Petri-net based evaluation of emergency response actions for preventing domino effects triggered by fire

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Abstract*: In industrial chemistry, many flammable materials are handled and/or stored in various facilities. It is possible that major fires occur at these facilities possibly leading to domino effects due to the failure of neighboring facilities caused by thermal radiation. It will take a certain time that thermal radiation causes nearby facilities to fail and that a domino effect occurs. The time needed for escalation to take place allows emergency actions as a response to the primary fire to prevent the propagation of the fire. In the present study, a Timed Colored Hybrid Petri-net (TCHPN) based methodology is introduced to evaluate different emergency response actions based on their efficiency in preventing or delaying the propagation of domino effects. A TCHPN model of emergency response to flammable liquid tank fire is established, and a time based analysis of emergency response actions for preventing domino effects is performed. Based on the simulation analysis, the probability of domino effects is calculated and response actions are compared.*

Keywords: pool fire; domino effect; emergency response; time analysis; Petri-net

1. Introduction

In the (petro-)chemical industry, a large number of hazardous materials are used in production or for storage purposes. Once an accident happens caused by these materials, devastation may follow. An accident involving large amounts of these hazardous materials usually has a large area of impact, and has an important effect on the surrounding facilities eventually even leading to domino effects.

A domino effect has several characteristics (Reniers and Cozzani, 2013): (i) a primary accident, which triggers other accidents to form an accident chain; (ii) a propagation effect, resulting from the effect of escalation vectors caused by the primary event on secondary targets; (iii) one or more secondary accidents. Many studies have been performed on domino effects in the process industries, involving topics such as risk assessment, escalation thresholds, prevention approaches, cross-plant prevention measurements, and anti-terrorism research.

For example, regarding risk assessment with respect to domino effects, Antonioni et al. (2009) developed a methodology for the quantitative assessment of risk due to a domino effect and applied it to the analysis of an extended industrial area. They applied recently developed equipment damage probability models for the identification of the final scenarios and for escalation probability assessment. Khakzad et al. (2013) introduced a methodology based on Bayesian network both to model domino effect propagation patterns and to estimate the domino effect probability at different levels. The probabilities of events can be updated in the light of new information, and the most probable path of the domino effect can be determined on the basis of the new data gathered. Based on the probabilistic models and the physical equations, Kadri et al. (2013) presented a methodology for quantitative assessment of domino effects caused by fire and explosion on storage areas. A human vulnerability model to the effects

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of over pressure and heat radiation were developed to estimate the individual and societal risk. Khakzad et al. (2014) provided a dynamic consequence analysis approach for risk assessment and management of domino effects and presented the application of Bayesian networks and conflict analysis to risk-based allocation of chemical inventories to minimize the consequences and to reduce the escalation probability.

For the escalation thresholds, Cozzani & Salzano (2004) studied the definition and assessment of overpressure threshold values for the damage to equipment caused by blast waves which are originated by primary accidental scenarios, and they proposed threshold values for different categories of process equipment, taking into account either damage levels or release intensities following the loss of containment. Cozzani et al.(2006) further studied the revision and the improvement of criteria for escalation credibility, based on the modelling of fire and explosion damage to process equipment due to different escalation vectors (heat radiation, overpressure and fragment projection), and proposed revised threshold values. Landucci et al. (2009) developed an approach for the quantitative assessment of the risk caused by escalation scenarios triggered by fire. Simplified models for the estimation of the vessel time to failure (ttf) with respect to the radiation intensity on the vessel shell were obtained using a multi-level approach to the analysis of vessel wall failure under different fire conditions.

In the (petro-)chemical industry, chemical plants are often physically located in groups and are rarely located separately. A plant's accident may thus affect other plants in the neighborhood through escalation. Khan & Abbasi (2001) illustrated the application of DEA (domino effect analysis) and the software DOMIFFECT (DOMIno eFFECT) to four closely spaced petrochemical facilities in an industrial complex. The studies revealed that major accidents—some involving the entire industrial park—can occur. Reniers et al. (2009) proposed a game-theoretic approach to interpret and model behavior of chemical plants within chemical clusters while negotiating and deciding on domino effects prevention investments. Cozzani et al. (2014) presented methodologies developed for the quantitative assessment of risk due to domino and NaTech scenarios in the case of industrial clusters or complex industrial areas. A specific effort was dedicated to the improvement of models for the calculation of equipment damage probability in these accident scenarios.

After the events of 11 September 2001, the risk of terrorist attacks in chemical plants has aroused people's attention. Reniers et al. (2008) provided a theoretical conceptualization on how to manage the prevention and the mitigation of intentionally induced domino effects in a possibly very complex industrial cluster. Reniers et al. (2014) further proved by case-study that chemical industrial areas may follow a power-law distribution, through representing such areas as mathematical 'danger networks'. Landucci et al. (2015b) carried out the analysis of industrial accidents induced by intentional acts of interference, focusing on accident chains triggered by attacks with home-made explosives. The effects of blast waves caused by improvised explosive devices were compared with those expected from a net equivalent charge of TNT by using a specific methodology for the assessment of stand-off distances.

Domino effects can cause great losses, so how to prevent domino effects has also been studied by some researchers. Reniers & Dullaert (2008) developed a simple and user-friendly software named "DomPrevPlanning" to support decision making on safety barriers to prevent/mitigate domino effects in a complex surrounding of chemical installations, and thereby considering multiple domino scenarios. Janssens et al. (2015) presented a decision model to support practitioners about where to locate safety barriers and mitigate the consequences of an accident triggering domino effects, based on the features of an industrial area that may be affected by domino accidents, and knowing the characteristics of the safety barriers that can be installed to stall the fire propagation between installations. Landucci et al. (2015a) developed a LOPA (layer of protection analysis) based quantitative assessment methodology, aimed at the definition and quantification of safety barrier performance in the prevention of escalation of domino events induced by fire.

In addition to safety barriers, emergency response can play an important role in preventing domino effects, but it has seldom been studied. The main escalation vectors that can trigger domino effects are

thermal radiation, overpressure, and fragments of explosion (Cozzani et al, 2005). As the duration of nearby facilities being influenced by overpressure or fragments is very short, the role of emergency response in preventing the domino effect in these cases is limited. However, the development of domino effects triggered by thermal radiation is often characterized by a longer duration. In such case, after the occurrence of a primary fire, effective emergency response which is carried out in time can prevent domino effects. Zhou et al. (2016) proposed a methodology based on Event Sequence Diagram (ESD) to evaluate and prioritize different emergency response actions based on their efficiency in preventing or delaying the propagation of domino effects triggered by fire. Owing to the advantages of Petri-nets in modeling and analysis of discrete events (and even continuous events), this paper uses Petri-net to analyze the role of emergency response actions in case of domino effect.

The concept of the Petri-net was proposed by Petri (1966). From then on, Petri-nets are widely used to model and analyze discrete event systems such as communication, manufacturing, and transportation systems. Petri-nets are a graphical and mathematical modeling tool applicable to many systems. They constitute a promising tool for describing and studying systems that are characterized as being concurrent, asynchronous, distributed, parallel, nondeterministic, and/or stochastic (Murata, 1989). In addition to the modeling of systems, tokens are used in Petri nets to simulate the dynamic and concurrent activities of the systems. A variety of high level Petri-nets are proposed to solve various problems. Hybrid Petri-net can be used to model a system if one part is discrete and another part is continuous. Timed Petri-net (TPN) augments PNs with time, such as firing durations, or time delays. In timed Petri-nets, the transitions fire in “real-time”, i.e., there is a (deterministic or random) firing/executing time associated with each transition, the tokens are removed from input places at the beginning of firing, and are deposited into output places when the firing terminates (Zuberek, 1991). Coloured Petri net (CPN) is a formalism which extends ordinary Petri nets by adding data types and modularity (Jensen, 1990).

In literature, Petri-nets have also been applied to the modeling and analysis of emergency response (Aye and Ni, 2011; Meng et al., 2011; Zhong et al., 2010; Zhou, 2013; Zhou and Reniers, 2016). In Zhou (2013), the emergency response process is considered as a hybrid system, and the emergency actions are divided into discrete actions and continuous actions according to their durations. During an emergency response, in addition to discrete events which can be completed quickly, there are some actions which have a long duration and may be affected by the development of the accident. These long duration actions can be looked as continuous processes. Besides, many handled materials in the process industry or some statuses of the emergency response are continuous and should be described as continuous variables. As a colored Petri Net can use colors to distinguish tokens, the hybrid Petri net model will be more compact and concise by integrating with colored Petri net. Because this study analyzes the actions of the emergency response process based on the time analysis, the Timed Colored Hybrid Petri-Net (TCHPN) is adopted to model the process.

This paper is structured as follows. Section 2 provides the definition of TCHPN and discusses its operating mechanism. Section 3 models the emergency response process based on TCHPN. Section 4 discusses the evaluation of emergency response actions, and Section 5 concludes this article.

2. Timed Colored Hybrid Petri-net

A Timed Colored Hybrid Petri-Net (TCHPN) is an eleven-tuple (Zhou & Reniers, 2016):

$$\text{TCHPN} = (\text{P, T, A, } \sum\text{, V, N, C, G, E, IN, } \tau_{Td})$$

(1) P: is a finite set of places. P can be split into two subsets P_D and P_C gathering, respectively, the discrete and the continuous places.

(2) T: is a finite set of transitions. T can also be split into two subsets T_D and T_C gathering, respectively, the discrete and continuous transitions.

(3) $A \subseteq P \times T \cup T \times P$, represents the sets of arcs connect places with transitions and transitions with places.

(4) $\sum$ represents a finite set of non-empty types, called color sets.

(5) V is a finite set of variable types, so that $Type[v] \in \sum$ for all $v \in V$ variables.

(6) $N : A \rightarrow P \times T \cup T \times P$ is a node function.

(7) C: $P \rightarrow \sum$ -represents the color set function that assigns a color set to each place.

(8) G: represents guard function that assigns a guard which is to filter and restrict possible events to each transition t.

(9) E: represents the function of arch expression assigning an arc expression to each arch.

(10) IN: is an initialization function.

(11) τ_{Td}: $T_d \rightarrow R^+$ is a function that associates discrete transitions with deterministic time delays.

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

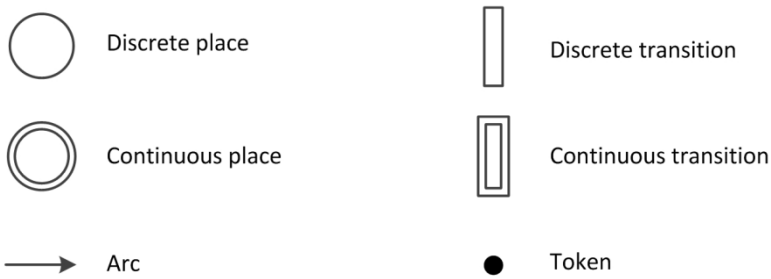

Fig. 1 Icons for the elements in the TCHPN model

The tokens are usually denoted by dots, and they can also be expressed by a number. The executing rules of the transitions are shown in Fig. 2 and Fig. 3, for discrete transitions and continuous transitions, respectively.

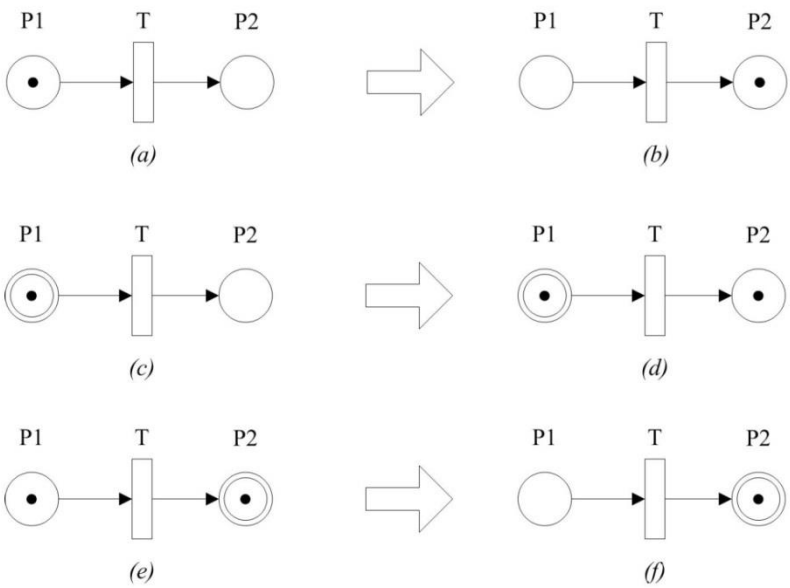

Fig. 2 Executing rules for a discrete transition

If each input place of a transition has at least the number of tokens with correct colors determined by the arc from the place to the transition, the transition can be enabled. If a discrete transition is enabled, it will execute and remove tokens indicated by the arcs from the input places. In the timed Petri-net, the execution of a discrete transition usually lasts for a certain time, and then tokens are put into the output

places. If a continuous transition is enabled, it can execute continuously. The termination of the execution of a continuous transition is determined by the state of the corresponding continuous place(s).

In Fig. 2, (a) indicates tokens in the input discrete place is subtracted by 1 (or the number marked on the input arc) after *T* occurs; and (b) indicates tokens in the output discrete place is added by 1 (or the number marked on the output arc) after *T* occurs; As a token in a discrete place represents a type of message or a command, (a) and (b) represent the transmission of the message or command, which may be transformed during *T* occurring.

(c) and (d) in Fig. 2 indicate the tokens in the continuous input places are not changed after *T* occurs. (e) and (f) in Fig. 2 indicate the tokens in the continuous output places are not changed after *T* occurs. However, the occurring of the discrete transition may access the color values of the continuous places.

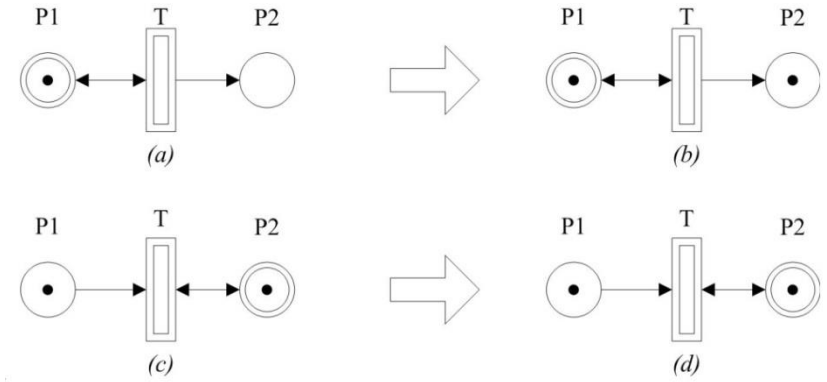

Fig. 3 Executing rules for a continuous transition

In Fig. 3, (a) and (b) indicate the tokens in the continuous input places are not changed. (c) and (d) indicate the tokens in the continuous output places are not changed. But the value of the token color in the continuous places can be accessed. (c) and (d) indicate the token in the inputting discrete place of a continuous transition is not consumed after the occurring of the transition, so that the transition can keep executing continuously. (a) and (b) represent the tokens in the discrete output place is added by 1 (or the number marked on the output arc) when *T* occurs, for example, when a fire is out of control, a new message (token) will be generated in the corresponding place to rearrange the emergency response actions. In *(a)* and *(b)*, P1 is continuous place, it is not only an input place of transition T, but also an output place of T. It is the same with P2 in *(c)* and *(d)*.

3. Modeling of emergency response process

For illustrative purposes, consider a storage plant comprising six atmospheric gasoline tanks which are taken as an illustrative example in Zhou et al. (2016). The layout of the plant is shown in Fig. 4. The diameters of the tanks (Tk1–Tk6) are 20m, and their heights are10m.The distance from Tk1 to Tk2 is 30m (center to center), and so is the distance from Tk1 to Tk3.

Fig. 4 Layout of the tanks

If one tank catches fire (e.g., if there is a tank fire at Tk1), the emergency response will be activated. The typical process of the emergency response contains the actions including “discover the fire and alarm”, “dispatch emergency teams”, “rush to the scene of the fire”, “prepare for firefighting”, “fight against the fire”, “cool adjacent tanks”, and so on. Based on TCHPN, the actions can be modeled as transitions, in which “fight against the fire” and “cool adjacent tanks” can be expressed as continuous transitions, which will impact the fire state (thermal radiation) continuously and whose termination also depends on the fire state, and other actions can be considered as discrete transitions. In addition, in the process of emergency response, there were some cases that the accident cannot be controlled (or the accident can even be expanded) because of wrong actions (e.g., using incorrect fire extinguishing agent, or locating at an incorrect firefighting position). Thus the correctness of the emergency actions should be considered during the analysis of the emergency response process. For the sake of brevity, the correctness of the relatively simple actions is not discussed, and only the correctness of the action “fight against the fire” is considered here. After chemical materials catch fire, there are often special requirements for the firefighting. Incorrect fire extinguishing agents, fire extinguishing methods or the timing of the firefighting may be ineffective, and may even lead to a worse accident. In this paper, only “correctly fight against the fire” and “incorrectly fight against the fire” are considered, and the action of “incorrectly fight against the fire” is assumed that it cannot change the state of the fire (thermal radiation).

Based on TCHPN, the model of the emergency response to the tank fire is established as Fig. 5. The meanings of the places and the transitions are shown in Table 1.

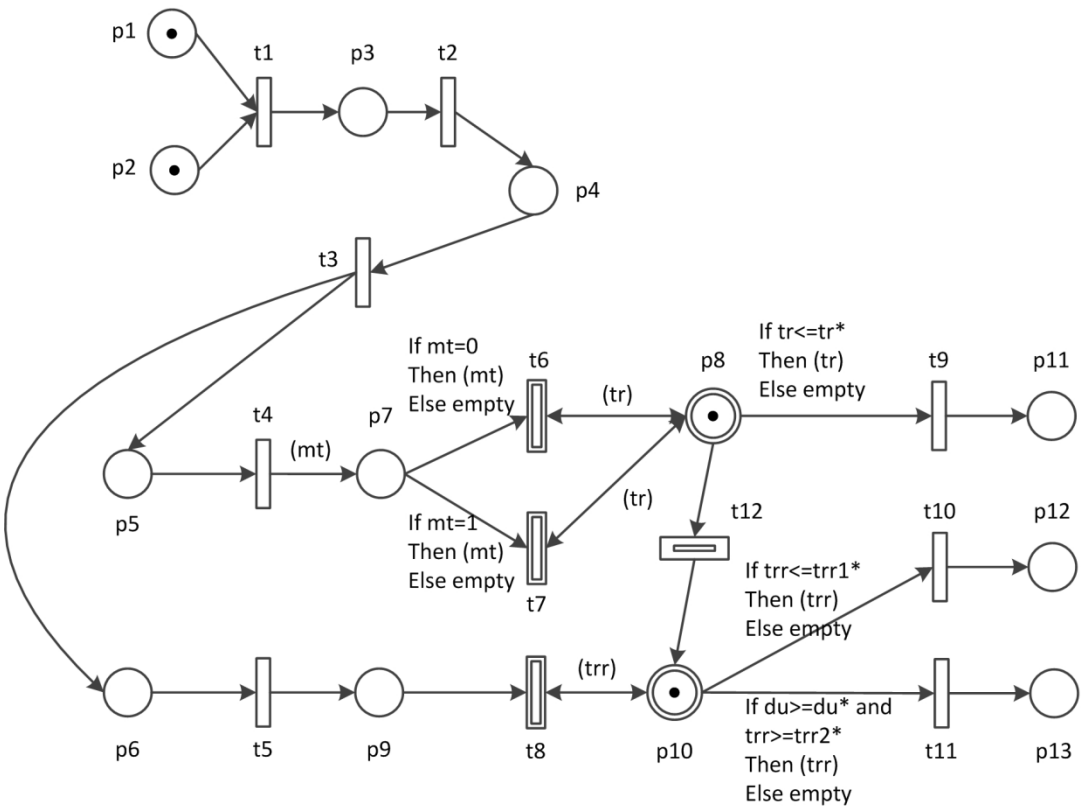

Fig. 5 TCHPN based model for emergency response to a tank fire

In the model, the transitions from t1 to t5 represent the corresponding discrete emergency response actions, and they all have a stochastic execution time. The transitions t6, t7 and t8 are continuous emergency actions. Three special discrete places t9, t10 and t11 which have zero execution time are added to express state transition. For example, when the thermal radiation indicated by the token color in p8 is less than or equal to a certain value *tr** (zero in this study), t9 will be enabled and it will execute immediately and put a token into place p11 to indicate that the fire is extinguished. Similarly, if the thermal radiation indicated by the token color in p10 is less than or equal to *trr1** (zero in this study, this is based on the assumption that cooling water will obstruct the thermal radiation), t10 will be enabled and it will execute immediately and put a token into place p12 to indicate that the fire is controlled. If the thermal radiation indicated by the token color in p10 is greater than or equal to *trr2**, and the duration *du* is greater than *du**, transition t11 is enabled and it will execute immediately to put a token into place p13 indicating the occurrence of a domino effect. In addition, a special continuous transition t12 is added to express the thermal radiation relationship between the source and the target.

Several colors are adopted to distinguish tokens. For the tokens in place p7, a color *mt* is used to express the firefighting method type, and the value 0 of *mt* indicates the correct method, the value 1 indicates the incorrect method. If the color value of the token in p7 is 0, it will enable transition t6; otherwise, it will enable t7. In the place p8, the token should have a color of *tr* which is a real type value indicating the thermal radiation emitted by the source. Similarly, in the place p9, the token should have a color of *trr* which is also a real type value indicating the thermal radiation received by the target.

Table 1 Meanings of the places and the transitions of the TCHPN model

Places	Meanings	Transitions	Meanings
p1	Occurring of fire	t1	Discover the tank fire
p2	Staff at the scene of the fire	t2	Dispatch the emergency response team
p3	Warning is received by the emergency department	t3	Rush to the scene of the fire

p4	Tasks are received by the emergency	t4	Prepare for firefighting
p5	Firefighting personnel is at the scene of fire	t5	Prepare for cooling
p6	Cooling personnel is at the scene of fire	t6	Correctly fight against the fire
p7	Firefighting is ready	t7	Incorrectly fight against the fire
p8	Thermal radiation of the fire tank	t8	Cool adjacent tanks
p9	Cooling is ready	t9	Extinguish the fire
p10	Thermal radiation received by the neighboring tank	t10	Control the fire
p11	Fire is extinguished	t11	Adjacent tank fail
p12	Fire is controlled	t12	Transfer thermal radiation
p13	Occurring of domino effect		

4. Evaluation of emergency response actions

This paper focuses on the analysis of the impact of emergency actions (discrete) on domino effects. In the TCHPN model of emergency response to a tank fire, there is always a token representing the fire state (thermal radiation) in the continuous places p8 and p10, respectively. Once the thermal radiation meets the conditions, it will make the transitions t9, t10 or t11 execute, and the system state may convert to “fire is extinguished”, “fire is controlled” or “occurring of domino effect”, respectively.

In the tank area shown in Fig. 4, after one tank catches fire, the neighboring tanks may fail due to the thermal radiation, and thus form a domino effect. Under the thermal radiation, one tank usually fails after a certain period of time. The time to failure (*ttf*) of a tank can be determined according to the relationship between thermal flux I (kW/m^2) and *ttf* (s) provided by Cozzani et al. (2005):

$$ln(ttf) = -1.13 ln(I) - 2.67\times10^{-5}V + 9.9 \quad (1)$$

Where, V is the volume in m^3.

To prevent a domino effect after a tank fire occurs, it is required that emergency response must reduce the emitted thermal radiation of the fire tank to a certain value (or put out the fire) before *ttf*, or reduce the received thermal radiation of the neighboring tanks to a certain value (by cooling water) before *ttf*. Because each emergency response action has a certain execution time, the received thermal radiation of the adjacent tank may not be reduced to the required value in the *ttf* time and the domino effect may occur.

In this study, there are two assumptions to simplify the discussion: (i) after the cooling water is sprayed out, it can cover the tank surface to obstruct the thermal radiation, thus the received thermal radiation of the protected tank immediately becomes zero. (ii) if the firefighting action is correct and carefully prepared, the performing of this action can quickly reduce the emitted thermal radiation to zero, that is, the fire is extinguished.

So, two durations with respect to emergency response are important for preventing the domino effect: one is the firefighting time which is the time from the beginning of the emergency response to the execution of the firefighting action, and is expressed as *Time_Fighting*; the other duration is the cooling time which is the time from the beginning of the emergency response to the performing of the cooling action, and is expressed as *Time_Cooling*. If both the two times are greater than or equal to the *ttf*, the domino effect may occur.

Let *Time_Response* = max(*Time_Fighting*, *Time_Cooling*), then the probability of domino effect (P_{domino}) under the condition that a tank catches fire can be expressed as follows:

$$P_{domino} = P\{Time\_Response \geq ttf\} \quad (2)$$

Based on time analysis, the domino effect under emergency response can be analyzed. In the storage tank area plant shown in Fig. 4, when Tk1 catches fire, Tk2 and Tk3 will receive the maximum intensity

of thermal radiation. These two tanks are most likely to fail due to thermal radiation. Based on Mudan's model (Mudan, 1984), the thermal radiation intensity received by Tk2 and Tk3 is about 12.5 kW/m2, and the *ttf* calculated by Eq. (1) for T2 and T3 is about 17 minutes.

In Zhou et al. (2016), the durations of the emergency response actions are discussed. They are also introduced here for the reader to understand the remainder of the paper. Peng (2010) studied the statistic law of fire response time and its correlation with the scale of urban fire (burned area and direct losses) based on the urban fire data of Japan and China. They analyzed 44505 valid fire records from1995 to 2003 obtained from the Disaster Prevention Research Institute of Japan, and each record containing information about fire beginning time, alarm time, responders arrival time, fighting time, fire reason, weather conditions, and losses, etc. They also analyzed 14391 fire records from 2000 to 2009 of a city in China. Through statistical analysis they found that the response times and the firefighting times follow log-normal distributions.

According to the data of Peng (2010), the expected times of "discover the fire and alarm", "dispatch emergency teams", "rush to the scene of the fire", "prepare for firefighting" and "prepare for cooling" are about 4, 2.5, 5, 3.5 and 3.5 minutes, respectively. From NFPA's report (Flynn, 2009) similar data can be derived. The parameters of log-normal distributions (Equation 3) of the durations of the transitions expressing the emergency response actions are shown in Table 2.

$$f(x)=\begin{cases}\dfrac{1}{\sqrt{2\pi}\sigma x}e^{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}}, & x>0\\ 0, & x\le 0\end{cases} \tag{3}$$

Table 2 Parameters of log-normal distributions for emergency action durations

Transitions	Expected value (min)	μ	σ
t1	4	1.30	0.40
t2	2.5	0.88	0.78
t3	5	1.56	0.31
t4\t5	3.5	1.20	0.34

Different from normal Petri-net simulation analysis which usually executes until no transition can be executed, in this study the termination of an emergency response process simulation depends on whether any of the three places p11, p12 and p13 has a token. If any one of the three places has a token, the execution of the model will terminate. Among them, when a token is put into place p13, it means the domino effect may occur. At this time, the executed and the executing transitions (actions) can be considered to contribute to the occurrence of domino effect, because their execution time is too long to prevent the domino effect in time.

Using the simulation analysis method, we can analyze the probability of the occurrence of the domino effect after the fire of a storage tank, and the probability of the domino effect under each emergency response action. The steps of the analysis are shown in Fig. 6.

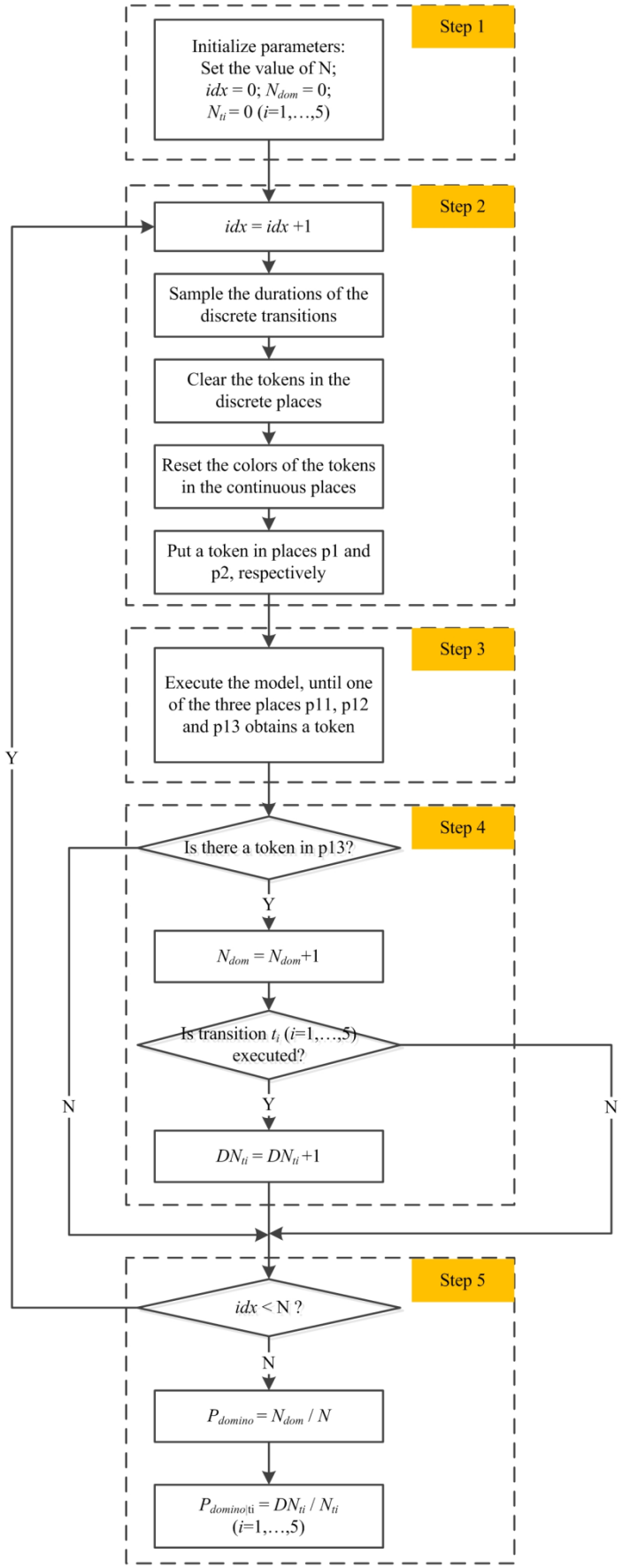

Fig. 6 Procedure to analyze the probability of domino effect

Step 1: Initialize the parameters of the analysis. Determine the simulation number N. Set the simulation index *idx* to zero. Let the number of domino effect N_{dom} be zero, and N_{ti} (the execution number of t_i, i=1,…,5) be zero. As the execution of a continuous emergency action depends on the fire state, only discrete emergency response actions are analyzed in this study.

Step 2: Let *idx* = *idx* +1. Sample the durations of the discrete transitions, clear the tokens in the discrete places, reset the colors of the tokens in the continuous places p8 and p10, and put a token in places p1 and p2, respectively.

Step 3: Execute the model, until one of the three places p11, p12 and p13 obtains a token.

Step 4: If there is no token in p13, go to Step 5, otherwise

$$N_{dom} = N_{dom}+1 \tag{4}$$

If transition t_i (i=1,…,5) is executed in this procedure,

$$DN_{ti} = DN_{ti} +1 \tag{5}$$

Step 5: If *idx* < N, go back to Step 2; otherwise calculate the probability of domino effect:

$$P_{domino} = N_{dom} / N \tag{6}$$

And calculate the probability of domino effect conditioned by the occurrence of transition t_i (i=1,…,5):

$$P_{domino|\mathrm{ti}} = DN_{ti} / N_{ti} \qquad (i=1,\ldots,5) \tag{7}$$

Based on a TCHPN tool developed in previous study (Zhou & Reniers, 2016), the model shown in Fig. 5 is established.

Let's look at the execution process of one sample simulation, to validate the operation of the model. Sample the durations of the discrete transitions according to their log-normal distributions. The durations are as follows (in minutes):

t1: 3.44 t2: 2.93 t3: 5.55 t4: 5.39 t5: 3.30

After execution of the model, simulation analysis results of the emergency response process are obtained and shown in Table 3. In the table, the *time* indicates the simulation time (min), and the *marking* represents the tokens in discrete places p1, p2, p3, p4, p5, p6, p7, p9, p11, p12 and p13. In this study, one place has at most one token to indicate whether it is in the corresponding state. The state time of p10 indicates the latest time of the corresponding thermal radiation which was received by the nearest tank Tk2. The thermal radiation may be influenced by firefighting or cooling.

Table 3 One sampling simulation analysis

Time	Marking	Thermal radiation received by Tk2	State time of p10	Executed transitions
0	(1,1,0,0,0,0,0,0,0,0,0)	12.50	0.0	
1	(1,1,0,0,0,0,0,0,0,0,0)	12.50	1.0	t1 t12
2	(1,1,0,0,0,0,0,0,0,0,0)	12.50	2.0	t1 t12
3	(1,1,0,0,0,0,0,0,0,0,0)	12.50	3.0	t1 t12
4	(0,0,1,0,0,0,0,0,0,0,0)	12.50	4.0	t1 t2 t12
5	(0,0,1,0,0,0,0,0,0,0,0)	12.50	5.0	t2 t12
6	(0,0,1,0,0,0,0,0,0,0,0)	12.50	6.0	t2 t12
7	(0,0,0,1,0,0,0,0,0,0,0)	12.50	7.0	t2 t3 t12
8	(0,0,0,1,0,0,0,0,0,0,0)	12.50	8.0	t3 t12
9	(0,0,0,1,0,0,0,0,0,0,0)	12.50	9.0	t3 t12
10	(0,0,0,1,0,0,0,0,0,0,0)	12.50	10.0	t3 t12
11	(0,0,0,1,0,0,0,0,0,0,0)	12.50	11.0	t3 t12
12	(0,0,0,0,1,1,0,0,0,0,0)	12.50	12.0	t3 t4 t5 t12
13	(0,0,0,0,1,1,0,0,0,0,0)	12.50	13.0	t4 t5 t12
14	(0,0,0,0,1,1,0,0,0,0,0)	12.50	14.0	t4 t5 t12
15	(0,0,0,0,1,1,0,0,0,0,0)	12.50	15.0	t4 t5 t12

16	(0,0,0,0,1,0,0,1,0,1,0)	0.00	15.22	t4 t5 t8 t10 t12

After Tk1 is on fire, the thermal radiation received by Tk2 is 12.5kW/m^2, until in the 16th minute (exactly at 15.22 minute), the action of cooling tanks (t8) executes and sprays water to cover the surface of tank Tk2 and makes the received thermal radiation of Tk2 become zero. At this time, transition t10 executes and puts a token into p12 to indicate the fire is controlled, and the execution of the simulation ends.

After 10^4 simulations, the domino effect probability of the failure of neighboring tank Tk2 (or Tk3) is 0.1908 when the probability of "correctly fight against the fire" in the model is assumed to be 50%, after tank Tk1 catches fire. If the probability of "correctly fight against the fire" is 100%, the domino effect probability of tank Tk2 failure is 0.1732. The domino effect failure probabilities of Tk2 conditioned by the execution of *ti* (*i*=1,…,5) are shown in Table 4.

Table 4 Domino effect probability conditioned by execution of *ti*

Transition	Domino effect probability
t1	0.1908
t2	0.1905
t3	0.1903
t4	0.1703
t5	0.1703

Transitions t1, t2 and t3 are necessary for preventing domino effects, and t4 and t5 are compared in this study. If in the emergency response process, there is only firefighting action and no cooling action, the domino effect probability of Tk2 is 0.6558; if there is only cooling action and no firefighting action, the domino effect probability is 0.2087. Compared t4 with t5, it is clear that t5 (cooling the adjacent tanks) is more important.

The results of this study are consistent with the analysis results of Zhou et al. (2016), but the probability of domino effect is different in the condition of t4 execution. Because the correct and incorrect firefighting actions are considered separately in the study of Zhou et al. (2016), and in the present study, they are all considered in t4.

It is worth noting that, the main escalation vectors that can trigger domino effects are thermal radiation, overpressure, and fragments due to explosion. But in this paper, only fire accidents are considered. For a fire accident, thermal radiation is the main escalation vector for causing domino effects (Cozzani et al, 2005; Cozzani et al., 2006). Other factors, e.g., the wind, may promote the spread of a fire, but an escalation of an event works through thermal radiation. For example, the facility in the downwind of a fire will receive greater thermal radiation than that without wind, and the facility in the upwind will receive less thermal radiation. If the assumption is changed, e.g., the wind is taken into account, the thermal radiation received by a target facility and the time to failure (ttf) of the facility may/will be changed accordingly. Although the value of ttf may/will probably change in that condition, the analysis process and the analysis approach are identical.

5. Conclusions

In the chemical industry, after a fire accident occurs, effective emergency response carried out in time can prevent domino effects and reduce losses. Emergency response is composed of a variety of emergency actions. The analysis of emergency response actions has an important role in emergency planning arrangements.

For fire accidents, the escalation vector of a domino effect is thermal radiation. The failure of other facilities close to a large-scale fire usually results from being under the influence of thermal radiation during a certain time. This period of time provides the possibility to prevent any domino effects, under

the condition that adequate emergency response actions are carried out. In this paper, based on the analysis of the execution time of each emergency response action, the probability of any domino effect in the tank area is studied.

The Petri-net approach has advantages to analyze the process of system development. Timed colored hybrid Petri-net was adopted to model and analyze emergency response relating to tank fire in this paper. Emergency response actions are represented as transitions, among which the discrete actions have stochastic execution times and the execution of continuous actions depends on the corresponding continuous states.

The emergency response actions are evaluated based on the developed TCHPN model, responding to a gasoline tank fire. Using the simulation approach, the duration of each emergency action is determined by sampling, and the execution process of the emergency response is illustrated. On this basis, the 10^4 sampling analysis is carried out to determine the probability of any domino effect in the case of a storage tank fire, as well as the probabilities of any domino effects under the condition that the emergency actions are executed. Two main emergency actions, firefighting and adjacent tanks cooling, are then compared. The results show that cooling adjacent tanks is much more important for preventing domino effects triggered by fire.

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References

Aye M. M. P., Ni L. T., (2011). A Petri Net Model for High Availability in Virtualized Local Disaster Recovery. 2011 International Conference on Information Communication and Management, Singapore.

Antonioni G, Spadoni G, Cozzani V., (2009). Application of domino effect quantitative risk assessment to an extended industrial area. Journal of Loss Prevention in the Process Industries 22(5), 614-624.

Cozzani V., Antonioni G., Landucci G., Tugnoli A., Bonvicini S., Spadoni G., (2014). Quantitative assessment of domino and NaTech scenarios in complex industrial areas. Journal of Loss Prevention in the Process Industries 28, 10-22.

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

Cozzani V., Gubinelli G., Salzano E., (2006). Escalation thresholds in the assessment of domino accidental events. Journal of Hazardous Materials A129, 1-21.

Cozzani V., Salzano E., (2004). Threshold values for domino effects caused by blast wave interaction with process equipment. Journal of Loss Prevention in the Process Industries 17(6), 437-447.

David R., Alla H., (2001). On Hybrid Petri Nets. Discrete Event Dynamic Systems 11(1), 9-40.

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

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 Safety143, 44-52.

Jensen K., (1990). Coloured petri nets: A high level language for system design and analysis. Lecture Notes in Computer Science 483, 342-416.

Kadri F., Chatelet E., Chen G., (2013). Method for quantitative assessment of the domino effect in industrial sites. Process Safety and Environmental Protection 91, 452-462.

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

Khakzad N., Khan F., Amyotte P., Cozzani V., (2014). Risk Management of Domino Effects Considering Dynamic Consequence Analysis. Risk Analysis 34(6), 1128-1138.

Khan F. I., Abbasi S.A., (2001). An assessment of the likelihood of occurrence, and the damage potential of domino effect (chain of accidents) in a typical cluster of industries. Journal of Loss Prevention in the Process Industries 14, 283-306.

Landucci G., Argenti F., Tugnoli A., Cozzani V., (2015a). 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(6), 1206-1215.

Landucci G., Reniers G., Cozzani V., Salzano E., (2015b). Vulnerability of industrial facilities to attacks with improvised explosive devices aimed at triggering domino scenarios. Reliability Engineering and System Safety 143, 53-62.

Meng D., Zeng Q., Lu F., et al., (2011). Cross-organization task coordination patterns of urban emergency response systems. Information Technology Journal 10 (2), 367-375.

Mudan K. S., (1984). Thermal radiation hazards from hydrocarbon pool fires. Progress Energy Combustion Science 10, 59-80.

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

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: Modelling, Prevention and Managing. Elsevier.

Reniers G., Dullaert W., Soudan K., (2009). Domino effects within a chemical cluster: A game-theoretical modeling approach by using Nash-equilibrium. Journal of Hazardous Materials 167, 289-293.

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

Reniers G.L.L., Dullaert W., Audenaert A., Ale B.J.M., Soudan K., (2008). Managing domino effect-related security of industrial areas. Journal of Loss Prevention in the Process Industries 21, 336-343.

Reniers G.L.L. , Sörensen K., Khan F., Amyotte P., (2014). Resilience of chemical industrial areas through attenuation-based security. Reliability Engineering and System Safety131, 94-101.

Zhong M., Shi C., Fu T., He L., Shi J., (2010). Study in performance analysis of China urban emergency response system based on petri net. Safety Science 48, 755-762.

Zhou J., (2013). Petri net modeling for the emergency response to chemical accidents. J. Loss Prev. Process Ind 26 (4), 766-770.

Zhou J., Reniers G. (2016). Petri-net based simulation analysis for emergency response to multiple simultaneous large-scale fires. Journal of loss prevention in the process industries 40, 554-562.

Zhou J., Reniers G., Khakzad N., (2016). Application of event sequence diagram to evaluate emergency response actions during fire-induced domino effects. Reliability engineering and system safety 150(6), 202-209.

Zuberek W. M., (1991). Timed Petri nets definitions, properties, and applications. Microelectronics Reliability 31(4), 627-644.