Probabilistic Petri-net addition enabling decision making depending on situational change : the case of emergency response to fuel tank farm fire

Reference:
Zhou Jianfeng, Reniers Genserik.- Probabilistic Petri-net addition enabling decision making depending on situational change : the case of emergency response to fuel tank farm fire
Reliability engineering and system safety - ISSN 0951-8320 - 200(2020), 106880
Full text (Publisher's DOI): https://doi.org/10.1016/J.RESS.2020.106880
To cite this reference: https://hdl.handle.net/10067/1684290151162165141

Probabilistic Petri-net addition enabling decision making depending on situational change: the case of emergency response to fuel tank farm fire tank farm fire

Jianfeng Zhou[a, *], Genserik Reniers [b, c, d]

a. School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou 510006, China

b. Faculty of Technology, Policy and Management, Safety and Security Science Group (S3G), TU Delft, 2628 BX Delft, The Netherlands

c. Faculty of Applied Economics, Antwerp Research Group on Safety and Security (ARGoSS), Universiteit Antwerpen, 2000 Antwerp, Belgium

d. CEDON, KULeuven, 1000 Brussels, Belgium

Abstract: Emergency response was usually not taken into account in the analysis of safety barriers to prevent fire-induced domino effects. When emergency response is considered, in addition to failure events, successful events may also have an impact on fire escalation, and there may be a dependency between pre- and post-events. To model such events and carry out probability analysis, a probabilistic Petri-net (PPN) approach is proposed. The definition of a PPN with the complementary arc and its execution mechanism are provided, and a probability reasoning algorithm reflecting the parallel processing of PPNs is developed. On this basis, a PPN model discussed in two parts for failure analysis of fire escalation prevention is established. The application of the methodology is demonstrated by fire prevention in a chemical storage tank farm, focusing on the influence of fire detection on follow-up actions. In addition to that the fire is not been found, the time at which the fire is found will also have an impact on the success of preventing the fire escalation. The influences of not considering/considering fire detection time are analyzed by the fault tree method and the PPN method, respectively, and there is a difference of about 11% between the results.

Keywords: domino effects; fire escalation; failure analysis; safety barriers; probabilistic Petri-net

1. Introduction

When a major fire accident occurs in an area where large amounts of flammable materials are

*Corresponding author. E-mail address: jf.zhou@gdut.edu.cn

stored in adjacent facilities, surrounding facilities may be damaged under the action of the heat radiation. In some cases the failure of the affected facilities can lead to loss of containment and an additional accident. The phenomenon that a relatively minor accident initiates a sequence of events causing damage over a much larger area and leading to far more severe consequences than the original event, is called a 'domino effect'.

Fire is a major primary event that may lead to domino effects. Darbra et al. (2010) found that fire was the primary event of domino effects in 52% of the cases and explosion in 48% of the cases according to 225 domino effect accidents which occurred in process/storage plants and in the transportation of hazardous materials. Abdolhamizadeh et al. (2011) drew conclusions from 224 domino effect accidents that fire was the initiating event in 43% of the cases and explosion in 57%. Hemmatian et al. (2014) analyzed 330 accidents involving domino effects and found that explosion was the primary event in 53% of the cases and fire in 47%. Secondary targets more likely affected by escalation were pressurized tanks, atmospheric tanks, process vessels and pipelines (Darbra et al., 2010; Reniers and Cozzani, 2013). Over the past decades, fire-induced domino effects have been responsible of several catastrophic accidents in the chemical and process industry. Some examples are successive fires involving solid oxidizer sodium chlorate which occurred at an agricultural chemical manufacturing plant (Russell et al., 2014), a fire and series of explosions which occurred at the Barton Solvents chemical distribution facility in Des Moines, Iowa, USA, in 2007 (CSB, 2008), and more recently, the fire and subsequent explosions that occurred in the hazardous goods warehouse of an international logistics company located in the Tianjin Harbour of China in 2015 (MAHBulletin, 2017).

As domino effects usually lead to catastrophic consequences and great losses, they have been recognized as a priority issue among the risk and safety management community, e.g., see the requirements of the EU Seveso-III Directive (Directive 2012/18/EU). There have been many attempts to model and assess the risk of fire induced domino effects (Gomez-Mares et al., 2008; Landucci et al., 2009; Hemmatian et al., 2015), however, less emphasis has been given to the failure analysis of safety barriers in prevention of fire escalation, especially the influence of emergency response on the failure analysis. When domino effects cannot be completely avoided, e.g. the safety distance between installations is not sufficient due to certain restrictions, for instance limited available land, prevention of domino effects mainly depends on safety barriers. Several studies have been carried out to assess the performance of safety barriers. Reniers and Dullaert (2008) developed a software named

“Dom-PrevPlanning” to support decision making on safety barriers to prevent/mitigate domino effects in a complex surrounding of chemical installations, and multiple domino scenarios were thereby considered. Janssens et al. (2015) proposed a safety barrier allocation model to prevent accident escalation based on cost criteria. Landucci et al. (2016) defined key performance indicators (KPIs) such as barriers’ availability and effectiveness to measure the performance of safety barriers in the prevention of fire induced domino accidents. Khakzad et al. (2018) developed a methodology based on Bayesian network to evaluate the impact of safety barriers on the propagation of domino scenarios triggered by fire. However, in previous works, impacts of emergency response on domino effects are usually not involved or handled in simplified ways, and mutual impacts between certain events, such as discovering fire and starting firefighting, are ignored.

The present study aims to carry out failure analysis of the prevention of fire escalation leading to domino effects, and puts particular emphasis on the impact of emergency response. The specific characteristic of a fire escalation is the time lapse between the start of secondary events with respect to the start of the primary fire (Reniers and Cozzani, 2013). This time lapse is generally termed “time to failure” (*ttf*), which represents the resistance of an installation to external fires (Landucci et al., 2009). The value of ttf is taken as the criterion for determining whether an emergency response has succeeded in preventing the escalation of a fire. Fault tree analysis can be used to perform the failure analysis, but some information cannot be reflected by it. For example, in a fault tree model, an event is usually considered to have only two states, "occurring" and "not occurring". An event that may lead to the top event "does not occur", this state is called the success event for the corresponding event, otherwise the failure event. When analyzing the failure of fire escalation prevention, not only the failure of emergency actions should be considered, but the success of the actions may also have an impact on it, e.g., the execution time of an action is too late. In addition, pre-and post-response actions also have an impact, if the previous action takes too much time, it is likely that the latter action will fail. If these factors are taken into account, fault tree modeling is not very suitable, and therefore a new modeling and analysis approach is needed. In this work, a probabilistic Petri-net approach which has a flexible structure is introduced to model and analyze the failure of fire escalation prevention.

Petri-net was originally proposed in Carl Adam Petri’s dissertation (Petri, 1966), and from then on it is widely used to model and analyze various systems in different fields. Petri-nets are a graphical and mathematical modeling tool composed of places, transitions, and arcs. In addition to modeling systems, tokens are used in Petri nets to simulate the dynamic and concurrent activities of systems. They are a promising tool for describing and studying relationships between parts of a system (Murata, 1989). There are many extensions to Petri nets. For example, colored Petri-nets which extend Petri-nets with data types, functions, and modules are completely backwards-compatible with the original Petri-net (Jensen and Kristensen, 2015), timed Petri-nets add properties that cannot be modeled in the original Petri net formalism (Zuberek and Kubiak, 1999). The main purpose of this study is to analyze the failure probability of fire protection according to the probability of basic events, so that the Petri-net tools for simulating a process are not suitable in this work. To perform probability analysis with Petri-net, several forms of the probabilistic Petri- net were proposed. For example, Lee et al. (2003) proposed possibilistic Petri-nets and a reasoning algorithm for modeling uncertainty reasoning with possibilistic information. Yen and Yu (2004) used a probabilistic version of conflict-free Petri nets, in which each marking (i.e., configuration) is associated with a transition probability function characterizing the firing of each enabled transition, to investigate problems closely related to dependability analysis in the context of probabilistic infinite-state systems. Albanese et al. (2008) proposed Probabilistic Petri-nets (PPN) to recognize human activities in restricted settings from surveillance videos. Liu et al. (2013) proposed a mixed model NPPN (Nondeterministic Probabilistic Petri Net) system to model and verify systems with qualitative and quantitative behaviours. Liu (2014) used the label-extended PPN (probabilistic Petri-net) system as the high-level model to check the PCTL (probabilistic computation tree logic) stochastic model. In this study, a probabilistic Petri-net (PPN) with the complementary arc, which enables PPN model to handle the effects of both "occurring" and "not occurring" of an event at the same time, is proposed to model the impacts between events subject to fire escalation prevention, and a matrix based probability reasoning algorithm of PPN is developed.

This paper is organized as follows: Section 2 briefly introduces safety barriers of fire protection. In Section 3, a fault tree model is developed for the failure analysis. Section 4 further discusses problems in the failure analysis of fire escalation prevention and provides the probabilistic Petri-net approach. An example illustrates the proposed approach in Section 5. Finally, the conclusions drawn from this work are presented in Section 6.

2. Safety barriers of fire protection

In order to delay or prevent escalation of fires, different types of safety barriers are usually utilized.

Three different categories of barriers are considered in this work (Landucci et al., 2015), which are active safety barriers, passive safety barriers, and emergency measures, respectively.

(1) Active safety barriers

This type of safety barriers can actively perform fire extinguishing or escalation prevention in the event of a fire. There are three common types of active safety barriers: fire detection and alarm systems, sprinkler systems, and water deluge systems.

The detection and alarm system detects and monitors potential fires. In the case of a fire, it alerts personnel of the existence of a fire, activates emergency alarms, and triggers other safety barriers. This safety barrier usually works automatically, through sensors and controllers. In addition, manual discovery of a fire can also send an alarm through this system.

The sprinkler system provides a water or fire-fighting foam sprinkler to protected facilities by suppressing the primary fire. It is typically used for atmospheric storage tanks for low flash point flammable liquids. After this barrier is activated, it may control the primary fire and reduce the emitting heat radiation, such that the possibility of damage to neighboring facilities and the escalation of the fire can be reduced.

The water deluge system aims at providing a spray curtain to shield the target facility from a primary fire. If it is activated in a fire, it sprays water to cover the surface of the protected vessel to reduce the heat radiation received by the wall of it, so that damage of the vessel may be prevented.

(2) Passive safety barriers

A passive barrier does not require either electrical power or external activation to trigger the protection action (Landucci et al., 2015). Its main aim is to increase the time lapse between the start of a primary fire and the escalation to other facilities. The usual passive safety barrier is the fireproof coating installed on the wall of a target vessel.

Since vessel failure is caused by the vessel wall heat-up and this is a relatively slow process under thermal radiation, the time to failure (*ttf*) of the vessels exposed to fire is a fundamental parameter in the analysis of domino accidents triggered by fire. The vessel *ttf* expresses the resistance of the target equipment to an external fire.

The *ttf* without passive protection can be determined according to the relationship between heat flux I (kW/m^2) and *ttf* (s) provided by Cozzani, et al. (2005):

Atmospheric vessels:

$$\ln(\mathrm{ttf}) = -1.128 \times \ln(\mathrm{I}) - 2.267 \times 10^{-5} V + 9.877 \quad (1)$$

Pressurized vessels:

$$\ln(\mathrm{ttf}) = -0.95 \times \ln(\mathrm{I}) + 8.85 \times V^{0.032} \quad (2)$$

where, V is the volume of the vessel (m^3).

According to the heat insulation effect of the material of a fireproof coating, a coefficient can be used to estimate the time to failure when the fireproof coating is installed to protect the target vessel.

$$ttf_p = \sigma \times ttf_0 \quad (3)$$

where, ttf_0 is the time to failure without fireproof coating; ttf_p is the time to failure with the protection of fireproof coating; σ is a coefficient.

(3) Emergency measures

When the fire alarm is received, emergency teams will get to the scene to extinguish the fire and cool the neighboring vessels as soon as possible. The firefighting actions may reduce the emitted heat radiation of a fire or the received heat radiation of neighboring vessels and thus prevent the escalation of the fire.

The success of emergency actions is influenced by many factors, including the training of emergency personnel, the adequacy of emergency resources, the appropriate emergency measures, etc. In this study, the impact of emergency response time on the escalation prevention is considered. If the duration from receiving a fire alarm to carrying out fire extinguishing or vessel cooling actions is too long, emergency teams cannot prevent the escalation of a fire anymore.

3. Failure analysis using fault tree

A typical fire scenario that may occur in a storage tank farm is taken as an example to discuss the failure analysis of fire escalation prevention. Flammable liquids (e.g. diesel oil) are stored in atmospheric tanks. Generally, each tank is equipped with a sprinkler system and a water deluge system. Smoke and flame detection systems are installed to detect fires and send out a fire alarm signal to trigger the sprinkler systems to extinguish fire and water deluge systems to cool neighboring tanks. The fire alarm signal is also sent to emergency teams so that they can rush to fight against the fire. Employees working in the tank farm can also activate the alarm system if they find a fire.

If a fire occurs at a tank, it may escalate to other adjacent tanks when safety barriers fail, for example, the fire might not not detected, the sprinkler system may not work, the water deluge system does not spew out water, and emergency teams can be late for firefighting may lead to the fire escalation. Fault tree not only can perform qualitative analysis, but the technique can also be used for quantitative analysis, and thus has been widely used in many fields, such as fault diagnosis, failure analysis and accident analysis. Fault tree can be used to calculate the failure probability of fire protection. Thus, fault trees are naturally employed to represent causal relationships leading to the failure of safety barriers of fire escalation. Referring to Tan et al. (2014), and according to the actual disposal process of fire accidents, the fault tree model is developed and shown in Fig. 1.

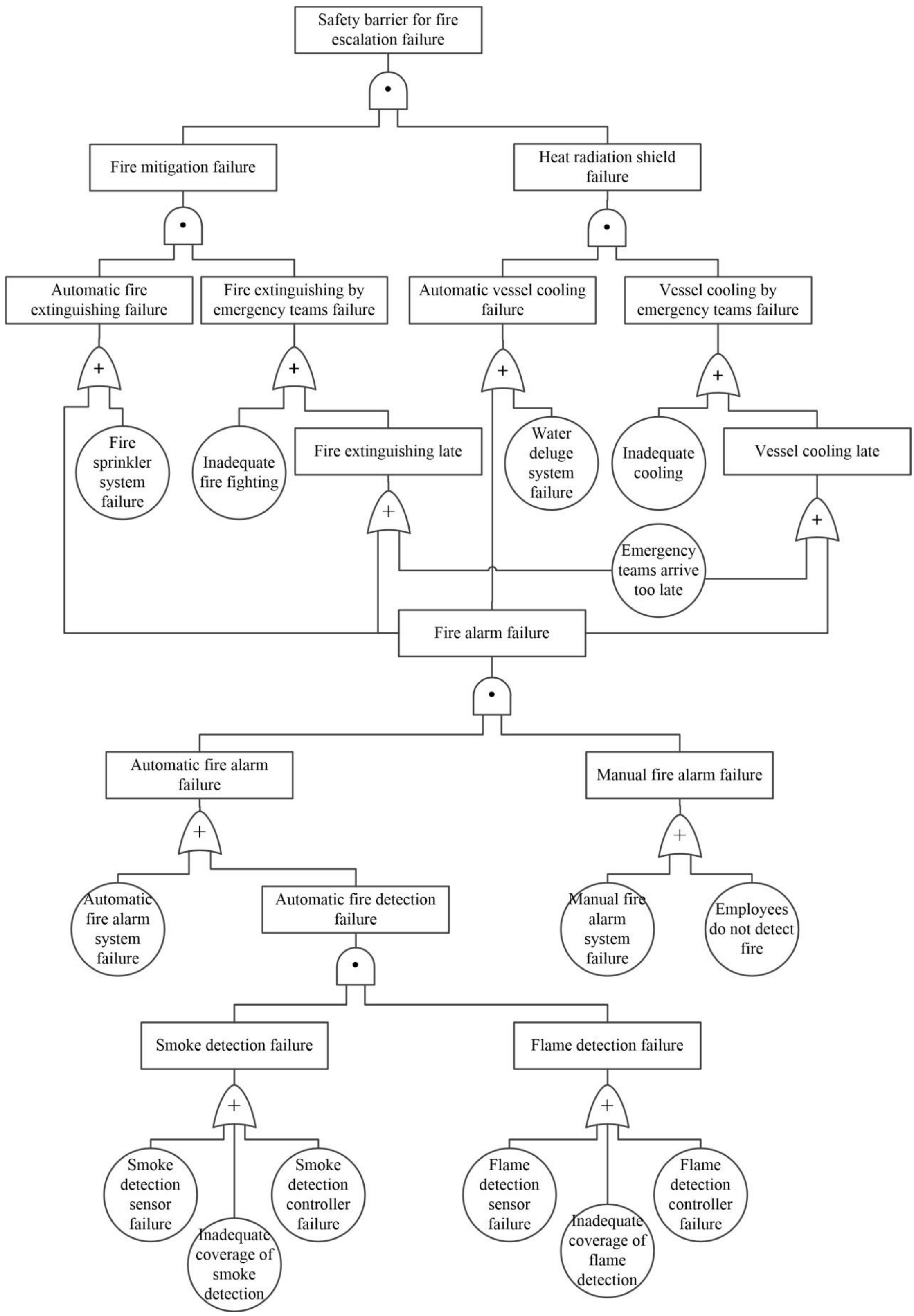

Fig. 1 Fault tree for the failure of safety barriers for fire escalation

The failure probabilities of some basic events in the fault tree model are adopted from Tan et al. (2014), which are obtained from OREDA Participants (2002), and estimated according to available data in process plants. In the fault tree model, the failure of basic events is assumed mutually exclusive and independent. Table 1 shows failure probabilities of basic events of the fault tree model.

Table 1 Failure probabilities of basic events.

Number	Basic events	Failure probability
1	Fire sprinkler system failure	0.1
2	Water deluge system failure	0.1
3	Inadequate fire fighting	0.02
4	Inadequate cooling	0.02
5	Automatic fire alarm system failure	0.021
6	Manual fire alarm system failure	0.05
7	Smoke detection sensor failure	0.08
8	Smoke detection controller failure	0.001
9	Inadequate coverage of smoke detection	0.07
10	Flame detection sensor failure	0.08
11	Flame detection controller failure	0.001
12	Inadequate coverage of flame detection	0.2
13	Employees do not detect fire	*
14	Emergency teams start fire-fighting too late	**

The probabilities of "employees do not detect fire" and "emergency teams are too late for fire extinguishing" need to be discussed. If the emergency response duration is longer than the minimum value of the time to failure of neighboring tanks, emergency teams are considered late for preventing fire escalation. There are several actions corresponding to emergency response processes after the occurring of a fire, mainly including "discover the fire", "dispatch emergency teams", "emergency teams run to the fire scene", and "emergency teams start fire-fighting". A statistical analysis of 44505 valid fire records from 1995 to 2003 within Japan and 14391 fire records from 2000 to 2009 of a city in China showed that the durations of these emergency actions satisfy a log-normal distribution (Peng, 2010). The expected value of "discover the fire" is about 4min, the expected value of "dispatch emergency teams" is about 2.5min, the expected value of "emergency teams run to the fire scene" is about 5min, and the expected value of "emergency teams start fire-fighting" is about 3.5min (Flynn, 2009; Peng, 2010). Fig. 2 and Fig. 3 show a log-normal distribution function of the duration of discovering the fire and a log-normal distribution function corresponding to the emergency response process from activating a fire alarm to starting fire-fighting, respectively. The horizontal axis of Fig. 2 and Fig. 3 represents the time (minutes), and the longitudinal axis represents the probability. In Fig. 2 and Fig. 3, τ_{th} is the threshold duration, and an emergency response duration greater than this threshold means that employees do not discover the fire, or emergency teams arrive too late. Generally, the minimum value of the time to failure of neighboring tanks can be taken as τ_{th}. Thus, given the value of *ttf*, the probabilities that “employees do not detect the fire” and “emergency teams are too late for fire extinguishing” can be estimated according to the function. For example, if the value of *ttf* is 15min, the probabilities that “employees do not detect the fire” and “emergency teams are too late for fire extinguishing” are 0.002 and 0.07, respectively.

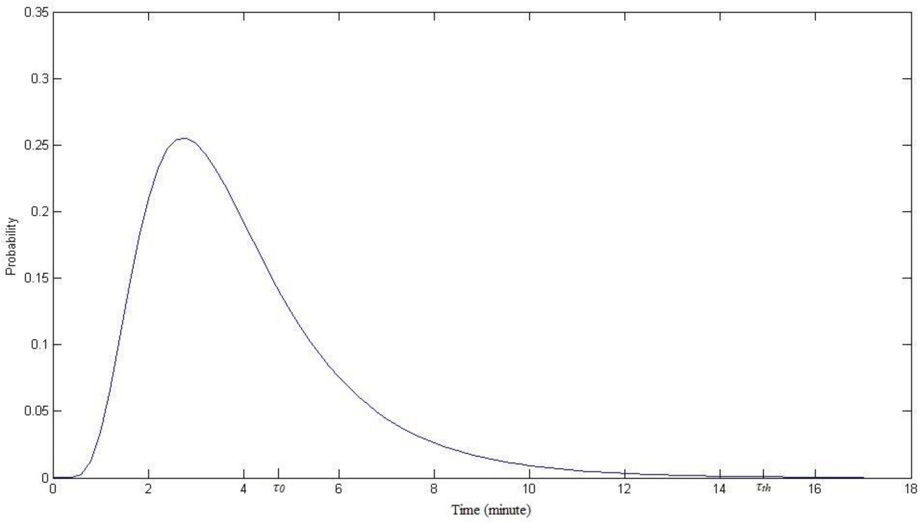

Fig. 2 Log-normal distribution of the duration of discovering fire

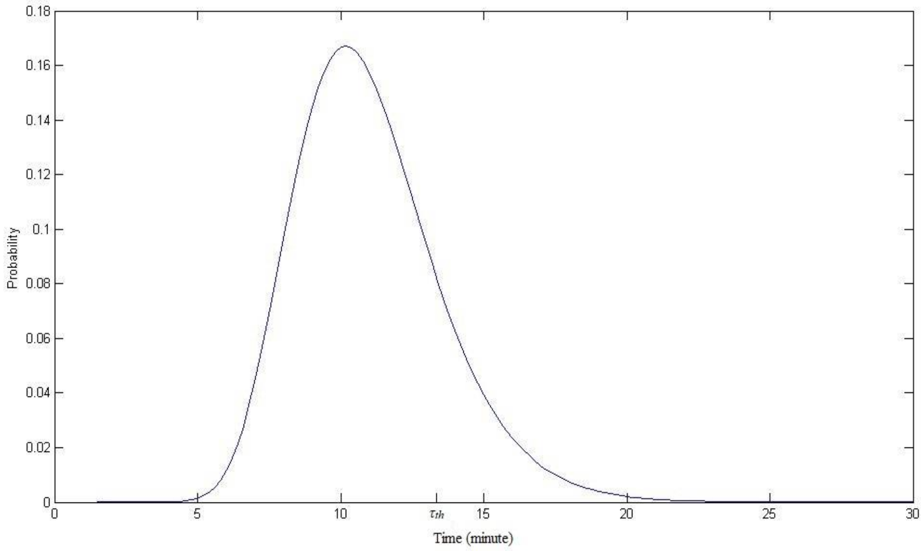

Fig. 3 Log-normal distribution of emergency response duration

4. Failure analysis using Petri-net

4.1 Further considerations of the failure analysis

In the aforementioned failure discussion of fire protection and the fault tree model, the prevention of fire escalation may fail only when all or part of the base events fail. However, considering emergency response, even if some basic events are successful, the prevention of fire escalation may still fail. These conditions are discussed hereafter:

The time of discovering a fire will impact the time that emergency teams arrive at the fire scene. Given that the automatic fire detection fails, the fire is discovered by employees and the discovery is a little late (but the time of fire discovery is earlier than the *ttf*), emergency teams may have not enough time to get to the fire scene even when all emergency actions go well. For example, the mean duration (τ) from fire ignition to the discovery of the fire is taken as the duration of discovering the fire. The probabilities that a fire is discovered with mean time τ can be calculated using the aforementioned log-normal distribution function and intervals $(0, \tau)$. In this case, the emergency teams have only a time of ttf-τ to rush to the scene.

Although a sprinkler system does not guarantee to extinguish all initial fires even when it works well, and water deluge systems may also not fully insulate protected tanks from heat radiation when they work properly, this study focuses on the influence of emergency response on the failure analysis of fire escalation prevention. Thus, these systems are considered to contribute to the failure of fire escalation prevention only when they fail.

In addition, although a fire may not escalate to neighboring tanks even if the emergency response duration is longer than *ttf* (or ttf_p), *ttf* is taken as the criterion for determining the failure of emergency response to fire escalation.

Because there are mutual influences between events and failure impacts of successful events, the conditions of failure analysis are difficult to model using a normal fault tree. In the following study, probabilistic Petri-net is utilized as a technique to model the relationships between events of fire escalation prevention, as well as to carry out a failure analysis.

4.2 Definition of probabilistic Petri-net

A probabilistic Petri net (PPN) is defined as a 7-tuple,

$$PPN = (P, T, I, O, M, A, U)$$

Where:

1) $P = \{p_1, p_2, \ldots, p_n\}$ is a finite set of places.

2) $T = \{t_1, t_2, \ldots, t_m\}$ is a finite set of transitions.

3) $I = P \times T \rightarrow \{0, 1\}$ is an n × m input matrix defining the directed arcs from places to transitions. I can also be split into two subsets I_C and I_H gathering, respectively, the common input matrix and the complementary input matrix; $I_C(p_i, t_j) = 1$, if there is a directed arc from p_i to t_j, and $I_C(p_i, t_j) = 0$, if there is no directed arc from p_i to t_j for i=1, 2, …, n, and j=1, 2, …, m; $I_H(p_i, t_j) = 1$, if there is a directed complementary arc from p_i to t_j, and $I_H(p_i, t_j) = 0$, if there is no directed complementary arc from p_i to t_j for i=1, 2, …, n, and j=1, 2, …, m. A directed complementary arc from p_i to t_j indicates the NOT relationship to the probability of place p_i for the input of transition t_i.

4) $O = P \times T \rightarrow \{0, 1\}$ is an n × m output matrix defining the directed arcs from transitions to places. $O(t_j, p_i) = 1$, if there is a directed arc from t_j to p_i, and $O(t_j, p_i) = 0$, if there is no directed arc from t_j to p_i for i=1, 2, …, n, and j=1, 2, …, m.

5) M: $P \rightarrow \{0, 1\}$ is a marking vector. $M = (\gamma_1, \gamma_2, \ldots, \gamma_n)$, $\gamma_i = 1$ if there is a token in p_i, and $\gamma_i = 0$ if there is no token in p_i. An initial marking is denoted by M_0.

6) A is a probability vector. $A = (\alpha_1, \alpha_2, \ldots, \alpha_n)$, where $\alpha_i \in [0, 1]$ means the probability of p_i, i = 1, 2, …, n.

7) U: $T \rightarrow [0, 1]$ is a probability vector indicating the probabilities of successful execution of the

transitions. $U = (\mu_1, \mu_2, \ldots, \mu_m)$, where $\mu_i \in [0, 1]$ means the value of the successful execution probability of t_i, $i = 1, 2, \ldots$, m.

The elements in PPN are represented as icons, as shown in Fig. 4.

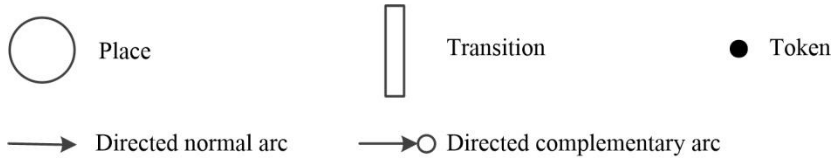

Fig. 4 Icons for the elements in the PPN model

The firing/execution of a set of transitions updates the probability vector and describes the dynamic reasoning process of the modeled system. If the probability of a place is known at a certain reasoning step, a token is assigned to the corresponding place, which is associated with the probability value between 0 and 1.

When a place p_i has no token, it means that the probability is unknown at that step and α_i=0. Hence, in the following two possible situations α_i is equal to zero: 1) there is no token in place p_i. This means that the probability of place p_i is unknown; and 2) there is a token with zero value in place p_i. This means that the probability of place p_i is known and equals zero. Marking vector M can be used to distinguish the two situations.

Denote the set of input places of transition t (the set of input transitions of place p) and the set of output places of transition t (the set of output transitions of place p) as ${}^*t$ (${}^*p$) and t^* (p^*), respectively.

4.3 Execution mechanism of PPN

Petri-net can be used for modeling the state transition system, e.g. the occurrence of one event leads to other events. Usually the states of a system (occurrence of events) can be represented by the places and the changing of the states can be represented by the transitions of a Petri-net. The execution of a transition means the state change of the system. The enabling and execution of the transitions must obey the following rules:

(i) **Enabling rule**: A transition t of a PPN is enabled in a marking M if

$$M(p_i)>0 \qquad for\ p_i \in {}^{\bullet}t \tag{4}$$

(ii) **Execution/firing rule**: If a transition is enabled, it can fire/execute. After transition t

fires/executes, the marking of the Petri-net changes to *M'*, where *M'* is given by

$$M'(p_i) = M(p_i) \qquad for\ p_i \in {}^{\bullet}t \tag{5}$$

$$M'(p_j) = 1 \qquad for\ p_j \in t^{\bullet} \tag{6}$$

The execution of transition t not only changes the number of tokens of its output places, but also updates the probabilities attached to the tokens and thus updates the probabilities of the output places. The basic execution of a transition is shown in Fig. 5. Fig. 5(a) shows the execution with directed normal arc connecting from input place p_1. In this condition, after the execution of transition t, the probability of place p_2 is:

$$\alpha_2 = \alpha_1 \times \mu \tag{7}$$

Fig. 5(b) shows the execution with a directed complementary arc connecting from input place p_1. In this case, after the execution of transition t, the probability of place p_2 is:

$$\alpha_2 = (1 - \alpha_1) \times \mu \tag{8}$$

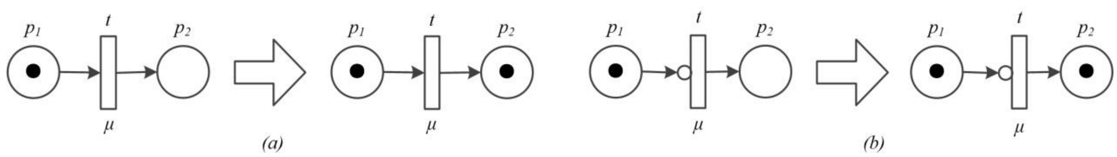

Fig. 5 Basic execution of a transition

In a fault tree, there are two basic relationships that several events impact another event. One is the “AND” relationship, and the other is the “OR” relationship. They can be modeled by PPN as shown in Fig. 6 (a) and (b), respectively.

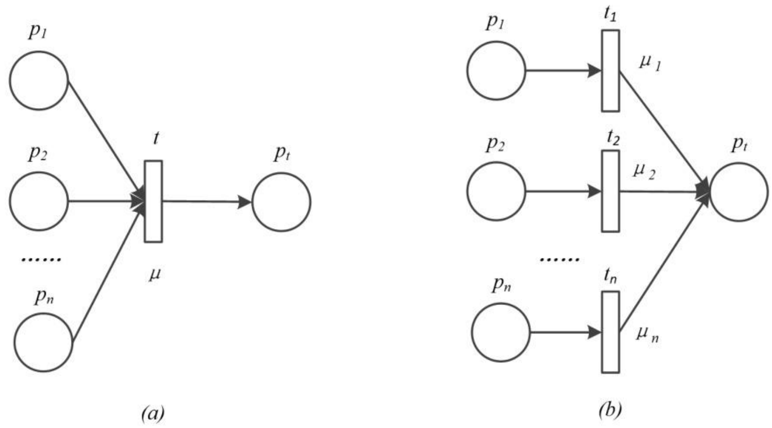

Fig. 6 Petri-net modeling of relationships of events

For the “AND” relationship shown in Fig. 6 (a), the transition t is enabled only when every one of its input places from p_1 to p_n has got a token. If the transition t is enabled, it can execute and the probability α_t which is associated with the token in the place p_t is determined according to Eq. (9).

$$\alpha_t = \prod_{i=1}^{n} (\alpha_i \times \mu) \tag{9}$$

For the “OR” relationship shown in Fig. 6 (b), if any place from p_1 to p_n has got a token, their corresponding transitions from t_1 to t_n will be enabled. If all transitions from t_1 to t_n execute, the probability α_t which is associated with the token in the place p_t is determined according to Eq. (10).

$$\alpha_t = 1 - \prod_{i=1}^{n} (1 - \alpha_i \times \mu_i) \tag{10}$$

4.4 Probability reasoning algorithm

In PPNs, all the enabled transitions can fire/execute at the same time. In order to represent the execution rules of PPNs formally, we define four operators in advance.

1) $\otimes$: $C = A \otimes B$, where A, B and C are ($m \times k$), ($k \times n$) and ($m \times n$) dimensional matrices, respectively, such that

$$c_{ij} = \prod_{x=1}^{k} (a_{ix} \times b_{xj}), \ \forall b_{xj} \neq 0 \tag{11}$$

Where, c_{ij}, a_{ix}, and b_{xj} are elements of the matrices C, A and B, respectively.

This operator is adopted to calculate the probability of events with an “AND” relationship. The probability of “OR” relationship events can be converted into the “AND” relationship probability.

2) $\circ$: $C = A \circ B$, where A, B and C are matrices of the same dimension, and

$$c_{ij} = a_{ij} \times b_{ij} \tag{12}$$

Where, c_{ij}, a_{ij}, and b_{ij} are elements of the matrices C, A and B, respectively.

This operator is adopted to implement the probability calculation with the successful execution probability of a transition.

3) !: C=!A, where A and C are matrices of the same dimension, and

$$c_{ij} = 1 - a_{ij} \quad \text{if } a_{ij} > 0 \tag{13}$$

$$c_{ij} = a_{ij}, \quad \text{otherwise} \tag{14}$$

where, c_{ij} and a_{ij} are elements of the matrices C and A, respectively.

This operator is used to reflect the impacts on probability of complementary arcs.

4) $\oplus$: C =A $\oplus$ B, where A, B and C are matrices of the same dimension, and

$$\begin{aligned} c_{ij} &= a_{ij} \times b_{ij} \quad \text{if } a_{ij} > 0 \text{ and } b_{ij} > 0 \\ c_{ij} &= a_{ij} + b_{ij} \quad \text{otherwise} \end{aligned} \tag{15}$$

Where, c_{ij}, a_{ij}, and b_{ij} are elements of the matrices C, A and B, respectively.

This operator is utilized to combine probabilities determined by common arcs and probabilities determined by complementary arcs.

Based on these special operators, the execution rules of a PPN can be formally described as follows:

Matrices I_C, I_H, O, U, A_0 and M_0 are given based on a PPN model, then

$$A_i = A_0 + \left(I - \left(I - \left(\left(A_{i-1} \otimes I_C\right) \oplus ! \left(A_{i-1} \otimes I_H\right)\right) \circ U\right) \otimes O^T\right) - M_0 \tag{16}$$

$$M_i = 1 - \left(I - M_{i-1} \otimes \left(I_C + I_H\right)\right) \otimes O^T \tag{17}$$

By iterating through these two formulas until A_i=A_{i-1}, probabilities of places and the marking of the PPN model can be obtained.

4.5 Fire escalation prevention failure modeling with PPN

For the failure analysis of fire escalation prevention discussed earlier, the PPN model is established, which is divided into two parts. Part one of the PPN model is shown in Fig. 7. The meanings of places of this part are listed in Table 2. Transitions represent relationships between places as shown in Fig. 6, so that their meanings are omitted. This part is consistent with the fault tree model, which only considers the failure of each component of the system.

Part two is shown in Fig. 8, which considers the failure of the fire protection system in the case of the success of some components. The meanings of additional places of part two are listed in Table 3. This part considers impacts on failure of two successful events, which are “Employees detect fire”(p_{30}), and “Manual fire alarm system works well”(p_{33}), respectively, through complementary arcs (under the condition that automatic fire detection or alarm fails). Places p_{30} and p_{31} are used to model the influences on failure analysis when employees successfully detect a fire and launch the fire alarm manually. It should be noted that the state represented by p_{30} only considers the conditions that automatic fire alarm fails. Place p_{34} indicates that emergency response teams arrive at the fire scene late (over ttf). Thus, if emergency teams arrive at the fire site later than *ttf*, the prevention for fire escalation is considered a failure. Obviously, the earlier the fire is detected, the more likely emergency teams can get to the fire scene in time.

The probability that p_{33} ("Manual fire alarm within τ") leads to p_{34} is determined by the value of μ_{30}, which indicates the successful execution probability of transition t_{30} and can be calculated according to parameters τ and τ_{th} of the log-normal probability function of emergency response actions.

Table 2 Meanings of places of part one of the PPN model

Place	Meanings	Place	Meanings
p_1	Smoke detection sensor failure	p_{16}	Emergency teams arrive too late (later than *ttf*)
p_2	Smoke detection controller failure	p_{17}	Fire extinguishing is later than *ttf*
p_3	Inadequate coverage of smoke detection	p_{18}	Vessel cooling is later than ttf
p_4	Flame detection sensor failure	p_{19}	Inadequate fire fighting
p_5	Flame detection controller failure	p_{20}	Inadequate cooling
p_6	Inadequate coverage of flame detection	p_{21}	Fire extinguishing by emergency teams failure (condition 1)
p_7	Manual fire alarm system failure	p_{22}	Vessel cooling by emergency teams failure (condition 1)
p_8	Employees do not detect fire	p_{23}	Fire sprinkler system failure
p_9	Smoke detection failure	p_{24}	Automatic fire extinguishing failure
p_{10}	Flame detection failure	p_{25}	Water deluge system failure
p_{11}	Manual fire alarm failure	p_{26}	Automatic vessel cooling failure
p_{12}	Automatic fire detection failure	p_{27}	Fire mitigation failure
p_{13}	Automatic fire alarm system failure	p_{28}	Heat radiation block failure
p_{14}	Automatic fire alarm failure	p_{29}	Fire escalation prevention failure (condition 1)
p_{15}	Fire alarm failure		

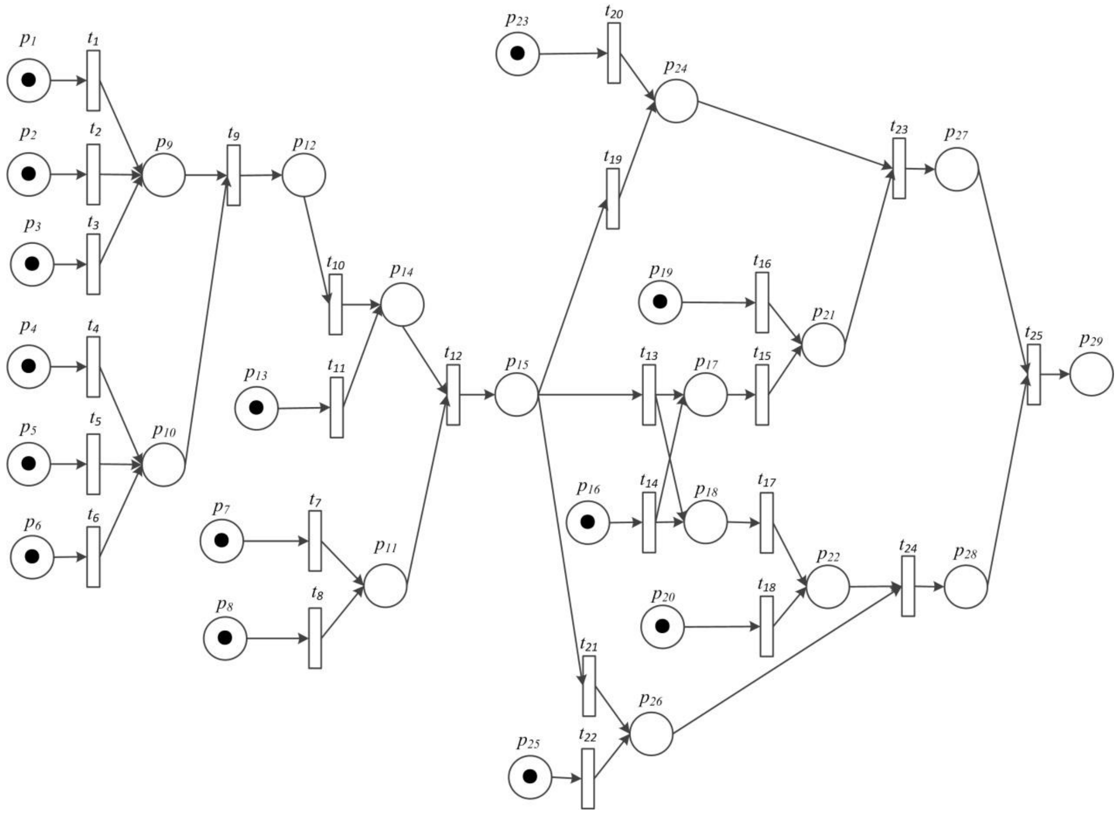

Fig. 7 PPN model of fire escalation prevention failure – part one, which only consider the influence of the component failure on the prevention of fire escalation.

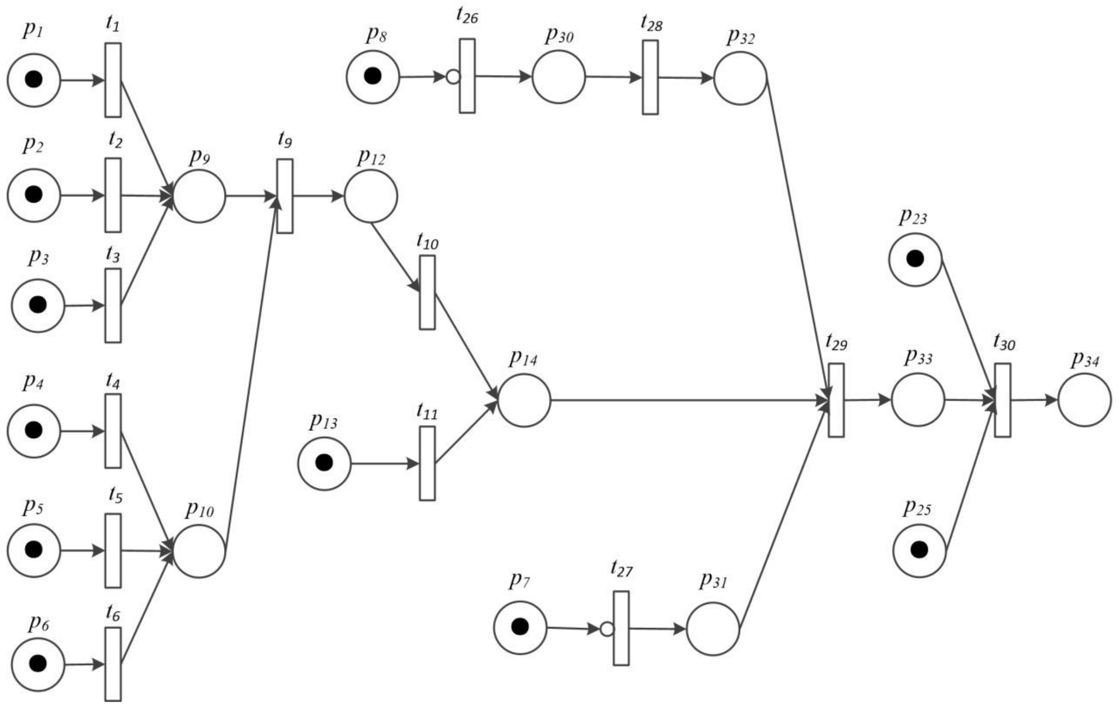

Fig. 8 PPN model of fire escalation prevention failure – part two, which considers the failure of

preventing fire escalation in the case of the success of some components/events

Table 3 Meanings of places of part two of the PPN model

Place	Meanings	Place	Meanings
p_{30}	Employees detect fire within ttf	p_{33}	Manual fire alarm within τ
p_{31}	Manual fire alarm system works well	p_{34}	Arriving of emergency teams at fire scene late (over ttf)
p_{32}	Employees detect fire within τ		

5. An illustrative example

A case study from Paltrinieri et al. (2011) and Khakzad et al. (2013) is adapted and modeled to illustrate the proposed failure analysis approach. Fig. 9 shows the layout of a tank farm comprised of eight atmospheric storage tanks with fixed roofs (D1-D8). Each tank contains gasoline with the capacity of 2,000 metric tons.

The heat radiation escalation vectors are listed in Table 4 (Khakzad et al., 2013).

Table 4 Heat Radiation Escalation Vectors (kW/m^2)

	D1	D2	D3	D4	D5	D6	D7	D8
D1	-	19.3	4.6	19.3	9.3	3.6	4.6	3.6
D2	19.3	-	19.3	9.3	19.3	9.3	3.6	4.6
D3	4.6	19.3	-	3.6	9.3	19.3	2.2	3.6
D4	19.3	9.3	3.6	-	19.3	4.6	19.3	9.3
D5	9.3	19.3	9.3	19.3	-	19.3	9.3	19.3
D6	3.6	9.3	19.3	4.6	19.3	-	3.6	9.3
D7	4.6	3.6	2.2	19.3	9.3	3.6	-	19.3
D8	3.6	4.6	3.6	9.3	19.3	9.3	19.3	-

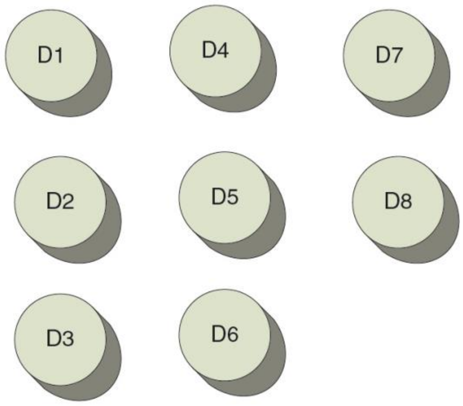

Fig. 9 Layout of atmospheric storage tanks in a tank farm

Assume sprinkler systems, water deluge systems, and fire detection systems are equipped in this tank farm, and emergency response times obey the aforementioned log-normal functions. If a fire occurs at tank D1, obviously D2 and D4 are most likely to fail because they are the closest to D1. In this condition, the time to failure (*ttf*) of D2 or D4 is about 10.7 minute.

So, the value of τ_{th} is determined to be 10.7min, and the mean time of discovering a fire (τ) is 4min.

The probabilities that employees do not detect the fire and that the emergency teams are too late for fire extinguishing are calculated to be 0.014 and 0.5, respectively, in the fault tree model. Further, using the fault tree model, the failure probability of fire escalation prevention is 2.8×10^{-3}.

As aforementioned, the PPN model of the failure analysis of the fire protection system is divided into two parts. The first part of the PPN model is shown as Fig.7, and the following matrixes can be obtained:

$$
I_C = \begin{bmatrix}
1000000000000000000000000 \\
0100000000000000000000000 \\
0010000000000000000000000 \\
0001000000000000000000000 \\
0000100000000000000000000 \\
0000010000000000000000000 \\
0000001000000000000000000 \\
0000000100000000000000000 \\
0000000010000000000000000 \\
0000000010000000000000000 \\
0000000000010000000000000 \\
0000000001000000000000000 \\
0000000000100000000000000 \\
0000000000010000000000000 \\
0000000000001000001010000 \\
0000000000000100000000000 \\
0000000000000010000000000 \\
0000000000000000100000000 \\
0000000000000001000000000 \\
0000000000000000010000000 \\
0000000000000000000000100 \\
0000000000000000000000010 \\
0000000000000000000100000 \\
0000000000000000000000100 \\
0000000000000000000001000 \\
0000000000000000000000010 \\
0000000000000000000000001 \\
0000000000000000000000001 \\
0000000000000000000000000
\end{bmatrix}
\qquad
O = \begin{bmatrix}
0000000000000000000000000 \\
0000000000000000000000000 \\
0000000000000000000000000 \\
0000000000000000000000000 \\
0000000000000000000000000 \\
0000000000000000000000000 \\
0000000000000000000000000 \\
0000000000000000000000000 \\
1110000000000000000000000 \\
0001110000000000000000000 \\
0000001100000000000000000 \\
0000000010000000000000000 \\
0000000000000000000000000 \\
0000000001100000000000000 \\
0000000000010000000000000 \\
0000000000000000000000000 \\
0000000000001100000000000 \\
0000000000001100000000000 \\
0000000000000000000000000 \\
0000000000000000000000000 \\
0000000000000011000000000 \\
0000000000000000110000000 \\
0000000000000000000000000 \\
0000000000000000001100000 \\
0000000000000000000000000 \\
0000000000000000000011000 \\
0000000000000000000000100 \\
0000000000000000000000010 \\
0000000000000000000000001
\end{bmatrix}
$$

I_h is a 29×25 zero matrix.

U=[1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1]

A_0=[0.08 0.001 0.07 0.08 0.001 0.2 0.05 0.014 0 0 0 0 0.021 0 0 0.5 0 0 0.02 0.02 0 0 0.1 0 0.1 0 0 0 0]

M_0=[1 1 1 1 1 1 1 1 0 0 0 0 1 0 0 1 0 0 1 1 0 0 1 0 1 0 0 0 0]

Using the probability reasoning algorithm, we can obtain the failure probability of fire escalation prevention (the value in place p_{29}) is 2.8×10^{-3}. The value is the same as that calculated by the fault tree model.

The second part of the PPN model is shown as Fig.8, and the following matrixes are obtained:

$$I_C = \begin{array}{cc} \begin{matrix} t_1 & t_2 & t_3 & t_4 & t_5 & t_6 & t_9 & t_{10} & t_{11} & t_{26} & t_{27} & t_{28} & t_{29} & t_{30} \end{matrix} & \\ \begin{bmatrix} 1&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&1&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&1&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&1&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&1&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&1 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&1 \\ 0&0&0&0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&1 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \end{bmatrix} & \begin{matrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \\ p_6 \\ p_7 \\ p_8 \\ p_9 \\ p_{10} \\ p_{12} \\ p_{13} \\ p_{14} \\ p_{23} \\ p_{25} \\ p_{30} \\ p_{31} \\ p_{32} \\ p_{33} \\ p_{34} \end{matrix} \end{array}$$

$$I_h = \begin{array}{cc} \begin{matrix} t_1 & t_2 & t_3 & t_4 & t_5 & t_6 & t_9 & t_{10} & t_{11} & t_{26} & t_{27} & t_{28} & t_{29} & t_{30} \end{matrix} & \\ \begin{bmatrix} 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&0&0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \end{bmatrix} & \begin{matrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \\ p_6 \\ p_7 \\ p_8 \\ p_9 \\ p_{10} \\ p_{12} \\ p_{13} \\ p_{14} \\ p_{23} \\ p_{25} \\ p_{30} \\ p_{31} \\ p_{32} \\ p_{33} \\ p_{34} \end{matrix} \end{array}$$

$$O = \begin{array}{cc} \begin{matrix} t_1 & t_2 & t_3 & t_4 & t_5 & t_6 & t_9 & t_{10} & t_{11} & t_{26} & t_{27} & t_{28} & t_{29} & t_{30} \end{matrix} & \\ \begin{bmatrix} 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 1&1&1&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&1&1&1&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&1&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&1&1&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&1 \end{bmatrix} & \begin{matrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \\ p_6 \\ p_7 \\ p_8 \\ p_9 \\ p_{10} \\ p_{12} \\ p_{13} \\ p_{14} \\ p_{23} \\ p_{25} \\ p_{30} \\ p_{31} \\ p_{32} \\ p_{33} \\ p_{34} \end{matrix} \end{array}$$

It should be noted that in matrixes I_c, I_h and O, the first row and the last column are used only to represent the composition of the matrix, they are not the actual matrix value.

Taking the mean time (τ) of discovering the fire as an example, based on the PPN model, the value of μ_{28} is determined according to the ratio of the probability between 0 and τ to the probability between

0 and τ_{th}. As τ is 4min and τ_{th} is 10.7min, the value of μ_{28} is 0.6075. In addition, μ_{30} is determined to be 0.98 according to the probability distribution function shown in Fig. 3 and the interval (6.7, ∞). Thus, the matrix of U is obtained as follows:

U=[1 1 1 1 1 1 1 1 1 1 1 0.6075 1 0.98];

The initial states of the model are determined by A_0 and M_0:

A_0=[0.08 0.001 0.07 0.08 0.001 0.2 0.05 0.014 0 0 0 0.021 0 0.1 0.1 0 0 0 0 0];

M_0=[1 1 1 1 1 1 1 1 0 0 0 1 0 1 1 0 0 0 0 0];

Using the probability reasoning algorithm, the failure probability of fire escalation prevention (the value in place p_{34}) is determined to be 3.3×10^{-4}. Therefore, the total probability of fire escalation prevention is 3.1×10^{-3}. Comparing with the result of the fault tree model, this result has a difference of about 11%.

The sooner a fire is discovered, the more time emergency teams will have to get to the scene of the fire. Fig. 10 shows how the probability of fire escalation prevention failure changes with the time the fire is discovered. The horizontal axis indicates the time (minute) when the fire is discovered, and the vertical axis indicates the total failure probability of fire escalation prevention.

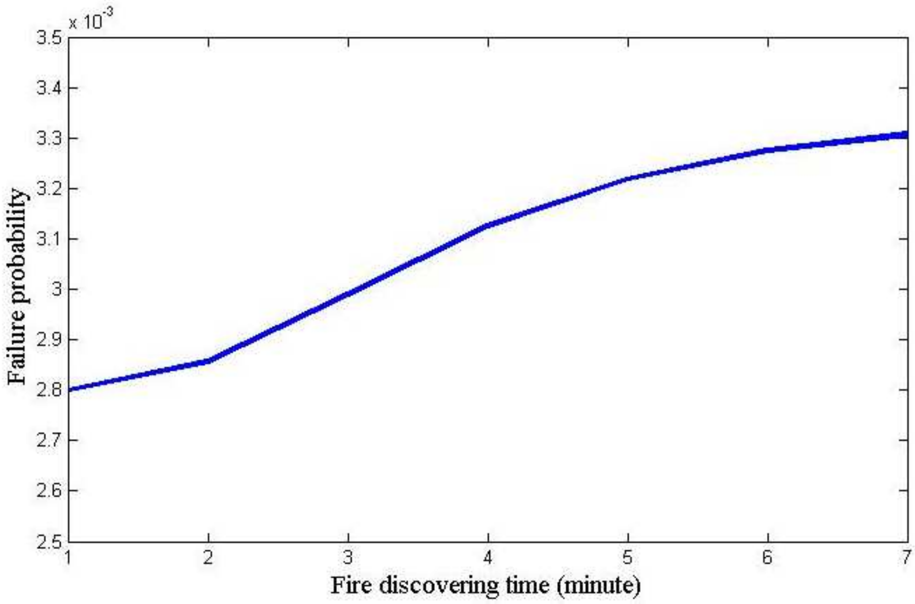

Fig. 10 Impact of fire discovering time on the failure probability of fire escalation prevention

6. Conclusions

If there are a lot of facilities in an area that store large amounts of flammable materials, fire protection is an important mission of safety management. With heat radiation, fire at a facility may escalate to other facilities and form a domino effect, which usually causes much greater losses than a primary fire. Although various safety barriers including active barriers, passive barriers have been analyzed for preventing fire escalation, the impact of emergency response are seldom involved and analyzed in detail.

Considering a typical environment that flammable liquids are stored in a storage tank farm, a fault tree model is developed to analyze the failure probability of fire escalation prevention. However, the fault tree model usually only analyzes the impact of the occurrence (failure) of the basic events on the occurrence of the top event. As the success of an emergency action may still affect the occurrence of the top event, and the emergency actions may influence each other, if these factors are taken into account in the analysis, it is difficult for ordinary fault trees to deal with them. Thus, an approach of probabilistic Petri-net (PPN) with the complementary arc is proposed. The definition and execution rules of PPN are provided, and an algorithm based on matrix operation is developed to embody the parallel execution of a PPN model. On this basis, a PPN model for failure analysis of fire escalation prevention is established.

The main contribution of this study can then be summarized as follows: (1) In considering the factors of fire escalation prevention, in addition to the safety barriers, the impact of emergency response is emphasized; (2) In addition to the failure of emergency response actions, the impact of the success of emergency actions and the dependency between the actions on fire escalation is considered. (3) A new modeling method based on PPN is proposed, which can overcome the shortcomings of fault trees. (4) The reasoning algorithm of PPN is developed.

An example of tank fire illustrates the proposed approaches. The fire discovering time may influence the follow-up emergency response actions, such as fire-fighting and tank tooling. As the fire discovering and the emergency response duration are assumed to satisfy log-normal distributions, influences of them on fire escalation prevention can be determined. For a fire occurs at a tank in the tank farm, the time to failure (ttf) of the nearest tank is 10.7min. For the 4min of average fire discovering time, using the fault tree model and the PPN model, the failure probabilities of fire escalation prevention are 2.8×10^{-3} and 3.1×10^{-3}, respectively. The PPN model includes two parts, the first part is consistent with the fault tree model, and the second part focuses on analyzing the impact of successful events on the system failure.

In the current study, the damage probability of safety barriers caused by a primary accident is not considered. In practice, primary accidents (especially major explosions or fires) often invalidate safety barriers. In these conditions, emergency response would have greater impacts on fire escalation prevention.

Acknowledgments

This work is supported by National Natural Science Foundation of China (No. 71673060).

References

Abdolhamidzadeh B., Abbasi T., Rashtchian D., Abbasi S. A., (2011). Domino effect in process-industry accidents-An inventory of past events and identification of some patterns. Journal of Loss Prevention in the Process Industries 24, 575-593.

Albanese M., Chellappa R., Moscato V., Picariello A., Subrahmanian V. S., Turaga P., Udrea O., (2008). A Constrained Probabilistic Petri Net Framework for Human Activity Detection in Video. IEEE Transactions on Multimedia 10(6), 982-996.

Cozzani V., Gubinelli G., Antonioni G., et al., (2005). The assessment of risk caused by domino effect in quantitative area risk analysis. Journal of Hazardous Materials A127, 14-30.

CSB, (2018). Static Spark Ignites Flammable Liquid during Portable Tank Filling Operation. http://www.csb.gov/barton-solvents-flammable-liquid-explosion-and-fire/

Darbra R. M., Palacios A., Casal J., (2010). Domino effect in chemical accidents: main features and accident sequences. Journal of Hazardous Materials 183, 565-573.

Directive 2012/18/EU., (2012). European Parliament and Council Directive2012/18/EU of 4 July 2012 on control of major accident hazards involving dangerous substances, amending and subsequently repealing council directive 96/82/EC. Official Journal of the European Communities, L197/1, Brussels.

Flynn J. D., (2009). Fire service performance measures. National Fire Protection Association.

Gomez-Mares M., Zarate L., Casal J., (2008). Jet fires and the domino effect. Fire Safety Journal 43, 583-588.

Hemmatian B., Abdolhamidzadeh B., Darbra R. M., Casal J., (2014). The significance of domino effect in chemical accidents. Journal of Loss Prevention in the Process Industries 29, 30-38.

Hemmatian B., Planas E., Casal J., (2015). Fire as a primary event of accident domino sequences: The case of BLEVE. Reliability Engineering and System Safety139, 141-148.

Janssens J., Talarico L., Reniers G., Sörensen K., (2015). A decision model to allocate protective safety barriers and mitigate domino effects. Reliability Engineering and System Safety 143, 44-52 .

Jensen K., Kristensen L. M., (2015).Colored Petri nets: a graphical language for formal modeling and validation of concurrent systems. Communications of the ACM 58, 61-70.

Khakzad N., Khan F., Amyotte P., Cozzani V., (2013). Domino Effect Analysis Using Bayesian Networks. Risk Analysis 33(2), 292-306.

Khakzad N., Landucci G., Cozzani V., Reniers G., Pasman H., (2018). Cost-effective fire protection of chemical plants against domino effects. Reliability Engineering and System Safety 169, 412-421.

Landucci G., Argenti F., Spadoni G., Cozzani V., (2016). Domino effect frequency assessment: The role of safety barriers. Journal of Loss Prevention in the Process Industries 44, 706-717.

Landucci G., Argenti F., Tugnoli A., Cozzani V., (2015). Quantitative assessment of safety barrier performance in the prevention of domino scenarios triggered by fire. Reliability Engineering and System Safety 143, 30-43.

Landucci G., Gubinelli G., Antonioni G., Cozzani V., (2009). The assessment of the damage probability of storage tanks in domino events triggered by fire. Accident Analysis and Prevention 41, 1206-1215.

Lee J., Liu K. F. R, Chiang W., (2003). Modeling Uncertainty Reasoning With Possibilistic Petri Nets. IEEE Transactions on Systems, Man and Cybernetics-Part B: Cybernetics 33(2), 214-224.

Liu Y., (2014). PCTL* Stochastic Model Checking Label-Extended Probabilistic Petri Net System Model. 2014 IEEE 5th International Conference on Software Engineering and Service Science, 287-290.

Liu Y, Miao HK, Zeng HW et al., (2013). Nondeterministic probabilistic Petri net - A new method to study qualitative and quantitative behaviors of system. Journal of Computer Science and Technology 28(1), 203-216.

MAHBulletin, (2017). Lessons Learned Bulletin No. 11, Chemical Accident Prevention &

Preparedness, Learning from emergency response – firefighter preparedness and protection. http://www.kas-bmu.de/publikationen/MAHB_Bulletin/mahb-bulletin-no11%20emergency%20response%20part2.pdf.

Murata T., (1989). Petri nets: Properties, analysis and applications. Proceedings of the IEEE 77(4), 541-580.

OREDA Participants, (2002). Offshore Reliability Data Handbook. Det Norske Veritas (DNV), Norway.

Paltrinieri N., Dechy N., Salzano E., Wardman M., Cozzani V., (2011). Lessons learned from Toulouse and Buncefield disasters: From risk analysis failures to the identification of atypical scenarios through a better knowledge management. Risk Analysis, doi: 10.1111/j.1539-6924.2011.01749.x.

Peng C., (2010). The Statistics Law of Fire Response Time and Its Correlation with the Scale of Urban Fire (Thesis for master's degree). University of Science and Technology of China.

Petri C. A., (1966). Communication with Automata. New York: Griffiss Air Force Base. Technical Report No. RADC- TR-65-377, Volume 1, Supplement 1.

Reniers G. Cozzani V., (2013). Domino effects in the process industries: modeling, prevention and managing. Oxford, UK: Elsevier.

Reniers G.L.L., Dullaert W., (2008). Knock-on accident prevention in a chemical cluster. Expert Systems with Applications 34(1), 42-49.

Russell A. O., Juan C. R., Todd M. H., (2014). Case Study of the Domino Effect in a Catastrophic Solid Oxidizer Fire. 10th Global Congress on Process Safety, New Orleans, LA, USA.

Tan Q., Chen G., Zhang L., Fu J., Li Z., (2014). Dynamic accident modeling for high-sulfur natural gas gathering station. Process Safety and Environmental Protection 92, 565-576.

Yen H.-C., Yu L.-P., (2004). Dependability analysis of a class of probabilistic Petri nets. Proceedings of the 10th IEEE Pacific Rim International Symposium on Dependable Computing, 373-380.

Zuberek W. M., Kubiak W., (1999). Timed Petri Nets in Modeling and Analysis of Simple Schedules for Manufacturing Cells. Computers and Mathematics with Applications 37, 191-206.