises the safe operation of pipelines, the public will be rewarded T_7 for government's feedback on pipeline hazards. The public will be rewarded T_{10} under the condition that pipeline operator carefully

Table 1

"Government-pipeline operator-the public" tripartite income matrix.

Participants, Strategies, Benefits	Government supervision α		Government does not supervise 1-α	
	Enterprise security investment β	Enterprise unsafe investment 1-β	Enterprise security investment β	Enterprise unsafe investment 1-β
Public supervision γ	$- C_1-T_5-T_7+T_1$ $- C_3-T_{10}+T_3+T_5+T_9$ $- C_5-T_9+T_7+T_{10}$	$- C_1+F-T_7+T_1$ $- F + C_4$ $- C_5+T_7$	$- C_2$ $- C_3-T_{10}+T_3+T_9$ $- C_5-T_9+T_{10}$	T_2-0.3 PL-C_2 -T_2-0.5 PL + C_4 -C_5-0.2 PL
Public unsupervised 1-γ	$- C_1-T_5+T_1$ $- C_3+T_3+T_5+T_9$ $- T_9$	$-C_1+F + T_1$ $-F + C_4$ 0	$- C_2$ $-C_3+T_3+T_9$ $-T_9$	T_2-0.3 PL-C_2 -T_2-0.5 PL + C_4 −0.2 PL

Table 2

Benefit functions of players.

Game player	Mixed benefit function	Maximum benefit function
The government	$[(T_2 - F - T_5 - 0.3PL)\beta - T_7\gamma C_2 - C_1 + F - T_2 + 0.3PL]\alpha + (0.3PL - T_2)\beta + T_2 + C_2 - 0.3PL$	$(T_2 - F - T_5 - 0.3PL)\beta - T_7\gamma + C_2 - C_1 + F + T_1 - T_2 + 0.3PL$
The pipeline operator	$[(F - T_2 + T_5 - 0.5PL)\alpha - T_{10}\gamma + T_2 - C_4 - C_3 + T_3 + T_9 + 0.5PL]\beta + (0.5PL - F + T_2 + T_3)\alpha - 0.5PL + C_4 - T_2$	$(F - T_2 + T_5 - 0.5PL)\alpha - T_{10}\gamma + T_2 - C_4 - C_3 + T_3 + T_9 + 0.5PL$
The public	$(T_7\alpha - C_5 + T_{10}\beta)\gamma + 0.2PL\alpha + 0.2PL\beta - 0.2PL\alpha\beta - T_9\beta - 0.2PL$	$T_7\alpha + T_{10}\beta - C_5$

Table 3

Game model variables and their values (used for illustrative purpose).

Variables	Description	Value
P	Accident probability	0.168
L	Accident loss	500
C_1	Government supervision cost	42.4
C_2	Administrative penalties imposed by the central government on the local governments	20
C_3	Costs of pipeline operator to implement protective measures	38
C_4	Safety investment costs saved by pipeline operator	60
C_5	Public supervision cost	12
T_1	The reputation of government for pipeline operation	20
T_2	Rent when government succeeds in rent-seeking (pipeline operator rent-seeking cost)	20
T_3	The income generated by the normal pipeline operation	40
T_5	The government rewards operators for implementing protective measures	3
T_7	The government rewards risk of public feedback channels	5
T_{10}	Pipeline operator rewards the public for feedback on pipeline risk	10
F	Government fines pipeline operator	35
T_9	The operator charges the public a pipeline maintenance fee	15

supervises pipeline's safe operation. If the public does not take supervision measures, pipeline operator will pay the pipeline maintenance fee T_9 when pipeline operator performs safety investments. If an accident occurs, the loss to the public caused by this accident is 0.2 PL whether the public conducts pipeline safety supervision.

In summary, a tripartite income matrix of "government-pipeline operator -public" is formed, as shown in Table 1.

3.1.4. *Nash equilibrium analysis of static game*

Based on the tripartite game income matrix, the income of government, pipeline operator and the public under different strategies can be solved. The optimal solution of maximum benefit for each player is corresponded to the maximum value of the mixed benefits function. The mixed benefit function and maximum benefit function of game players are shown in Table 2.

It is supposed that $U = T_2 - (F + T_5 + 0.3PL)$, $V = (C_2 + F + 0.3PL + T_1) - (C_1 + T_2)$, $M = (F + T_5) - (T_2 + 0.5PL)$, $N = (T_2 + T_3 + T_9 + 0.5PL) - (C_4 + C_3)$. The maximum benefit functions are equal to zero, and can be solved together:

$$\begin{cases} \alpha = \dfrac{T_{10} \times V - T_7 \times N + C_5 \times U}{T_7 \times (M + U)} \\ \beta = \dfrac{T_7 \times N - T_{10} \times V + C_5 \times M}{T_{10} \times (M + U)} \\ \gamma = \dfrac{C_5 \times M \times U + T_7 \times N \times U + T_{10} \times M \times V}{T_7 \times T_{10} \times (M + U)} \end{cases} \tag{1}$$

Through Eq. (1), it can be seen that increasing the intensity of the central administrative penalties and the upper limit of fines will encourage the government to increase the supervision rate. However, if the unreasonable regulatory system of government leads to excessively high regulatory costs or failure to strictly combat rent-seeking behavior of government, the government's strict control of pipeline operation safety will be reduced. When the regular operation of pipeline brings benefits to pipeline operator, the pipeline operator will increase the degree of safety investment. When the safety cost invested by pipeline operator is too large, the pipeline operator will reduce its safety investment. Appropriately increasing the rewards of the government and pipeline operator for the public reporting of potential hazards will help guide the public's intentions for the safety supervision.

In the game, regardless of the opponent's strategy choice, the player will choose a certain strategy, then the strategy is called the dominant strategy. If a player's chosen strategy is optimal, as determined by the strategy of all other players, then the combination is defined as a Nash equilibrium. Nash equilibrium is the best result for all players involved, and if one of the players wants to increase their gains, it will cause the other players to have less benefits.

There are two possible solutions for Nash equilibrium: pure strategy and mixed strategy. In complete information game, the pure strategy means that players can only choose a specific strategy. On the contrary, the mixed strategy refers to that the player chooses a certain decision with a certain probability under the given information. This paper uses a mixed strategy to solve the income of local government, pipeline operators and the public under different strategies.

In the game model, the value of each parameter should be determined before running the model. Since there were not deterministic methods that can be used to estimate these values. In general, they can be assigned based on the expert knowledge and accident investigation. In this study, these values are estimated considering the expert evaluation and previous accident report, as shown in Table 3. It should be noticed that these values are just used for the illustrative purpose. They can be replaced when the practical values are available. Incorporating them into Eq. (1) to solve $\alpha = 0.7006$, $\beta = 0.8497$, $\gamma = 0.2185$, that is, the Nash equilibrium of mixed strategy is (0.7006, 0.8497, 0.2185) in risk management of urban natural gas pipeline. It means that the government has the strong supervision in this situation, and pipeline operator has a higher investment in the pipeline safety management. The degree of public supervision in the third-party damage of urban natural gas pipelines is low. This is because the government and pipeline operator have carried out the sufficient safety supervision and investment.

3.2. *Evolutionary game of pipeline risk management*

In evolutionary game theory, humans are not seen as rational

Table 4
Adaptability analysis of the players.

Game players	Adaptability of $M_x(x = \alpha,\beta,\gamma)$	Adaptability of M_{1-x}	Average adaptability	Regulatory variation rate $f(x)$
The government	$-(F+T_5)\beta - T_7\gamma + F - C_1 + T_1$	$(0.3PL - T_2)\beta + T_2 - C_2 - 0.3PL$	$\alpha M_\alpha + (1-\alpha) M_{1-\alpha}$	$\alpha(1-\alpha)[C_2 - C_1 + T_1 + F - T_2 + 0.3PL + (T_2 - F - T_5 - 0.3PL)\beta - T_7\gamma]$
The pipeline operator	$T_5\alpha - T_{10}\gamma + T_3 - C_3 + T_9$	$(T_2 - F + 0.5PL)\alpha + C_4 - T_2 - 0.5PL$	$\beta M_\beta + (1-\beta) M_{1-\beta}$	$\beta(1-\beta)[T_2 - C_4 - C_3 + T_3 + T_9 + 0.5PL + (F - T_2 + T_5 - 0.5PL)\alpha - T_{10}\gamma]$
The public	$(T_7 + 0.2PL)\alpha + (T_9 + T_{10} + 0.2PL)\beta - 0.2PL\alpha\beta - C_5 - 0.2PL$	$0.2PL\alpha - (T_9 - 0.2PL)\beta - 0.2PL\alpha\beta - 0.2PL$	$\gamma M_\gamma + (1-\gamma) M_{1-\gamma}$	$\gamma(1-\gamma)\gamma(1-\gamma)[T_7\alpha + (2T_9 + T_{10})\beta - C_5]$

Table 5
Different player strategy choices based on stability analysis.

Variables	Conditions	$f'(0)$	$f'(1)$	Strategy selections
$\alpha = 0$ $\alpha = 1$	$C_2 - C_1 + T_1 + F - T_2 + 0.3PL + (T_2 - F - T_5 - 0.3PL)\beta - T_7\gamma = 0$	–	–	The government reaches a balanced and stable state
	$C_2 - C_1 + T_1 + F - T_2 + 0.3PL + (T_2 - F - T_5 - 0.3PL)\beta - T_7\gamma < 0$	< 0	> 0	Non-supervision strategy is increasingly being chosen by the government
	$C_2 - C_1 + T_1 + F - T_2 + 0.3PL + (T_2 - F - T_5 - 0.3PL)\beta - T_7\gamma > 0$	> 0	< 0	Supervision strategy is increasingly being chosen by the government
$\beta = 0$ $\beta = 1$	$T_2 - C_4 - C_3 + T_3 + T_9 + 0.5PL + (F - T_2 + T_5 - 0.5PL)\alpha - T_{10}\gamma = 0$	–	–	The pipeline operator's safety investment has reached a balanced and stable state
	$T_2 - C_4 - C_3 + T_3 + T_9 + 0.5PL + (F - T_2 + T_5 - 0.5PL)\alpha - T_{10}\gamma < 0$	< 0	> 0	No-safe input state is gradually selected by pipeline operator
	$T_2 - C_4 - C_3 + T_3 + T_9 + 0.5PL + (F - T_2 + T_5 - 0.5PL)\alpha - T_{10}\gamma > 0$	> 0	< 0	Safe input status is gradually selected by pipeline operator
$\gamma = 0$ $\gamma = 1$	$T_7\alpha + (2T_9 + T_{10})\beta - C_5 = 0$	–	–	The public supervision reaches a balanced and stable state
	$T_7\alpha + (2T_9 + T_{10})\beta - C_5 < 0$	< 0	> 0	Non-supervision strategy is increasingly being chosen by the public
	$T_7\alpha + (2T_9 + T_{10})\beta - C_5 > 0$	> 0	< 0	Supervision strategy is increasingly being chosen by the government

players, though they usually achieve game equilibrium through trial-and-error methods. The chosen equilibrium is a process function to reach equilibrium. The choice of multiple equilibria in the game will be affected by historical and institutional factors.

The evolutionary game theory has the following characteristics: the research object is a particular group that varies over time; the game's purpose is to understand the dynamic process of group evolution and explain why the group will reach this state and how to achieve it. The factors affecting group variation have some randomness and perturbation phenomenon (mutation) and can present a certain regularity through the selection mechanism during game evolution. The predictive or explanatory ability of most evolutionary game theories depends on the group selection process. The group selection process has a certain inertia. At the same time, this process has the potential energy for mutation, which continuously produces new variants or features.

Establishing the general evolutionary game model mainly depends on selection and mutation. The selection implies that strategies with higher payments are adopted by more participants; The mutations imply that some individuals choose a different group strategy randomly (which may obtain the high payment or the lower payment). Mutations are also a selection, although only good strategies can survive. The mutation is also a process of constant trial, learning, and imitation.

The Jacobi matrix method is proposed to calculate the evolutionary stability strategy (ESS). The stability of equilibrium points between players in evolutionary games can be explained by Jacobi's local stability. In order to reflect the relationship more clearly, the replicator dynamic equation is introduced. The principle of replicator the dynamic equation is that at a certain point in time, each player is bounded rational, can dynamically adjust their own strategy choices, and is more inclined to adopt strategies with higher-than-average returns.

3.2.1. *Adaptation analysis of evolutionary game model*

Based on the interest cost assumption of the tripartite group, it is supposed that the government's regulatory adaptation degree is M_α, the government's non-regulatory adaptation degree is $M_{1-\alpha}$, and the average adaptability of government is $\overline{M}_{\alpha,1-\alpha}$. Based on the evolutionary game theory, it is assumed that the government will imitate the behavior of game strategies with the higher returns. If the supervision rate adopted by government is α at a particular moment, then the change of the supervision rate at the next moment is related to the supervision rate at the present moment (Friedman, 1998). The regulatory variation rate can be expressed as:

$$f(\alpha) = \frac{\partial \alpha}{\partial t} = \alpha\left(M_\alpha - \overline{M}_{\alpha,1-\alpha}\right) \tag{2}$$

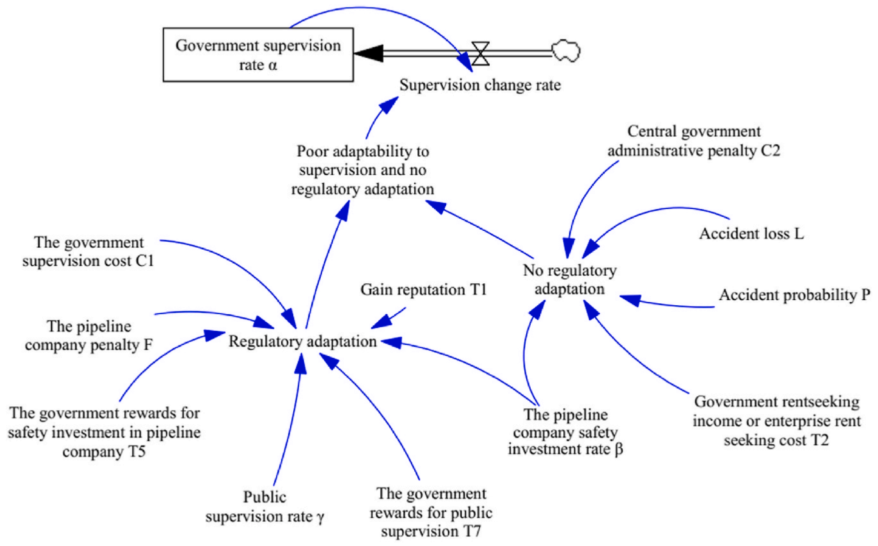
In the same way, it is supposed that the pipeline operator's adaptability for safety investment is M_β, and the pipeline operator's adaptability for not making safety investment is $M_{1-\beta}$; the adaptability of the public supervision is M_γ, and the adaptability of the public non-supervision is $M_{1-\gamma}$. The adaptability analysis of the players is shown in Table 4.

3.2.2. *Stability analysis of evolutionary game model*

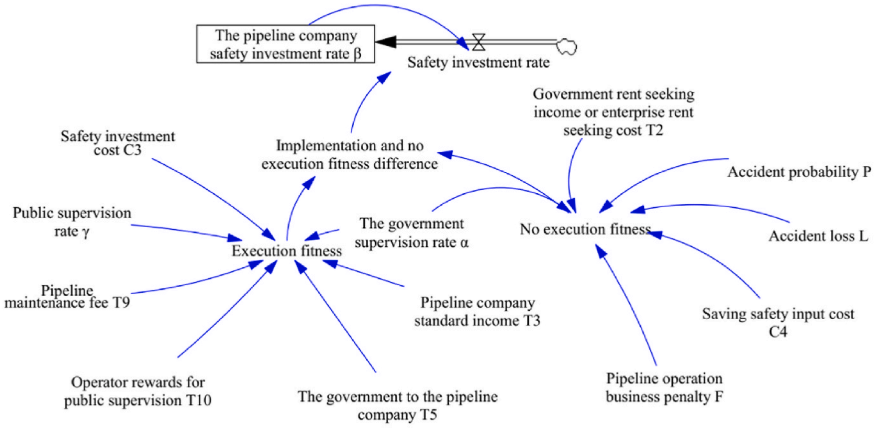
According to Friedman's theory (Friedman, 1991), if $f(x) = 0$, and $f'(x) < 0$, x is the evolutionary stable strategy (ESS) adopted by the game partiers. According to Table 4, when $f(\alpha) = 0, f(\beta) = 0$ and $f(\gamma) = 0$, the stabilization strategies selected by the government, the pipeline operator and the public are shown in the following Table 5.

$\alpha = 0$, $\alpha = 1$ indicate that the government makes pure strategy choices. When $C_2 - C_1 + T_1 + F - T_2 + 0.3PL + (T_2 - F - T_5 - 0.3PL)\beta - T_7\gamma = 0$, the strategic choice of the government has nothing to do with the supervision rate. Regardless of the value of the supervision rate adopted by government, the strategic choice of government will remain unchanged. When $\alpha = 0$, $\alpha = 1$, that is, the government adopts the complete supervision, and no supervision at all, the government's strategic choice will keep the initial strategy relatively stable without the sudden changes in the strategy (Liu et al., 2019).

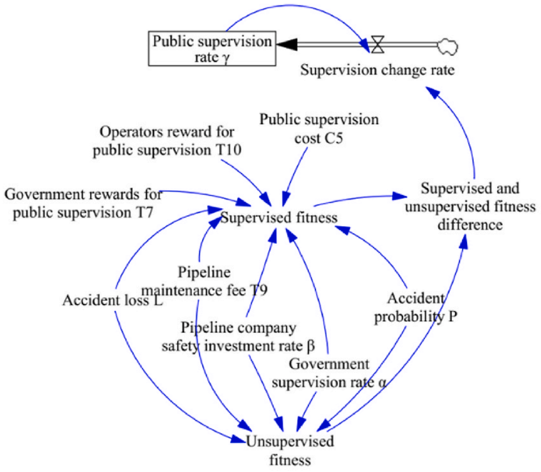
$\beta = 0, \beta = 1$ indicate that the pipeline operation makes pure strategy choice. When $T_2 - C_4 - C_3 + T_3 + T_9 + 0.5PL + (F - T_2 + T_5 - 0.5PL)\alpha - T_{10}\gamma = 0$, pipeline operator's strategic choice has nothing to do with the safety investment rate. Among them, $\beta = 0$, $\beta = 1$ is the pure strategy choice of pipeline operator. When $T_2 - C_4 - C_3 + T_3 + T_9 + 0.5PL + (F - T_2 + T_5 - 0.5PL)\alpha - T_{10}\gamma = 0$, the pipeline operator's strategic choice has nothing to do with the safety investment rate. When $\beta = 0, \beta = 1$, that is, if the pipeline operator invests in safety or not, the



a. SD model of the government



b. SD model of the pipeline operator



c. SD model of the public

Fig. 4. Sub-model of game system.

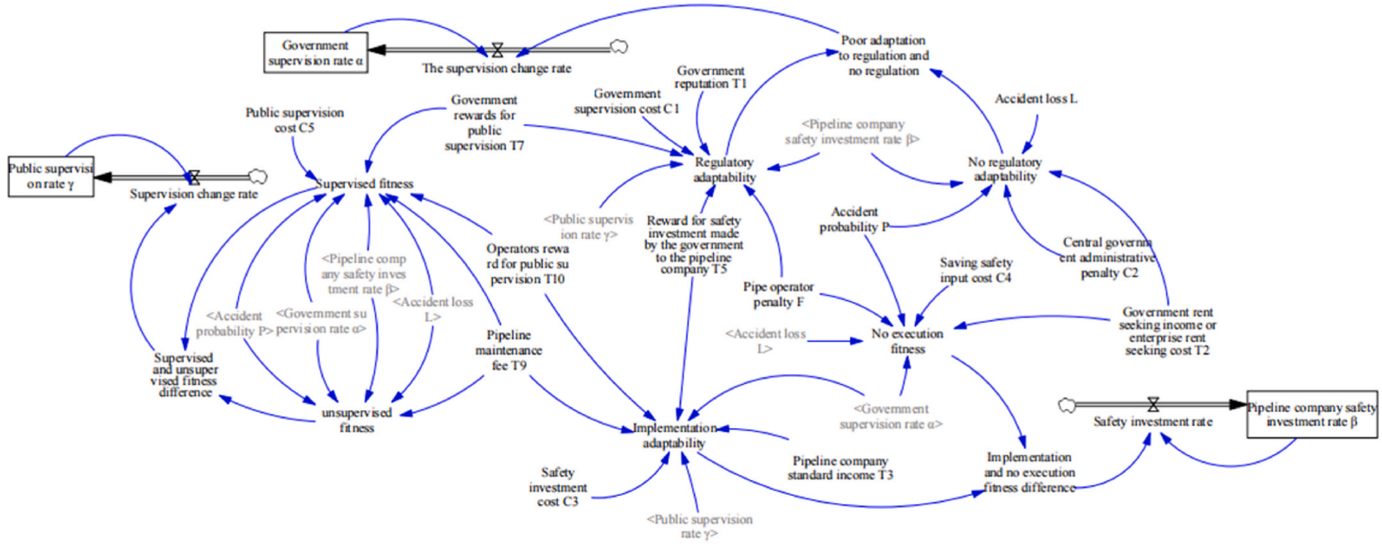


Fig. 5. SD model of the risk management game system.

pipeline operator's strategic choice will remain relatively stable.

$\gamma = 0$, $\gamma = 1$ indicate that the public makes pure strategy choices. When $T_7\alpha + (2T_9 + T_{10})\beta - C_5 = 0$, the public's strategic choices have nothing to do with the rate of supervision. When $\gamma = 0, \gamma = 1$, that is, if the pipeline operator invests in safety or not, the pipeline operator's strategic choice will remain relatively stable.

According to Table 4, the third-party damage management, and control evolutionary game replication dynamic equations of urban natural gas pipelines can be obtained as:

$$F(\alpha,\beta,\gamma) = \begin{cases} f\left(\alpha\right) = \dfrac{\partial\alpha}{\partial t} = \alpha\left(1-\alpha\right)\left[C_2 - C_1 + T_1 + F - T_2 + 0.3PL + \left(T_2 - F - T_5 - \right.\right. \\ \qquad \left.\left. 0.3PL\right)\beta - \gamma\right] \\ f\left(\beta\right) = \dfrac{\partial\beta}{\partial t} = \beta\left(1-\beta\right)\left[T_2 - C_4 - C_3 + T_3 + T_9 + 0.5PL + \left(F - T_2 + T_5 - \right.\right. \\ \qquad \left.\left. 0.5PL\right)\alpha - T_{10}\gamma\right] \\ f(\gamma) = \dfrac{\partial\gamma}{\partial t} = \gamma(1-\gamma)[T_7\alpha + (2T_9 + T_{10})\beta - C_5] \end{cases} \tag{3}$$

The replicator dynamic equation represents the speed and direction of the game process. When the replicator dynamic equation is 0, it means that the game process has reached a relatively stable state. Let $F(\alpha,\beta,\gamma) = 0$, the equilibrium point of the evolutionary game system of the third-party damage risk management of urban natural gas pipelines can be obtained as: A1 (0, 0, 0), A2 (0, 0, 1), A3 (1, 0, 0), A4 (1, 0, 1), A5 (1, 1, 0), A6 (0, 1, 0), A7 (0, 1, 1), A8 (1, 1, 1), A9 (α^*,β^*,γ^*). Among them, (α^*, β^*, γ^*) is the solution of Eq. (4).

$$\begin{cases} C_2 - C_1 + T_1 + F - T_2 + 0.3PL + (T_2 - F - T_5 - 0.3PL)\beta - \gamma = 0 \\ T_2 - C_4 - C_3 + T_3 + T_9 + 0.5PL + (F - T_2 + T_5 - 0.5PL)\alpha - T_{10}\gamma = 0 \\ \gamma(1-\gamma)[T_7\alpha + (2T_9 + T_{10})\beta - C_5] = 0 \end{cases} \tag{4}$$

By constructing Jacobin matrix and judging the positive and negative relationship between the determinant of the matrix and the trace, the stability of the equilibrium point can be obtained, from this, judge whether there is an evolutionary equilibrium state between the government, the pipeline operator and the public. However, the calculation is more complicated due to the many parameters in the evolutionary game system. Besides, it is difficult to judge the positive and negative relationship between the matrix determinant and the trace. In addition, the use of traditional methods cannot directly reflect the evolution process of the game participants' strategy choices caused by changes in external variables.

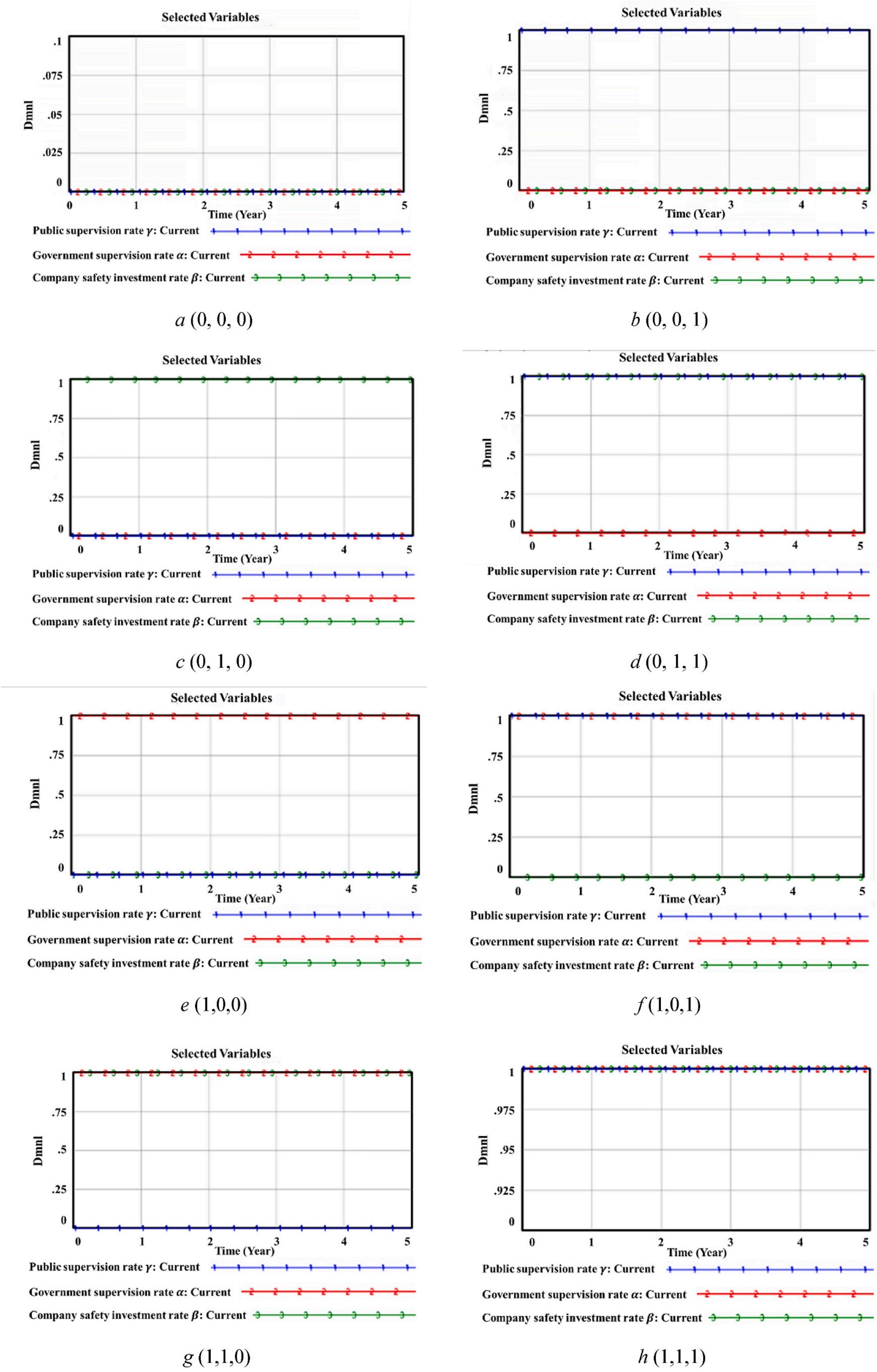
3.3. *Dynamic evaluation of risk management strategy with SD simulation*

SD is a crucial method for modeling dynamic complex systems, which combines system science theory with the computer simulation technology to analyze the system feedback structure and strategy effectiveness. In the evolution game of risk management of urban natural gas pipelines, the individuals in the groups of all parties of the game constantly learn and imitate other individuals to adjust their strategic choices by comparing and observing their interests. The influence of different influencing factors on the game result is analyzed.

3.3.1. *SD model for evolutionary game of risk management*

The evolutionary game model of "government-pipeline operator-and the public" consists of three sub-models: the government SD model, the pipeline operator SD model, and the public SD model, as shown in Fig. 4.

The government SD model is consisted by two types of state variables, one rate variable and six external variables, as shown in Fig. 5. The variables are represented by two strategies, supervision, and non-supervision, respectively. The rate variable is the rate of change of the supervision strategy, and the external variables are the parameters determined in Table 3.



a (0, 0, 0)

b (0, 0, 1)

c (0, 1, 0)

d (0, 1, 1)

e (1,0,0)

f (1,0,1)

g (1,1,0)

h (1,1,1)

Fig. 6. System evolutionary game simulation process of initial pure strategy.

The pipeline operator SD model is consisted by two state variables, one rate variable, and seven external variables. The variables are represented by two strategies of making safety investments and not making safety investments. The rate variable is the rate of change of the safety investment strategy, and the external variables are the parameters determined in Table 3.

The public SD model is consisted by two state variables, one rate variable, and six external variables. The variables are represented by two strategies, supervised and unsupervised, respectively. The rate variable is the rate of change of the supervised strategy, and the external variables are the parameters determined in Table 3.

Set up SD model for risk management game system of urban natural gas pipelines, INITIAL TIME = 0, FINAL TIME = 5, TIME STEP = 1, Units for Time: Year, Integration Type: Euler. The system dynamics equation in the SD model is shown as follows:

(1) Government supervision rate = INTEG (supervision change rate, initial);
(2) Supervision change rate = the government supervision rate × (1 − government supervision rate) × poor adaptability to supervision and non-supervision;
(3) Poor adaptation to regulation and non-regulation = regulatory adaptation − non-regulatory adaptation;
(4) Regulatory adaptability = the pipeline operator penalty F – the government supervision cost C1 − (the pipeline operator penalty F + the government rewards for safety investment in the pipeline operator T5) × the pipeline operator safety investment rate β – the government to the public supervision awards T7 × the public supervision rate γ;
(5) Non-regulatory adaptability = the government rent-seeking income (enterprise rent-seeking cost) T2 − central the government administrative penalty C2 − 0.3 × accident probability P × accident loss L + [0.3 × accident probability P × accident loss L – government rent-seeking income (enterprise rent-seeking cost) T2] × pipeline operator safety investment rate β;
(6) Safety investment rate of pipeline operator = INTEG (safety investment variation rate, initial);
(7) Safety investment rate = pipeline operator safety investment rate × (1 − pipeline operator safety investment rate) × poor implementation and non-implementation adaptability;
(8) Implementation and non-execution fitness difference = execution fitness − non-execution fitness;
(9) Implementation adaptability = reward for safety investment made by the government to the pipeline operator T5 ×government supervision rate α − operators reward for the public supervision T10 × public supervision rate γ + pipeline operator 's standard income T3 − safety investment cost C3 + pipeline maintenance fee T9;
(10) Non-implementation adaptability = saving safety input cost C4 – government rent-seeking income (enterprise rent − seeking cost) T2 − 0.5 × accident probability P × accident loss L + [the government rent-seeking income (enterprise rent-seeking cost) T2 – the pipeline operation business penalty F + pipeline operator standard income T3 + 0.5 × accident probability P × accident loss L] × government supervision rate α;
(11) Public supervision rate = INTEG (supervision change rate, initial);
(12) Supervision change rate = the public supervision rate × (1 – the public supervision rate) × poor adaptability of supervision and non-supervision;
(13) Supervised and unsupervised fitness difference = supervised fitness − unsupervised fitness;
(14) Supervision adaptability = (government rewards for the public supervision T7 + 0.2 × accident probability P × accident loss L) × government supervision rate α + (pipeline maintenance fee T9 + pipeline operator rewards for the public supervision T10 + 0.2 × accident probability P × accident loss L) × safety investment rate of the pipeline operator β − 0.2 × accident probability P × accident loss L × the government supervision rate α × the pipeline operator's safety investment rate β – the public supervision cost C5 − 0.2 × accident probability P × accident loss L.

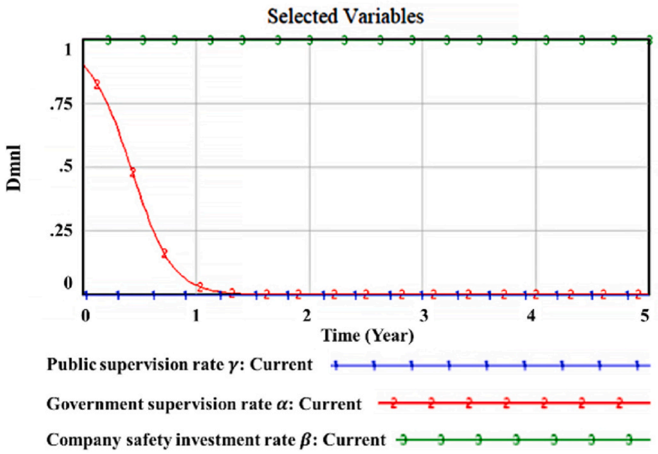


Fig. 7. The initial strategy is mutated from (1, 1, 0) to (0.9, 1, 0).

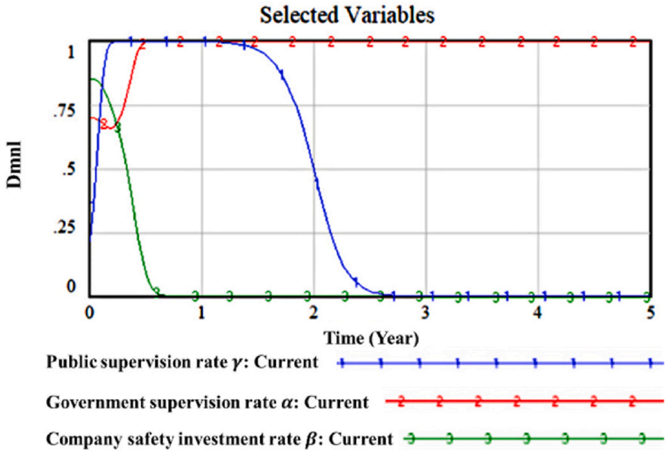
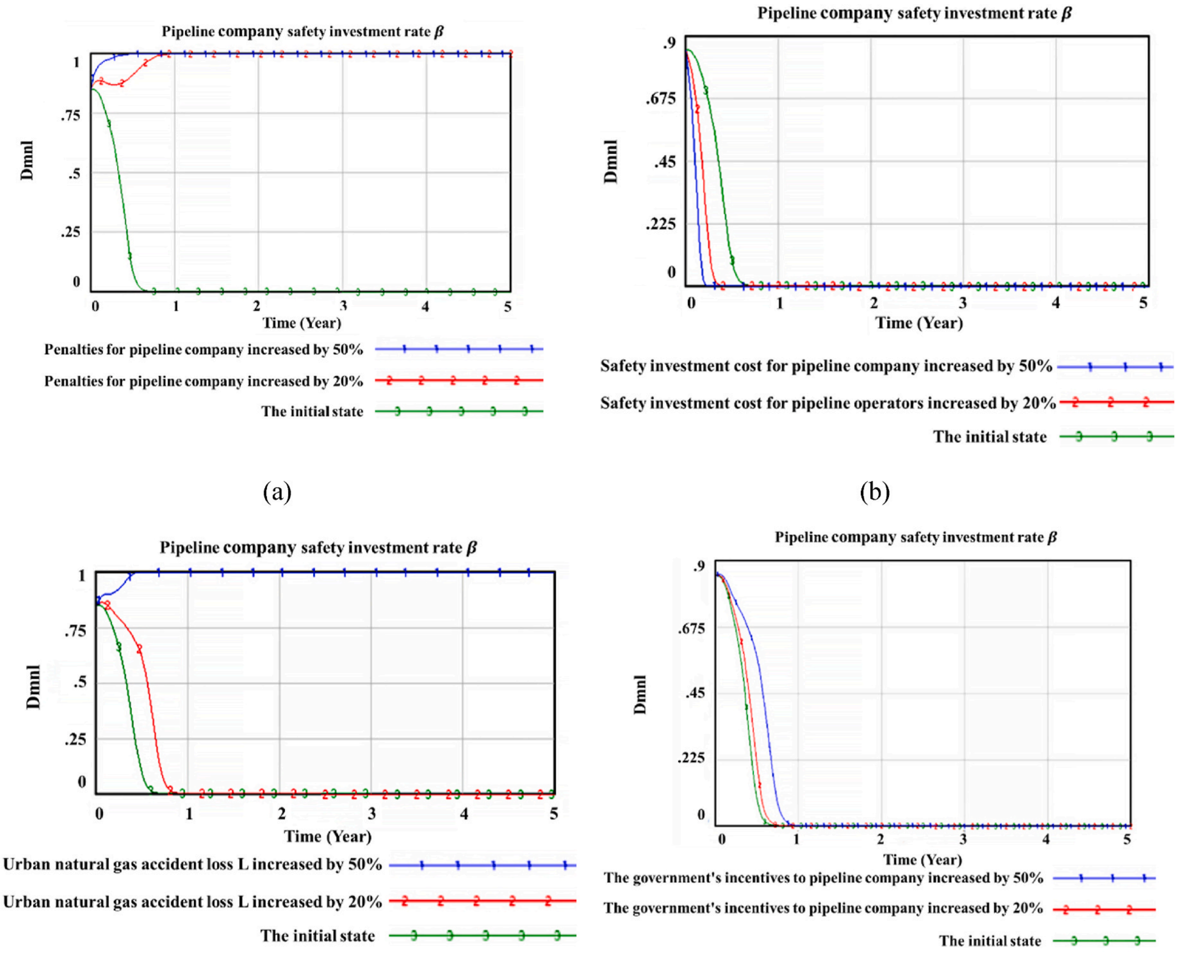


Fig. 8. Game evolution process under the initial strategy.

3.3.2. *Game simulation of risk management strategy*

It can be seen that, government, pipeline operator and the public have a total of 8 strategy combinations when making pure strategy choices, namely A1 (0, 0, 0), A2 (0, 0, 1), A3 (1, 0, 0), A4 (1, 0, 1), A5 (1, 1, 0), A6 (0, 1, 0), A7 (0, 1, 1), A8 (1, 1, 1), the simulation results are shown in Fig. 6.

When game partier chooses pure strategies in the initial stage of the game, there is no change in the strategy, and the game system reaches a relatively balanced state. However, the equilibrium state is partly unstable; if one player takes the initiative to adjust its strategy choice slightly, the system equilibrium state will be broken. Taking the initial strategy (1, 1, 0) as an example, when the government's initial strategy $\alpha = 1$ suddenly changes to $\alpha = 0.9$, the mutation result of evolutionary game system is shown in Fig. 7. It can be seen from Fig. 7 that when the initial strategic state of pipeline operator and the public remain unchanged, the government's supervision degree slightly decreased, and the evolution process has undergone significant changes. It shows that when pipeline operators have always maintained a high safety investment, at this time, the government, the main game player, will have higher benefits when it chooses a more conservative degree of



(a)　(b)

(c)　(d)

Fig. 9. Influencing factors analysis of Evolutionary game strategy (*a*) F, (*b*) C3, (*c*) L and (*d*) T5.

supervision. Therefore, based on the evolutionary game theory, at this time, the government will change its own strategic choices through learning and imitation. Through analysis, the pure strategy points of evolutionary stability in this paper are A3 (1, 0, 0) and A7 (0, 1, 1).

By taking the input of the degree of input from government, pipeline operator, and the public in the third-party damage risk control mechanism of urban natural gas pipelines derived from the static game theory, that is, $\alpha = 0.7006$, $\beta = 0.8497$, $\gamma = 0.2185$, The game evolution process of the stakeholders is shown in Fig. 8. In the early stage of the game, the safety investment rate of pipeline operator showed a clear downward trend, reaching a state of $\beta = 0$ in about six months. At the same time, the supervision rate of the government has declined in the early stage of supervision. With the continuation of the supervision process, the government has continued to reduce safety investment rate of pipeline operator, and the fines have been greater. Therefore, the supervision rate will gradually rise, eventually forming a state of $\alpha = 1$. In addition, the public supervision rate shows a trend of “rising-steady-declining”, and stabilizes at $\gamma = 0$. Therefore, the three-party evolutionary game of third-party damage risk control for urban natural gas pipelines finally forms a stable state of (1, 0, 0), that is, the government conducts safety supervision, pipeline operator does not make safety investments, and the public does not conduct corresponding supervision and management.

Through the analysis of the three-party evolutionary game process of “government-pipeline operator-public”, which shows that the game result under this game condition is apparently not in compliance with risk control requirements. As the first responsible party in the life cycle risk management of urban natural gas pipelines, pipeline operators should increase the rate of safety investment to ensure the stable operation of natural gas pipelines. The main reason for the game result in Fig. 8 is that pipeline operator’s profit from violating regulations not to make safety investments is higher, and pipeline operator’s income from regular the pipeline operation is lower. As a result, pipeline operator is more likely to operate illegally for high profits. The government-imposed penalties on a number of pipeline companies for the illegal operations, leading to a gradual increase in the supervision rate of the government.

3.3.3. *Influencing factors of evolutionary game strategy*

After the pure strategy analysis, by exploring the influence of external variables on the tripartite game process, the pipeline operators can increase the safety investment rate in urban natural gas pipelines risk management and make the game results more in line with actual requirements.

3.3.3.1. Effect of the fined amount F of pipeline operator. Based on the original data, increase the pipeline operator’s penalties by 20% and 50%, and observe the impact of penalties on the safety investment rate of the pipeline operator, as shown in Fig. 9(a). Pipeline operator’s safety investment rate showed a downward trend as the game progressed, and the investment rate is zero in about six months. When the penalty amount increased by 20% and 50%, pipeline operator’s game strategy changed, and the safety investment rate gradually increased as the game progressed, and finally stabilized at $\beta = 1$. In addition, by comparing the simulation result curves of 20% and 50% increase in the penalty amount, it can be found that the greater the penalty amount, the faster pipeline operator's safety investment rate will increase. It shows that the amount of penalization imposed on the pipeline operator has a positive effect on their safety investment. The higher the penalization, the faster the increase in the pipeline operator's safety investment rate.

3.3.3.2. Effect of safety investment of the pipeline operator C3. Pipeline operator's safety investment cost is increased by 20% and 50%, and the impact of the safety investment cost on the pipeline operator's safety investment rate is analyzed, as shown in Fig. 9(b). It can be seen from Fig. 9(b) that the safety investment rate of the pipeline operator shows a downward trend as the game progresses in the three scenarios. However, it can be seen that with the increase in safety input costs, the pipeline operator's safety input rate curve gradually declines faster, which shows that the safety input cost has a hindering effect on the pipeline operator's safety investment rate. The higher the cost of safety investment, the lower the intention of the pipeline operator to invest in safety.

3.3.3.3. Effect of accident loss L. Pipeline accidents are undoubtedly a direct way to cause the pipeline operator's loss of interest. The changes in the pipeline operator's safety investment rate are shown in Fig. 9(c) by changing the accident loss analysis. It can be seen from Fig. 9(c) that when the accident loss increases by 20%, the pipeline operator's safety investment rate decreases more slowly than in the original scenario, and the accident loss continues to increase by 50%. It is found that the pipeline operator's strategy has changed, from $\beta = 0$ turns into $\beta = 1$. This shows that the accident's severity will arouse the attention of the pipeline operator. The more serious the accident, the greater the safety investment made by the pipeline operator.

3.3.3.4. Effect of the government rewarding pipeline operator with T5. This study assumed that government will give the incentive policies when pipeline operator makes the reasonable safety investments, Fig. 9 (d) describes the changes in pipeline operator's strategy when the government gives pipeline operator with 20% and 50% increase in rewards. It can be seen from Fig. 9(d), the safety investment rate of the pipeline operator is reduced from the initial value to $\beta = 0$ in the three scenarios. However, the rate of decline in pipeline operator's safety investment rate has gradually slowed down as the amount of the rewards increases. As the reward amount is lower than the income brought by normal operation to the pipeline operator, the pipeline operator has not changed its game strategy, and a small increase will not cause a significant change in the pipeline operator's income. This shows that government's reward for pipeline operator has a positive effect on pipeline operator's safety investment. The greater the reward, the more inclined pipeline operator to make safety investment. However, the incentives are less sensitive to the safety investment rate of pipeline operator.

4. Summary and conclusions

This paper develops a game theory methodology for risk management of urban natural gas pipelines. By analyzing the strategic choices of government, pipeline operator, and the public in risk management, a "government-pipeline operator-public" collaborative management model is constructed using static game theory. The assessment of costs and benefits is brought into the static game model. The model reaches equilibrium when the government supervision rate is 0.7006, pipeline operator safety investment rate is 0.8497, and the public supervision rate is 0.2185. The methodology can be generic for risk management of urban infrastructures.

Considering the irrationality of players and the asymmetry of information in real case, the evolutionary game model is constructed using the evolutionary game payment matrix of "government-pipeline operator-public". The dynamic replication equation is obtained by solving the fitness of different strategies of the players, and the equilibrium points are pure strategy choice of government, pipeline operator, public and specific mixed strategy choice of them. Since it is very complicated to analyze players' dynamic strategy choice by using evolutionary game model, SD model is introduced to assist analysis. The result is that government conducts safety supervision, pipeline operator does not make safety investment, and the public does not conduct supervision and management. Through SD model, it is concluded that the penalty amount, the severity of accident consequences, and the amount of government rewards are directly proportional to pipeline operator's safety investment rate. The security input cost is inversely proportional to the security input rate. Through the outcomes of this study, the safety of urban natural gas pipeline can be guaranteed by the government raising the fine amount appropriately or the pipeline operator reducing the safety input cost.

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