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Petri-net based simulation analysis for emergency response to multiple simultaneous large-scale fires

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Abstract: In the field of hazardous chemicals, there are many flammable materials located in different places within an industrial area. It is possible that major fires occur at the same time due to terrorism or vandalism (i.e. a security point of view). These fires might lead to domino effects at different locations around. Whether the fire emergency response preparedness, which is organized to fight against one of the fires, can handle the multiple fires, is studied in this article and a Petri-net based simulation approach is proposed. Through Petri-net based simulation, the process of fire-fighting can be revealed. A model of fighting against three fires is established, and the strategies of fire fighters staffing arrangements are analyzed. The results show that in most cases the distribution according to fire severity is better than the average distribution, but in some conditions the average distribution strategy prevails. Different backup staffing strategies are also compared, and the results indicate that the improvement by increasing staffing backups also depends on the fire conditions.

Keywords: Simultaneous fires; Simulation analysis; Emergency response strategy; Counter-terrorism emergency

1. Introduction

In the chemical industry, there are many flammable materials located in production and storage areas. It is possible that major fires occur simultaneously due to terrorism or vandalism (multiple simultaneous fires may also occur due to safety-related reasons (by coincidence), but the probability is extremely low). General preparedness of fire emergency response is mainly organized to allocate personnel and emergency resources for one of the fires. Whether the emergency preparedness is able to handle multiple fires has not been studied yet, although there were a few studies on simultaneous multiple fires (Liu, Liu, & Deng, 2007; Liu, Liu & Lozano, 2013).

In the production or storage area of a petrochemical area, the thermal radiation of a fire might damage the neighboring equipment or tanks and cause secondary accidents. This is usually called "domino effect". Simultaneous fires in different places within an isolated area might lead to domino effects at several locations around. Although there are many studies on domino effects triggered by fire, involving the topics such as escalation thresholds (Cozzani, Gubinelli, & Salzano, 2006; Landucci et al., 2009), prevention approaches (Cozzani, Tugnoli, & Salzano, 2009; Landucci et al., 2015; Reniers et al., 2005), cross-plant prevention investments (Reniers, 2010), anti-terrorist attack (Reniers & Audenaert, 2014), and so on, how to deal, from a fire-fighting arrangement perspective, with the threat of possible multiple simultaneous large-scale fires is seldom involved. Nevertheless, although from a safety point of view this may be a situation characterized with an extremely low probability (perceived as impossible), from a security point of view (terrorist attack), this could be a

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possible threat scenario. A simulation analysis method is therefore proposed in this paper to model and analyze the process of emergency response to multiple fires. Through simulation, the defects in preventing multiple domino effects in an emergency response can be revealed, and the preparedness can be improved.

There are many actions in an emergency response process, especially under multiple simultaneous fires circumstances. Petri-net is a powerful modeling and analysis tool for these actions, for example, it can define under which conditions an action is enabled and what happens when it occurs. Petri-net is a graphical modeling and analysis tool, mainly composed of places, transitions and directed arcs. Such a Petri-net approach may reveal the behavior of a system not only concerning occurrences of single transitions but also sets of occurring transitions which can be in different relationships such as causal relationship (Lorenz et al., 2009), concurrency (Auer et al., 2014), choice (Jiao et al., 2004), or total ordering. There are many extensions to Petri nets. Some of them are completely backwards-compatible with the original Petri net (e.g. colored Petri nets), some add properties that cannot be modeled in the original Petri net formalism (e.g. timed Petri nets). Various Petri nets are widely used in various fields, including process industries (Angeli et al., 2007; Grunt & Bris, 2015; Wu et al., 2010) and emergency responses (Karmakar and Dasgupta, 2011; Meng, et al., 2011; Zhong et al., 2010).

In a previous study (Zhou, 2013), a hybrid Petri-net modeling and analysis approach for emergency response was proposed, considering discrete actions and continuous actions according to the characteristics of emergency response. In this paper, the approach is improved to model and analyze the emergency response to multiple simultaneous fires. Section 2 of this paper gives the definition of the timed colored hybrid Petri-net, based on which a model and an illustrative analysis example of emergency response to multiple fires is presented in Section 3. The conclusions from this work are discussed in Section 4.

2. Timed Colored Hybrid Petri-net

The time characteristic is very important in the process of emergency response. Petri-net can deal with time in several ways, including timed transition (Aybar & İftar, 2008), timed place (Mejia & Odrey, 2005) and timed arc (Valero, Frutos-Escrig, & Cuartero, 1999). In this paper, timed transition is utilized according to the need of the analysis. Based on the definition of colored hybrid Petri-net (CHPN) in Zhou (2013), the timed colored hybrid Petri-net (TCHPN) is defined as follows by introducing the time factor:

A Timed Colored Hybrid Petri Net (TCHPN) is an eleven-tuple

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

Where, definitions of $P, T, A, \sum, V, N, C, G, E, IN$ are the same as the CHPN defined in Zhou (2013). A new tuple τ_{Td} is added.

(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. A token in a discrete place represents a type of message or a command. It is associated with a color such that different messages and commands can be identified. A token's color determines which transition is enabled by the token. A token in a continuous place represents a state, which is time-variant so that it is measured by a real number and can be a vector.

(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; the sets P and T are disjointed. A continuous transition must have at least one output continuous place which indicates the status of the transition, like the relationship between the fire-fighting action and the fire status. The continuous transition and this continuous place form a self-loop. That is, the state of the continuous place can not only

influence the occurring of the continuous transition, but also be influenced by the executing of the transition.

(3) $A \subseteq P \times T \cup T \times P$, represents the sets of arcs connecting 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 a guard function that assigns a guard which is to filter and restrict possible events to each transition t so that

$$\forall t \in T : [Type(G(t)) = Bool \wedge Type(Var(G(t))) \subseteq \sum \ ]$$

(9) E: represents the function of arch expression which assigns an arc expression to each arch so that

$$\forall a \in A : [Type(E(a)) = C(p(a))_{MS} \wedge Type(Var(E(a))) \subseteq \sum \ ]$$

Where, $p(a)$ is the place of $N(a)$ and C_{MS} denotes the set of all multi-sets over C.

(10) IN: is an initialization function. It is defined from P into expressions such that

$$\forall p \in P : [Type(IN(p)) = C(p(s))_{MS} \wedge Var(IN(p)) = \emptyset]$$

where:

Type(expr) denotes the type of an expression,

Var(expr) denotes the set of variables in an expression,

$C(p)_{MS}$ denotes a multi-set over $C(p)$.

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

R+: The set of nonnegative real numbers.

τ_{Td} indicates the executing time of a discrete transition. For a continuous transition, it can keep executing continuously after it is enabled, its executing time depends on some other conditions. Thus, the executing time of a continuous transition is not defined here. Transitions represent the actions in emergency response, the delay time of a transition indicates the executing time of the corresponding emergency response action.

A token element is a pair (p, c) where $p \in P$ and $c \in C(p)$. A binding element is a pair (t, b) where $t \in T$ and $b \in B(t)$. By $B(t)$ the set of all bindings for t is denoted. The set of all token elements is denoted by TE while the set of all binding elements is denoted by BE.

A marking M is a multi-set over TE while a step is a non-empty and finite multi-set over BE. The initial marking M_0 is the marking which is obtained by evaluating the initialization expressions.

Let $\bullet t$ $(\bullet p)$ and $t\bullet (p\bullet)$ 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), respectively.

A transition is enabled if each of its input places contains the multi-set specified by the input arc inscription (possibly in conjunction with the guard), and the guard evaluates to true.

If a discrete transition is enabled, and its delay time is satisfied, it can occur. Occurring of an enabled discrete transition t_{dj} at marking M changes the marking into M'. For the discrete places p_{id} with color u_{id} and p_{kd} with color u_{kd}, the continuous places p_{ic} with color u_{ic} and p_{kc} with color u_{kc},

$$M'(p_{id}, u_{id}) = M(p_{id}, u_{id}) - 1 \quad for\ p_{id} \in \bullet t_{dj} \wedge G_i(\bullet t_j) = True \tag{1}$$

$$M'(p_{kd}, u_{kd}) = M(p_{kd}, u_{kd}) + 1 \quad for\ p_{kd} \in t_{dj}\bullet \wedge G_k(t_j\bullet) = True \tag{2}$$

$$M'(p_{ic}, u_{ic}) = M(p_{ic}, u_{ic}) \qquad \text{for } p_{ic} \in \bullet t_{dj} \wedge G_i(\bullet t_j)=True \tag{3}$$

$$M'(p_{kc}, u_{kc}) = M(p_{kc}, u_{kc}) \qquad \text{for } p_{kc} \in t_{dj}\bullet \wedge G_k(t_j\bullet)=True \tag{4}$$

(1) indicates tokens in the input discrete place is subtracted by 1 after t_{dj} occurs; and (2) indicates tokens in the output discrete place is added by 1 after t_{dj} occurs; As a token in a discrete place represents a type of message or a command, (1) and (2) represent the transmission of the message or command, which may be transformed during t_{dj} occurring. They are shown in Fig. 1 *(a)* and *(b)*, where *(a)* indicates the state before T occurs, and *(b)* represents the state after T occurs.

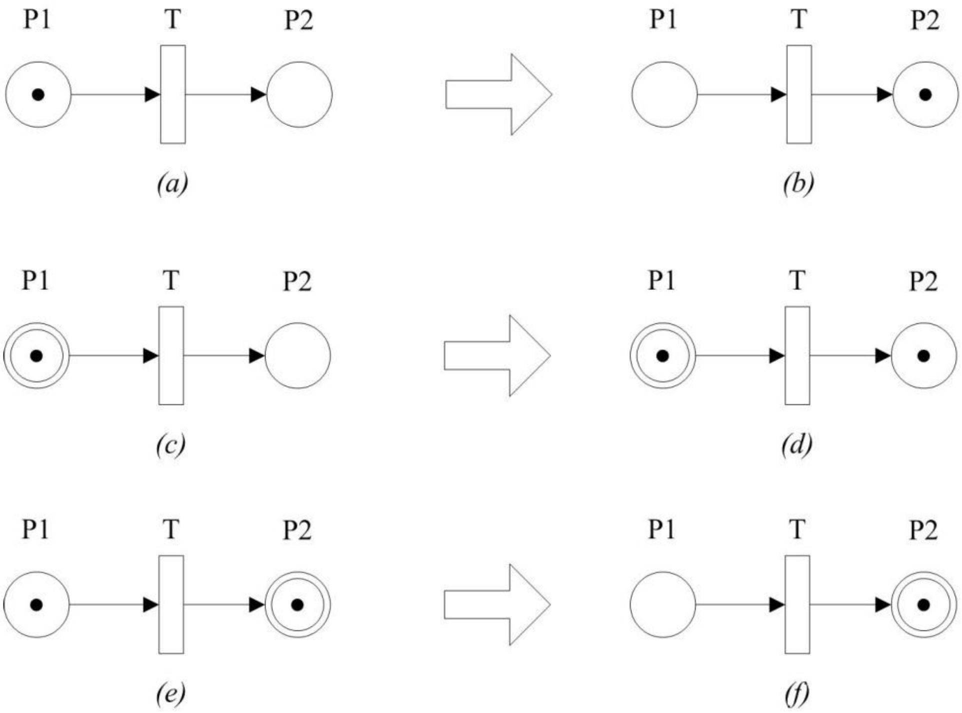

Fig. 1 Executing rules for a discrete transition

(3) and (4) indicate the tokens in the continuous input and output places are not changed after t_{dj} occurs. But the occurring of the discrete transition may access the color values of the continuous places. Equation (3) is shown in Fig. 1 *(c)* and *(d)*, and equation (4) corresponds to Fig. 1 *(e)* and *(f)*.

If a continuous transition is enabled, it can occur. Take the fire-fighting action as an example, if the conditions are satisfied (e.g. firemen arrive at the scene, resources are ready), the fire-fighting action can be performed. A continuous transition can continue its executing after it occurs. Thus, we define that the occurring of a continuous transition does not remove the tokens from its input continuous places, but can access the attribute (color) values of the places. This definition corresponds to the circumstance like that the fire-fighting action influences the fire status.

In reality, a continuous process like fighting against a fire may also be changed by a temporary event or a command. To model this, it needs to define the relationship between the continuous transition and the discrete places.

Occurring of an enabled continuous transition t_{cj} changes the marking from M into M'. For the continuous places p_{ic} with color u_{ic} and p_{kc} with color u_{kc}, and the discrete places p_{id} with color u_{id} and p_{kd} with color u_{kd},

$$M'(p_{ic}, u_{ic}) = M(p_{ic}, u_{ic}) \qquad \text{for } p_{ic} \in \bullet t_{cj} \wedge G_i(\bullet t_j)=True \tag{5}$$

$$M'(p_{kc}, u_{kc}) = M(p_{kc}, u_{kc}) \qquad \text{for } p_{kc} \in t_{cj}\bullet \wedge G_k(t_j\bullet)=True \tag{6}$$

$$M'(p_{id}, u_{id}) = M(p_{id}, u_{id}) \qquad \text{for } p_{id} \in \bullet t_{cj} \wedge G_i(\bullet t_j)=True \tag{7}$$

$$M'(p_{kd}, u_{kd}) = M(p_{kd}, u_{kd})+1 \qquad \text{for } p_{kd} \in t_{cj}\bullet \wedge G_k(t_j\bullet)=True \tag{8}$$

Equations (5) and (6) indicate the tokens in the input and output continuous places are not changed. But the value of the color u_j can be accessed. Equation (7) indicates 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. Equation (8) represents the tokens in the output discrete place is added by 1 when t_{cj} occurs under certain conditions ($G_k(t_j\bullet)=True$), 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. These executing rules of continuous transitions are shown in Fig. 2. 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)*.

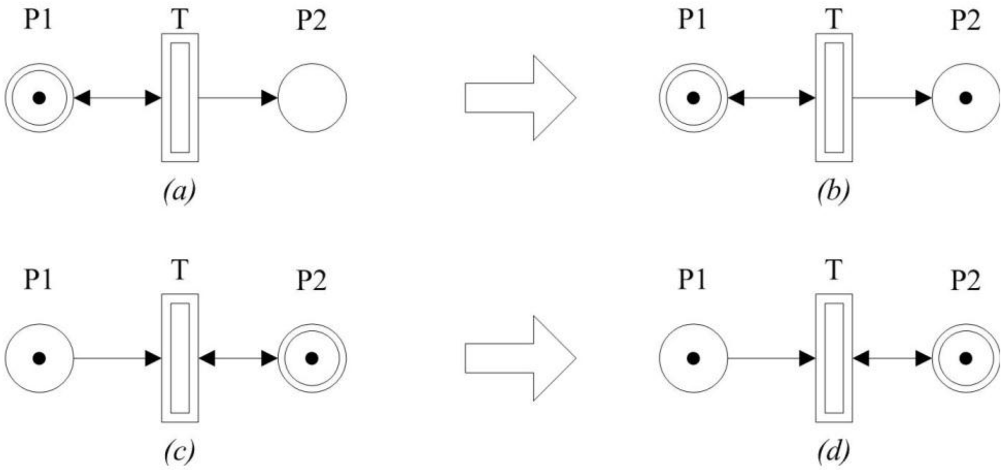

Fig. 2 Executing rules for a continuous transition

3. Modeling and analysis of emergency response to multiple fires

3.1 Model developing for the emergency response in case of multiple fires

If major fires simultaneously occur in an isolated area, can the fire fighters cope with this situation? Furthermore, which firefighting strategy is the more optimal one? These questions can be analyzed by modeling the emergency response based on colored hybrid Petri-net. To simplify the problem, assume that the fires have no mutual interaction, and their simultaneous effects are not considered.

The TCHPN based model of the emergency response to three major fires is shown in Fig. 3. The interpretation of places and transitions for Fig. 3 is given in Table 1. Meanings of the colors in the model are shown in table 2.

Table 1 Interpretation of Places and Transitions in Fig. 1

Places		Transitions	
P1	occurring of fire	T1	activate emergency response
P2	emergency response team is on duty	T2	go to the scene
P3	emergency response actived	T3	make emergency response decision
P4	arrived at the scene and ready to fight	T4	determine extinguishing strategy
P5	decision of extinguishing	T5	try to extinguish fire1
P6	policy of fire-fighting	T6	try to extinguish fire2
P7	extinguishing media	T7	try to extinguish fire3
P8i	status of fire i	T8	measure fire status
P9	measured result	T9	evacuate
P10	end of emergency response	T10	terminate emergency response

P12	decision of assisstance request	T11	request assistance
P13	assisstance request	T12	reinforce
P14	other emergency organization is ready		

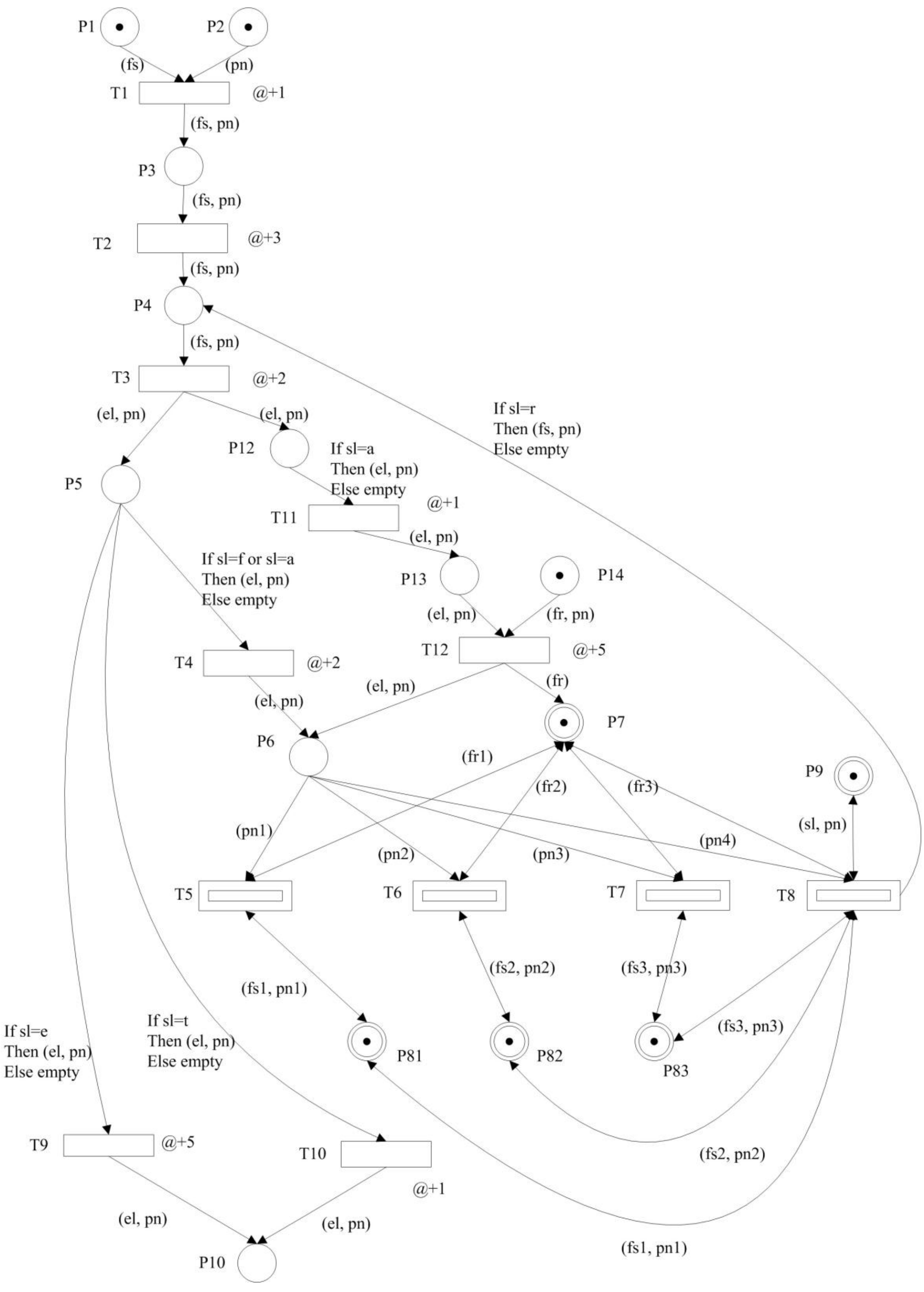

Fig. 3 TCHPN model of emergency response to three fires

SL is the result of a decision. It can be either of the following values:

(1) ‘t’, it means the fires are put out and the emergency response process would successfully

terminate.

(2) ‘e’, it means the fire(s) is(are) out of control and the fire fighters should be evacuated.

(3) ‘r’, it means the fire fighters should be rearranged. There are several conditions that may result in value ‘r’: (i) A fire is extinguished; (ii) A fire tends to escalate. This can be assessed based on measuring the heat radiation due to the fires.

(4) ‘f’, it represents that the fire fighters should fight against the fires.

(5) ‘a’, it represents that the assistance is required for extinguishing the fires. Under this circumstance, the fire fighters should also fight against the fires.

FR represents the fire-fighting resources (water, foam, etc.). A real number is used to indicate its value. In this study, the resources are supposed sufficient, but in reality the fire-fighting process may be constrained by them.

TR represents the thermal radiation. It is a time-variant so that a real number is used to indicate its value. This study is mainly based on the thermal radiations of the fires.

FL represents the fire level. The fires can be divided into different levels and the fire fighters can take corresponding actions according to the levels. In this simulation analysis, the fire level is not actually used (thermal radiation is directly used to classify the fires) and can be reserved for future study.

PN represents the number of fire fighters.

In addition, there are several other colors utilized in the model. FS is a color containing two parts, namely TR and FL; EL is also a compound color containing SL and FS. The variables in Fig.3 are the instances of the colors.

There are expressions on the arcs. They are used to filter and restrict the tokens, for example, the arc from P1 to T1 has an expression “(ps)”, which means the enabling of T1 needs a token with color FS in place P1.

Table 2 Meanings of the colors

Color	Value	Meaning
SL	t	Termination of emergency response
	e	Evacuation
	r	Rearrangement
	f	Fighting against fires
	a	Assistance is required
FR		Fire-fighting resource (water, foam, etc.)
TR		Thermal Radiation
FL		Fire Level
PN		Person Number
FS		Compound color of TR and FL
EL		Compound color of SL and FS

For a fire accident, thermal radiation is the main escalation vector (Cozzani, Gubinelli, & Salzano, 2006). The monitoring and control of thermal radiation is an important task of emergency response to multiple fires. The equipment or tanks nearby might fail under certain thermal radiation and the accident might escalate. So, the analysis of emergency response here is based on the control of thermal radiation. The emergency response decisions in the model are made according to the thermal radiation received in a certain distance to a fire (the distance to the nearest equipment or tank). Although the actually received thermal radiation from a fire might be greater than zero when the fire is extinguished, the received thermal radiation value equaling zero is taken as a sign/assumption that a fire is extinguished in this analysis. When the received thermal radiation rises close to the escalation threshold, it indicates that the fire is out of control and might result in a domino effect, and the fire fighters should evacuate under this circumstance.

Several decisions are involved in the extinguishing process, for example, under what circumstances the fire fighting can be performed? Under what conditions the fire fighters should evacuate? The rules are determined as follows:

a) The varying function of thermal radiation. During the process of fire extinguishing, the thermal radiation of a fire is varying. In this simulation, the variation is based on the number of emergency response personnel fighting against the fire. Cheng & Zou (2011) proposed a model to describe the fire spread speed under conditions of firefighters extinguishing a fire. If the lateral fire spread speed without fire fighting is γ, the average extinguishing speed of each fire fighter is λ, and the number of fire fighters is x, then, the fire will be controlled when $\lambda x>\gamma$. Based on this idea, the following relationship is determined.

$$r(t+\Delta t)=\begin{cases} r(t)\text{-}0.2\times pn\times \Delta t, & r/2\le pn \\ r(t)+0.2\times (r(t)/2-pn)\times \Delta t, & r/2>pn \end{cases} \tag{9}$$

Where, $r(t)$ indicates the radiation at time t; pn is the number of fire fighting people; Δt is the time increment (minutes).

This relationship is based on the assumption that one fireman can extinguish a fire with 2 kW/m^2 thermal radiation in 10 minutes (It is shown that the heat flux of typical firefighter exposure is about 2.5 kW/m^2 (NIST, 2013)). The extinguishing capacity of a fireman greatly depends on the fire resources and the training. Here the resources are supposed to be sufficient.

b) The decision function. The transition of "make emergency response decision" needs a function to obtain the results (*sl*). The thermal radiation value of 15kW/m^2 is taken as the upper limit, since 15kW/m^2 is the escalation threshold for atmospherical tanks (Reniers and Cozzani, 2013). When the thermal radiation received by neighboring tank exceeds 15kW/m^2, the domino effect will occur. Therefore, with reference to table 2, we may assume the following parameters:

$$sl=\begin{cases} 'e', & r\ge 13.5 \\ 'a', & 7.5<r<13.5 \\ 'f', & 0<r\le 7.5 \\ 't', & r=0 \end{cases} \tag{10}$$

Why the evacuation takes place at 13.5 kW/m2 is based on a fire classification. Fires are classified to ten levels with a level span of 1.5kW/m2.

3.2 An illustrative example

3.2.1. Initial values of the simulation

To perform the simulation analysis, some values should be determined beforehand. In the model shown in Fig. 3, there are several discrete transitions (actions) whose executing time should be determined. Flynn (2009) and Upson and Notarianni (2010) studied the emergency times in their reports. Peng (2010) studied the statistics law of urban fire response time based on 44505 valid fire records from 1995 to 2003 obtained from the Disaster Prevention Research Institute of Japan and 14391 fire records from 2000 to 2009 of a China city (remark that the name of the city was not mentioned in the study). According to these studies, appropriate assumptions of the times for the illustrative purposes are made. For example, NFPA 1710 recommends 80 seconds for turnout time for fire and special operations response, and 240-second travel time (Flynn, 2009). Thus, five minutes required for reinforcements are determined. The travel time of the first line responders is considered shorter. Times of several emergency response actions are not involved in these studies, they are determined by comparing with other times determined according to the emergency time studies.

The execution time (in minutes) of discrete transitions are as follows: T1: 1; T2: 3; T3: 2; T4: 2; T9: 5; T10: 1; T11: 1; T12: 5.

For the continuous transitions t5, t6, t7 and t8 (corresponding to fighting against the three fires and measuring the thermal radiation, respectively), the refresh interval is the time unit (one minute).

3.2.2. Analysis of the arrangement of fire fighters

Suppose there are 6 emergency responders of the first line, and 6 of emergency backup. The emergency resources are enough, so that only the arrangement of fire fighters is analyzed in this paper. In the model established above, one person is needed to monitor the fire conditions (measuring thermal radiations), other people engage in the fire extinguishing.

The emergency response process can be analyzed through the simulation. As the continuous places always have their tokens, we only need to consider the marking changes in discrete places P1, P2, P3, P4, P5, P10, P12, P13 and P14. (P1, P2, P3, P4, P5, P10, P12, P13, P14) represents the marking of the system. When fires occur, the marking of the system is (1,1,0,0,0,0,0,0,0), which means P1 and P2 have a token, respectively. At this time, T1 is enabled and can execute. During the first minute, T1 keeps executing (the duration of T1 is assumed one minute), which means the emergency team activates the emergency response, and then T1 puts a token into P3 and removes the tokens in P1 and P2. Thus, the marking of the system is changed to (0,0,1,0,0,0,0,0,0), which enables the transition T2, and T2 (indicating "go to the fire scene") can execute. In this way, the system evolves forward.

Let's use an example to illustrate the simulation analysis of the emergency response to multiple simultaneous fires. Suppose there are three fires occurring together, one is very severe, the other two are relatively minor fires. When the emergency responders start to fight against the fires, the thermal radiations of fire1, fire2 and fire3 are 11kW/m^2, 4kW/m^2, and 3kW/m^2, respectively. If the fire fighters are assigned to the fires averagely, the process of the emergency response is shown as Table 3. The factor *Pni* (*i*=1, 2, 3) in the table indicates the number of fire fighters.

The whole process of the emergency response can be revealed through simulation. It can be confirmed that which actions are in execution and what condition the system is at a certain time. For example, at the 10th minute, the three groups of fire fighters are fighting against the fires (corresponding to transitions t5, t6, and t7), the monitor is measuring the fire status (t8), and the backup responders are reinforcing (t12). From the simulation, the variation of the fire status (thermal radiation) can also be obtained.

From table 3, it can be seen that at minute 9 the fire fighters are assigned to the three fires, two for fire1, two for fire2 and one for fire3. The fire extinguishing actions (corresponding to T5, T6 and T7) start at minute 9. Then, the thermal radiations of the three fires keep varying. Owing to the inadequate firemen, the thermal radiations of fire1 and fire3 rise. The thermal radiation of fire2 declines because the number of firemen is not less than the critical value of fire fighters. At minute 13 the backups take part in the fire fighting (they are requested at minute 8, corresponding to the executing of T11). At minute 13, the thermal radiation of fire1 exceeds 13.5 kW/m^2, and an evacuation message is created (a corresponding token is put into P4 by T8).

From the result of the simulation, the emergency response process is finished after 20 minutes, and the fires are not controlled. The thermal radiation of fire1 grows close to the escalation threshold, and all fire fighters have to evacuate.

Table 3 Emergency response process with average distribution of fire fighters

Time	Marking	Fire1	Pn1	Fire2	Pn2	Fire3	Pn3	Executed transitions
1	(1,1,0,0,0,0,0,0,0)	11.00	0	4.00	0	3.00	0	t1
2	(0,0,1,0,0,0,0,0,0)	11.00	0	4.00	0	3.00	0	t1
3	(0,0,1,0,0,0,0,0,0)	11.00	0	4.00	0	3.00	0	t2
4	(0,0,1,0,0,0,0,0,0)	11.00	0	4.00	0	3.00	0	t2
5	(0,0,0,1,0,0,0,0,0)	11.00	0	4.00	0	3.00	0	t2
6	(0,0,0,1,0,0,0,0,0)	11.00	0	4.00	0	3.00	0	t3
7	(0,0,0,0,1,0,0,1,0)	11.00	0	4.00	0	3.00	0	t3
8	(0,0,0,0,1,0,0,0,1)	11.00	0	4.00	0	3.00	0	t11 t4
9	(0,0,0,0,0,1,0,0,1)	11.00	2	4.00	2	3.00	1	t12 t4 t8
10	(0,0,0,0,0,1,0,0,1)	11.70	2	3.60	2	3.10	1	t5 t6 t7 t12 t8
11	(0,0,0,0,0,1,0,0,1)	12.47	2	3.20	2	3.21	1	t5 t6 t7 t12 t8
12	(0,0,0,0,0,1,0,0,1)	13.32	2	2.80	2	3.33	1	t5 t6 t7 t12 t8
13	(0,0,0,1,0,0,0,0,0)	14.25	4	2.40	4	3.46	3	t5 t6 t7 t12 t8
14	(0,0,0,1,0,0,0,0,0)	14.25	4	2.40	4	3.46	3	t3
15	(0,0,0,0,1,0,0,1,0)	14.25	4	2.40	4	3.46	3	t3
16	(0,0,0,0,1,0,0,0,1)	14.25	4	2.40	4	3.46	3	t11 t9
17	(0,0,0,0,1,0,0,0,1)	14.25	4	2.40	4	3.46	3	t9
18	(0,0,0,0,1,0,0,0,1)	14.25	4	2.40	4	3.46	3	t9
19	(0,0,0,0,1,0,0,0,1)	14.25	4	2.40	4	3.46	3	t9
20	(0,0,0,0,0,0,1,0,1)	14.25	4	2.40	4	3.46	3	t9

As the fire fighters may be rearranged according to the fire statuses (for example, after one fire is extinguished, the corresponding fire fighters will assign to other fires), the arrangement strategies of the fire fighters can be compared based on the simulation analysis. For the fires shown in the example above, if the fire fighters are assigned to the fires according to the severity of the fires (according to the proportion of a fire's thermal radiation to the thermal radiation sum of all fires), the emergency response process is shown as Table 4.

From table 4, it can be seen that at the 9th minute three fire fighters are assigned to fire1, one fire fighter is assigned to fire2, and one fire fighter is assigned to fire3. Thermal radiations of all three fires keep rising before the backups participate in the fire fighting at minute 13. However, the thermal radiations of the fires do not exceed the evacuation critical value of 13.5 kW/m^2. After the backups join in, the fires are controlled. The process is finished at the 34th minute and the fires are extinguished.

Table 4 Emergency response process with people distribution on fire severity

Time	Marking	Fire1	Pn1	Fire2	Pn2	Fire3	Pn3	Executed transitions
1	(1,1,0,0,0,0,0,0,0)	11.00	0	4.00	0	3.00	0	t1
2	(0,0,1,0,0,0,0,0,0)	11.00	0	4.00	0	3.00	0	t1
3	(0,0,1,0,0,0,0,0,0)	11.00	0	4.00	0	3.00	0	t2
4	(0,0,1,0,0,0,0,0,0)	11.00	0	4.00	0	3.00	0	t2
5	(0,0,0,1,0,0,0,0,0)	11.00	0	4.00	0	3.00	0	t2
6	(0,0,0,1,0,0,0,0,0)	11.00	0	4.00	0	3.00	0	t3
7	(0,0,0,0,1,0,0,1,0)	11.00	0	4.00	0	3.00	0	t3
8	(0,0,0,0,1,0,0,0,1)	11.00	0	4.00	0	3.00	0	t11 t4
9	(0,0,0,0,0,1,0,0,1)	11.00	3	4.00	1	3.00	1	t12 t4 t8
10	(0,0,0,0,0,1,0,0,1)	11.50	3	4.20	1	3.10	1	t5 t6 t7 t12 t8
11	(0,0,0,0,0,1,0,0,1)	12.05	3	4.42	1	3.21	1	t5 t6 t7 t12 t8
12	(0,0,0,0,0,1,0,0,1)	12.66	3	4.66	1	3.33	1	t5 t6 t7 t12 t8

13	(0,0,0,0,0,1,0,0,0)	13.32	7	4.93	2	3.46	2	t5 t6 t7 t12 t8
14	(0,0,0,0,0,1,0,0,0)	11.92	7	5.02	2	3.06	2	t5 t6 t7 t8
15	(0,0,0,0,0,1,0,0,0)	10.52	7	5.12	2	2.66	2	t5 t6 t7 t8
16	(0,0,0,0,0,1,0,0,0)	9.12	7	5.24	2	2.26	2	t5 t6 t7 t8
17	(0,0,0,0,0,1,0,0,0)	7.72	7	5.36	2	1.86	2	t5 t6 t7 t8
18	(0,0,0,0,0,1,0,0,0)	6.32	7	5.49	2	1.46	2	t5 t6 t7 t8
19	(0,0,0,0,0,1,0,0,0)	4.92	7	5.64	2	1.06	2	t5 t6 t7 t8
20	(0,0,0,0,0,1,0,0,0)	3.52	7	5.81	2	0.66	2	t5 t6 t7 t8
21	(0,0,0,0,0,1,0,0,0)	2.12	7	5.99	2	0.26	2	t5 t6 t7 t8
22	(0,0,0,1,0,1,0,0,0)	0.72	7	6.19	2	0.00	2	t5 t6 t7 t8
23	(0,0,0,1,0,1,0,0,0)	0.00	7	6.41	2	0.00	2	t5 t6 t7 t3 t8
24	(0,0,0,1,0,1,0,0,0)	0.00	7	6.65	2	0.00	2	t5 t6 t7 t3 t8
25	(0,0,0,0,1,1,0,1,0)	0.00	7	6.91	2	0.00	2	t5 t6 t7 t3 t8
26	(0,0,0,0,1,1,0,0,1)	0.00	7	7.20	2	0.00	2	t5 t6 t7 t11 t4 t8
27	(0,0,0,0,0,1,0,0,1)	0.00	0	7.52	11	0.00	0	t5 t6 t7 t4 t8
28	(0,0,0,0,0,1,0,0,1)	0.00	0	5.32	11	0.00	0	t5 t6 t7 t8
29	(0,0,0,0,0,1,0,0,1)	0.00	0	3.12	11	0.00	0	t5 t6 t7 t8
30	(0,0,0,0,0,1,0,0,1)	0.00	0	0.92	11	0.00	0	t5 t6 t7 t8
31	(0,0,0,1,0,0,0,0,1)	0.00	0	0.00	11	0.00	0	t5 t6 t7 t8
32	(0,0,0,1,0,0,0,0,1)	0.00	0	0.00	11	0.00	0	t3
33	(0,0,0,0,1,0,0,0,1)	0.00	0	0.00	11	0.00	0	t3
34	(0,0,0,0,0,0,1,0,1)	0.00	0	0.00	11	0.00	0	t10

3.2.3. Simulation results

The simulations show that in most conditions the fire fighter distribution according to fire severity is better than the average distribution. But in some conditions the average distribution strategy is better. For example, the thermal radiations of the three fires are 8 kW/m^2, 1 kW/m^2, and 3kW/m^2, respectively, the fires will be extinguished and the process will be finished at the 24th minute by distributing the fighters according to fire severity, while the fires will be extinguished and the process will be finished at the 23rd minute by using the average distribution strategy.

Sampling the thermal radiations of fire1 every 1 kW/m^2 from 3 kW/m^2 to 13.5 kW/m^2, the thermal radiations of fire2 and fire3 every 1 kW/m^2 from 0 kW/m^2 to 13.5 kW/m^2, we can obtain 2156 different fire conditions. The results of the two different fire fighter distribution strategies are shown in Fig. 4. There are 729 conditions (area A and B) in which the fires are extinguished successfully and 1427 conditions (area C) that the fires are out of control by using the distribution of fire fighters according to fire severity. By using average distributions, there are 459 conditions (area A) in which the fires are extinguished successfully, and there are 1697 conditions (area B and C) that the fires are out of control. Among the 1697 conditions in which the fires can not be controlled by using average distributions, there are 270 conditions (area B) in which the fires can be extinguished by using the distribution of fire fighters according to fire severity.

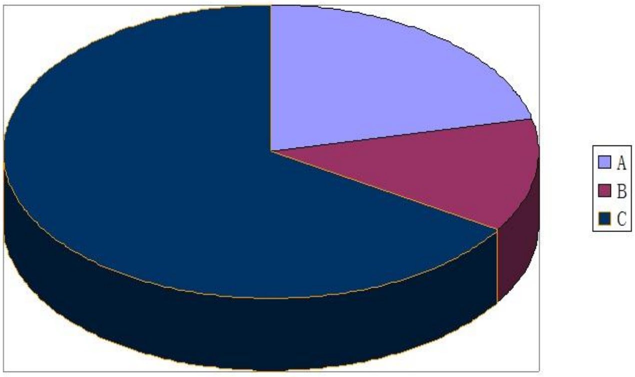

Fig. 4 Simulation results in 2156 different fire conditions by using the two different fire fighter distribution strategies

As shown in Fig. 5, among the 459 conditions in which the fires can be extinguished by both strategies, there are 323 conditions (area A) that the distribution on fire severity is better, and there are 44 conditions (area B) that the average distribution is better, the effects of the two methods are the same for the remaining cases.

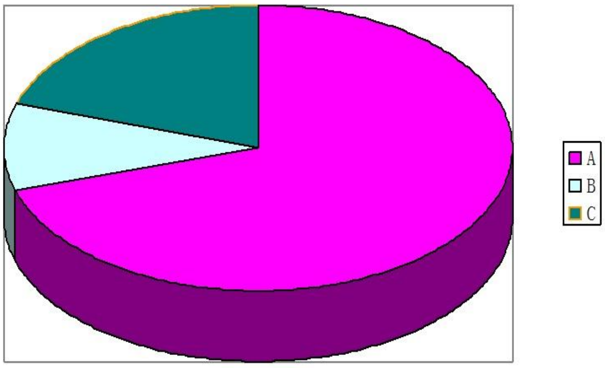

Fig. 5 Comparison when the fires can be extinguished by both strategies

Similarly, the fire fighters allocation between the first line and the backup can also be analyzed. Under the evacuation circumstance determined above, increasing of backups will improve the emergency response in some fire conditions, while in some other fire conditions the increasing of backups has no significant improvement in the emergency response. For example, the number of the first line emergency responders is 6 (5 firefighters + 1 person for carrying out the measurement), the numbers of the backups are 6 and 12 (firefighters), respectively. Suppose the fire fighters are assigned according to fire severity. Sample the thermal radiations of fire1 every 1 kW/m^2 from 3 kW/m^2 to 13.5 kW/m^2, the thermal radiations of fire2 and fire3 every 1 kW/m^2 from 0 kW/m^2 to 13.5 kW/m^2, we can also obtain 2156 different fire conditions. The simulation results are shown in Fig. 6. There are 729 conditions (area A and B) in which the fires are extinguished successfully and 1427 conditions (area C and D) that the fires are out of control with 6 backups. Among the 729 conditions, there are 681 conditions (area A) that the fighting time is shortened with 12 backups (the best situation is that the time is reduced with 17 minutes). Among the 1427 conditions, if the backups are increased to 12 fire fighters, there are 376 conditions (area B) that the fires can be extinguished, and 1051 conditions (area C) that fires are also out of control.

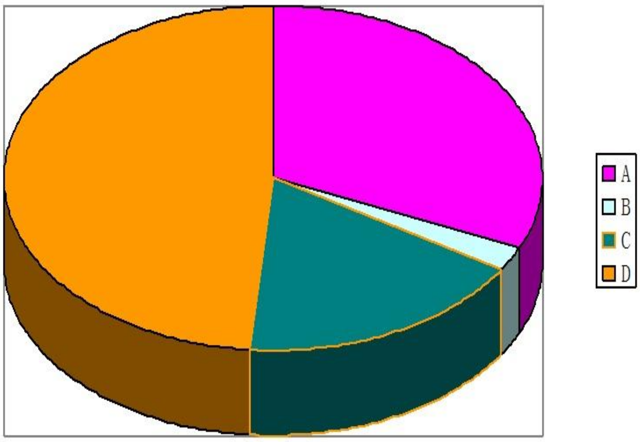

Fig. 6 Results of different backup strategies

4. Conclusions

There are large amounts of flammable materials in the production or storage areas in hazardous chemical parks. If multiple fires occur at the same time, the emergency response should be analyzed to improve the preparedness.

Petri-net can be used to analyze the process of system development. Timed colored hybrid Petri-net based modeling and analysis for the emergency response to multiple simultaneous fires is proposed in this paper. The goal is to reveal the fire fighting process and analyze the assignment of fire fighters. Taking three simultaneous fires as an example, the TCHPN based model for emergency response is presented. From the point of view of fire accident escalation (domino effect) prevention, the fighting process is influenced by the control of thermal radiation. An illustrative example with three specific thermal radiation fires is presented. It can be seen from the simulation that the executing actions (corresponding to the transitions) and the system status (e.g. system markings and fire thermal radiations) at any time during the emergency response can be revealed. This is valuable to determine the defects of the emergency response process.

Based on the TCHPN model of emergency response, the fire fighter distribution strategies during the emergency response to multiple fires are analyzed in this paper. The distribution according to fire severity and the average distribution are compared, and the results show that under certain different conditions, each strategy has its own advantage. Two backup strategies of fire fighters are compared, too. The analysis results show that the effect of increasing the backups is not necessarily enhanced, it depends on the specific fire conditions. Through the analysis we can obtain which strategy is better under certain conditions. This can help improve the preparedness under different conditions.

The TCHPN approach can model discrete events and continuous events, which are common in the process industry. It can also analyze time constrained problems. Application of TCHPNs to emergency response to multiple simultaneous fires is original and may result in many other studies in process industries, in particular with regard to planning and scheduling issues.

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