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Simulation analysis of the use of emergency resources during the emergency response to a major fire

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Abstract: During an emergency response to an accident or disaster, emergency response actions often need to use various emergency resources. The use of resources plays an important role in the successful implementation of emergency response, but there may be conflicts in the use of resources for emergency actions. According to the emergency response in case of an oil fire, two types of emergency response models with dynamic structure are established by using Resource-Oriented Timed Colored Hybrid Petri-Net (RO-TCHPN). Type 1 model does not establish a special conflict avoidance mechanism for emergency actions, while Type 2 model uses a queuing method to avoid possible conflicts in the use of limited resources by multiple actions. In this paper, the two types of models are simulated and analyzed, including (1) emergency response process simulation, which analyzes and determines the time and the conditions of the potential conflicts occurring; and (2) comparison analysis, analyzing the improvement of the Type 2 model as compared with the Type 1 model. Increasing emergency resources to reduce or avoid conflicts and whether all the fire-trucks should be fully filled at the beginning of an emergency response, are also discussed based on the simulation.

Key words: emergency response actions; emergency resources; Petri nets; simulation analysis

1. Introduction

Various resources are often used in the process of emergency response. Especially with respect to accidents in the process industries, there are special requirements for emergency resources during the emergency response process. For example the treatment of a chemical fire requires the use of appropriate fire extinguishing agents. The use of emergency resources may have great impacts on the emergency response.

In literature, there are many studies about the problem of emergency resources in the emergency response to various accidents or disasters. One is the emergency resources allocation, which focuses on determining the optimal facility/resource location in decision support systems. Most of these methodologies in literature aim at detecting the minimum response time to the disasters so that they can be put into the emergency response at minimum cost (Hawe et al., 2015; Wang et al., 2014; Zhang et al., 2012). Another area of research on emergency resources is the scheduling of resources, which mainly deals with the problems or the optimization of resource dispatching in the process of emergency response (Zhang et al., 2011; Li & Li, 2012; Ren et al., 2012). In addition, in view of the shortage of emergency

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resources possibly restricting the emergency response, some researchers have also studied the demand forecasting of emergency resources, to determine the minimum requirement of resources for effective emergency response (Liu et al., 2012; Wang et al., 2009). Although all these studies are important for improving the efficiency of emergency response, they do not deal with the obvious relationships between emergency resources and emergency response actions. All emergency resources are used by various emergency response actions. Different actions in the use of emergency resources may form different relationships, such as the sequential use of resources, the parallel use of resources, the cyclic use of resources, and so on. The use of emergency resources may also result in conflict between the emergency response actions when carried out, which will affect the smooth progress of the emergency response. Aiming at the use of emergency resources in the emergency response to a major fire accident in the process industry, this paper performs a simulation analyses based on Petri-net models.

Petri-net is a powerful tool for modeling the relationships among emergency response actions. Petri-net was proposed by Dr. Petri in 1962 when he developed the information flow model of the computer operating system (David and Alla, 1994). It is a graphical modeling and analysis tool, including elements like places, transitions, arcs and tokens. Firstly, Petri nets are widely used in modeling and analysis of discrete event systems. In order to model and analyze more complex systems, a number of extensions are formed on the basis of ordinary Petri-net. For example, in order to model and analyze the continuous event system, hybrid Petri-net is proposed by introducing continuous places and continuous transitions to the common Petri-net. In order to analyze the duration of the events, timed Petri-nets are proposed by assigning times to the places or transitions. In order to simplify the common Petri-net model, colored Petri-nets are proposed.

Petri-net is very suitable for modeling the relationship between the various parts of the system, such as sequential, parallel, conflict, etc. Besides, a Petri-net model can be executed. The execution of a transition consumes token(s) from incoming place(s) and produce token(s) to outgoing places. This mechanism can help revealing the evolution process of a system and determining under which conditions a transition is enabled and what will happen after it occurs. Thus, using Petri-nets to model and analyze the process of emergency response can help us to find the problems that may exist in this process. In literature, Petri-net has been applied to the modeling and analysis of emergency response (Aye and Ni, 2011; Karmakar and Dasgupta, 2011; Meng et al.,2011; Zhong et al., 2010; Zhou, 2013; Zhou and Reniers, 2016a).

A few studies also utilize Petri-nets to analyze the emergency actions using emergency resources. Liu et al. (2015) present a formal method to model and analyze emergency response processes by taking uncertain activity execution duration, resource quantity, and resource preparation duration into account, based on an E-Net that is a Petri-net based formal model for an emergency response process constrained by resources and uncertain durations. Li et al. (2016) propose a Petri-net based approach to model and analyze the time and resource issues of subway fire emergency response processes, involving resource conflict detection methods along with corresponding algorithms, and a priority criterion constituting of key-task priority strategy and waiting-short priority strategy, and optimizing the whole process execution time. Both these two studies analyze emergency action conflicts according to time analysis based on the actions' execution duration (each action execution duration is classified into the minimum duration and the maximum duration), and the conflicts can only be caused by reusable resources.

During the sequential use of reusable resources, one action can delay or block the execution of succeeding actions, but this is not considered as a conflict of emergency actions in this study. This paper focuses on the emergency action conflicts due to simultaneously using the same resource. Some simulation analyses for the emergency response actions constrained by emergency resources based on two types of Petri-net models are performed: one model does not consider conflict avoidance measures, while the other model does so. In Section 2, the two types of Petri-net models are described. The simulation analysis and discussions are performed in Section 3. At last, some conclusions of this study are drawn in Section 4.

2. Petri-net based model

2.1 RO-TCHPN

In Zhou (2013), the emergency response actions are divided into discrete processes and continuous processes according to their durations. During an emergency response, in addition to discrete events which can be completed soon, there are some actions which have 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. So, the emergency response is a hybrid system. Colored Petri Net (CPN) which uses colors to distinguish tokens is an extension of ordinary Petri net. Based on colored Petri net, the hybrid Petri net model will be more compact and concise. As this study is based on the time to analyze the performance of the emergency response process, the Timed Colored Hybrid Petri-Net (TCHPN) is adopted to model the process.

The following definitions need to be given and explained before it is possible to draft the network.

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

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

(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.

A TCHPN satisfying the following conditions is called a resource-oriented TCHPN (RO-TCHPN):

(1) The discrete places P_D can be split into two subsets P_{DS} and P_{DR}, the discrete state and

the discrete resource places.

(2) The continuous places P_C can be split into two subsets P_{CS} and P_{CR}, the continuous state and the continuous resource places respectively.

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

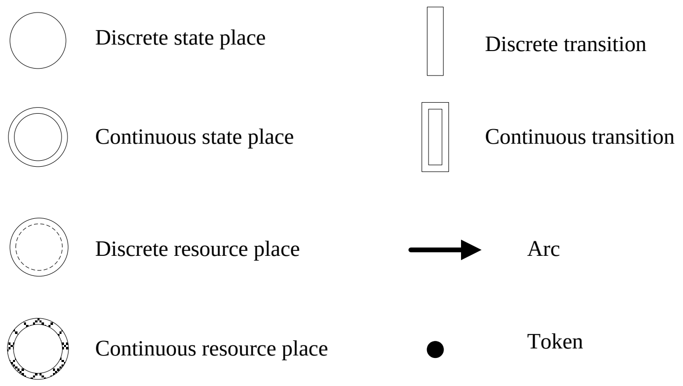

Fig. 1 Icons for the elements in the RO-TCHPN model

The tokens are usually denoted by dots, and they can also be expressed by a number. The executing rule of a transition in RO-TCHPN is the same as that of a TCHPN. The rules are shown in Fig. 2 and Fig. 3, for discrete transitions and continuous transitions, respectively.

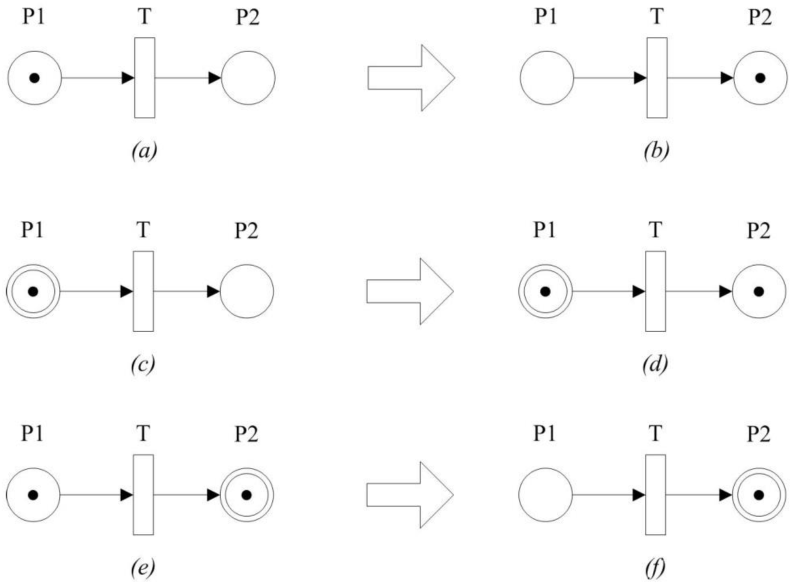

Fig. 2 Executing rules for a discrete transition

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. The interaction between a discrete resource place or a continuous resource place and the discrete transition is similar to that between state places and the discrete transition.

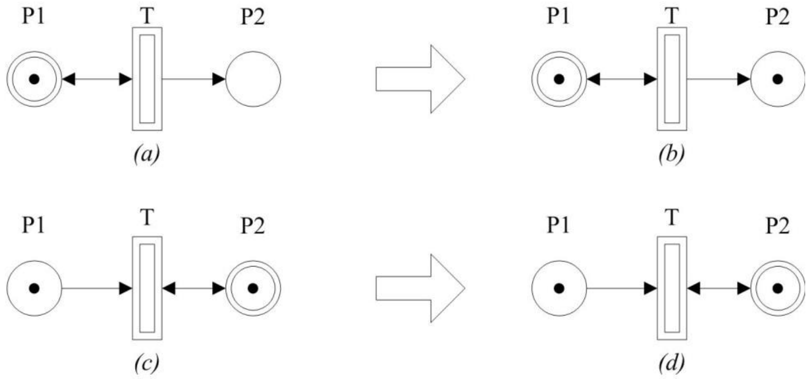

Fig. 3 Executing rules for a continuous transition

In Fig. 3, (a) and (b) indicate the tokens in the input continuous places are not changed. (c) and (d) indicate the tokens in the output continuous 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 output discrete 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)*. The interaction between a discrete resource place or a continuous resource place and the continuous transition is similar to that between state places and the continuous transition.

2.2 Dynamic structure models for an illustrative example

During an emergency response after an accident, emergency actions often require certain emergency resources. The adequate use, or the lack thereof, of emergency resources will affect the efficiency and even the success of emergency response activities or processes. In a previous study (Zhou and Reniers, 2016b), the cooperation modes of emergency actions on using resources are analyzed, and Petri-net models for these cooperation modes are provided. On this basis, an approach to detect emergency action conflicts resulting from resource-use is proposed. For conflicts caused by limited resources sharing, the queuing system which is modeled by a Petri-net and integrated into the model of emergency actions, is adopted to avoid conflicts. Based on this previous study, this paper focuses on the simulation analysis of the emergency response process constrained by emergency resources.

Take the emergency response to an oil fire as an example. In a previous study (Zhou & Reniers, 2016a), the emergency response process of multiple simultaneous fires was analyzed. For simplicity, only one fire is considered in this paper and the focus is on the impacts that the using of emergency resources has on the emergency response actions. After the oil leaks and catches fire, the emergency response organization (fire brigade) receives the fire alert and is dispatched to put out the fire with necessary fire-fighting resources, including fire trucks, PPE (Personal Protective Equipment), fire extinguishing agents, and so on. Fire trucks and corresponding fire extinguishing agents (water or foam) have great impacts on the success of the emergency response, therefore, this paper focuses on the use of fire trucks and fire extinguishing agents.

The resource-oriented Petri-net model is shown in Fig. 4. The model does not specifically consider the queuing system integrated conflict avoidance in the use of emergency resources and is called Type 1 model for the purpose of comparison in this paper. The transitions and places and their meanings are shown in Table 1. There are N fire trucks being dispatched out to extinguish the fire. Arrays are adopted to represent the fire-trucks and relating places and transitions (relating to fire-fighting and refilling). Thus, the model has certain dynamic characteristics, that is, changing the number of fire-trucks of the model can change the model structure. This dynamic structure can easily analyze the impacts related to the different quantities of emergency resources (fire-trucks and refilling equipment). Initially, the fire trucks are considered filled with water and foam concentrate. To extinguish an oil fire, the foam solution which is made up of foam concentrate and water in a certain proportion is necessary. During the fire-fighting, the water or foam concentrate of each fire truck may be exhausted and the fire truck needs to be refilled. In most conditions, water in the fire truck is the bottleneck. The N refilling actions (RT[*i*]) of N fire trucks share the same fire hydrants (Pr8) which are also emergency resources. The number of fire hydrants is represented by the tokens in place Pr8. If the fire hydrants are insufficient, the simultaneous water refilling actions of multiple fire trucks may cause the conflict. The Type 1 model does not provide a mechanism to avoid this conflict. Thus, another model which integrates the queuing system into the emergency response process to avoid conflict of resource using is provided and named Type 2 model in this paper. As the conflicts of emergency actions on using resources are mainly caused by resource-sharing, that is, more than one emergency response action uses limited resources simultaneously, the queuing method manages the use of resources according to the principle of "first-come first-served". The Type 2 model is shown in Fig. 5, and the additional transitions and places are shown in Table 3. In this model, the number of the refilling equipment (fire hydrants) is represented by the tokens in place qp3.

Table 1 Transitions and places of the Petri-net model shown in Fig. 4

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	RT[*i*] *	refill fire truck *i*
P10	fire state	FT[*i*] *	try to extinguish fire with fire truck *i*
P11	end of emergency response	T9	measure fire states
P12	under fire fighting	T10	evacuate
FP[*i*] *	fire truck *i* is ready for firefighting	T11	terminate emergency response
RP[*i*] *	water of fire truck *i* is exhausted		
FPr[*i*] *	fire truck *i* filled with water		
RPr[*i*] *	fire truck *i* without water		
Pr1	fire trucks		
Pr6	thermal radiation detection equipment		

Pr7	firefighting water or foam
Pr8	fire hydrants

*i = 0, 1, …, N-1

Table 2 Meanings of the colors (Zhou & Reniers, 2016)

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
FS		Compound color of TR and FL
EL		Compound color of SL and FS
TK*	Tk*i*	Fire truck *i*, *i* = 0, 1, …, N-1
FF*		Firefighting foam solution
TF*		A fire truck of foam solution
TD*		Thermal radiation detection equipment

* This color is introduced in the present study.

In Fig. 4 and Fig. 5, the color SL is used to determine the corresponding emergency response actions. There are three transitions (T4, T10, and T11) indicating fire-fighting, evacuating, and successfully putting out the fire connected from place P5, the execution of the transitions are determined by the token color SL of P5. This means different fire conditions can lead to different emergency actions. The color TR represents the thermal radiation (fire state) received by the nearest tank. The value of color TR of the token in place P10 is constantly changing due to the execution of transitions FT[i], and it will influence the value of color SL (through the transition T9). The color FF is the firefighting foam solution which is consumed constantly by the firefighting actions (transitions FT[i]) and is supplemented through the refilling actions (RT[i] in Fig. 4 and qt2 in Fig. 5).

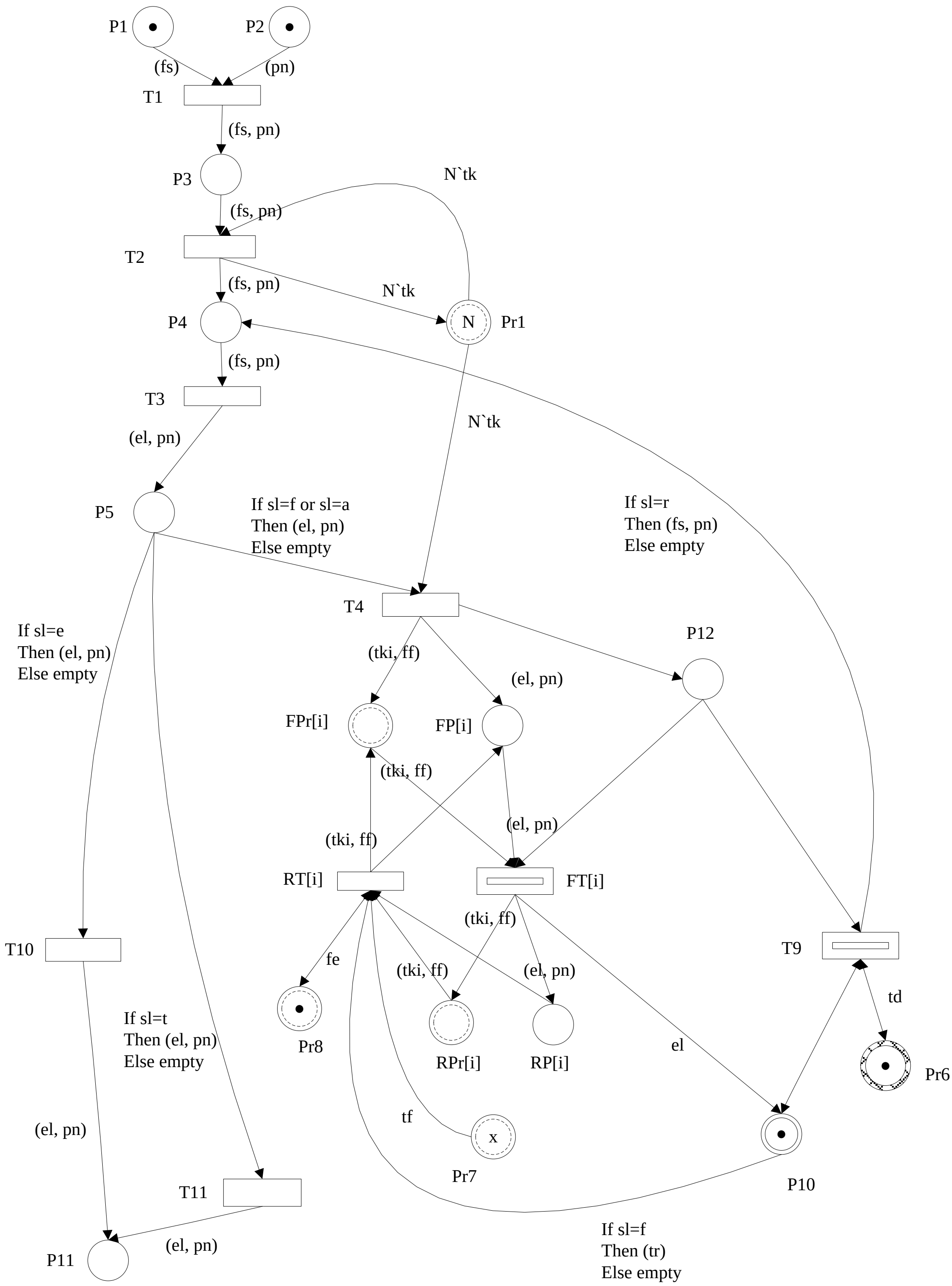

Fig. 4 Type 1 model (without queuing refilling system)

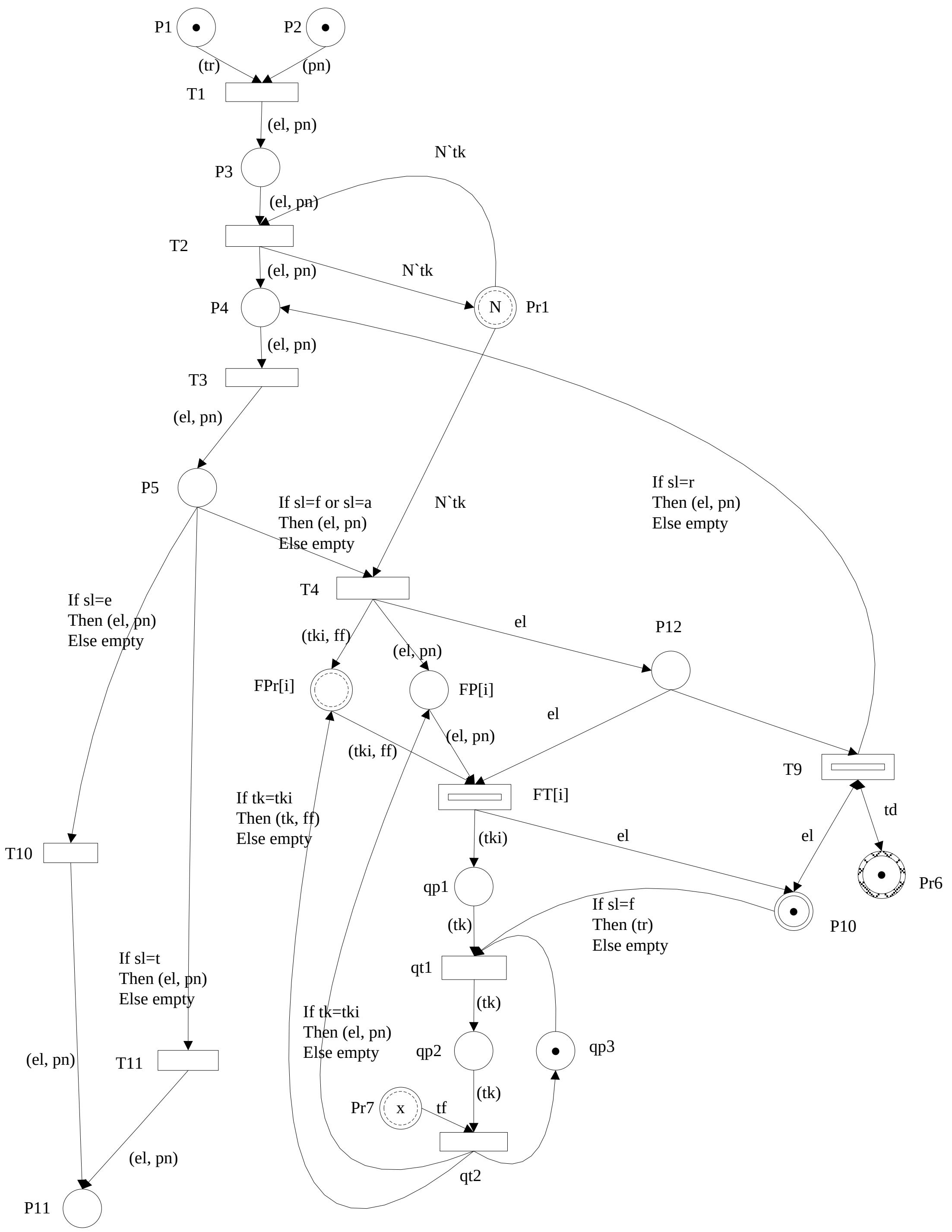

Fig. 5 Type 2 model (with queuing refilling system)

Table 3 Additional transitions and places of the Petri-net model shown in Fig. 5

Transitions		Places	
qt1	Obtain the right to use resource	qp1	Queue buffer
qt2	Use the resource	qp2	The resource is being used
		qp3	The resource is idle

3. Simulation and discussion

The simulation analysis in this paper is divided into two parts. The first is to reveal the evolution process of the emergency response process through the simulation. If there exist conflicts among the emergency response actions, we can find out when and under which conditions a conflict will occur. The second is to compare the two models in the effect of resource use on emergency response based on simulations.

Before performing the simulation analysis, some parameters and data should be determined.

3.1 Determination of the simulation parameters

The first parameter required by the simulation analysis is the fire states for fire-fighting and evacuation. For a fire accident, thermal radiation is the main escalation vector (Cozzani et al., 2006), and 15 kW/m^2 is the escalation threshold for atmospherical tanks (Reniers and Cozzani, 2013). When the thermal radiation received by neighboring tank exceeds 15 kW/ m^2, domino effect may occur. Therefore, with reference to Table 2, we may assume the following parameters (Zhou and Reniers, 2016a):

$$sl = \begin{cases} 'e', & r \geq 13.5 \\ 'a', & 7.5 < r < 13.5 \\ 'f', & 0 < r \leq 7.5 \\ 't', & r = 0 \end{cases} \tag{1}$$

Fires are simply classified to ten levels with a level span of 1.5kW/m^2 from 0 kW/m^2 to 15 kW/m^2. The values of SL are determined according to these fire levels. In this study assistance / reinforcement is not considered, thus the SL value ‘*a*’ also represents fire-fighting.

The second parameter is the consumption velocity of fire extinguishing agents. Suppose all fire trucks in this study can store 3 tons of water and 1 ton of foam concentrate. The mixing ratio for the foam solution is 3%, that is, 3 liters of foam concentrate need 97 liters of water. The water consumption velocity of a fire truck is about 500L/min when the fire truck is fighting for a fire. The expansion of the foam solution is 6. Thus, we can obtain that 3 tons of water can last for about 6 minutes and 1 ton of foam concentrate can last for 67 minutes. The use of water for a fire-truck is more critical for fire extinguishing. In this study, we focus on the use of fire water and the foam concentrate can be considered sufficient. If all fire-trucks are initially filled with water, and the water consumption velocities of the fire-trucks are the same, obviously they need to be refilled at the same time and may result in conflicts when fire hydrants are insufficient. But in reality, there are differences among the fire-trucks in the use of fire water. To model this, a normal distribution function is adopted, namely, the water consumption velocity $V \sim N(500, 20^2)$.

The third parameter is the change rate of thermal radiation under fire-fighting. One fire truck will generate about 3092L foam solution (500/0.97 * 6 = 3092). Assume the average height of the foam solution for oil fire-fighting is 0.1m, thus, 3092L foam solution can cover 30.9 m^2. This corresponds to 0.1 to 0.2 kW/m^2 changes of thermal radiation 30 to 45 meters away from the fire center (this estimation is based on a pool fire model and takes the diesel as an example). So, assume one fire truck can barely control a 2 kW/m^2 fire in ten minutes, if the fire trucks are increased, thermal radiation will be reduced proportionally, and vice versa. Therefore, the following relationship is determined.

$$r(t+\Delta t)=\begin{cases} r(t)\text{-}0.2\times(tn-r(t)/2)\times\Delta t, & r/2<tn \\ r(t)+0.2\times(r(t)/2-tn)\times\Delta t, & r/2>tn \\ r(t)-0.1\times\Delta t, & r/2=tn \end{cases} \quad (2)$$

Where, *r(t)* indicates the radiation at time *t*; *tn* is the number of fire fighting trucks; Δt is the time increment (minutes).

The durations (in minutes) of the discrete transitions are as follows: T1: 1; T2: 3; T3: 2; T4: 2; RT*i* (refilling transitions): 1; T10:4; T11: 1.

3.2 Simulation analysis of emergency response process

Suppose there is only one fire hydrant that can be used for water refilling and it can only serve one fire-truck at the same time. Consider five fire-trucks are dispatched to fight against a 6 kW/m^2 thermal radiation fire. The emergency response process based on the Type 1 model is shown in Table 4. In the table, time represents the system evolution time (in minutes). Marking indicates the tokens in places P1, P2, P3, P4, P5, P11, P12, Pr1, respectively.

Based on the normal distribution function discussed above, the water consumption velocities of the five fire-trucks are 517, 507, 500, 477 and 466 L/min, respectively. At the 10th minute, the five fire-trucks begin their fire-fighting. At the end of the 15th minute, three fire-trucks exhaust their water and need to be refilled, among which one fire-truck with the highest water consumption velocity obtains the fire hydrant and can be refilled, the other two fire-trucks have to wait. As there is only one fire hydrant, after the refilling fire-truck is refilled and the fire hydrant is released, the two waiting fire-trucks will compete to use the fire hydrant. Thus the conflict occurs and both the two fire-trucks cannot use the fire hydrant. After other fire-trucks exhaust their water, they also want to be refilled and this strengthens the conflict (after the 15th minute). At last, the fire-fighting fails, and all fire-trucks have to evacuate (T10).

Table 4 Fire-fighting process without the queuing refilling subsystem

Time	Marking	Fighting	Waiting	Refilling	Thermal radiation	Executed transitions
0	(1,1,0,0,0,0,0,5)	0	0	0	6	
1	(0,0,1,0,0,0,0,5)	0	0	0	6	T1
2	(0,0,1,0,0,0,0,5)	0	0	0	6	T2
3	(0,0,1,0,0,0,0,5)	0	0	0	6	T2
4	(0,0,1,0,0,0,0,5)	0	0	0	6	T2
5	(0,0,0,1,0,0,0,5)	0	0	0	6	T2
6	(0,0,0,1,0,0,0,5)	0	0	0	6	T3
7	(0,0,0,0,1,0,0,5)	0	0	0	6	T3
8	(0,0,0,0,1,0,0,5)	0	0	0	6	T4
9	(0,0,0,0,0,0,1,0)	0	0	0	6	T4
10	(0,0,0,0,0,0,1,0)	5	0	0	5.6	FT[0] FT[1] FT[2] FT[3] FT[4] T9
11	(0,0,0,0,0,0,1,0)	5	0	0	5.16	FT[0] FT[1] FT[2] FT[3] FT[4] T9
12	(0,0,0,0,0,0,1,0)	5	0	0	4.68	FT[0] FT[1] FT[2] FT[3] FT[4] T9
13	(0,0,0,0,0,0,1,0)	5	0	0	4.14	FT[0] FT[1] FT[2] FT[3] FT[4] T9

14	(0,0,0,0,0,0,1,0)	5	0	0	3.56	FT[0] FT[1] FT[2] FT[3] FT[4] T9
15	(0,0,0,0,0,0,1,0)	2	2	1	3.51	FT[0] FT[1] FT[2] FT[3] FT[4] T9
16	(0,0,0,0,0,0,1,0)	0	4	0	3.87	RT[0] FT[3] FT[4] T9
17	(0,0,0,0,0,0,1,0)	1	4	0	4.05	FT[0] T9
18	(0,0,0,0,0,0,1,0)	1	4	0	4.26	FT[0] T9
19	(0,0,0,0,0,0,1,0)	1	4	0	4.48	FT[0] T9
20	(0,0,0,0,0,0,1,0)	1	4	0	4.73	FT[0] T9
21	(0,0,0,0,0,0,1,0)	1	4	0	5	FT[0] T9
22	(0,0,0,0,0,0,1,0)	0	5	0	5.5	FT[0] T9
23	(0,0,0,0,0,0,1,0)	0	5	0	6.05	T9
		……				
32	(0,0,0,1,0,0,0,0)	0	5	0	14.28	T9
33	(0,0,0,1,0,0,0,0)	0	5	0	14.28	T3
34	(0,0,0,0,1,0,0,0)	0	5	0	14.28	T3
35	(0,0,0,0,1,0,0,0)	0	5	0	14.28	T10
36	(0,0,0,0,1,0,0,0)	0	5	0	14.28	T10
37	(0,0,0,0,1,0,0,0)	0	5	0	14.28	T10
38	(0,0,0,0,0,1,0,0)	0	5	0	14.28	T10

Correspondingly, the emergency response process of the Type 2 model can also be simulated. Let the marking represent the tokens in places P1, P2, P3, P4, P5, P11, P12, Pr1, QP1, QP2 and QP3, respectively. There is one token initially set in the place QP3 which means one fire hydrant can be used at the same time. The emergency response process is shown as Table 5. The water consumption velocities of the five fire-trucks are determined according to the normal distribution function as 526, 512, 504, 472 and 467 L/min, respectively. At the end of the 15th minute, there are only two fire-trucks fighting against the fire, the other three fire-trucks have exhausted their water. There are two fire-trucks waiting in the queue (there are two tokens in the place QP1) and one fire-truck is enabled to refill (there is one token in the place QP2). The transition QT1 is considered to be able to occur immediately if it is enabled. After this time, other fire-trucks which have exhausted their water also go into the queue and the fire-trucks in the queue are refilled one by one. Finally the fire is successfully extinguished and the emergency response process is terminated after 30 minutes.

Table 5 Fire fighting with the queuing refilling subsystem

Time	Marking	Fighting fire-trucks	Thermal radiation	Executed transitions
0	(1,1,0,0,0,0,0,5,0,0,1)	0	6	
1	(0,0,1,0,0,0,0,5,0,0,1)	0	6	T1
2	(0,0,1,0,0,0,0,5,0,0,1)	0	6	T2
3	(0,0,1,0,0,0,0,5,0,0,1)	0	6	T2
4	(0,0,1,0,0,0,0,5,0,0,1)	0	6	T2
5	(0,0,0,1,0,0,0,5,0,0,1)	0	6	T2
6	(0,0,0,1,0,0,0,5,0,0,1)	0	6	T3

7	(0,0,0,0,1,0,0,5,0,0,1)	0	6	T3
8	(0,0,0,0,1,0,0,5,0,0,1)	0	6	T4
9	(0,0,0,0,0,0,1,0,0,0,1)	0	6	T4
10	(0,0,0,0,0,0,1,0,0,0,1)	5	5.6	FT[0] FT[1] FT[2] FT[3] FT[4] T9
11	(0,0,0,0,0,0,1,0,0,0,1)	5	5.16	FT[0] FT[1] FT[2] FT[3] FT[4] T9
12	(0,0,0,0,0,0,1,0,0,0,1)	5	4.68	FT[0] FT[1] FT[2] FT[3] FT[4] T9
13	(0,0,0,0,0,0,1,0,0,0,1)	5	4.14	FT[0] FT[1] FT[2] FT[3] FT[4] T9
14	(0,0,0,0,0,0,1,0,0,0,1)	5	3.56	FT[0] FT[1] FT[2] FT[3] FT[4] T9
15	(0,0,0,0,0,0,1,0,2,1,0)	2	3.51	FT[0] FT[1] FT[2] FT[3] FT[4] QT1 T9
16	(0,0,0,0,0,0,1,0,4,0,1)	0	3.87	FT[3] FT[4] QT2 T9
17	(0,0,0,0,0,0,1,0,3,0,1)	1	4.05	FT[0] QT1 QT2 T9
18	(0,0,0,0,0,0,1,0,2,0,1)	2	4.06	FT[0] FT[1] QT1 QT2 T9
19	(0,0,0,0,0,0,1,0,1,0,1)	3	3.86	FT[0] FT[1] FT[2] QT1 QT2 T9
20	(0,0,0,0,0,0,1,0,0,0,1)	4	3.45	FT[0] FT[1] FT[2] FT[3] QT1 QT2 T9
21	(0,0,0,0,0,0,1,0,0,0,1)	5	2.79	FT[0] FT[1] FT[2] FT[3] FT[4] T9
22	(0,0,0,0,0,0,1,0,0,1,0)	4	2.27	FT[0] FT[1] FT[2] FT[3] FT[4] QT1 T9
23	(0,0,0,0,0,0,1,0,1,0,1)	3	1.9	FT[1] FT[2] FT[3] FT[4] QT2 T9
24	(0,0,0,0,0,0,1,0,1,0,1)	3	1.49	FT[0] FT[2] FT[3] FT[4] QT1 QT2 T9
25	(0,0,0,0,0,0,1,0,0,0,1)	4	0.84	FT[0] FT[1] FT[3] FT[4] QT1 QT2 T9
26	(0,0,0,0,0,0,1,0,0,1,0)	4	0.12	FT[0] FT[1] FT[2] FT[3] FT[4] QT1 T9
27	(0,0,0,1,0,0,0,0,1,0,1)	3	0	FT[0] FT[1] FT[2] FT[4] QT2 T9
28	(0,0,0,1,0,0,0,0,1,0,1)	3	0	T3
29	(0,0,0,0,1,0,0,0,1,0,1)	3	0	T3
30	(0,0,0,0,0,1,0,0,1,0,1)	3	0	T11

3.3 Comparison analysis

To analyze whether the improved model integrating the queuing subsystem into the Petri-net based emergency response model has some effects on the emergency response, a comparison analysis is performed.

The durations of transitions including T1, T2, T3, T4, T10 and T11 have no impacts on the use of fire-fighting resources. Their durations are considered to be fixed. The differences of refilling times for RT[*i*] or QT2 can be considered very small under the operation of trained fire fighters. The water consumption velocities of the fire-trucks have large differences due to different fire-fighting tasks, and they are considered to obey a normal distribution in the previous analysis. Thus, a simple Monte Carlo Simulation (MCS) method was used to analyze the success rate under different circumstances of emergency resource use.

To compare success rates of the two types of models under different conditions, the fire-trucks vary from 1 to 12, the refilling equipment (fire hydrants in this study) vary from 1 to the number of fire-trucks, and the thermal radiation (fire status) varies from 1 to 15 kW/m^2. The flow chart of the simulation is shown in Fig. 6.

Take five fire-trucks and one fire hydrant as an example, the success rate of the two types of model under different fire statuses are shown in Fig. 7. When the fire thermal radiation is smaller than or equal to 4 kW/m^2, the emergency responses represented by both models can certainly extinguish the fire, and when the fire thermal radiation is greater than or equal to 8 kW/m^2, the emergency responses represented by both models will fail. But in the interval 4 kW/m^2-8 kW/m^2, the Type 2 model has a better performance.

Similarly, the success rate comparison under the condition of eight fire-trucks and one fire hydrant is shown in Fig. 8. It can be seen that the Type 2 model still has a better performance than the Type 1 model.

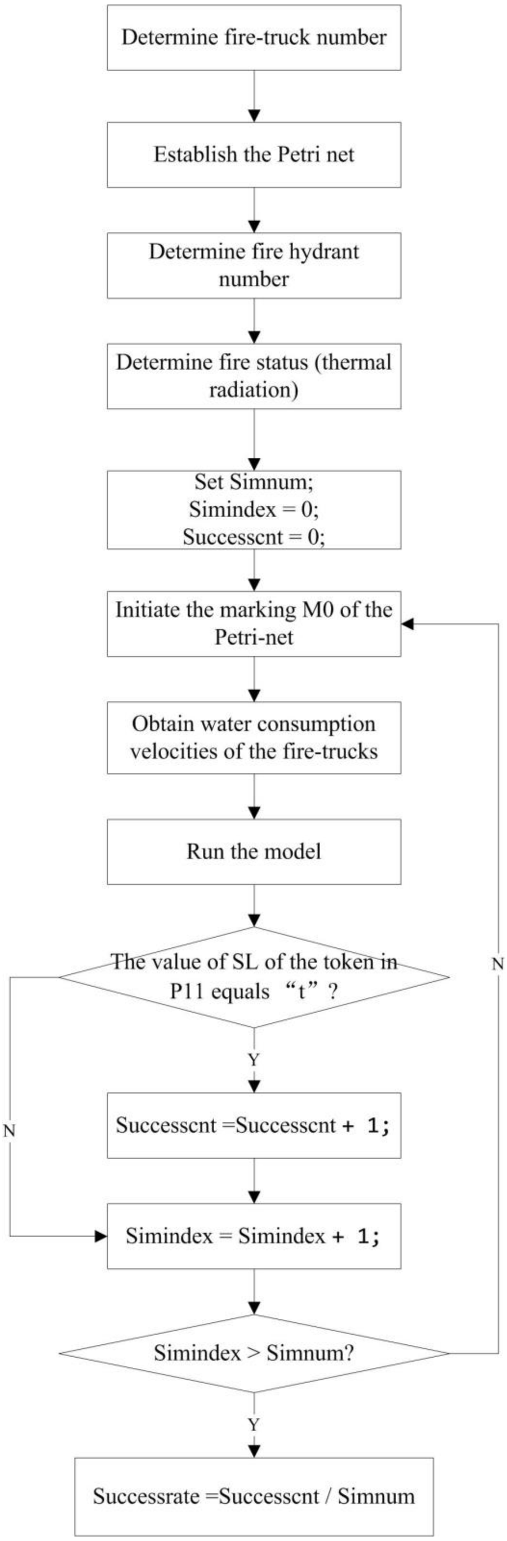

Fig. 6 Success rate simulation flow chart

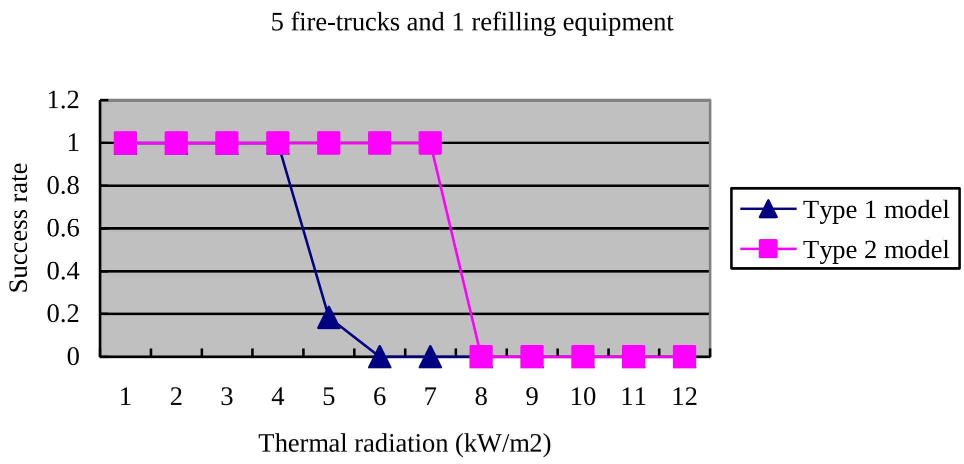

Fig. 7 Comparison under 5 fire trucks and 1 refilling equipment

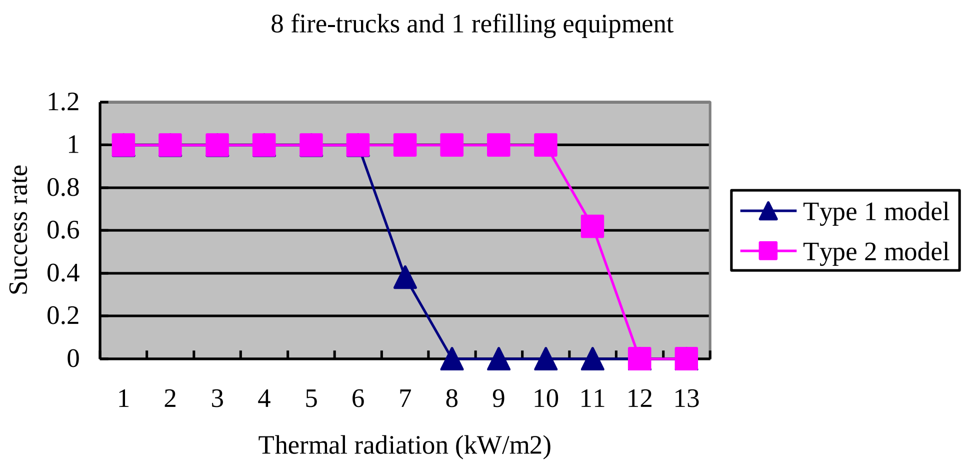

Fig. 8 Comparison under 8 fire trucks and 1 refilling equipment

The conflicts in the use of emergency resources in the Type 1 model are made by limited resources. Obviously if the emergency resources are increased, the conflicts will decrease and the performance of the emergency response will be improved. But how many refilling resources are suitable for definitely distinguishing a fire?

Fig. 9 shows the relationship between the success rate and the refilling equipment under 5 fire-trucks against a 6 kW/m^2 fire. For the Type 2 model (with queuing refilling subsystem) the fire can be extinguished successfully even if there is only one fire hydrant. For the Type 1 model, if the fire hydrants are less than or equal to 2, the emergency response will definitely fail. But when the fire hydrants are increased to 3, there is about 0.73 of the probability of success to extinguish the fire. And if the number of fire hydrants is increased to 4 or more, the fire can be definitely put out.

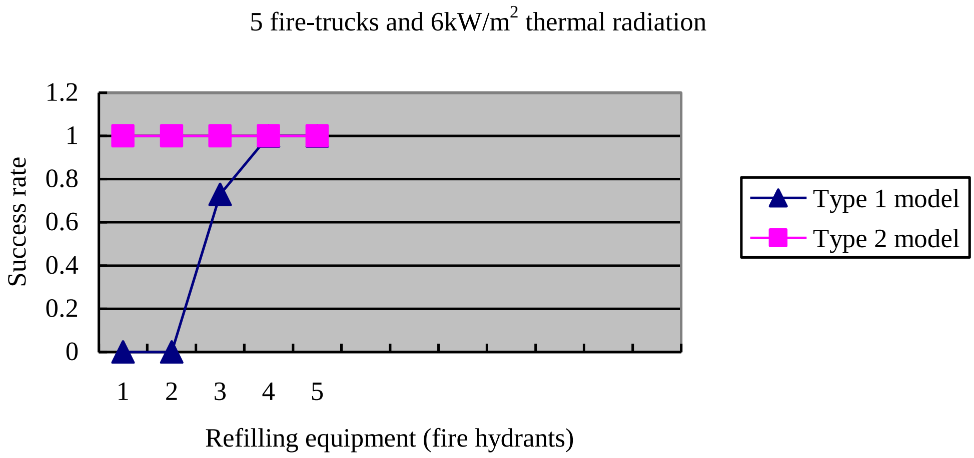

Fig. 9 Success rate under 5 fire trucks and a fire with 6kW/m^2 thermal radiation

Similarly, increasing the refilling resources can also improve the capability of the emergency response represented by the Type 2 model. Fig. 10 shows the relationship between the success rate and the refilling equipment under 5 fire-trucks against an 8 kW/m^2 fire for the type 2 model. When there is only one fire hydrant, the fire cannot be put out. When there are five fire hydrants, the fire can be extinguished definitely. And there is a probability of success when the number of fire hydrants is greater than one and less than five.

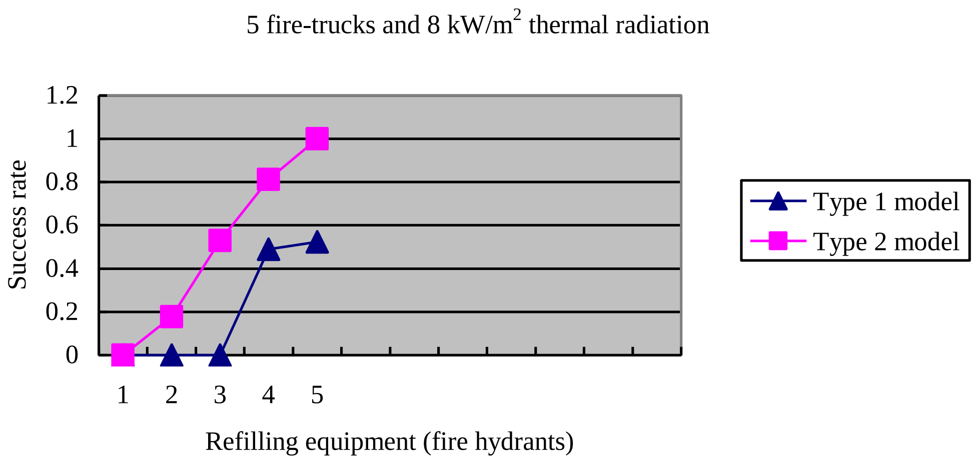

Fig. 10 Success rate changes with the number of refilling equipment under 8kW/m^2 thermal radiation

At the beginning of the emergency action, the fire-trucks are filled with water. If they have differences in the amount of water load, the question can be pored whether the conflict or queuing phenomenon can be reduced, and whether the performance can be improved.

Assuming that the initial loading amount Y of the fire-trucks obeys a "half" normal distribution, that is, let $Y^* \sim N(3000, 400)$,

$$\text{If } Y^* <= 3000, \text{ Then } Y = Y^*;\ \text{If } Y^* > 3000, \text{ Then } Y = 6000 - Y^* \tag{3}$$

Take five fire-trucks fight against a fire under one hydrant as an example. For the Type 1 model, the results shown in Table 6 can be obtained. Where, success rate 1 indicates the success rate obtained when all fire-trucks are all initially fully loaded, and success rate 2 indicates the success rate obtained when the water of the fire-trucks is stochastically loaded according to formula (3). From the results it can be seen that the strategy of initially fully filling has a better effect.

Table 6 Comparison of fire loading strategies for the Type 1 model

fire-trucks	fire hydrants	thermal radiation	success rate 1	success rate 2
5	1	1	1	1
5	1	2	1	1
5	1	3	1	1
5	1	4	1	0.805
5	1	5	0.184	0.004
5	1	6	0	0
5	1	7	0	0
5	1	8	0	0
5	1	9	0	0
5	1	10	0	0

For the Type 2 model, a similar result can be obtained, but the difference between the two strategies is very small (they are almost the same).

Through the analysis, we can obtain that the fire-trucks should be fully filled at the beginning of an emergency response, and be put into the fire-fighting together.

4. Conclusions

An emergency response process is composed of a series of emergency response actions. During an emergency response to an accident or disaster, many emergency response actions require the use of emergency resources. Some actions may conflict with each other due to the use of resources. Therefore, it is necessary to analyze the use of resources to detect and avoid conflicts.

The contributions of this work can be summarized as follows:

(1) RO-TCHPN based dynamic models for the process with resource sharing in an emergency response. Petri-net has some advantages in the modeling of emergency response actions, especially the relationship between actions. Two types of RO-TCHPN models are established to model the emergency response to an oil fire: one (Type 1 model) does not specifically consider the avoidance of conflict, the other (Type 2 model) uses queuing method to deal with possible conflicts when multiple actions use the same limited resources.

(2) Emergency response process simulation under the two resource using approaches. For the illustrative example of responding to an oil fie accident, the simulation parameters are discussed based on some assumptions or estimations. Through the emergency response process simulation, the evolution of the emergency response can be revealed and when and under which conditions a conflict will occur, can be determined if this conflict exists.

(3) Performance comparison analysis of the two resource using approaches. This analysis

focuses on whether the improved model (Type 2) which integrates a queuing subsystem into the Petri-net based emergency response model has some effects on the emergency response. The results show that the Type 2 model has better performance than the Type 1 model due to conflict avoidance. The number of refilling resources needed to distinguish a fire under the circumstances described by the two types of models is also analyzed. Furthermore, we discuss whether all the fire-trucks should be fully filled at the beginning of a fire-fighting. The results indicate that it is optimal if they are fully filled under both types of models.

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