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Disaster Chain Scenarios Evolutionary Analysis and Simulation Based on Fuzzy Petri Net: A Case Study on Marine Oil Spill Disaster

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ABSTRACT In a complex environment, a single disaster will generate a series of secondary disasters to form disaster chains. The simulation and prediction of the evolutionary direction of the disaster chain is a key aspect as well as a challenging problem during the emergency management of a disaster chain, accordingly there are two technical problems, the first one is how to describe the form of the disaster chains and the other one is how to model the evolution of the disaster chains. In order to solve these problems, this paper leverage Fuzzy Petri net as a powerful mathematical modelling tool, which can be used for the analysis of process evolution. Based on the traditional fuzzy Petri nets, a Disaster-Chain Fuzzy Petri net (DCFPN) method is proposed for describing the form of disaster chains and analyzing the evolutionary direction with the dynamic observed data. Based on the DCFPN method, this study constructs a general oil spill DCFPN model and takes the petrochemical spill incident in Fujian Province of China as a study case. The DCFPN model is used to dynamically deduce the evolutionary process of the case of oil spill disaster chain, reconstruct the evolutionary direction of the disaster chain, and analyze the riskiest path. The study found that the disaster chain scenarios deduced from the DCFPN model were consistent with the real situation, and this result would be useful for providing a scientific basis for the 'chain-cutting disaster mitigation' strategy for emergency management of disaster chains.

INDEX TERMS Fuzzy Petri net, disaster chain evolution analysis, dynamic deduction, chain-cutting disaster mitigation, oil spill disaster chain.

I. INTRODUCTION

In recent years, with the rapid development of social economy and rise in population, human activities have led to an increase in the frequency of natural and manmade disasters. Disaster prevention and mitigation have become one of the 20 most important global issues in the 21st century [1]. The frequency of single disasters has reduced owing to the influence of complex environment and human factors. However, many disasters will cause a series of secondary disasters after they occur, forming a disaster chain effect, which makes the primary disaster more complicated. Marine oil spills, as a kind of marine environmental disaster, has an extremely complex disaster chain, which will cause great harm to the marine environment once it occurs. For the United States, the most serious oil spill was that from the Deep-Water Horizon platform in the Gulf of Mexico on April 20, 2010 and this accident caused a lot of oil leaks, which led to an economic and environmental tragedy [2]. For China, there have been many oil spills in history, such as the Penglai 19-3 oil spill accident on June 11, 2011. This accident spilled heavy crude oil, causing great harm to the environment and will have a long-term impact on the Bohai Bay of China [3]. In addition to oil spill monitoring and oil spill diffusion models, oil spill research needs to pay attention to the impact of oil spill disaster chain on ecology, environment, human health, etc., and sometimes this disaster may trigger a public opinion crisis and large-scale mass incidents. Therefore, research on the disaster chain is critical for disaster emergency management.

There are three issues in the study of disaster chains. Firstly, which secondary disasters may be caused by a primary disaster? Secondly, which path in a disaster chain

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should be prevented in a specific scenario, considering the risk associated with it? Lastly, what kind of disposal measures can be used for chain-cutting disaster mitigation? The first issue relates to the knowledge construction of the disaster chain. Chen *et al*. [4]–[7] have studied natural disaster chains such as earthquake disaster chain, geological disaster chain, typhoon disaster chain, rain and snowstorm disaster chain, and have analyzed the evolution of specific disasters and the characteristics of the derivative chain. Ke *et al*. [8] constructed six marine disaster chains and summarized the characteristics of the impact of marine disasters. These studies of specific disaster chains can help to the knowledge construction. Ontology, which is used as a modelling tool to describe concepts on semantic and knowledge level, provides a new approach for the investigation of natural disasters [6]. Chen *et al.* [9] have proposed a top-down refinement method for modelling the complex disaster chain evolution process—the spatio-temporal evolution process Multi-level description Framework for Disaster Chain (STMFDC). Overall, the research on knowledge construction of disaster chain is relatively mature and can be used as reference.

The second issue mentioned above relates to identifying the path with the greatest risk in the disaster chain. In order to emphasize the interrelationship between disaster processes and establish their corresponding risk assessment methods, several terms, such as disaster chain, cascade effect, domino effect, chain reaction, and induced effect, have been proposed to describe the phenomenon of 'a disaster triggers another disaster' [10]. In qualitative aspects, Zhou *et al*. [7] proposed a conceptual model for risk assessment of a regional disaster chain, in which the sensitivity of the hazard-formative environment is the core factor as well as the main difference compared with the risk assessment of a single disaster. However, it is a big challenge to evaluate the risks of all links in a disaster chain together. In quantitative aspects, an event tree model is used to estimate the probability of primary disaster-induced secondary disasters in the disaster chain [11]. Li *et al.* [12] proposed a probability model for disaster chain in emergencies. Later, Wang *et al.* [13] established a risk assessment model for an earthquake disaster chain using a Bayesian network, which is often used to analyze uncertainty and probability. In addition, since Petri nets and directed networks can describe the relationship between discrete events, they have been used to analyze the hazards of each secondary disaster based on the accessibility analysis of each node. It is easy to analyze the degree of hazard of the entire set of cascading disasters [14], [15]. However, there are limitations in dynamically deducing the consequences of various possible disaster chains in actual scenarios.

The third issue is to study the significance of the disaster chain. It is of great significance in disaster prevention and mitigation to find the paths in a disaster chain that have the greatest risk and analyze the triggering factors between two disasters in a disaster chain. By controlling the triggering factors, the effect of chain-cutting disaster mitigation can be achieved. Petri nets (PNs) are considered to be one of the suitable mathematical models for discrete systems, and widely used in system control and fault diagnosis [16]–[18]. However, Petri nets can also model the disaster chains and express the triggering factors, which makes them useful in assessments of safety, reliability, and risk [19]. Vernez *et al.* [20] discussed the use and application prospects of Petri nets in the field of risk analysis and accident modelling. Tuncel and Alpan proposed a method based on timed Petri net for risk assessment and real-time control of supply chain (SC) networks [21]. In addition, from the perspective of emergency response, Zhang *et al.* [22] proposed a colored stochastic Petri net to evaluate the security and complexity of the emergency response procedure and the reasonableness of the resource flow so as to effectively analyze the potential deficiencies of the emergency response procedure. Presently, there are few studies on simulating disaster chains with Petri nets. The stochastic Petri net (SPN) was used to model the process of mining subsidence disaster chains combined with Markov chain [14]. The transition of the Petri net simulates the triggering mechanism of a disaster chain well. It can express the process of disaster chain evolution more intuitively than event tree and Bayesian network.

However, the proposed Fuzzy Petri net (FPN) is a new technique for quantitative analysis of risk assessment in disaster chains. FPNs are often used for fault detection and diagnosis of power systems and smart distribution systems, etc. [23]–[25]. A comprehensive risk assessment framework based on FPNs in combination with the analytic hierarchy process (AHP), entropy method (EM), and cloud model has been proposed by Guo *et al*. for long-distance oil and gas transportation pipelines [26]. On the other hand, Zhou *et al*. [27] used weighted FPNs (WFPNs) to propose a method for security risk assessment in the chemical industry. The use of WFPNs helps this method to model the interrelationships between the risk factors and determine the importance of the risk factors, thus ensuring meaningful risk assessment. Regarding disaster chains, an FPN based reversed reasoning approach was proposed to analyze the emergency response actions impacting domino effects [28]. FPN is utilized to deduce the consequence-antecedent relationship between an accident and the emergency response actions. However, FPNs have not been used to analyze the forward evolution process of a disaster chain and quantitatively analyze the risks. This paper aims to establish a new disaster chain evolution analysis model. While analyzing and simulating the evolution process of the disaster chain, it can quantitatively analyze the risks of the individual paths in a disaster chain, identify the path with the greatest risk, and control the key triggers to achieve the goal of chain-cutting disaster mitigation.

This paper consists of five sections. The first section introduces the significance of the topic and the status of related research. The second section introduces the model theory of disaster chain and FPN, and proposes an improved Disaster-Chain Fuzzy Petri net (DCFPN) model. The third section constructs an oil spill DCFPN and designs a series of membership functions. The fourth section analyzes the petrochemical spill incident in Fujian Province of China as an example and simulates additional scenarios to verify the validity and feasibility of the model; the fifth section summarizes the study.

II. DISASTER CHAIN FUZZY PETRI NET MODEL

A. DISASTER CHAIN MODEL

In the process of disaster evolution and development, a series of secondary disasters can be formed through the continuous action of the hazard-formative environment and the disaster-bearing body, which results in a disaster chain.

1) FORMAL EXPRESSION

A formal expression of the disaster chain was proposed by Chen *et al.* [9]. In this paper, the simplified disaster chain (DISCHAIN) is defined as a triple: DISCHAIN = (TSO_{chain}, TSE_{chain}, TSC_{chain}) where

Temporal-Spatial objects (TSO_{chain}) is the collection of all disaster-bearing bodies in the disaster chain. In the case of the oil spill disaster chain, aquaculture areas and ecologically protected areas are spatiotemporal objects of the disaster chain.

Temporal-Spatial events (TSE_{chain}) is the collection of all secondary events of the disaster chain that cause harm, such as water pollution and human poisoning.

Temporal-Spatial constraints (TSC_{chain}) are these include triggering factors and triggering constraints to control the evolution of the disaster chain.

Figure 1 illustrates the disaster chain; TSE_{chain}-1 poses a hazard to TSO_{chain}-1, and the overlapping part is the hazard area. Under TSC_{chain}-1, TSE_{chain}-2 is triggered, which causes additional harm to TSO_{chain}-2.

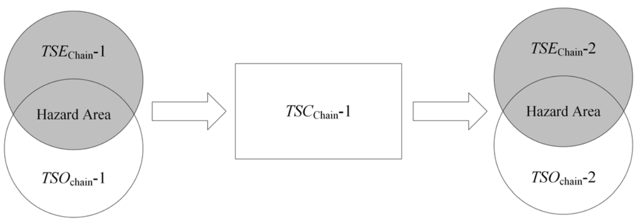


FIGURE 1. Formal illustration of disaster chain.

2) BASIC TYPES OF DISASTER CHAINS

The basic types of disaster chains are serial disaster chain, concurrent disaster chain, and coupled disaster chain.

Figure 2 shows the serial disaster chain: TSE_{chain}-1 triggers TSE_{chain}-2. The linear structure of the serial disaster chain is relatively simple and can significantly help to distinguish between precursor disasters and subsequent disasters.

Figure 3 shows the concurrent disaster chain: TSE_{chain}-1 triggers TSE_{chain}-2 and TSE_{chain}-3 simultaneously in a short time. The structure of the concurrent disaster chain is more complicated and the probabilities of subsequent disasters in the concurrent disaster chain are equal.

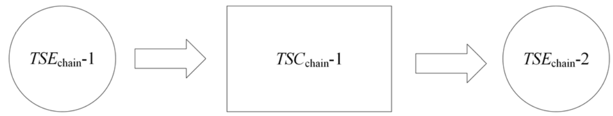


FIGURE 2. Serial disaster chain.

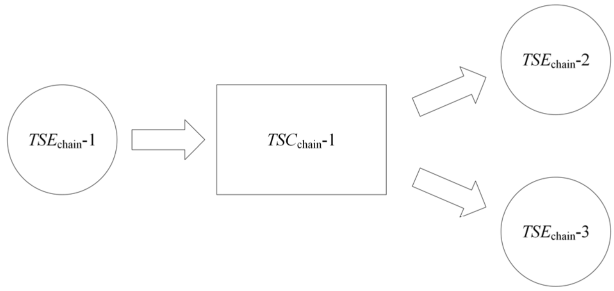


FIGURE 3. Concurrent disaster chain.

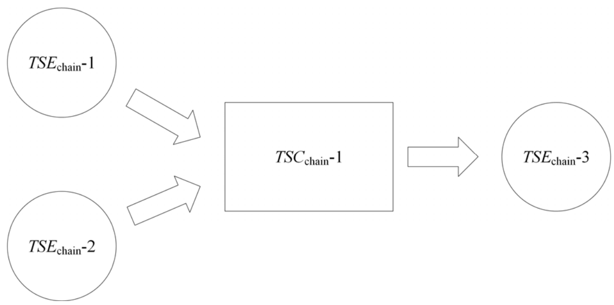


FIGURE 4. Coupled disaster chain.

Figure 4 shows the coupled disaster chain: TSE_{chain}-1 and TSE_{chain}-2 together trigger TSE_{chain}-3 under TSC_{chain}-1. Coupling can be divided into four types: generation coupling, acceleration coupling, aggravation coupling, and conversion coupling [29]. From the perspective of disaster chain risk, this paper focuses on aggravation coupling, that is, both TSE_{chain}-1 and TSE_{chain}-2 will trigger TSE_{chain}-3, and the risks will increase.

B. FUZZY PETRI NET

FPNs are extensions of traditional Petri nets and are suitable for describing concurrent systems with fuzzy behaviors. FPNs rely on fuzzy mathematics and can transform from qualitative analysis to quantitative analysis.

An FPN is a combination of Petri nets and production rules. The place represents a proposition. The token of the place is a value from 0 to 1, indicating the truth value of the proposition. The transition of the FPN has a fire threshold, and the threshold of the transition is a value from 0 to 1.

FPNs can be defined as an eight-tuple [30]: FPN = (P, T, D, I, O, f, α, β) where

$P = \{p_1, p_2, p_3 \ldots p_n\}$ refers to the finite set of places

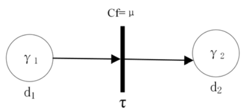
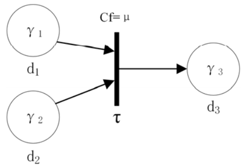
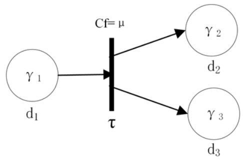
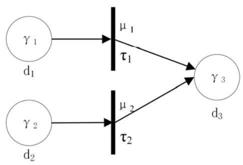
$T = \{t_1, t_2, t_3 \ldots t_m\}$ refers to the finite set of transitions

$D = \{d_1, d_2, d_3 \ldots d_n\}$ refers to the finite set of propositions

$I: P \rightarrow T$ is an input mapping

$O: T \rightarrow P$ is an output mapping

TABLE 1. Basic form and calculation formula of FPN.

Basic form	Calculation formula
	$\gamma_2=\gamma_1*\mu$, $(\gamma_1>\tau)$
	$\gamma_3=\min(\gamma_1, \gamma_2)*\mu$, $(\gamma_1,\gamma_2>\tau)$
	$\gamma_2=\gamma_1*\mu$, $(\gamma_1>\tau)$ $\gamma_3=\gamma_1*\mu$, $(\gamma_1>\tau)$
	$\gamma_3=\max(\gamma_1*\mu_1,\gamma_2*\mu_2)$, $(\gamma_1,\gamma_2>\tau)$

$f: P \to [0,1]$ represents the degree of truth of the proposition

$\alpha: T \to [0,1]$ represents the degree of truth of the transition

$\beta: P \to D$ is the mapping between the place and the proposition.

Any complex FPN can be split into four simple forms. The basic form and calculation formula are shown in Table 1.

C. DISASTER CHAIN FUZZY PETRI NET

The traditional FPN is mostly used for fault diagnosis. It is not suitable for calculating the risk of a disaster chain. Therefore, based on the disaster chain theory in Section II, this paper proposes an improved FPN theory called Disaster-Chain Fuzzy Petri net (DCFPN) and describes its calculation method.

1) DEFINITION OF DCFPN

DCFPN is a seven-tuple: $DCFPN = (P, T, I, O, A, U, \lambda)$ where

$P = \{p_1, p_2, \cdots, p_n\}$ refers to a finite set of disasters, called the set of places. A place corresponds to a secondary disaster in the disaster chain.

$T = \{t_1, t_2, \cdots, t_m\}$ refers to a finite set of triggering factors, called the set of transitions. A transition corresponds to the triggering factors of a secondary disaster.

I is the input of the transition. $I = \{w_{ij}\}$, $w_{ij} \in \{0, 1\}$. When p_i is the input of t_j (that is, there is a directed arc of p_i to t_j), $w_{ij} = 1$, otherwise $w_{ij} = 0$.

O is the output of the transition. $O = \{\gamma_{ij}\}$, $\gamma_{ij} \in \{0, 1\}$. When p_i is the output of t_j, $\gamma_{ij} = 1$, otherwise $\gamma_{ij} = 0$.

$A = \{\alpha_1, \alpha_2, \cdots, \alpha_m\}, \alpha_i \in [0, 1]$ refers to the truth values of a place. It represents the risk of secondary disasters.

$U = \{\mu_1, \mu_2, \cdots, \mu_m\}$, $\mu_j \in [0, 1]$ refers to the truth values of a transition. It represents the confidence of the triggering factors of secondary disasters.

$\lambda = \{\lambda_1, \lambda_2, \cdots, \lambda_m\}$. Each transition node has a fire threshold, $\lambda_i \in [0, 1]$. The next secondary disaster is triggered when the confidence of the triggering factors is greater than the threshold.

The correspondence between DCFPN and disaster chain is shown in Table 2. The truth values of the place represent the risk of secondary disasters and are the focus of this paper. The risks in this paper combine the probabilities and hazards. The greater the risk, the more is the seriousness of the disaster chain.

TABLE 2. Correspondence between DCFPN and disaster chain.

Disaster chain	DCFPN
Secondary disaster	Place (P)
Triggering factors of the secondary disaster	Transition (T)
Risks of the secondary disaster	Truth values of place
Confidence of triggering factors	Truth values of transition
Triggering constraints of the secondary disaster	Threshold of transition

2) CALCULATION MODEL OF DCFPN

The token value of all the places in the DCFPN does not disappear during the operation of the network. Therefore, each secondary disaster place will calculate a truth value of 0 to 1, representing the risk of the secondary disaster. Three basic forms of the disaster chain are proposed in the previous chapter. Under the premise of ignoring the complex coupling effect of disasters, the calculation model of the DCFPN can be summarised into the following three basic types.

(1) Serial DCFPN structure: The disaster P_1 triggers the disaster P_2 under the action of the triggering factor T_1. Its DCFPN structure is shown in Figure 5.

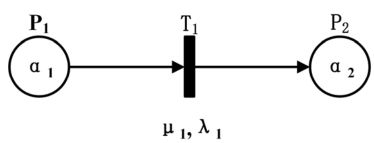


FIGURE 5. Serial DCFPN structure.

The calculation method for the truth value of the place is

$$\alpha_2 = \alpha_1 \cdot \mu_1, \quad (\mu_1 \geq \lambda_1) \tag{1}$$

(2) Concurrent DCFPN structure: The disaster Pz triggers the disasters $P_1, P_2, P_3 \ldots P_n$ under the action of the triggering factor T_1. Its DCFPN structure is shown in Figure 6.

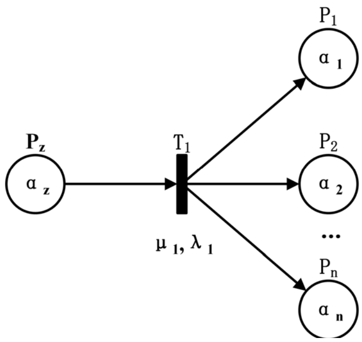


FIGURE 6. Concurrent DCFPN structure.

The calculation method for the truth value of the place is

$$\alpha_1, \alpha_2, \cdots, \alpha_n = \alpha_z \cdot \mu_1, \quad (\mu_1 \geq \lambda_1) \tag{2}$$

(3) Coupled DCFPN structure: The disasters $P_1, P_2, P_3 \ldots P_n$ respectively trigger the disaster P_z under the action of the triggering factors $T_1, T_2, T_3 \ldots T_n$, and the risk increases. Its DCFPN structure is shown as Figure 7.

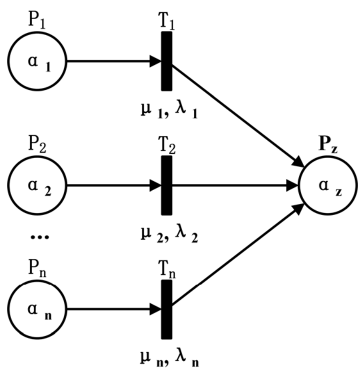


FIGURE 7. Coupled DCFPN structure.

The calculation method for the truth value of the place is

$$\alpha_z = 1 - \prod_{i=1}^{n} (1 - \alpha_i \cdot \mu_i), \quad (\mu_i \geq \lambda_i) \tag{3}$$

These three DCFPN basic types can express single chains, concurrent chains and coupled chains and any combination of them can express extremely complex disaster chain model.

3) CONSTRUCTION OF MEMBERSHIP FUNCTION

In the traditional FPN, the proposition has uncertainty because of which the truth values of the place are usually calculated by the membership functions. However, in DCFPN, the truth values of the place represent the risks of the secondary disaster and they are calculated by models. The truth values of the transition, that is, the triggering factors, are uncertain and need to be expressed by the membership functions. Therefore, this section will discuss the construction of the membership function for the truth values of the transition.

The membership function is based on fuzzy control, making it possible to quantify some fuzzy conditions. If any element x in U has $A(x) \in [0, 1]$ corresponding to it, then A is called a fuzzy set on U. $A(x)$ is called the membership of x to A. When x changes in U, $A(x)$ is a function called the membership function of A. The closer the degree of membership of $A(x)$ is to 1, the higher is the degree to which x belongs to A; the closer the degree of membership of $A(x)$ is to 0, the lower is the degree that x belongs to A.

For example, $A(x)$ is a membership function representing the fuzzy set 'old'. When age $x \leq 50$, $A(x) = 0$ indicates that x is not a member of the fuzzy set A (i.e. 'old'). When $x \geq 100$, $A(x) = 1$ indicates that x is completely a member of A. When $50 < x < 100$, $0 < A(x) < 1$, and the closer x is to 100, the closer $A(x)$ is to 1. This method of expression is obviously more reasonable than saying 'People over 100 years of age are old, and people under 50 years of age are not old'.

The membership function is usually determined based on expert experience, and then gradually revised and improved through practice testing. In the DCFPN model proposed in this paper, the truth values of the transition, that is, the triggering factors may be whether a certain type of disaster-bearing body is affected. For example, 'When oil spills affect aquaculture areas, it will cause large-scale destruction of aquatic life'. The aquaculture area is the disaster-bearing body, and the trigger condition of the disaster chain is the overlay area between the oil spill and the aquaculture area. Therefore, considering the hazard and the exposure of the disaster-bearing body together [31], this paper proposes a method for determining the membership function by spatial analysis of the geographic information system.

As shown in Figure 8, S_h is defined as the disaster-affected area, S_b is the area of the disaster-bearing body, and S_o is the overlay area obtained by the overlay analysis of S_h and S_b; it represents the area of the disaster-bearing body.

Define the membership function of the overlay analysis $A(x)$ as

$$A(x) = \frac{S_o}{S_b} \tag{4}$$

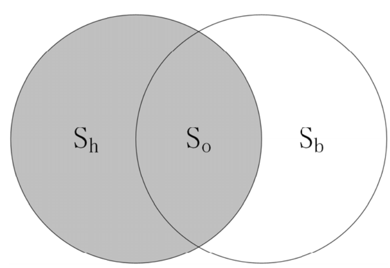


FIGURE 8. Relationship among S_h, S_b, and S_o.

If $A(x)$ is 0, the disaster does not affect the disaster-bearing body. If $A(x)$ is 1, the disaster-bearing body is 100% affected. The closer $A(x)$ is to 0, the smaller is the risk of the disaster; the closer $A(x)$ is to 1, the greater is the risk of the disaster. Using this membership function to calculate the truth values

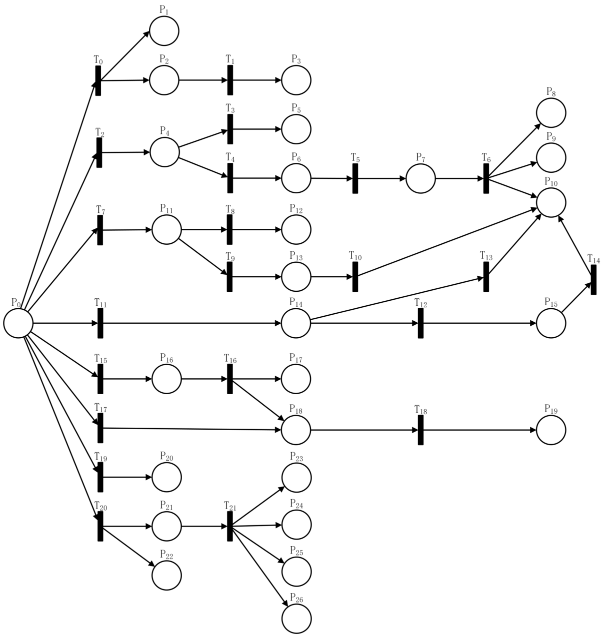


FIGURE 9. DCFPN for oil spill.

of the transition can effectively express the risk of this type of disaster chain.

In the DCFPN model proposed in this paper, there is another construction method for the membership function based on network public opinions. Zeng and Xu have proposed a method for the early warning system of network public opinion [32]. In their article, network public opinion is divided into four levels based on score of 30 to 150, with level I being the most serious and level IV being the least serious. Based on this method, the score of network public opinion can be normalised as follows.

$$x_i' = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{5}$$

x_i' is the value after normalisation. x_{max} is the maximum value of 150, and x_{min} is the minimum value of 30. In this paper, the membership function describing the network public opinion is constructed as follows.

Define the membership function of the network public opinion index $B(x)$ as

$$B(x) = x_i' \tag{6}$$

x_i' is the normalised network public opinion index with values between 0 and 1. There are many ways to evaluate the network public opinion. A network public opinion index that is normalized and has value between 0 and 1 can be used in this paper.

III. MODELLING THE OIL SPILL DISASTER CHAIN BASED ON DCFPN

A. OIL SPILL DISASTER CHAIN BASED ON DCFPN

An oil spill has a huge impact on the marine life, ecological environment, human economic activity area, and ordinary residents living by the sea. It may also cause secondary disasters such as fires and explosions. The casualties of the oil spill may even trigger social mass incidents.

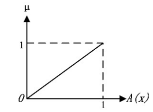
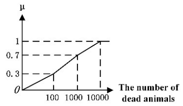
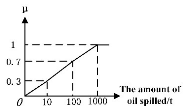
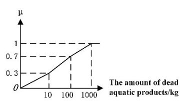
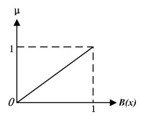
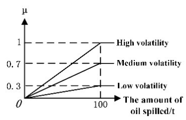
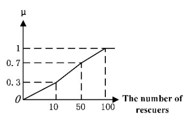
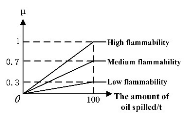
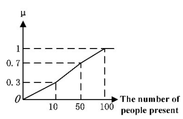
This paper identifies the secondary and derivative disasters that may be triggered by the oil spill, and considers the environment, animal and plant, human health, transportation of hazardous chemicals, maritime traffic, coastal industries, etc. to construct a general oil spill disaster chain. It is expressed in the form of a DCFPN, as shown in Figure 9.

The DCFPN for an oil spill comprises 26 places and 21 transitions. Each place represents the risk of one secondary disaster, which combines the probability and degree of the hazard, and each transition represents a factor that triggers a

TABLE 3. Descriptions of semantic symbols of the DCFPN.

Symbol	Semantic (Place)	Symbol	Semantic (Transition)
P_0	Oil spill	T_0	Nature reserve
P_1	Ecological destruction	T_1	Dead animals not disposed in time
P_2	Wildlife death	T_2	Amount of oil spill
P_3	Animal epidemic event	T_3	Urban water supply area
P_4	Water pollution	T_4	Aquaculture area
P_5	Urban water supply interruption	T_5	Inflow into the market
P_6	Aquatic death	T_6	Negative network public opinion
P_7	Food contamination	T_7	Volatility of oil
P_8	Market fluctuation	T_8	Oil spill responders
P_9	Unsalted aquatic products	T_9	Coastal residential area
P_{10}	Social mass incident	T_{10}	Negative network public opinion
P_{11}	Air pollution	T_{11}	Flammability of oil
P_{12}	Responder poisoning	T_{12}	Human existence
P_{13}	Mass poisoning event	T_{13}	Negative network public opinion
P_{14}	Hazardous chemicals explosion	T_{14}	Negative network public opinion
P_{15}	Injury and death	T_{15}	Maritime traffic area
P_{16}	Maritime traffic disruption	T_{16}	Unconditional trigger
P_{17}	Freight break	T_{17}	Scenic Area
P_{18}	Tourism damage	T_{18}	Unconditional trigger
P_{19}	Service industry damage	T_{19}	Controversial sea area
P_{20}	Foreign-related events	T_{20}	Shoreline
P_{21}	Shore beach pollution	T_{21}	Coastal industrial area
P_{22}	Soil pollution		
P_{23}	Industrial production damage		
P_{24}	School suspension		
P_{25}	Transport industry damage		
P_{26}	Market instability		

TABLE 4. Membership function and threshold of each transition.

Transition	Membership function graph	Membership function	Threshold
$T_0/T_3/T_4/T_9$ $/T_{15}/T_{17}/T_{19}$ $/T_{20}/T_{21}$		$\mu = A(x) = \frac{S_o}{S_b}$	λ=0
T_1		$\mu = \begin{cases} \frac{3}{1000}x, 0 \le x < 100 \\ \frac{4}{9000}x + \frac{23}{90}, 100 \le x < 1000 \\ \frac{3}{90000}x + \frac{2}{3}, 1000 \le x < 10000 \\ 1, x \ge 10000 \end{cases}$	λ=0.1
T_2		$\mu = \begin{cases} \frac{3}{100}x, 0 \le x < 10 \\ \frac{4}{900}x + \frac{23}{90}, 10 \le x < 100 \\ \frac{3}{9000}x + \frac{2}{3}, 100 \le x < 1000 \\ 1, x \ge 1000 \end{cases}$	λ=0
T_5		$\mu = \begin{cases} \frac{3}{100}x, 0 \le x < 10 \\ \frac{4}{900}x + \frac{23}{90}, 10 \le x < 100 \\ \frac{3}{9000}x + \frac{2}{3}, 100 \le x < 1000 \\ 1, x \ge 1000 \end{cases}$	λ=0
$T_6/T_{10}/T_{13}/$ T_{14}		$\mu = B(x)$	λ=0.5
T_7		$\mu = \begin{cases} \frac{1}{100}x, \text{High volatility} \\ \frac{7}{1000}x, \text{Medium volatility} \\ \frac{3}{1000}x, \text{Low volatility} \end{cases}$	λ=0
T_8		$\mu = \begin{cases} \frac{3}{100}x, 0 \le x < 10 \\ \frac{1}{100}x + \frac{1}{5}, 10 \le x < 50 \\ \frac{3}{500}x + \frac{2}{5}, 50 \le x < 100 \\ 1, x \ge 100 \end{cases}$	λ=0
T_{11}		$\mu = \begin{cases} \frac{1}{100}x, \text{High flammability} \\ \frac{7}{1000}x, \text{Medium flammability} \\ \frac{3}{1000}x, \text{Low flammability} \end{cases}$	λ=0
T_{12}		$\mu = \begin{cases} \frac{3}{100}x, 0 \le x < 10 \\ \frac{1}{100}x + \frac{1}{5}, 10 \le x < 50 \\ \frac{3}{500}x + \frac{2}{5}, 50 \le x < 100 \\ 1, x \ge 100 \end{cases}$	λ=0
T_{16}/T_{18}	μ=1		λ=0

secondary disaster. The meaning of each place and transition is shown in TABLE 3.

The types of places and transitions in this general oil spill DCFPN have been determined and other parameters such as the truth values of place and transition are temporarily empty. In the subsequent analysis and simulation process, the other DCFPN parameters will be filled in with the input of data of different scenarios.

B. MEMBERSHIP FUNCTIONS OF OIL SPILL DISASTER CHAIN

As shown in Figure 10 and TABLE 3, T_0, T_3, T_4, T_9, T_{15}, T_{17}, T_{19}, T_{20}, and T_{21} are all disaster-bearing bodies, which means the oil spill affects the disaster-bearing body. The membership functions of these transitions are constructed by the method of overlay analysis in Section 2.3.3. The membership function of T_1 is constructed with the number of dead animals. The membership functions of T_2, T_7, and T_{11} are constructed with the amount of oil spill. The membership function of T_5 is constructed with the number of dead aquatic products flowing into the market. The membership functions of T_6, T_{10}, T_{13}, and T_{14} are replaced by the network public opinion index. The membership functions of T_8 and T_{12} are constructed with the number of people, and T_{16} and T_{18} are unconditionally triggered directly. The membership function is based on relevant standards and expert experience, as shown in TABLE 4.

Taking the amount of oil spill as an example, the membership function is determined according to the scale of the oil spill. The oil spill less than 10 tons is a small-sized accident with a degree of membership between 0 and 0.3. The oil spill between 10 and 100 tons is a medium-sized accident with a degree of membership between 0.3 and 0.7. The oil spill between 100 and 1000 tons is a large-sized accident with a degree of membership between 0.7 and 1. The oil spill more than 1000 tons is a particularly serious accident with a degree of membership of 1.

In TABLE 4, the volatility is divided into three levels—low volatile oils such as heavy oil, medium volatile oils such as heavy kerosene and light crude oil, and highly volatile oils such as gasoline and light diesel. The flammability is also divided into three levels—low flammable oils such as heavy oil, medium flammable oils such as heavy kerosene and light crude oil, and highly flammable oils such as gasoline and light kerosene.

IV. CASE STUDY

Based on the established DCFPN model, this section introduces the case of petrochemical spill in Fujian Province of China and conducts dynamic evolution reconstruction and risk calculation for the process of this oil spill to explore the idea of disaster mitigation.

A. STUDY AREA

The study area of this case is located in Quangang District, Quanzhou City, Fujian Province, China. Fujian Province is located on the southeast coast of China, adjacent to Zhejiang Province in the northeast, bordering Jiangxi Province in the northwest, Guangdong Province in the southwest, and Taiwan Province in the southeast. As Figure 10 shows on its left side, Quangang District is located in the central part of Fujian Province, east of Meizhou Bay, adjacent to Hui'an County in the south, with a sea area of 119 square kilometers.

This case was triggered by the leakage of a petrochemical transportation ship of Fujian Donggang Petroleum chemical industry Co., Ltd. in Quangang District. As Figure 10 shows on its right side, the area marked with red lines is Fujian Donggang Petroleum chemical industry Co., Ltd. and the red solid circle indicates the approximate spill point of this

FIGURE 10. Specific location and distribution of the study area (Image source: Google Earth).

case. The areas marked with blue lines are the three villages affected by the petrochemical spill in this case, namely Xiaocuo Village, Shangxi Village and Fengqian Village. The areas marked with yellow lines are aquaculture areas which is one of the important disaster-bearing bodies that may be affected by oil spills.

B. CASE DESCRIPTION

On November 4, 2018, a petrochemical spill occurred at Donggang Petroleum Chemical Industry Co., Ltd in Quangang District, Quanzhou City, Fujian Province, China. In the early morning of November 4th, Fujian Donggang Petroleum Chemical Industry Co., Ltd. carried out petrochemical loading operations, and leaked at the hose connecting the sea area of the dock. The Quanzhou Municipal Government initially determined that the incident was an environmental pollution incident caused by a safety production responsibility accident and the incident directly affected the sea area of about 0.6 square kilometres.

At 3 or 4 in the morning on the 4th, the villagers of Xiaocuo Village smelled a very pungent smell of gasoline, only to find that it was leaking from the nearby dock. According to the circular, the damage to the culture was concentrated in about 300 mu in the cage culture area of Xiaocuo, involving 152 households and 99 units of breeding area, of which 20 units were empty boxes, and 20 units in the 79 units were sinking.

In addition, the spilled petrochemical spread to the beach, causing great harm to the coastal environment, industry and residents. As of 17:00 on November 8, Quangang District Hospital received a total of 52 such patients who were treated for exposure to pollutants, including 42 outpatient clinics and 10 inpatients. The damage caused by the petrochemical to the human body includes two aspects. One is to affect the human skin through the water, and more importantly, it has strong volatility. Once inhaled by the body, volatiles may cause some acute damage to people.

It was notified on November 8 that Donggang Petroleum Chemical Industry Co., Ltd. estimated the leakage amount to be 6.97 tons. After the investigation, on the afternoon of November 25th, the Quanzhou Municipal Government held a follow-up press conference. The investigation team found that in the report of the petrochemical spill in Quangang, the enterprises involved deliberately concealed the facts and the actual leakage reached 69.1 tons. Therefore, the case triggered a public opinion crisis and large-scale mass incidents. (Source: XINHUANET) [33]

C. ANALYSIS AND SIMULATION OF PETROCHEMICAL SPILL DISASTER CHAIN BASED ON DCFPN

DCFPN can dynamically analyze and simulate the evolution process of the petrochemical spill disaster chain based on the continuous updating of input data. Through the simulation of different scenarios of the petrochemical spill disaster, the path with the greatest risk in the disaster chain can be quantitatively analyzed and controlled purposefully. In this chapter, DCFPN is used to analyze the real scenarios of the petrochemical spill disaster to verify the rationality of the model and simulate two hypothetical scenarios to find the path with the greatest risk. Because of the sensitive information about this case study, most of the data was retrieved by public information released by government or authoritative media.

According to the case description, this petrochemical spill disaster can be roughly divided into three key stages which correspond to three key scenarios, namely the initial petrochemical spill scenario, the shore beach pollution scenario and the public opinion crisis scenario:

(1) The initial petrochemical spill scenario (S_0): At 0:51 a.m. on November 4, the petrochemical began to leak. This kind of petrochemical was highly flammable and highly volatile and the amount of spill reached 6.9 tons. The contaminated aquaculture area was mainly concentrated in the vicinity of Xiaocuo Village, with a damaged area of about 300 mu, which represented approximately 25% of all aquaculture areas in the study area. According to the news report, the affected sea area is about 0.6 square kilometres. Measured on Google Earth, the research sea area is about 2.5 square kilometres. Therefore, it can be estimated that the affected area of the maritime traffic is about 25%. [33].

(2) The shore beach pollution scenario (S_1): At 4:30 in the morning of November 4, about 50 responders were dispatched and the cleaning operation in the boom was completed. However, some of the slop petrochemical moved to the adjacent shore under the effect of the wind and triggered a series of derived events. According to the news report, the shoreline to be cleaned is approximately 4 kilometres [34]. Measured on Google Earth, the length of the study coast is approximately 4 kilometres. According to the news report, Xiaocuo Village, Shangxi Village and Fengqian Village were affected by the oil spill [35]. Measured on Google earth, the affected area was estimated to be about 0.55 square kilometres and the residential area within the total study area is approximately 2 square kilometres. Therefore, it can be estimated that the affected residential area is about 25%. Assuming that the coastal industrial area is evenly distributed along the coastline, the damaged industrial area is approximately 25%.

(3) The public opinion crisis scenario (S_2): At 10:20 a.m. on November 4, the relevant departments found that the actual petrochemical spill reached 69 tons, which created a public opinion crisis. According to the public opinion monitoring data of WORDEMOTION [36]: from 0:00 on November 4 to 11:00 on the 10th, there were 113675 discussion materials related to the event. The discussion reached the peak at 8:00 on November 8th and showed a significant decline at 12 o'clock. The number of people affected exceeded 740 million, accounting for 87% of the total number of Chinese Internet users (854 million) [37]. This ratio will be used as network public opinion index for subsequent model calculations.

The parameter calculation results and risk of petrochemical spill disaster chain in these three key scenarios are shown in TABLE 5, TABLE 6, TABLE 7, Figure 11, Figure 12 and Figure 13.

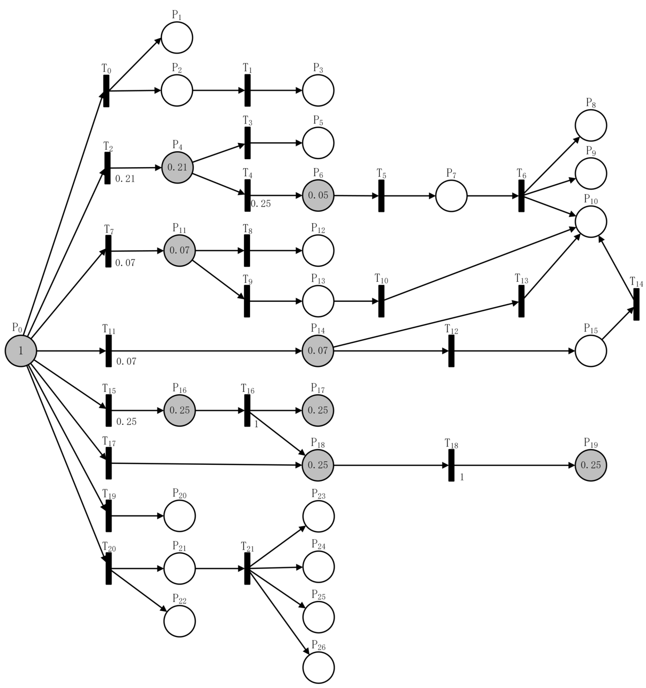


FIGURE 11. Risk of petrochemical spill disaster chain in the initial petrochemical spill scenario (S_0).

As Figure 11 shows, the disaster paths that may occur in the initial petrochemical spill scenario are 'oil spill–water pollution–aquatic death', 'oil spill–air pollution', 'oil spill–hazardous chemicals explosion', 'oil spill–maritime traffic disruption–freight break', and 'oil spill–maritime traffic disruption–tourism damage–service industry damage'. Because the oil spill occurred in the early hours of the morning, the risk of a series of secondary disasters caused by maritime traffic disruption was reduced. Air pollution and explosion of hazardous chemicals are caused by the high volatility and high flammability of petrochemicals. In the path 'oil spill–water pollution–aquatic death', we need to pay attention to the treatment of dead aquatic organisms to prevent subsequent disaster chains. In the initial petrochemical spill scenario, the path with the greatest risk is 'oil spill–maritime traffic disruption–tourism damage–service industry damage'. Therefore, in this key scenario, we need to solve the problem caused by oil spills to maritime traffic.

TABLE 5. Parameter calculation result of the initial petrochemical spill scenario (S_0).

Transition	Input Data	Truth values of transition	Place	Truth values of place
T_0	0	0	P_0	1
T_1	0	0	P_1	0
T_2	6.9t	0.21	P_2	0
T_3	0	0	P_3	0
T_4	25%	0.25	P_4	0.21
T_5	0	0	P_5	0
T_6	0	0	P_6	0.05
T_7	High Volatility, 6.9t	0.07	P_7	0
T_8	0	0	P_8	0
T_9	0	0	P_9	0
T_{10}	0	0	P_{10}	0
T_{11}	High Flammability, 6.9t	0.07	P_{11}	0.07
T_{12}	0	0	P_{12}	0
T_{13}	0	0	P_{13}	0
T_{14}	0	0	P_{14}	0.07
T_{15}	25%	0.25	P_{15}	0
T_{16}	1	1	P_{16}	0.25
T_{17}	0	0	P_{17}	0.25
T_{18}	1	1	P_{18}	0.25
T_{19}	0	0	P_{19}	0.25
T_{20}	0	0	P_{20}	0
T_{21}	0	0	P_{21}	0
			P_{22}	0
			P_{23}	0
			P_{24}	0
			P_{25}	0
			P_{26}	0

As shown in Figure 12, with responders dispatched, 'responder poisoning' and 'injury and death' appear in the shore beach pollution scenario. As a part of the oil spill affects the beach, it affects the coastal industries and the health of the coastal residents. Overall, due to the small quantity of the oil spill, the risk of each path in the oil spill disaster is low, and

TABLE 6. Parameter calculation result of the shore beach pollution scenario (S_1).

Transition	Input Data	Truth values of transition	Place	Truth values of place
T_0	0	0	P_0	1
T_1	0	0	P_1	0
T_2	6.9t	0.21	P_2	0
T_3	0	0	P_3	0
T_4	25%	0.25	P_4	0.21
T_5	0	0	P_5	0
T_6	0	0	P_6	0.05
T_7	High Volatility, 6.9t	0.07	P_7	0
T_8	50	0.7	P_8	0
T_9	25%	0.25	P_9	0
T_{10}	0	0	P_{10}	0
T_{11}	High Flammability, 6.9t	0.07	P_{11}	0.07
T_{12}	50	0.7	P_{12}	0.05
T_{13}	0	0	P_{13}	0.02
T_{14}	0	0	P_{14}	0.07
T_{15}	25%	0.25	P_{15}	0.05
T_{16}	1	1	P_{16}	0.25
T_{17}	0	0	P_{17}	0.25
T_{18}	1	1	P_{18}	0.25
T_{19}	0	0	P_{19}	0.25
T_{20}	25%	0.25	P_{20}	0
T_{21}	25%	0.25	P_{21}	0.25
			P_{22}	0.25
			P_{23}	0.06
			P_{24}	0.06
			P_{25}	0.06
			P_{26}	0.06

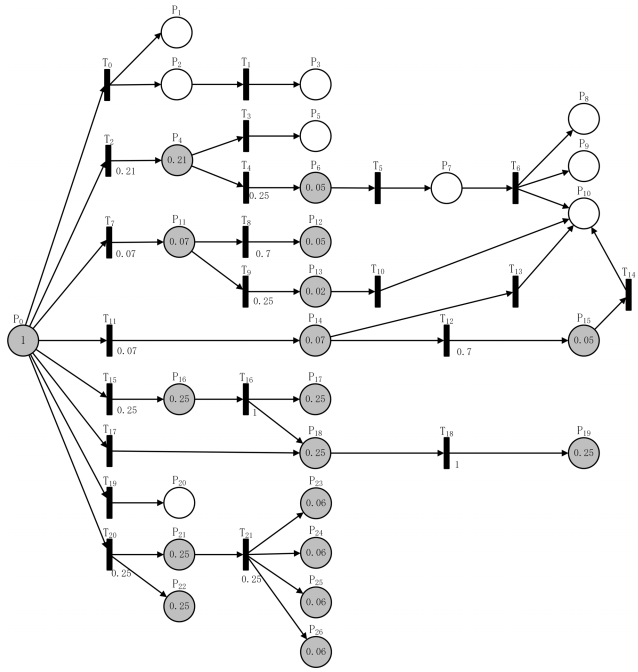


FIGURE 12. Risk of the oil spill disaster chain in the shore beach pollution scenario (S_1).

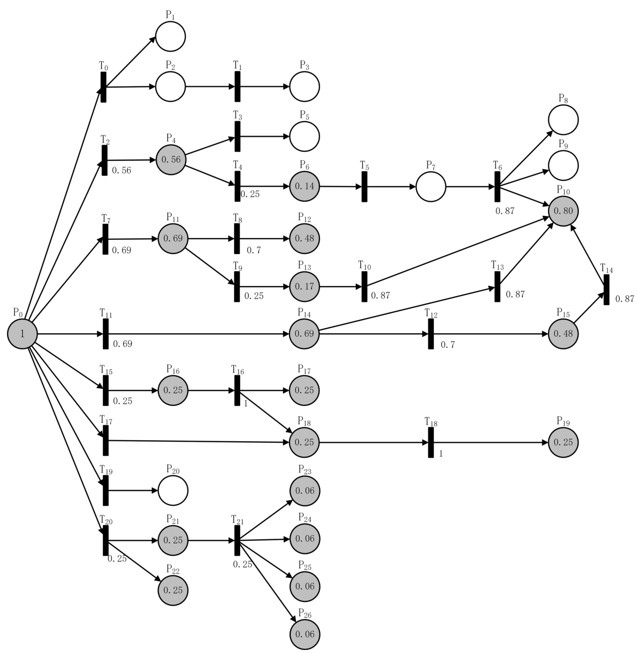


FIGURE 13. Risk of the oil spill disaster chain in the public opinion crisis scenario (S_2).

in this key scenario, we need to solve the problem caused by oil spills on maritime traffic.

In the public opinion crisis scenario, the actual oil spill increased to 69 tons, and a public opinion crisis broke out, triggering social mass incidents. As Figure 13 shows, the path with the greatest risk is P0→P10. P10 represents social mass incidents, which is the most prominent problem affecting China's social stability. On the one hand, China's environment, resources, society, and other related problems have led to more social mass incidents. On the other hand, mass incidents are socially sensitive events, and the Chinese government attaches great importance to them. In this key scenario, it is crucial for government to control negative online public opinion.

According to the report of Southern Weekly [38], after the accident, a large number of complaints were reported, triggering a series of mass incidents and causing panic in the local area. Some of the angry Quangang people chose to flee, and some of them blocked the door, and some of

TABLE 7. Parameter calculation result of the public opinion crisis scenario (S_2).

Transition	Input Data	Truth values of transition	Place	Truth values of place
T_0	0	0	P_0	1
T_1	0	0	P_1	0
T_2	69t	0.56	P_2	0
T_3	0	0	P_3	0
T_4	25%	0.25	P_4	0.56
T_5	0	0	P_5	0
T_6	87%	0.87	P_6	0.14
T_7	High Volatility, 69t	0.69	P_7	0
T_8	50	0.7	P_8	0
T_9	25%	0.25	P_9	0
T_{10}	87%	0.87	P_{10}	0.80
T_{11}	High Flammability, 69t	0.69	P_{11}	0.69
T_{12}	50	0.7	P_{12}	0.48
T_{13}	87%	0.87	P_{13}	0.17
T_{14}	87%	0.87	P_{14}	0.69
T_{15}	25%	0.25	P_{15}	0.48
T_{16}	1	1	P_{16}	0.25
T_{17}	0	0	P_{17}	0.25
T_{18}	1	1	P_{18}	0.25
T_{19}	0	0	P_{19}	0.25
T_{20}	25%	0.25	P_{20}	0
T_{21}	25%	0.25	P_{21}	0.25
			P_{22}	0.25
			P_{23}	0.06
			P_{24}	0.06
			P_{25}	0.06
			P_{26}	0.06

them blocked at Gate 2 of Donggang Petroleum Chemical Industry for protest. The sea fish cultured in Xiaocuo Village died in large numbers and the government has requested to suspend the fishing and sale of aquatic products in the sea area of Xiaocuo Village, which led to a huge loss in the aquaculture industry. Due to the volatility and toxicity of the petrochemical, many villagers inhaled toxic gases and 10 of them were hospitalized. These facts prove that the results obtained by the DCFPN model are reasonable.

In order to test the flexibility of the model to different transition parameters, the paper added two hypothetical scenarios based on the analysis of the public opinion crisis scenario.

TABLE 8. Unified division standard of hypothetical values.

Hypothetical value	Meaning of the value
0	Completely impossible to trigger
25%	25% probability trigger
50%	50% probability trigger
75%	75% probability trigger
100%	Fully possible to trigger

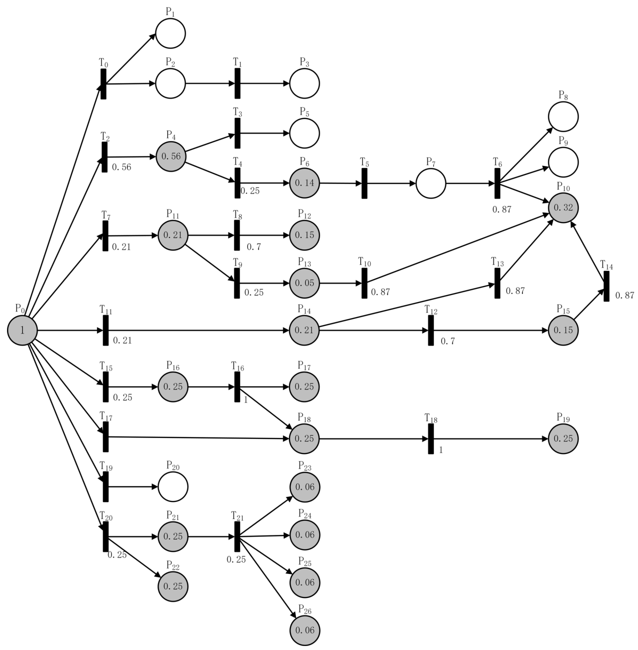


FIGURE 14. **Simulating the risk of oil spill disaster chain caused by heavy oils (S_3).**

As shown in Table 8, five hypothetical values are designed, which can be used to simulate five different levels.

The first hypothetical scenario (S_3) is to change the type of oil. This scenario is to simulate the evolution trend of disaster chains after the leakage of oils with low volatility and low flammability. In this experiment, low volatility and low flammability are substituted into the membership function for calculation and the values of T_7 and T_{11} have changed from 0.69 to 0.21. As Figure 14 shows, it can be found that the evolution path of the disaster chain with the greatest risk has changed from $P_0 \rightarrow P_{10}$ to $P_0 \rightarrow P_4$. The risk of secondary disasters caused by heavy oil leakage is reduced and the water pollution with relatively high risk should be paid attention to by the government.

The second hypothetical scenario assumes that the petrochemical spill further spreads and seriously harms the coast (S_4) which has a huge impact on coastal industries, human health, environmental pollution, etc. Therefore, this experiment chooses a 75% hypothetical range instead of a 25% true range and the values of T_9, T_{20} and T_{21} have changed from 0.25 to 0.75. As Figure 15 shows, the risk of secondary

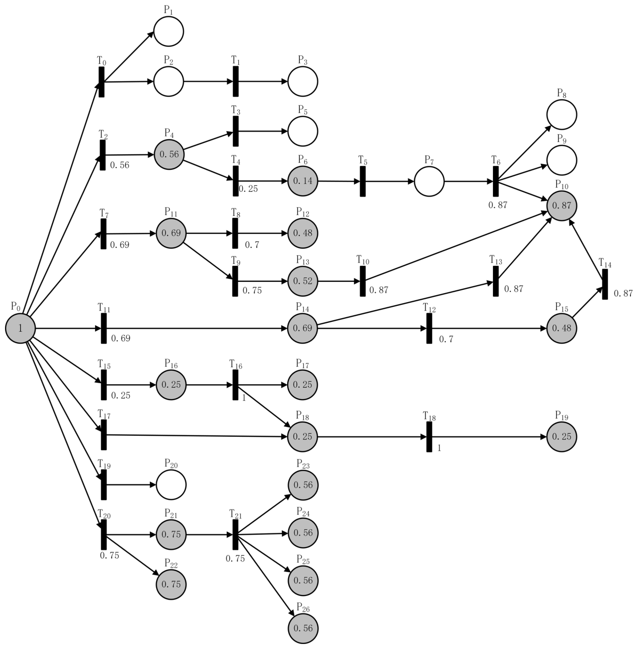


FIGURE 15. Simulating the risk of oil spill disaster chain when seriously harm the coast (S_4).

disasters associated with the coast has greatly increased. The evolution path of the disaster chain with the greatest risk is still $P_0 \rightarrow P_{10}$, but the risk of P_{13}, namely the risk of mass poisoning event has changed from 0.17 to 0.52. In addition, the risk of shore beach pollution and soil pollution has also increased and it is likely to trigger 'industrial production damage', 'school suspension', 'transport industry damage' and 'market instability'. Through the simulation of two hypothetical scenarios, different disaster chain evolution trends are obtained, which proves that the DCFPN model is flexible and able to support different scenario deduction in the field of disaster emergency.

In order to more intuitively show the simulation effect of the model on different scenarios, the paper puts the three scenarios S_2, S_3 and S_4 together and compares the highest risk chain, the second highest risk chain and the third highest risk chain of these three scenarios. By comparing the risk of each node of in the oil spill DCFPN, the chain formed from the initial node to the node with the highest risk is the 1st risk chain. By analogy, the 2nd risk chain and the 3rd risk chain can be obtained. As Table 9 shows, the 1st, the 2nd and the 3rd risk chain are different in each scenario. It means that the secondary disasters which need to focus on in each scenario are also different. This experiment further demonstrates that the model proposed in this paper can adapt to different types of scenarios and can simulate the risk changes of disaster chains in different scenarios.

D. KEY TRANSITION ANALYSIS OF PETROCHEMICAL SPILL DCFPN

The transitions of DCFPN has a controlling effect on the evolution of disaster chain. By changing the input parameters

TABLE 9. Comparative analysis of disaster chain risks of S_2, S_3 and S_4.

	S_2	S_3	S_4
The 1st risk chain	$P_0 \rightarrow P_{10}$	$P_0 \rightarrow P_4$	$P_0 \rightarrow P_{10}$
The 2nd risk chain	$P_0 \rightarrow (P_{11}, P_{14})$	$P_0 \rightarrow P_{10}$	$P_0 \rightarrow (P_{21}, P_{22})$
The 3rd risk chain	$P_0 \rightarrow P_4$	$P_0 \rightarrow (P_{16}, P_{17}, P_{18}, P_{19}, P_{21}, P_{22}, P_{23}, P_{24}, P_{25}, P_{26})$	$P_0 \rightarrow (P_{11}, P_{14})$
…	…	…	…

of the transition, we can compare the different evolution results of the disaster chain, so as to find the control measures to reduce the risk of such a disaster chain. This chapter selects several secondary disasters that are of concern in the petrochemical spill disaster chain for research.

Owing to China's special social background, social mass incidents are very harmful in a complex disaster chain and need to be focused on while mitigating the effects of the emergency disaster reduction. In this petrochemical spill in Fujian Province of China, mass incidents did occur, making this case more typical and more meaningful.

In order to explore the ways to reduce the risk of mass incidents, this section takes $P_0 \rightarrow P_{10}$ as an example and focuses on the transition between P_0 and P_{10}. The values of T_7, T_8, T_{10}, T_{11}, T_{12}, and T_{14} are relatively high and correspond to oil spill, network public opinion index, and human existence. Then, the authors vary these transitions and explore the change in the disaster risk.

Keeping the other conditions unchanged, the result obtained by varying the number of people present in the area is shown in Figure 16. The increase in the number of people present will lead to an increase in the risk of social mass incidents, but the curve rises slowly. It means that it is not worthwhile to reduce the number of people in order to reduce casualties because the clean-up of oil spills requires personnel strength. Therefore, the best solution is to minimize the presence of unrelated people while ensuring the necessary clean-up personnel.

The results for variation in the network public opinion index while keeping the other conditions unchanged are shown in Figure 17. When the network public opinion index is less than 0.4, the risk of social mass incidents is almost zero. Once the network public opinion index exceeds 0.4, the risk of social mass incidents rises rapidly with the increase in the network public opinion index. Therefore, timely monitoring of network public opinion can significantly reduce the risk of social mass incidents.

Figure 18 shows the results obtained by varying the quantity of oil spill while keeping the other conditions unchanged. The oil spill causes water pollution. Oil spill exceeding 5 tons will cause air pollution and social mass incidents. The risk of these three types of disasters will increase with the increase in

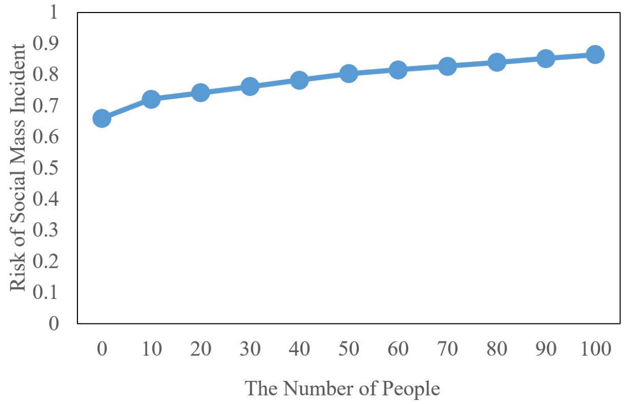


FIGURE 16. Risk of social mass incident with variation in the number of people.

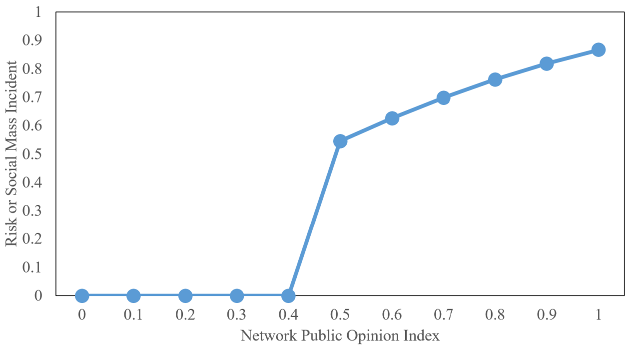


FIGURE 17. Risk of social mass incident with variation in the network public opinion index.

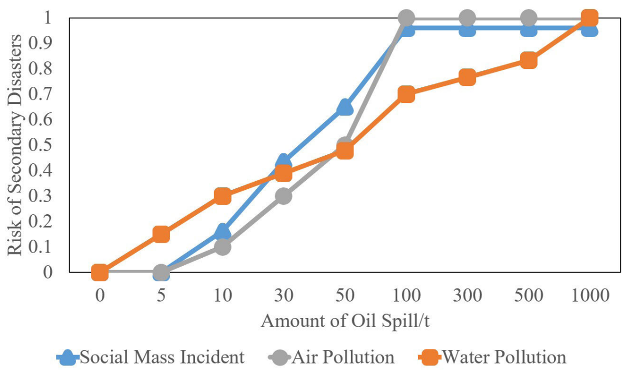


FIGURE 18. Risk of secondary disasters with variation in the quantity of oil spill.

the quantity of oil spill. When the oil spill exceeds 100 tons, the risk of each type of disaster reaches a high level. Therefore, timely detection of oil spills and initiation of emergency response to curb the spread of the oil will help reduce the risk of various secondary disasters.

V. CONCLUSIONS

In this study, we focus on disaster chains instead of on single disaster itself. It is very useful for top management decision makers. Like this case study in this paper, the oil spill disaster may cause the environment pollution, which is environmental disaster, but this disaster also may result in social problems like mass incidents, which are social security incidents. The environmental disaster and social security incidents are very different types of disaster for emergency management. So the method we proposed in this article helps for mastering the possible evolution direction of the disaster chain in advance and controlling the key triggers of the disaster chain in a timely manner, which will contribute significantly toward disaster mitigation.

Firstly, we developed a method to describe the general disaster chains based on Fuzzy Petri net (DCFPN), which is an improvement of the traditional fuzzy Petri net and is capable of quantitatively simulating the disaster chains. The structure of DCFPN has different forms according to different types of disaster chains. The three DCFPN basic types, which are serial construction, concurrent construction and coupled construction, can express single chains, concurrent chains and coupled chains and any combination of them can describe extremely complex disaster chains.

Secondly, this article constructed a general DCFPN of an oil spill disaster chain based on oil spill knowledge. Then, taking the petrochemical spill incident in Fujian Province of China as a specific case, we constructed three real scenarios of this incident and used real dynamically observed data to verify the validity of the model. In addition to this, we simulated two additional hypothetical scenarios to deduce the evolutionary path of the disaster chains and analyze the path with the greatest risk. The study found that the disaster chain scenarios deduced from the DCFPN model were consistent with the real situation, and this result would be useful for providing a scientific basis for the 'chain-cutting disaster mitigation' strategy for emergency management of oil spill disaster chains.

The research provided a method to model the disaster chains and deduce the evolutionary path of the disaster chains, and took a real incident for analysis and simulation. However, because of the limited acquisition sensitive data, some parameters of the model maybe need more precision, but it is still useful and important for top management decision makers.

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