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DOI
10.1016/j.jlp.2022.104835

Publication date
2022

Document Version
Final published version

Published in
Journal of Loss Prevention in the Process Industries

Journal of Loss Prevention in the Process Industries 79 (2022) 104835

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Dynamic analysis of fire induced domino effects to optimize emergency response policies in the chemical and process industry

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A R T I C L E I N F O

Keywords:
Fire accident
Domino effect
Time analysis
Petri-net
Emergency response

A B S T R A C T

A fire accident is one the most dangerous accidents that may lead to knock-on effects, especially in the plants dealing with large quantities of hazardous substances. Different from other accidents, e.g., explosions, fires can last certain period of time and the thermal radiations emitted by them have a synergistic effect. At the same time, the heat-up of target installations under the effect of thermal radiation is also a process that takes a certain amount of time. These characteristics make fire induced domino effects a dynamic process. During an emergency response due to a fire accident, emergency personnel may arrive at the fire scene at different times, so they may face different accident situations. In this work, an adaptive timed Petri-net (ATPN) based approach is proposed to model the propagation of fires and perform a dynamic analysis of potential domino effects. The definition of ATPN as well as the enabling and execution rules is provided. Through simulations, not only the probabilities of fires in different installations, but also the probabilities of the fire extension propagated over time can be obtained. An example of a tank farm fire illustrates the approach. Our developed approach for carrying out a dynamic analysis of domino effects is helpful for emergency preparation.

1. Introduction

Fire is a type of major accident that may cause great losses, especially in the process industries. Process systems usually deal with large amount of hazardous materials with flammable or explosive characteristics, which usually have a large impact range of accidents. In process plants there are often many installations in a limited area, making an accident in a given installation likely to escalate to neighboring installations, possibly leading to so-called domino effects (Khan and Abbasi, 1998).

Statistical studies of fire accidents show that almost half of domino effects are triggered by fire (Darbra et al., 2010; Abdolhamidzadeh et al., 2011; Hemmatian et al., 2014). Many researchers studied domino effects triggered by fire in many ways. For example, Masum Jujuly et al. (2015) used a three-dimensional computational fluid dynamics (CFD) approach based on ANSYS CFX-14 to simulate liquefied natural gas (LNG) pool fire and its domino effects. Ghasemi and Nourai (2017) proposed a methodology using a new concept in maximizing storage safety to determine the water application rate for protection of storage tanks against thermal radiation. Zhang et al. (2017) proposed an agent-based approach to analyze the propagation of domino effects in the chemical and process industries, and synergistic effects and temporal dependencies of fire induced domino effects were considered. Chen et al. (2018b) used a Bayesian network to analyze propagation patterns and the occurrence probability of pool fire induced domino effects in a tank farm. Chen et al. (2018a) proposed a methodology to model the spatial-temporal evolution of fire induced domino effects, including a Domino Evolution Graph (DEG) model and a Minimum Evolution Time (MET) algorithm.

If neighboring installations receive the thermal radiations emitted from a fire accident, they will be heated up and their walls may fail unless they are adequately protected, such as by thermal insulation and water deluge system. Fires can usually last for a period of time and may thereby trigger domino effects, such that emergency response may influence the development of a fire accident. Prevention or mitigation of domino effects through emergency response has also been studied in some previous works, e.g., Khakzad et al. (2017) considered emergency response in the evaluation of fire protection system performance in the domino effects. Bucelli et al. (2018) proposed a methodology for the

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https://doi.org/10.1016/j.jlp.2022.104835
Received 18 October 2021; Received in revised form 13 June 2022; Accepted 1 July 2022
Available online 7 July 2022

performance assessment of safety barriers including emergency response, with regard to preventing the propagation of cascading events. Hosseinnia et al. (2018) developed a multi-plant emergency response decision tool for cross-plant consequences (domino effects). Zhou and Reniers (2016, 2020, 2021, 2022) studied the role of emergency response in preventing domino effects from different perspectives, such as cooperation of actions, resources using, and the influence of arrival times.

However, in domino effects triggered by fire, a primary fire escalating to secondary fires, may still escalate to other installations to form higher level domino effects. Hence fire induced domino effects have dynamic characteristics, that is, at different time a fire may propagate to a different extent. When emergency response personnel arrive at a fire accident scene with emergency resources at different times, they may face different situations and the personnel or resources may not be enough for the fire-fighting and may fail to extinguish the fire or prevent the fire from escalating. For example, on October 23, 2009, a large explosion occurred at the Caribbean Petroleum Corporation (CAPECO) which is located in Bayamón, Puerto Ricoa, resulting in an escalation of fires at 17 tanks. By the time the earliest fire departments arrived at the front gate of CAPECO, the fire had propagated to approximately 103 acres (1500 feet by 1500 feet), so that it could not be controled anymore (U.S. Chemical Safety and Hazard Investigation Board, 2015). Therefore, dynamic analysis of fire induced domino effects is helpful for fire-fighting preparation. Although in some previous studies, higher-level domino effects have been studied and several approaches have been proposed to estimate the probability of domino accidents, such as Monte Carlo simulation (Abdolhamidzadeh et al., 2010; Rad et al., 2014), Bayesian networks (Khakzad et al., 2013; Yuan et al., 2016), and a matrix based modeling approach (Zhou and Reniers, 2018), dynamic analysis of fire induced higher level domino effects are seldom involved.

The aim of this study is to develop a novel methodology based on Petri-net (PN) to model the domino effect of fires and perform dynamic analysis for the sake of emergency response. Petri-net is a powerful modeling tool and is widely used to model and analyze various systems, in addition to early applications for modeling of discrete event systems. The advantage of Petri-nets lies not only in its graphical modeling and its precise mathematical theory, but also in its executability. Petri-nets are a graphical and mathematical modeling tool composed of places, transitions, and arcs. They are easy to describe and study relationships between parts of a system . Petri-net models are executable, and removing and creating tokens with the execution of transitions can simulate the dynamic and concurrent activities of a system. In this paper, Petri-net is utilized to model the thermal radiation impacts of one installation on another installation, considering fire-related accidents.

The rest of this paper is organized as follows: Section 2 discusses the characteristics of fire induced domino effects, including the approach of dynamic calculation of time to failure (*ttf*) of installations under fires. In Section 3, the adaptive timed Petri-net is proposed to model and perform dynamic analysis of domino effects. An example illustrates the proposed approach in Section 4, probabilities of fire at installations and domino effect levels over time are discussed. Finally, Section 5 draws some conclusions from this work.

2. Characteristics of fire induced domino effects

2.1. Dynamic characteristics

In a fire-induced domino effect, installations near to other fires may be damaged mainly through thermal radiations. Thermal radiation is also subject to the synergistic effect, indicating that the amount of thermal radiation received by a nearby installation is the sum of thermal radiation received from each fire. Therefore, in the domino effect, when a new installation is on fire, the thermal radiation received by other surrounding installations will change, and the damage possibility of the installations will change accordingly. At the same time, thermal radiation must take some time to cause damage to an installation, the time is called the time to failure (*ttf*). As new fires occur at different times during a domino effect, the total thermal radiation of a surrounding installation increases at different times.

Moreover, the duration of an installation fire is determined by the amount of fuel it stores. When the fuel runs out, the fire will extinguish, and the thermal radiation received by other installations will be reduced at some point in time due to the extinguishment of the fire.

Thus, during fire-induced domino effects, the thermal radiation received by an installation may change dynamically over time and then impact the fire propagation dynamically.

These dynamic characteristics should be considered when modeling. Two points need to be considered: the first is the synergistic effect of thermal radiation, and the other is the combustion of fuels. In terms of time characteristics, the effect of thermal radiation makes an installation having a failure time *ttf*, and the *ttf* will vary according to the change of the received thermal radiation. In addition, the combustion of the fuel in an installation has a certain duration. When the material which is contained in an installation is determined, the duration can be considered as a definite value, which can be calculated by the burning velocity and the mass of the material.

For the sake of emergency response, in this work, the worst-case of fire duration is taken into account. Therefore, the time of fire at an installation is analyzed according to the earliest possibility of fire occurrence in a domino effect, that is, once the *ttf* of an installation is reached, the fire occurrence is judged according to the corresponding escalation probability and the fire probability after damage.

2.2. Escalation probability

Probit models have been adopted to estimate the escalation probability of installations (Cozzani et al., 2005; Antonioni et al., 2009; Landucci et al., 2009). In general, the probit value Y can be determined according to Eq. (1):

$$Y = a + b\ln(x) \tag{1}$$

where, a and b are coefficients for the probit obtained by regression of experimental data. The probit model is a mathematic model, and the variable x has different meanings in different applications. For the escalation probability analysis of fires, x usually means the time to failure (ttf). In other circumstances, x may have other meanings, e.g., for the escalation probability analysis of explosions, x usually means the overpressure.

As the main escalation vector of a fire is the thermal radiation, the failure of an installation is caused by the wall heat-up and this is a slow process. The time to failure (*ttf*) of the installations exposed to fire is a fundamental parameter to determine the probability of domino accidents induced by fire.

In this study, the probit model presented in Cozzani et al. (2001) is adopted:

$$Y = 9.25 - 1.85 \times \ln(ttf / 60) \tag{2}$$

After the probit Y is obtained, the escalation probability, P_{esc}, can be calculated as:

$$P_{esc} = \varphi(Y - 5) \tag{3}$$

where, φ is the cumulative density function of standard normal distribution, that is,

$$P_{esc} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} e^{-\frac{u^2}{2}} du \tag{4}$$

2.3. Dynamic ttf

In the previous study (Zhou et al., 2021), a "thermal dose" approach was proposed to calculate the dynamic ttf of a vessel under the circumstance that multiple fires occurred at different times.

In the analysis of fire induced domino effects, the following formulas are often used to estimate the ttf of a target vessel (Cozzani et al., 2005):

$$\textit{Atmospheric vessel}: \ ln(ttf) = -1.128 \times ln(Q) - 2.667 \times 10^{-5} \times V + 9.877 \tag{5}$$

$$\textit{Pressurized vessel}: \ ln(ttf) = -0.947 \times ln(Q) - 8.835 \times V^{0.032} \tag{6}$$

where, Q is the thermal radiation received by the vessel (kW/m^2), V is the volume (m^3) of the vessel and ttf is the time to failure of the vessel expressed in seconds.

According to Eqs. (5) and (6), a "thermal dose" D_{th} that is needed to cause the vessel to fail can be derived. D_{th} is defined as follows:

$$D_{th} = Q^{\alpha} \cdot ttf \tag{7}$$

where α is a constant. For an atmospheric vessel, the thermal dose is:

$$D_{th} = Q^{1.128} \cdot ttf = e^{-\left(2.667 \cdot 10^5 \cdot V - 9.887\right)} \tag{8}$$

For a pressurized vessel the thermal dose is:

$$D_{th} = Q^{0.947} \cdot ttf = e^{-\left(8.835 \cdot V^{0.032}\right)} \tag{9}$$

When analyzing the domino effect, the volume of the target vessel can be determined and can be considered to be a constant. Thus, D_{th} is a constant, representing the "critical" thermal dose at which a target vessel may fail when the thermal radiation received by it exceeds this value.

If the received thermal radiation varies with time, the following expression may be inferred for the thermal dose:

$$D_{th} = \int_0^{ttf} Q^{\alpha} dt \tag{10}$$

If multiple fires occur at different times, under the assumption that the received thermal radiation remains unchanged until a new fire occurs, Eq. (9) may be expressed as:

$$D_{th} = \sum_{i=1}^{n} Q^{\alpha}_{o,i} \cdot \Delta t_i \tag{11}$$

where $Q^{\alpha}_{o,i}$ is the overall thermal radiation value received by the target vessel on each time interval, Δt_i is the duration of the time interval i and n is the total number of time intervals, corresponding to the total number of fires considered in the analysis. The received overall radiation $Q_{o,\ n}$ of the target vessel after the n-th time interval may thus be expressed as:

$$Q_{o,n} = \sum_{i=1}^{n} Q_i \tag{12}$$

where, Q_i represents the amount of heat radiation received by the target vessel in the i-th time interval.

As the critical thermal dose D_{th} can be calculated from Eq. (8) or Eq. (9) and it is a constant, the time to failure of the vessel can be calculated using Eq. (11) if the occurring time of all fires is known. Thus, the *ttf* when the vessel will be damaged in the n-th time interval can be calculated as follows:

$$ttf = \sum_{i=1}^{n-1} \Delta t_i + \Delta t \tag{13}$$

where Δt is the n-th time interval representing the time period from the occurrence of the n-th fire to the failure of the vessel, and $\Delta t_i = t_i\text{-}t_{i\text{-}1}$ is the time interval from the occurrence of the i-*th* fire to that of the (i-1)-*th* fire. Since the occurring time of each fire is assumed to be known, Δt is the only unknown parameter in Eq. (13). Nonetheless Δt may be calculated as follows based on Eq. (11), and Eq. (8) or Eq. (9) for the vessel of interest:

$$\Delta t = \frac{D_{th} - \sum_{i=1}^{n-1} Q^{\alpha}_{o,i} \cdot \Delta t_i}{Q^{\alpha}_{o,n}} \tag{14}$$

Whenever a new fire occurs or an existing fire is extinguished, the ttf of the target equipment will change. Therefore this *ttf* can be considered to be a "dynamic *ttf*".

3. Adaptive timed Petri-net

3.1. Definitions

According to the characteristics of fire induced domino effects, an adaptive timed Petri-net (ATPN) is utilized to model and analyze.

Definition 1. An ATPN is defined as a seven-tuple:

ATPN = (P, T, A, C, F, τ, M).

(1) *P*: is the place set. Places are used to represent states in this work.
(2) *T*: is the transition set. Transitions are used to represent changes of states. According to different behaviors in state change, *T* is divided into two subsets T_r and T_b, respectively. T_r is a type of adaptive timed transition, which can adjust its execution duration according to the information of its input places and used to represent the effect of thermal radiations; T_b is normal timed transition and represents the burning of materials in this work. One transition of T_r connects to only one place, representing the thermal radiation impacts on the corresponding installation.
(3) $A \subseteqq P \times T \bigcup T \times P$: represents directed arcs connecting from places to transitions or from transitions to places. Arcs can also be divided into two subsets, A_n is normal directed arcs which restrict token requirement of the execution of transitions; and A_h is inhibitor arcs, when they obtain a token, the transition they point to cannot be enabled.
(4) *C*: *P*→*N* is the capacity restrictions of places, which maps places to positive integer numbers. *C*(*p*) indicates the maximum number of tokens that place *p* can hold. As a place represents a state in this study, each place can only have at most one token indicating the corresponding state occurs.
(5) *F*: is a function that determines durations of transitions.
(6) *τ*: is a set of nonnegative real numbers representing durations of transitions.
(7) *M*: *P*→{0, 1} is the marking of a Petri-net, which means that a place *p* has a non-negative integer tokens. In this work, a place can only have zero or one token. The initial marking of a Petri-net is usually denoted as M_0.

To facilitate the description in the following part, denote ***•t (•p)*** as input places of transition *t* (input transitions of place *p*) and ***t•(p•)*** as output places of transition *t* (output transitions of place *p*).

The execution of an ATPN model is based on its enabling rule and execution rule. For the transitions T_r, their behavior is different from that of normal Petri-net transitions. A T_r transition must be able to obtain thermal radiation information from multiple input places representing the emitter, and determine its execution duration by a function. In basic Petri-nets, a transition can not be enabled if any of its input places do not have the required tokens. But in this study, a transition of T_r should be enabled if any of its input places have one token, because any burning installation has impact on a non-fire installation. Thus, the following enabling rules and execution rules are given to define the behaviors of transitions.

Definition 2 (Enabling rule 1). A T_r transition t_r is enabled if any of its input places contain one token in a marking M_i. That is,

$$\forall\ \ p \in {}^{*}t_r \ \mathit{and}\ t_r \in T_r,\ \exists M_i(p)==1$$

Definition 3 (Enabling rule 2). A T_b transition t_b is enabled if all its input places contain one token.

$$M_i(p)==1, \forall p \in {}^{*}t_b$$

Definition 4 (Execution rule 1). If a T_r transition t_r is enabled, it recalculates its duration. If its execution duration is satisfied, it puts one token into its output places according to a stochastic function f_{ex}. The execution of an enabled transition t_r at marking M_i changes the marking into M_{i+1}.

If f_{ex} (t_r) = true then

$$M_{i+1}(p)==1, \forall p \in t_r^{*} \ \ \text{and} \ \ M_i \smile p \frown \ll 0$$

The stochastic function f_{ex} is used to meet the requirement of the probit model of fire-induced domino effects.

Definition 5 (Execution rule 2). If a T_b transition t_b is enabled, it can execute. When its execution duration is satisfied, it puts one token into its output places. Execution of an enabled transition t_b at marking M_i changes the marking into M_{i+1}. The execution result is as follows,

$$M_{i+1(p)} = 0,\ \forall p \in {}^{*}t_b$$

$$M_{i+1(p)} = 1,\ \forall p \in t_b^{*}$$

The elements in ATPN are represented as icons, which are shown in Fig. 1.

It should be noted that if the T_r transition t_r is enabled and its execution duration is satisfied, but the stochastic function f_{ex} is false, the execution of the transition will not put the token to its output place. When an input place of transition t_r obtains a token after the corresponding *ttf*, t_r should determine the value of the f_{ex} to re-determine whether to put the token to the output place. This corresponds to the fact that an installation is not damaged after its *ttf*, but the received thermal radiation increases and the probability of damage increases accordingly.

3.2. Analysis process

Based on the ATPN model of fire propagation, the possible fire propagation paths can be revealed, and on this basis, Monte-Carlo simulation can be used to analyze the fire probability of each installation under the domino effect.

The simulation process of single fire propagation is shown in Fig. 2 and Fig. 3, where, Fig. 2 is the main flow, including two main steps:

Step 1. Initialization and preparation. The variable *idx* is the sequence number of time (in minutes), the initial value of it is set to be one, indicating that the simulation starts at the first minute. The fuel volume stored in each vessel is sampled according to a certain distribution, the burning duration after the vessel catches fire is calculated, and the execution time of the corresponding transitions is set. Then, put a token in the place that represents the primary fire to start the simulation.

Step 2. Execute all enabled transitions over time, until there is no transition enabled anymore. If there is a place which obtains a token, this means that the fire propagates to a new installation, so record the fire time.

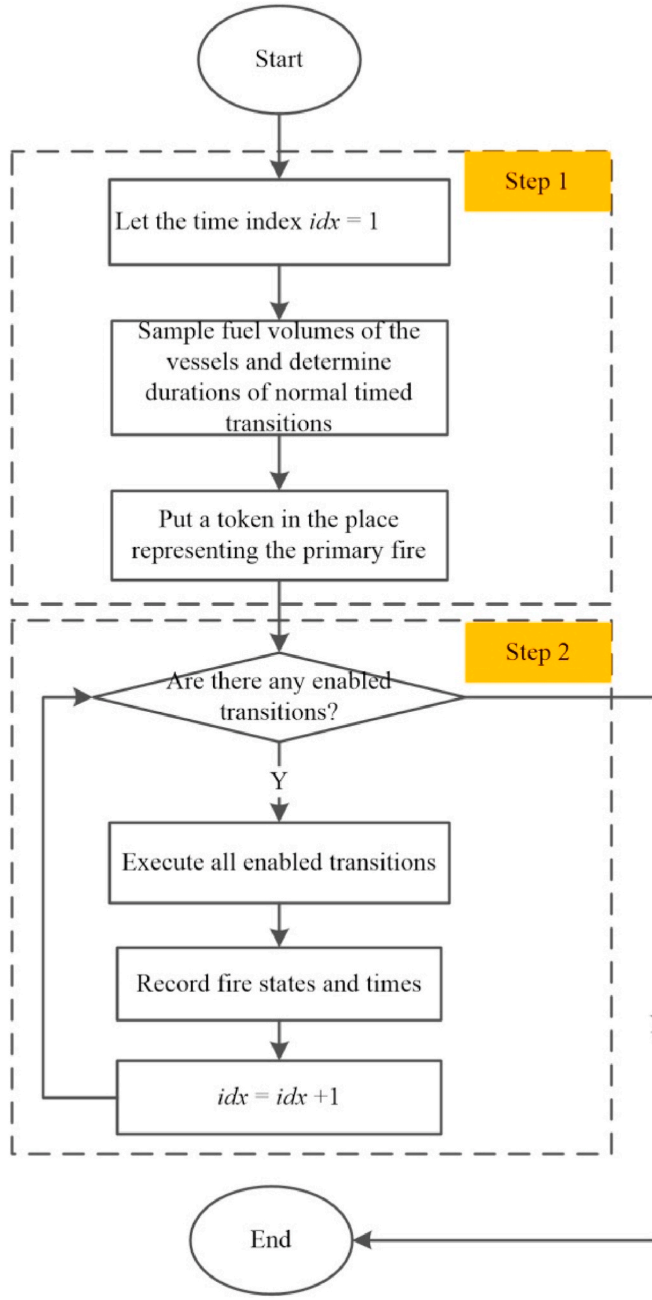

Fig. 2. Main flowchart of a simulation.

In a certain minute, the execution process of an enabled transition is shown in Fig. 3. The execution contains the following steps:

Step A: Select an enabled transition, e.g., t_i. Determine the total received thermal radiation according its input places.

Step B: If the total received thermal radiation changes, recalculate the *ttf* according to Eq. (13) and determine the value of function f_{ex} based on the new *ttf*.

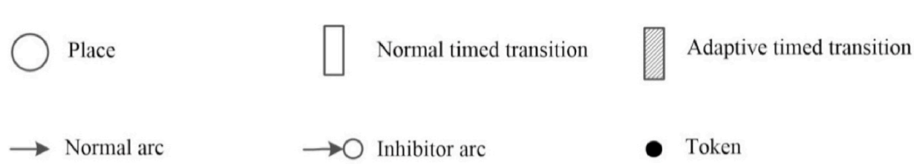

Fig. 1. Elements in ATPN

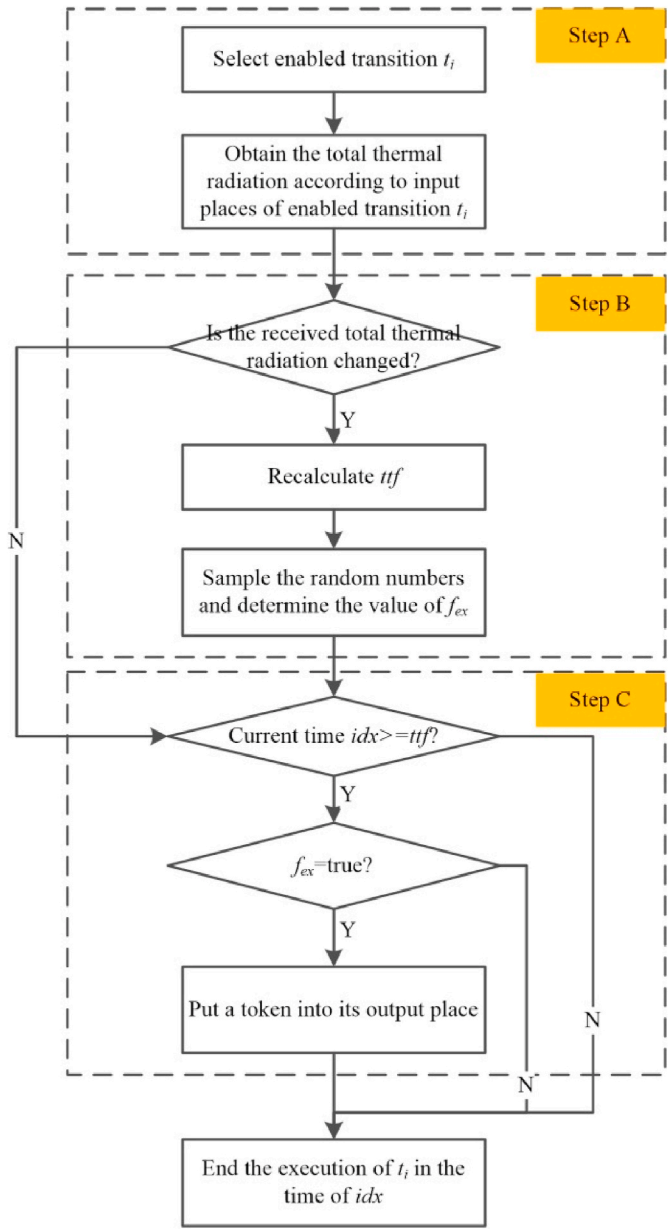

Fig. 3. Flowchart of the execution of enabled transition t_i.

The value of function f_{ex} is determined as follows,

$$f_{ex} = f_p \ and \ f_f \tag{15}$$

$$f_p \ll \begin{cases} \text{true}, & \text{if } \ \text{normalnum}(0,\ 1) < Y - 5 \\ \text{false}, & \text{otherwise} \end{cases} \tag{16}$$

$$f_f \ll \begin{cases} \text{true}, & \text{if } \ \text{random}() < P_{\text{fire}} \\ \text{false}, & \text{otherwise} \end{cases} \tag{17}$$

where, *normalnum* (*x, y*) is a function to generate random number satisfying normal distribution with a mean value of *x* and a variance of *y*, and *random* () is a function generating uniformly distributed random number between 0 and 1.

Function f_p is utilized to meet the requirement of Eq. (3), and function f_f is adopted to satisfy the requirement of fire accident likelihood/probability P_{fire} after an installation is damaged.

Step C: If the current execution time is smaller than *ttf* which is determined by transition t_i, transition t_i does not put a token to its output place. This means that the time of the effect of thermal radiation has not reached the *ttf*, so that the corresponding installation is not damaged. If the current execution time is greater than *ttf*, transition t_i puts a token to its output place according the value of f_{ex}. If the value of f_{ex} is true, a token is created and put into the output place, indicating that the installation is damaged and catches fire under the effect of thermal radiation. If the value of f_{ex} is false, transition t_i does not put token to its output place, this means that the installation is not damaged or on fire even if the thermal radiation time is longer than the *ttf*.

During the simulation of a fire domino effect, if a place representing the state of an installation obtains a token, the value of the state and time of state change can be recorded for further analysis.

On the basis of single fire propagation, a large number of replications of fire propagation simulation can be used for probability analysis.

4. An example

Fig. 4 shows the layout of four atmospheric storage tanks in a process plant. All tank fires are regarded as pool fires and safety barriers are not taken into account. The mass of fuel in the tanks is assumed to obey a normal distribution with the average of 5 tons and the standard deviation of 2 tons (maximum 10 tons). Since each tank is surrounded by a catch basin, the pool fire diameter is also assumed to be equal to the diameter of the catch basin. The diameter of the catch basin of Tank1and Tank3 is 8 m, and the diameter of the catch basin of Tank2 and Tank4 is 10 m. The distance between the wall of Tank3 and the side of the catch basin of Tank1 is 4 m, the distance between the wall of Tank2 and the side of the catch basin of Tank1 is 5 m.

There are several methods that can be used to estimate the thermal radiation between facilities in the event of fires. Mudan (1984), McGrattan et al. (2000) and van den Bosch and Weterings (2005) introduced some usually used models for accident effect analysis of pool fires, such as the point source model and the solid flame model to analyze the heat radiation from a pool fire. There are also more complex models, such as the Computational Fluid Dynamics (CFD) based model (Chun et al., 2009). Some software tools are also available to analyze the effects of thermal radiation, e.g., ALOHA (U.S Environmental Protection Agency, 2013) has been used to determine the heat radiations in many domino effect studies in the process industry (Khakzad and Reniers, 2015; Chen et al., 2018a,b; Duenas Santana et al., 2021). In this work, the Mudan method introduced in Hurley (2016) is used to estimate the fire thermal radiation between tanks. The thermal radiations of one tank fire acting on other tanks are given in Table 1.

If Tank1 catches fire, the thermal radiations received by Tank2, Tank3, and Tank4 are 15 kW/m^2, 18 kW/m^2, and 7 kW/m^2, respectively. If the fire escalates to Tank2, the thermal radiation received by Tank3 and Tank4 would become 28 kW/m^2 and 29 kW/m^2, respectively. The changing of received thermal radiations will impact the fire probabilities of the tanks.

The ATPN model of fire propagation is established as shown in Fig. 5, and the places and transitions in the model are explained in Table 2.

Let's assume that the primary fire occurs at Tank1, so that a token is initially put into place p_1. Using the model, we can perform a simulation

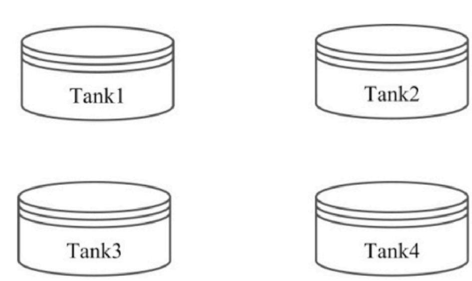

Fig. 4. Layout of four tanks.

Table 1
Thermal radiation on each target (kW/m^2).

	Tank1	Tank2	Tank3	Tank4
Tank1	–	15	18	7
Tank2	18	–	10	22
Tank3	18	7	–	15
Tank4	10	22	18	–

analysis. It should be noted that the failure time in the following discussions indicates that the corresponding tank will not be damaged within this time. When the lasting time of a fire exceeds a certain threshold time, the tank may be damaged (determined by the value of f_{ex}). Different from the time to failure (*ttf*), the failure time is determined according to the *ttf* and the current time.

Scenario 1. There is no escalation of the fire

The duration (in minute) of transitions is determined according to the thermal radiation or sampled mass:

t2:15.451 t3:12.579 t4:36.501 t5:17.267 t6:40.276 t7:52.106 t8:45.966.

The accident process is shown in Table 3. Tank3 has the minimum failure time, which is 12.579 min. If the fire time is less than 12.579 min, no storage tank is damaged. When the *ttf* of 12.579 min is met, the value of f_{ex} is used to determine whether Tank3 is on fire. In this case, the probit value if 4.566, and the normal distribution random number is 0.997, so that the value of f_{ex} of transition t_3 is false. Thus, Tank3 is not damaged. Similarly, when the *ttf* of Tank2 is met, the value of f_{ex} of transition t_2 is also false (probit value is 4.185, normal distribution random number is 1.022, and the uniform distribution random number is 0.048). Tank2 is not damaged, either. In the 18th minute (17.267), the fuel in Tank1 burns out and the fire goes out.

Scenario 2. Secondary fires

This is the situation that the fire at Tank1 only escalates to one of other tanks (e.g., Tank1→Tank3). The following example shows the possible escalation of the fire, the simulation process is listed in Table 4.

The duration (in minute) of transitions is as follows:

t2:15.451 t3:12.579 t4:36.501 t5:41.150 t6:15.272 t7:40.123 t8:18.728.

At the time of 12.579 min, Tank3 has been resistant to thermal radiation coming from Tank1 for a period of time up to its *ttf*, the value of

Table 2
Meanings of places and transitions in the Petri-net model.

Place	Meaning	Transition	Meaning
p_1	Tank1 is on fire	t_1	Thermal radiation impacts on Tank1
p_2	Tank2 is on fire	t_2	Thermal radiation impacts on Tank2
p_3	Tank3 is on fire	t_3	Thermal radiation impacts on Tank3
p_4	Tank4 is on fire	t_4	Thermal radiation impacts on Tank4
p_5	Fuel in Tank1 is burned out	t_5	Tank1 burns
p_6	Fuel in Tank2 is burned out	t_6	Tank2 burns
p_7	Fuel in Tank3 is burned out	t_7	Tank3 burns
p_8	Fuel in Tank4 is burned out	t_8	Tank4 burns

Table 3
Simulation that fire at Tank1 does not escalate to other tanks.

Time	Marking	Failure time			f_{exi}	Executed transitions
		Tank2	Tank3	Tank4		
0	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		
1	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
2	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
3	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
4	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
5	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
6	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
7	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
8	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
9	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
10	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
11	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
12	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
13	(1,0,0,0,0,0,0,0)	15.451	–	36.501	f_{ex3}: false	t2, t4, t5
14	(1,0,0,0,0,0,0,0)	15.451	–	36.501		t2, t4, t5
15	(1,0,0,0,0,0,0,0)	15.451	–	36.501		t2, t4, t5
16	(1,0,0,0,0,0,0,0)	–	–	36.501	f_{ex2}: false	t4, t5
17	(1,0,0,0,0,0,0,0)	–	–	36.501		t4, t5
18	(0,0,0,0,1,0,0,0)	–	–	36.501		t4, t5

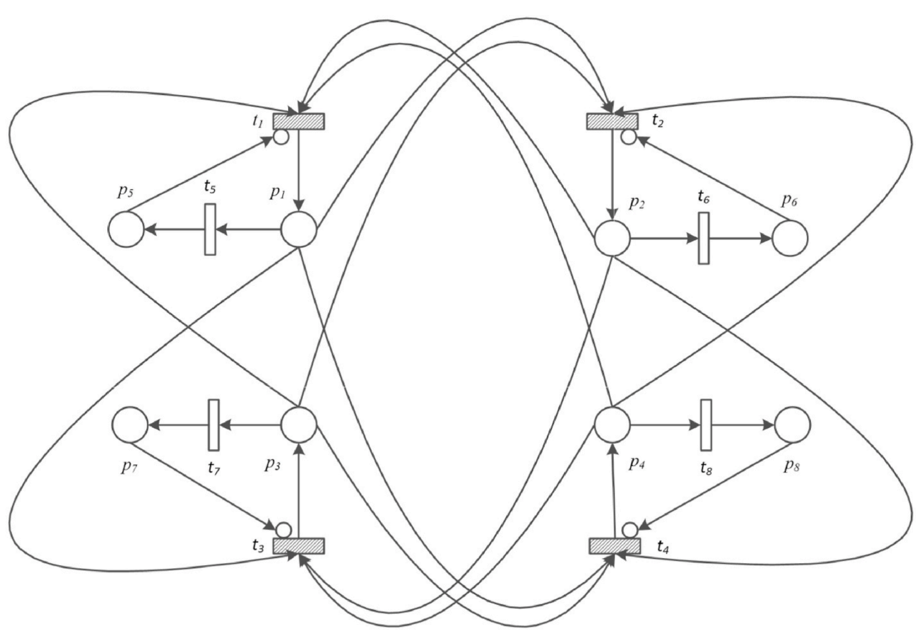

Fig. 5. ATPN model of fire propagation.

Table 4
Simulation of fire escalation from Tank1 to Tank3.

Time	Marking	Failure time			f_{exi}	Executed transitions
		Tank2	Tank3	Tank4		
0	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		
1	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
2	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
3	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
4	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
5	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
6	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
7	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
8	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
9	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
10	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
11	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
12	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
13	(1,0,1,0,0,0,0,0)	14.443	–	19.153	f_{ex3}: true	t2, t3, t4, t5, t7
14	(1,0,1,0,0,0,0,0)	14.443	–	19.153		t2, t4, t5, t7
15	(1,0,1,0,0,0,0,0)	–	–	19.153	f_{ex2}: false	t4, t5, t7
16	(1,0,1,0,0,0,0,0)	–	–	19.153		t4, t5, t7
17	(1,0,1,0,0,0,0,0)	–	–	19.153		t4, t5, t7
18	(1,0,1,0,0,0,0,0)	–	–	19.153		t4, t5, t7
19	(1,0,1,0,0,0,0,0)	–	–	19.153		t4, t5, t7
20	(1,0,1,0,0,0,0,0)	–	–	–	f_{ex4}: false	t4, t5, t7
… …						
41	(1,0,1,0,0,0,0,0)	–	–	–		t5, t7
42	(0,0,1,0,1,0,0,0)	–	–	–		t5, t7
43	(0,0,1,0,1,0,0,0)	–	–	–		t7
… …						
52	(0,0,1,0,1,0,0,0)	–	–	–		t7
53	(0,0,0,0,1,0,1,0)	–	–	–		t7

Table 5
Simulation of fire escalation from Tank1 to Tank3 and then to Tank2.

Time	Marking	Failure time			f_{exi}	Executed transitions
		Tank2	Tank3	Tank4		
0	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		
1	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
2	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
3	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
4	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
5	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
6	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
7	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
8	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
9	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
10	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
11	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
12	(1,0,0,0,0,0,0,0)	15.451	12.579	36.501		t2, t3, t4, t5
13	(1,0,1,0,0,0,0,0)	14.443	–	19.153	f_{ex3}: true	t2, t3, t4, t5, t7
14	(1,0,1,0,0,0,0,0)	14.443	–	19.153		t2, t4, t5, t7
15	(1,1,1,0,0,0,0,0)	–	–	16.598	f_{ex2}: true	t2, t4, t5, t6, t7
16	(1,1,1,0,0,0,0,0)	–	–	16.598		t4, t5, t6, t7
17	(1,1,1,0,0,0,0,0)	–	–	–	f_{ex4}: false	t5, t6, t7
… …						
34	(1,1,1,0,0,0,0,0)	–	–	–		t5, t6, t7
35	(0,1,1,0,1,0,0,0)	–	–	–		t5, t6, t7
36	(0,1,1,0,1,0,0,0)	–	–	–		t6, t7
… …						
43	(0,1,0,0,1,0,1,0)	–	–	–		t6, t7
44	(0,1,0,0,1,0,1,0)	–	–	–		t6
… …						
56	(0,1,0,0,1,0,1,0)	–	–	–		t6
57	(0,0,0,0,1,1,1,0)	–	–	–		t6

f_{ex} of transition t_3 is true (the probit value is 4.566, the normal distribution random number is −0.727, and the uniform random number is 0.322), this means Tank3 catches fire under the thermal radiation from Tank1. At this time, the failure time of Tank2 changes from 15.451 min to 14.443 min and the failure time of Tank4 changes from 36.501 to 19.153 min due to the increase of received thermal radiation. However, at the time of 14.443 min, the sampled value of f_{ex} of transition t_2 is false (the probit value is 4.985, the normal distribution random number is 0.491, and the uniform random number is 0.676), so Tank2 is not on fire. At the time of 19.153 min, f_{ex} of transition t_4 is false so that Tank4 does not catch fire, either. The process ends when fuels in Tank1 and Tank3 burn out. In this process, the primary fire only escalates to form a secondary fire.

The possible propagation paths to form a secondary fire also include Tank1→Tank2. As the thermal radiation received by Tank4 is less than the threshold value of escalation (15 kW/m^2), the ttf of Tank4 does not work.

Scenario 3. Tertiary fires

In this case, the fire escalates to a tank, and then escalates to another tank due to the synergistic effects of thermal radiation. Table 5 shows the simulation process that the fire escalates to Tank3, and then to Tank2.

The durations of transitions are determined as follows:

t2:15.451 t3:12.579 t4:36.501 t5:34.387 t6:42.542 t7:29.760 t8:34.930.

Similar to the example of Scenario 2, Tank 3 catches fire at 12.579 min due to the effect of thermal radiation from Tank1. At 15.451 min, Tank2 also catches fire as the value of f_{ex} of transition t2 is true (the probit value is 4.985, the normal distribution random number is −0.436, and the uniform random number is 0.186). Note the changes of the failure time of Tank4. When Tank3 is on fire at 12.579 min, the failure time of Tank4 changes from 36.501 min to 19.153 min, and then changes to 16.598 min at 14.443 min when Tank2 is also on fire. But at 16.598 min, the value of f_{ex} of transition t4 is false (the probit value is 6.431, the normal distribution random number is −0.678, and the uniform random number is 0.738), so that Tank4 is not on fire. The propagation process forms a tertiary fire.

The possible propagation paths to form tertiary fires include Tank1→Tank3→Tank2, Tank1→Tank2→Tank3, Tank1→Tank3→Tank4, and Tank1→Tank2→Tank4.

Scenario 4. Quaternary fires

In the process shown in Table 5, if the value of f_{ex} of transition t4 is true at 16.598 min, Tank4 will be considered on fire. Then the domino effect will form a quaternary fire. The simulation process of quaternary fires is ignored here.

Based on the thermal radiations of a tank on each target, the possible propagation paths to form quaternary fires are Tank1→Tank3→Tank2→Tank4, Tank1→Tank3→Tank4→Tank2, Tank1→Tank2→Tank3→Tank4, and Tank1→Tank2→Tank4→Tank3.

Using the Monte Carlo simulation method, random numbers are generated according to the probability distributions, and the fire probability at each tank can be determined by a large number of experiments. After 10^4 experiments, the fire probabilities of tanks are obtained as shown in Table 6.

Based on the ATPN model, time characteristics of fire accidents at tanks can also be analyzed. Simulations show that among the escalations to only one tank, the earliest time of Tank3 catching fire is 12.579 min, and the earliest time of fire at Tank2 is 15.451 min. Their proportions are shown in Fig. 6, where it accounts for about 80% that the fire escalates to Tank3 and about 20% for escalating to Tank2.

Table 6
Fire probability of tanks.

	Tank2	Tank3	Tank4
Probability	0.136	0.197	0.104

For fires propagating to the tertiary level, the percentage of the number of occurrences across time periods is shown in Fig. 7, taking 2 min as an interval. In the 14th and 15th minutes, we see the highest possibility that the fire at Tank1 develops into tertiary fires. The second highest possibility concerns the interval of the 16th and 17th minutes, together with the interval of the 20th and 21st minutes,. The possibility of the interval of the 22nd and 23rd minutes shows the lowest value.

For fires propagating to the quaternary level, the distribution over time is shown in Fig. 8, with an interval of 2 min. The number of times that happens in the interval of 20th and 21st minutes is the highest, the percentage is 36%. The next is the interval of the 18th and the 19th minutes, the percentage is 33%. The interval of the 16th and the 17th minutes has the percentage of 18%, the interval of the 22nd and the 23rd minutes has the percentage of 9%, and the percentage in the interval of the 24th and the 25th minutes is 4%.

In order to better reflect the domino effect on emergency response, the fire propagation state within a specified time is analyzed, corresponding to the fire situation faced by the emergency personnel when they arrive at the scene of the accident. To do this, each simulation no longer ends with no transitions being enabled, but with a given time. After the given time is met, the state of each tank can be recorded to determine the fire propagation. The probability of fire at each tank caused by domino effect over time is shown in Fig. 9. If emergency response personnel reach the fire site at the 15th minute, the fire probability of Tank2 is 0.04, that of Tank3 is 0.16, and Tank4 cannot catch fire. But when they arrive at the fire site at the 20th minute, the fire probability of Tank2 is 0.12, the fire probability of Tank3 is 0.16, and the fire probability of Tank4 is 0.07.

Fig. 10 shows the relationship between domino effect level and time. For the fire only escalates to the secondary level, the probability is higher in the period from the 13th to the 19th minute, and stabilizes to about 0.12 after the 20th minute. From the 15th minute, the fire may escalate to the tertiary level, and it might escalate to the quaternary level from the 17th minute. Starting from the 23rd minute, the probability of fire propagating to the tertiary level and the quaternary level is basically the same, which is about 0.06.

According to the relationship between domino effect level and time, it is possible to determine the accident environment when emergency response personnel arrive at the scene of the accident at different times. For example, after Tank1 catches fire, if emergency response personnel arrive at the scene at the 15th minute, the probability that the fire propagates to only one tank is 0.12, the probability that the fire has propagated to two tanks (tertiary fire) is 0.04, and the fire cannot propagate to three tanks (quaternary fire). If they arrive at the scene at the 20th minute, the probability that the fire propagates to only one tank

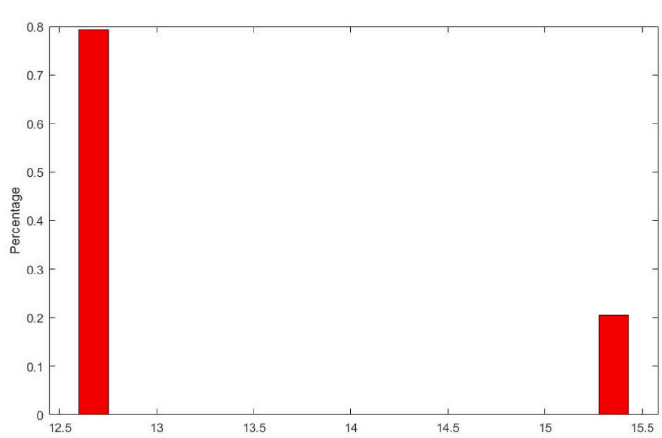

Fig. 6. Percentage of secondary level accidents occurring at different times.

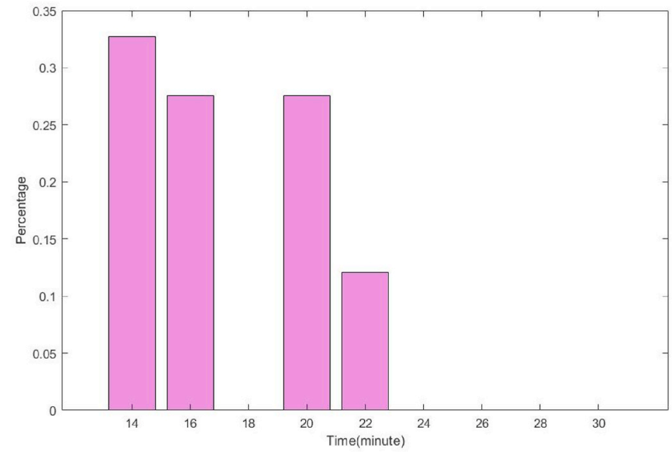

Fig. 7. Percentage of tertiary level accidents occurring at different times.

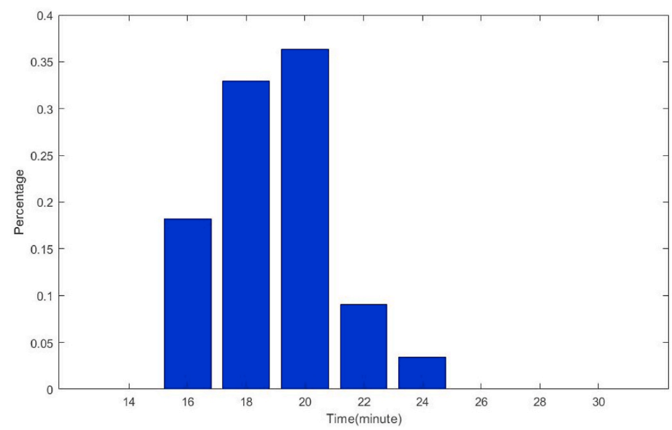

Fig. 8. Percentage of quaternary level accidents occurring at different times.

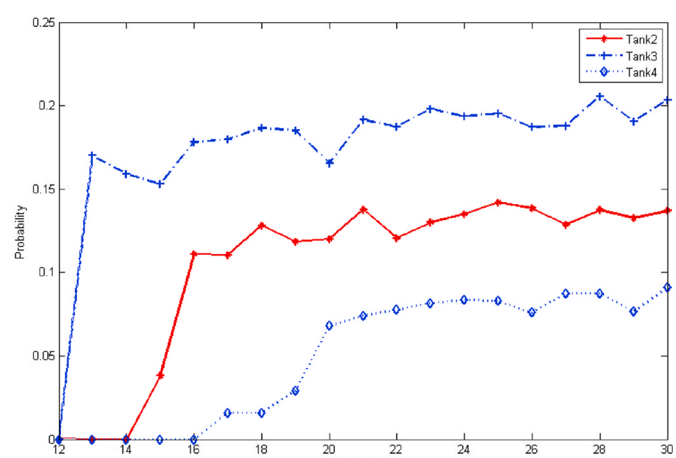

Fig. 9. Fire probabilities of tanks over time.

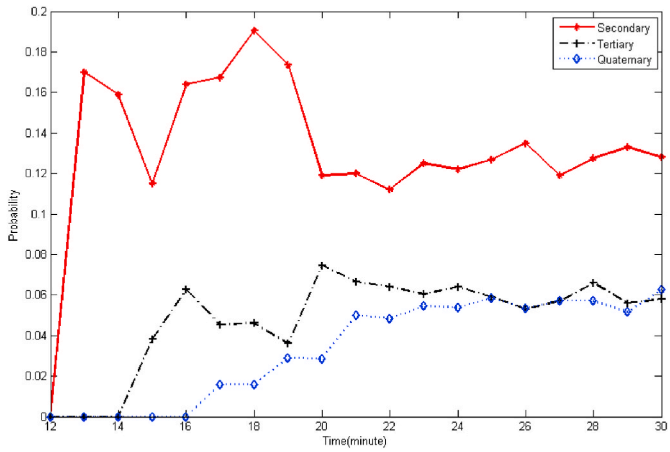

Fig. 10. Probabilities of domino effect level over time.

is 0.11, the probability that the fire has propagated to two tanks (tertiary fire) is 0.08, and the probability that the fire has propagated to three tanks (quaternary fire) is 0.03.

5. Conclusions

In areas where large quantities of flammable substances are stored, fires in one installation may escalate to other installations, resulting in a domino effect. The secondary fires may still induce fires at other installations. A fire may propagate from one installation to another when there are many installations in the impacted area.

As the thermal radiation of a fire has the heat-up process to damage neighboring installations, it will take some time that a fire escalates to other installations. During the propagation of a fire, different installations may catch fire at different times, and thermal radiations from multiple sources are characterized by a synergistic effect on a target installation. This causes the thermal radiation received by an installation to change at different times, leading to the fact that the failure time of the installation may change over time.

After the primary fire occurs, emergency response is usually put in place to extinguish the fire as soon as possible. It will take the emergency personnel some time to arrive at the fire scene and begin to fight the fire, so that they may face different fire situations when they arrive at different times. Dynamic analysis of fire-induced domino effects can help emergency response personnel to prepare for fighting fires in advance. The worst-case of fire escalation time is taken into account for the sake of emergency response, that is, the escalation of a fire is thought to occur when the *ttf* of a target installation is satisfied.

In this work, an adaptive timed Petri-net (ATPN) approach is proposed to model the domino effect of fire propagation and perform time analysis. The definition of ATPN and the analysis process based on ATPN for fire induced domino effects are provided. An example of storage tank fire is utilized to illustrate the approach. Through simulation, fire propagation scenarios are discussed and the fire probability of each tank is obtained. The fire probability of each tank and the probability of a possible domino effect varying with time are also discussed.

Credit author statement

Jianfeng Zhou: Conceptualization, Methodology, Writing - Original Draft. Genserik Reniers: Validation, Writing - Review & Editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

Acknowledgments

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

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