Analysis of emergency response for accident of oil and gas pipeline based on Stochastic Petri Net

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ABSTRACT

Emergency response plays an important role in reducing the loss of an accident. And the excellent plan is important to ensure the high efficiency of the emergency response system. However, actions of emergency response arranged in emergency plan can hardly be assessed before the plan is used. Stochastic Petri Net (SPN) is proposed to analyze the performance of emergency response for oil and gas pipeline accident. The results show that the average execution time of SPN model can be used to evaluate effectiveness of emergency response. Then place average mark number indicates that emergency decision-making is the most important segment to optimize emergency work flow. And utilization rate of transition shows that decreasing the cost time of maintenance is the key to improve efficiency of emergency response.

Keywords

Emergency response, oil and gas pipeline accident, performance, SPN.

INTRODUCTION

Pipeline transportation plays an important role in the oil and gas transportation system for its advantages in energy consumption, remote centralized management and economy. However, the pipeline failure will occur after long time service for various factors and may result in enormous economic loss, great casualties and severe environmental pollution. Emergency response is very important to reduce the property loss and casualty of an Oil and Gas Pipeline Accident (OGPA). And a good emergency plan can ensure the high efficiency of the emergency response (Zhou, 2013). Therefore, the performance analysis of emergency plan has become more and more important.

In order to ensure efficiency of emergency activity, some studies have done on emergency plan for OGPA. Taber, McCabe, Klein and Pelot (2013) investigated the interactive whiteboard as an Emergency Response Focus Board (ERFB) for offshore emergency response teams during a training and assessment process. They have tested participants and indicated the significant factors influenced the dynamic ERFB which given the information available and offered relevant recommendations. Cruz and Krausmann (2009) studied the offshore oil and gas facilities and emergency response following hurricanes. More than 600 hazardous materials releases triggered by hurricanes were identified and analyzed. The results of the study may offer recommendations for better disaster planning for oil and gas facilities under major storms and flood events. SKogdalen, Khorsandi andVinnem (2012) categorized hazards and EER (evacuation, escape and rescue) operations, analyzed the sequence of every step and suggest to improve EER operations and comprehensive analysis of the systems aimed. Shahriar, Sadiq and Tesfamariam (2012) analyzed the risk of Oil and Gas pipelines using fuzzy based bow-tie analysis. The results were beneficial to risk management, decision-making and also help to make decisions in emergency. However, their studies didn't focus on the comprehensive effectiveness of emergency response and they didn't consider the net performance of emergency response process.

Petri nets are useful and powerful models which are based on strict mathematical theories (Murata, 1989). It is an available discrete event modeling and analysis tool widely used to simulate and analysis the flows of production process and information system (Cheung 1996; Ernesto, 2002; Fung, Au and Ip 2003; Chew, Dunnett and Andrews, 2008; Garg, 2013; Andreas and Mathias, 2015). Many analysis and confirmation methods have been developed and many mature analysis tool are available (Baarir, Beccuti, Cetrotti and Pierro, 2009; Yang, Yu, Qian and Sun, 2012). It was also applied to analyze the emergency response systems (Zhong, Shi, Fu, He and Shi, 2010; Karmakar and Dasgupta, 2011; Zhou, 2013) and Petri nets is easily extended to model a system.

A Stochastic Petri net (SPN) is extended from a Petri net (Molloy, 1981). Stochastic modeling has provided powerful methods for performance evaluation which based on Continuous Time Markov Chains (CTMCs) (Marin, Balsamo and Harrison, 2012) and each transition is associated with a random variable (Florin, Fraize and Natkin, 1991). SPN was used as a new and effective method to evaluate the performance of a system (Molly, 1982; Marson, Conte and Balbo, 1984; Lin and Marinescu, 1988). It plays an important role in this respect and has been applied to performance evaluation successfully.

In fact, the emergency response actions for OGPA cannot be replayed completely. And then, the performance of emergency plan step stochastic fluctuates around the average. Therefore, the emergency response process can be seen upon as a prototypical discrete event system with stochastic characteristics. And the SPN model can be generated to mimic the stochastic process. Accordingly, in this paper, SPN is proposed to model the emergency response actions for OGPA and analyze the performance.

SECTIONSS STOCHASTIC PETRI NETS

Definition: A Petri net (PN) is a five-tuple (Murata, 1989)

$$PN = (P, T, F, W, M_0)$$

(1) P: $P=\{P_1, P_2, P_3, \cdots, P_m\}$, P is a finite set of places. It is drawn as circle.

(2) T: $T=\{T_1, T_2, T_3, \cdots, T_n\}$, T is a finite set of transitions. It is drawn as rectangles.

(3) F: $F \subseteq (P \times T) \cup (T \times P)$, is a set of arcs. An arc connects a transition to a place or place to a transition.

(4) W: $F \rightarrow \{1, 2, 3, \cdots\}$, is a set of arc weight of functions.,

(5) M_0: $P \rightarrow \{1, 2, 3, \cdots\}$, is the initial marking.

(6) $P \cap T = \emptyset$ and $P \cup T \neq \emptyset$.

A transition is enabled if and only if each of its input places contains at least one token. The firing of a transition removes one token from each input place and places one token in each output place.

Based on the definition of SPN, SPNs are timed transition Petri Nets with atomic firing and a negative exponentially distributed random variable for every transition. A SPN model is defined as following.

Definition: A Stochastic Petri net (SPN) is a six-tuple

$$SPN = (P, T, F, W, M_0, \lambda)$$

Where, P, T, F, W and M_0 have the same meanings as those of a Petri net.

$\boldsymbol{\lambda=\{\lambda_1, \lambda_2, \lambda_3, \cdots, \lambda_m\}}$, is a set of average firing (implementation) rates of transitions. It is assumed subject to the exponential distribution.

In one SPN model, events and conditions are used to describe a system. And the firing of a transition means the task. The Markov random process is the foundation of mathematical solving. A SPN is isomorphic to a continuous time Markov Chain. A continuous random variable which is subject to exponential distribution is used to describe the transition delays for firing from the beginning of enabling to the actual firing. Steps for the SPN applied to the evaluation of system performance. Firstly, the system is abstracted into the SPN model. Second, determine the states of SPN and construct the SPN isomorphism of Markov Chain. Lastly, analysis and evaluation the performance of system based on the steady state probability of Markov Chain and provide the recommendations for the optimization of system structure.

EMERGENCY RESPONSE MODELING

The emergency rescue of OGPF was included many controlling factors and variable factors. It requires the coordination of different departments under limited time and supplies. The process of emergency rescue for OGPA is divided into Alarm, Emergency decision-making, Action and Recovery 4 steps and detailed as following.

Step Ⅰ When the event occurs, the control center receives the alarm and informs the emergency response command group after confirming the alarm information and analyzing the severity of the accident.

Step Ⅱ The emergency decision is made by decision support system or expert team based on the type and the scenarios of accident.

Step Ⅲ Action is divided into two parts. One is about scene security, including evacuating, isolating and protecting. Another is about emergency repairing and accident controlling. The evaluation must be done after emergency action. And if the accident is out of control, the response level will be expanded and the emergency response will be restarted.

Step Ⅳ Recover scene and terminate emergency response when the accident is controlled effectively.

After analyzing the emergency response process of OGPA, the appropriate simplified SPN model is established to analyze the effectiveness and performance of emergency response system as shown in Figure 1. It is known that, the input and output conditions are needed for every place and transition to obtain the steady state solution, during the analysis of isomorphic Markov Chain. Therefore, in the model, instantaneous transition T10 is introduced into places P1 and P9 and used to enhance connectivity of SPN model. And then, the other places and transitions are in actual response process.

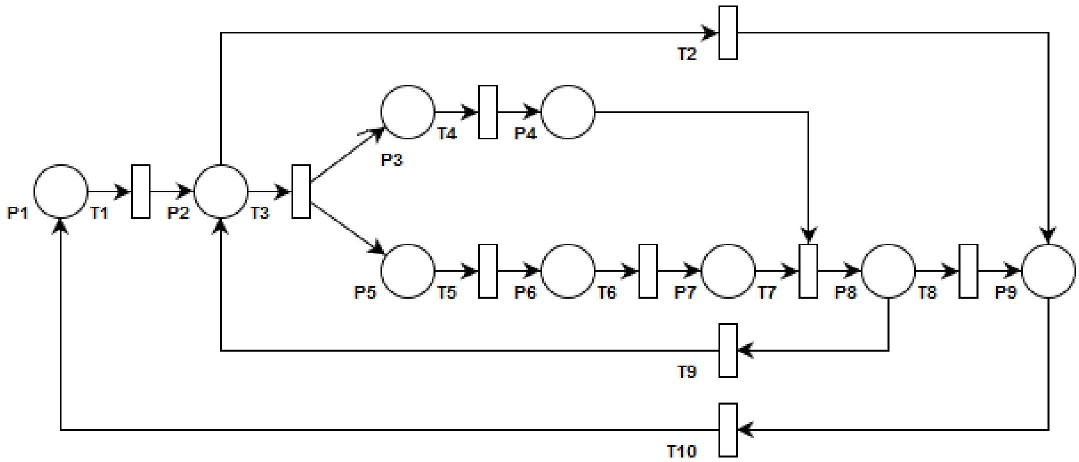

Figure 1. Stochastic Petri Net of Emergency Response

Places		Transitions	
P_1	Alarm information of pipeline accident	T_1	Handle alarm call of emergency
P_2	Accident classification information	T_2	Close alarm, summary alarm information
P_3	Scene security information	T_3	Report to the superior
P_4	Scene security status feedback information	T_4	Scene security
P_5	Accident parameters	T_5	Emergency plan making
P_6	Emergency repair plan information	T_6	Emergency repair plan executing
P_7	Emergency action implementation information	T_7	Emergency effectivity evaluation
P_8	Evaluation information	T_8	Recovering
P_9	Emergency response terminated	T_9	Emergency upgrade
		T_{10}	Nonsense

Table 1, Interpretation of Places and Transitions for Figure. 1

ANALYSIS AND DISCUSSION

Efficiency analysis

In this paper, the method of *T*-invariant is used to determine the emergency system SPN model whether meet the standards of efficiency of boundedness and liveness. The definition of *T*-invariant is as following.

$N = (P, T, F)$ is assumed as a net. $|P|=m$, $|T|=n$, A is incidence matrix for N, if X is a vector in n dimension which meets $A^T X = 0$, the X named a *T*-invariant of the net of N.

The T-invariant is obtained after calculation as following.

X_1^T= (1, 1, 1, 1, 1, 1, 1, 1, 0, 0); X_2^T= (0, 1, 1, 1, 1, 1, 0, 0, 0, 1); X_3^T= (1, 0, 0, 0, 0, 0, 0, 1, 1, 0)

According to the boundedness theorem of PN, X is positive integer vector which is considered the necessary and sufficient condition for N is the structural boundedness net. And the value of *T*-invariant is contributed to the equations $A^T X=\mathbf{0}$. Therefore, emergency model is the PN model with boundedness. Where, when the vector component of *T*-invariant is *1*, the transition is enabled (firing), while *0* is opposite. X_1^T, X_2^T and X_3^T reflect the process relationship in different circumstances respectively. Take X_1^T as an example, X_1^T means the transition of T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8 are firing which also represent the firing sequence of emergency process. Accordingly, the emergency response model is an active PN on account of it is possible that all transitions will be firing and all tasks will be implemented.

Performance analysis

The performance index can be acquired from actual firing (implementation) rate of transition. For evaluating the applicability of OGPA SPN model and guiding the emergency of OGPA with SPN model, an example is given. The data of this example is from the emergency drill of Sichuan Gas Transmission Pipeline Center for Sichuan to East Gas Transmission. Time delay and corresponding average implemented rate of transitions are given parameters respectively as $T_1, \cdots, T_{10}$ and $\lambda_1, \cdots, \lambda_{10}$, which are shown in Table 2. Time delay is normalized and one time unit is 30mins.

Transition time delay	Time unit	Average implemented rate	Parameter
T_1	1	λ_1	1
T_2	1	λ_2	1
T_3	2	λ_3	0.5
T_4	4	λ_4	0.25
T_5	1	λ_5	1
T_6	22	λ_6	0.045
T_7	2	λ_7	0.5
T_8	2	λ_8	0.5
T_9	2	λ_9	0.5
T_{10}	2	λ_{10}	0.5

Table 2 Time Unit and Average Implemented rate

The steady-state probability of each state mark is obtained according to the SPN algorithm shown as Table 3.

State mark steady state probability	$P(M_0)$	$P(M_1)$	$P(M_2)$	$P(M_3)$	$P(M_4)$	$P(M_5)$	$P(M_6)$	$P(M_7)$	$P(M_8)$	$P(M_9)$
Value	0.0690	0.0552	0.0221	0.0055	0.0749	0.0135	0.5388	0.0557	0.0276	0.1381

Table 3 Steady State Probability of Each State Mark

The performance indexes of the model are calculated from the steady-state probability of each state marking: the average mark number of place, the utilization ratio of transition and the average execution time of the system.

Places average mark number

Places average mark number reflects the work frequency of places, which is represented by $P[M(P_i)]$. Known from Table 4, the average mark number of P_4 and P_6 are bigger than others. It indicates that information during the whole process is more possible accumulated in these places. As we know, P_4 (scene security status feedback information) is the information sent to command center and P_6 (emergency repair plan information) is the information made by command center. So, the critical link of emergency response is command center. In fact, the command center receives information feedback from many departments and makes decisions within a short time, where the information is blocked easily. Thus, emergency decision-making is the key to optimize the emergency work flow.

Places	Average mark number	Value
P_1	$P[M(P_1)]$	0.0775
P_2	$P[M(P_2)]$	0.0517
P_3	$P[M(P_3)]$	0.1034
P_4	$P[M(P_4)]$	0.5609
P_5	$P[M(P_5)]$	0.0259
P_6	$P[M(P_6)]$	0.5471
P_7	$P[M(P_7)]$	0.0643
P_8	$P[M(P_8)]$	0.0517
P_9	$P[M(P_9)]$	0.1550

Table 4 Average Mark Number of Places

Utilization rate of transition

Utilization rate of transition reflects the time cost in each activities of the entire emergency response process, which is represented by $U(T_i)$. Resulting from Table 5, $U(T_6)$ is much bigger than others, which indicates that the process of emergency plan executing is time consuming. Therefore, improving the emergency equipment and decreasing the cost time of maintenance is the key to improve efficiency of emergency response.

Transitions	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
Utilization rate of transition	$U(T_1)$	$U(T_2)$	$U(T_3)$	$U(T_4)$	$U(T_5)$	$U(T_6)$	$U(T_7)$	$U(T_8)$	$U(T_9)$	$U(T_{10})$
Value	0.0775	0.0517	0.0517	0.1034	0.0529	0.5741	0.0517	0.0517	0.0517	0.1550

Table 5 Utilization rate of transition

Average execution time

The time performance of emergency response can be obtained from the average execution time of SPN model which is important for long distance pipeline accident emergency response. The average execution time of a subsystem in SPN can be calculated by equation (1).

$$T = \frac{\sum P[M(P_i)]}{R} = \frac{\sum P[M(P_i)]}{\lambda_1 U(T_1)} \qquad (1)$$

Where, $\sum P[M(P_i)]$ is the sum of places average mark number in SPN. R is the mark flow rate which flows into SPN, which can be represented by $\lambda_1 U(T_1)$ in this SPN model.

Obviously, it can be calculated that the average execution time is 20.48 hours. This time is useful for predicting duration of emergency response. But importantly, it can be used to evaluate the effectiveness of emergency system.

CONCLUSION

Efficient emergency plan plays a critical role in emergency response. But during earlier stage of emergency decision-making, there are many factors must be taken into consideration and the performance analysis of emergency is difficult. For this reason, in this paper, the SPN model of OGPA emergency response system has been built. This model gives performance evaluation model and method of OGPA emergency response. Firstly, effectiveness and performance have been analyzed by average execution time of model. And then, emergency decision-making is the most important segment to optimize emergency work flow, known from places average mark number of model. Finally, according to the result of utilization rate of transition, improving the emergency equipment and decreasing the cost time of maintenance is the key to improve efficiency of emergency response.

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