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Petri-net based modeling and queuing analysis for resource-oriented cooperation of emergency response actions

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Abstract: 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. Different emergency actions form certain relationships on using emergency resources. The cooperation modes of emergency actions on using resources are analyzed in this paper, 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. An example of an emergency response activity related with a fire accident is used to demonstrate the modeling method. The conflicts are analyzed and a queuing system is used to avoid simultaneously employing the same resource.

Key words: emergency resource; Petri-net modeling; conflict detection; conflict avoidance; queuing system

1. Introduction

Major industrial accidents in the process industry can cause huge losses, and effective emergency response can greatly reduce the losses. An emergency response process consists of a series of emergency response actions, usually requiring certain emergency resources to achieve their objectives. For some major accidents involving hazardous materials, the use of emergency resources might be the key factor for successfully responding to the accident. Since there is a certain relationship between emergency actions and the use of emergency resources, this relationship should be analyzed to avoid conflicts when planning the emergency actions.

Emergency resources are important for emergency management. There are many studies on how to effectively use emergency resources when responding to various accidents or disasters, covering emergency resources' allocation, scheduling, demand prediction, etc.

Emergency resources allocation focuses on determining the optimal facility location in decision support systems. Most of these methodologies in literature are for detecting the minimum response time to the disasters so that they can be cleared at minimum cost. For example, Tzeng, Cheng, and Huang (2007) provide a fuzzy multiple-objective mathematical programming model to formulate the emergency resources allocation problem. Their objective functions contain the

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minimum of the cost, the total arrival time, and the maximum satisfaction of the basic support of the disasters. Sheu (2007) presents a fuzzy clustering optimization approach for the operation of emergency logistics co-distribution responding to the relief demands in the crucial rescue period. Zhang et al. (2012) formulate the emergency resource allocation problem with constraints of multiple resources and possible secondary disasters, and model the multiple resources and multiple emergency response depots problem considering multiple secondary disasters by an integer mathematical programming. Wang et al. (2014) propose a method of generating a task network for emergency response based on the snowball procedure and an associated method of analyzing a task network based on social network analysis, in order to contribute to reasonable resource allocation and targeted collaboration. Hawe et al. (2015) use agent-based simulation to determine the allocation of resources for a two-site incident, minimizing the latest hospital arrival times for critically injured casualties.

Emergency resources scheduling mainly deals with the problems of resources dispatching. Zhang et al. (2011) built an emergency resource scheduling model, including multiple suppliers with a variety of resources, a single accident site and some restrictions. They applied an adaptively mutate genetic algorithm to figure out a superior solution. Li & Li (2012) develop an emergency resource dispatching model in which the demand for resource is random and the transportation channel can be unreliable. Considering large scale disasters, such as earthquakes, and floods, often lead to traffic network uncertainty including connectivity uncertainty and travel time uncertainty, Ren et al. (2012) present a multi-period dynamic transportation model of variety emergency materials based on a CTM network, and design a corresponding hybrid genetic algorithm to solve the problem.

The demand on emergency resources refers to the minimum requirements needed for effective response to any emergencies. If emergency resources are insufficient, an emergency response activity cannot be performed successfully. Wang et al. (2009) introduce a work flow model and present an efficient resource requirement analysis algorithm to determine the minimum resource set that, if satisfied, the workflow can be executed without the occurrence of resource shortage. Liu et al. (2012) present a method for emergency resource demand prediction using case-based reasoning (CBR), the results are obtained by analyzing the attributes of cases based on risk analysis, establishing the case library and using the case-based reasoning technique.

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. The emergency resources are consumed/used by a series of emergency actions, and may restrict the performing of these actions. For example, different emergency actions may need to use the same resource sequentially, however, if the former action does not release the resource, the latter action cannot use it. The use of resources in different ways forms different relationships among emergency actions, such as sequence, choice, and concurrency. To analyze emergency actions in an emergency response, the relationships among emergency actions on using resources need to be modeled.

The Petri-net approach represents a powerful modeling and analysis tool. It can formally describe the flow of activities in complex systems. It is particularly suited to represent logical interactions among different parts or activities in a system. Typical situations that can be modeled by Petri-nets are synchronization, sequentiality, concurrency and conflict. Petri-nets have for instance been used to model and analyze emergency responses (Karmakar and Dasgupta, 2011;

Meng, et al., 2011; Zhong et al., 2010; Zhou, 2013).

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.

This study focuses on modeling cooperation of emergency actions with respect to using emergency resources, and conflict detection and avoidance approaches. Firstly, emergency resources and emergency actions are formally defined according to their features in Section 2. Then, a colored hybrid Petri-net based modeling approach for emergency response actions is presented in Section 3. Section 4 proposes a conflict detection and -avoidance approach with respect to emergency actions. A simple illustrative example is discussed in Section 5. Conclusions are drawn in Section 6.

2. Formal specifications

2.1 Formal specifications of emergency resources and actions

During an emergency response activity or process, various kinds of emergency resources may be used. According to features of emergency resources, we can divide them into several categories:

i. Consumptive resources and reusable resources: some emergency resources can be reused (e.g., certain personal protective equipment) and some emergency resources can not be reused (e.g., firefighting foam or water);

ii. Discrete resources and continuous resources. This division is relative. It depends on the condition in which the resource is used. For example, water can be looked as a continuous resource when it is taken through a fire hose connected to a fire hydrant, it can also be considered as a discrete resource when it is used through a fire truck or a bucket for instance.

Thus, the emergency resources can be formally described as following:

Definition 1: An emergency resource (ER) is a three-tuple

ER = < ResourceName, ResourceProperty, ResourceType >

Where: ResourceName: name of an emergency resource;

ResourceProperty = {0, 1}, property of a resource, 0 - reusable, 1- consumptive;

ResourceType = {0, 1}, type of a resource, 0 - discrete, 1- continuous.

During an emergency response activity or process, all emergency resources constitute a resource set ResourceSet = $\{ ER_i | i \in \mathbb{N} \}$, where $\mathbb{N}$ indicates the natural number.

In an emergency response activity or process, the resources are used by various emergency response actions. The execution of an emergency response action is constrained by two main factors, one is the system state (or message/command), and the other is the emergency resource. A system state can start or stop an emergency action, while whether an emergency action can be performed and how long an emergency action will last is constrained by the resources the action requires. After an action is carried out, a new system state will be formed, and certain resources may be generated/released. Thus, the emergency response action is defined as follows:

Definition 2: An emergency response action (ERA) is a five-tuple

ERA = <*ActionName*, *PreState*, *PostState*, *PreActionResource*, *PostActionResource* >

Where, *ActionName*: the name of an emergency response action;

PreState = $\{PrState_i|i\in\mathbb{N}\}$, the state set that must be satisfied prior to the execution of this emergency action;

PostState= $\{PoState_i|i\in\mathbb{N}\}$, the state set which is generated after the execution of this emergency action;

PreActionResource = $\{PrAR_i|i\in\mathbb{N}\}$, the resources required by the execution of this action, $PrAR_i \in$ ResourceSet;

PostActionResource = $\{PoAR_i|i\in\mathbb{N}\}$, the resources generated/released by the execution of this action, $PoAR_i \in$ ResourceSet;

During an emergency response process, all emergency response actions constitute an action set $ERAs = \{ ERA_i|i\in\mathbb{N}\}$.

All emergency response actions constitute an emergency response process (ERP), which is defined as following:

Definition 3: An emergency response process (ERP) is a three-tuple

ERP = < ERAs, ResourceSet, Relations >

Where,

(1) ERAs = $\{ ERA_i|i=1, 2, \ldots, n\}$ is an emergency response action (ERA) set, n indicates the number of emergency response actions.

(2) ResourceSet = $\{ ER_i|i =1, 2, \ldots , m\}$ is a resource set, m indicates the number of emergency resources.

(3) Relations$\subseteq$ ERAs×ERAs is a relation set, representing relations among emergency response actions.

There are many relations among emergency response actions, especially in the use of emergency resources. The relations will be discussed in the following section.

2.2 Illustrative example

In Zhou & Reniers (2016), an illustrative example of responding to multiple simultaneous fires in the process industry is presented. In that study, the emergency resources are not considered at all, or they are considered sufficient. In this study, some necessary emergency resources for firefighting are taken into account. The resources are listed in Table1:

Table 1 Emergency response actions and required resources responding to fires

Resource	Name	Property	Type
ER1	fire trucks	0	0
ER2	firefighting foam	1	1

ER3	firefighting water	1	1
ER4	Thermal radiation detection equipment	0	0
ER5	foam filling equipment	0	0
ER6	fire hydrants	0	0

There are many other resources which may be required in the emergency response process and which are not considered here. For example, firefighters are needed for this firefighting process, but they are not considered as a separated resource because all actions need to be performed by them. The information of firefighters is merged into the system state or the controlling messages.

The emergency response actions in this process are listed in Table 2.

Table 2 Emergency response actions fighting against fires

Action	Name	PreActionResource	PostActionResource
ERA1	activate emergency response	∅	∅
ERA2	go to the scene	{ ER1}	{ ER1}
ERA3	make emergency response decision	∅	∅
ERA4	determine extinguishing strategy	∅	∅
ERA5	try to extinguish fires	{ ER1, ER2, ER3}	{ ER1}
ERA6	measure fire status	{ER4}	{ER4}
ERA7	evacuate	∅	∅
ERA8	terminate emergency response	∅	∅
ERA9	request assistance	∅	∅
ERA10	reinforce	{ ER1}	{ ER1}

3. Petri-net based modeling of emergency response actions

3.1 Resource-oriented Colored Hybrid Petri-net

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

Definition 4 (Zhou & Reniers, 2016): A Timed Colored Hybrid Petri-Net (TCHPN) is an eleven-tuple

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

(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 which assigns 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.

Definition 5: 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.

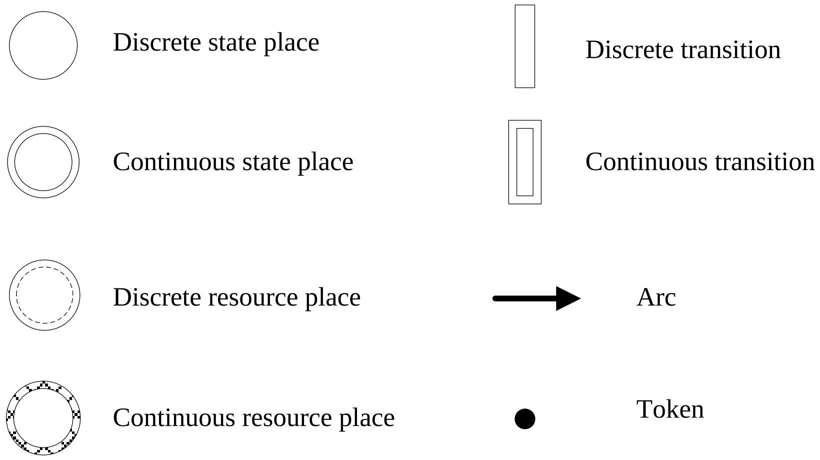

Fig. 1 Icons for the elements in the RO-TCHPN model

The firing rule of a transition in RO-TCHPN is the same as that of a TCHPN. The tokens are usually denoted by dots, and they can also be expressed by a number.

3.2 Modeling approach

The modeling of the emergency response process in this paper focuses on two aspects, one is the emergency response flow control, and the other is the use of emergency resources. The flow of an emergency response process is determined by the system state: the emergency command department will send different messages or commands to perform appropriate emergency actions according to the state the system is in.

The Petri-net model of a discrete emergency action is shown in Fig. 2. According to Definition 2, the discrete emergency action is converted into a discrete transition, the PreState is converted to input places of this transition, and the PostState is converted into output places of this transition. The modeling of a continuous emergency action is similar. It should be noted that a continuous transition must connect to a continuous place which reflects the state changing caused by the continuous transition.

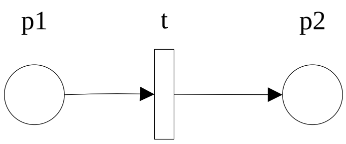

Fig. 2 Petri-net model of discrete emergency action

As already indicated, in the process of an emergency response activity, the execution of an emergency action usually needs some emergency resources. Thus, modeling of an emergency action should take both the emergency response process control and the using of emergency resources into account.

According to Definition 2, the *PreActionResource* is converted to input resource places, and the *PostActionResource* is converted into output resource places of a transition. Fig. 3 indicates that the execution of a discrete emergency action (transition t) which is in a state (place p1) and requires a discrete resource (place pr).

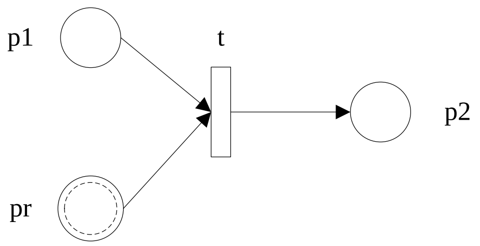

Fig. 3 Petri-net model of a transition needing a discrete emergency resource

There are different emergency response cooperation modes of emergency actions in the use of resources. The cooperation may greatly influence the use of emergency resources, and even the efficiency of an emergency response.

The cooperation of emergency actions in use of emergency resources can be divided into the following modes:

(1) Sequential

The emergency actions are executed sequentially. The following two cases fall into this category: (i) after action era1 uses resource ‘pr’, action era2 uses it; (ii) action era1 prepares resource ‘pr’, then action era2 uses it.

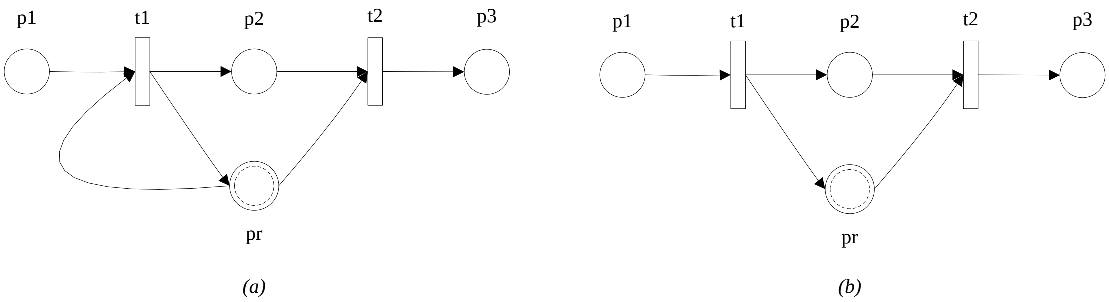

Fig. 4 Petri-net model for emergency actions executing in sequence

The sequential mode is shown in Fig. 4, where, Fig. 4 (a) indicates that two transitions (corresponding to two emergency actions) use an emergency resource denoted by pr sequentially. Fig. 4 (b) indicates that transition t1 prepares resource pr, and then transition t2 uses it.

(2) Sharing

Two or more emergency actions use an emergency resource at the same time. The Petri-net model of this mode is shown in Fig. 5. Both the executions of transitions t1 and t2 require an emergency resource pr. It is worth noting that the sharing mode of using emergency resources might result in conflict. When the amount of resources meet the requirements of t1 and t2 simultaneously, t1 and t2 can be executed in parallel; but when the resources are not sufficient for both t1 and t2, there might be a conflict between t1 and t2.

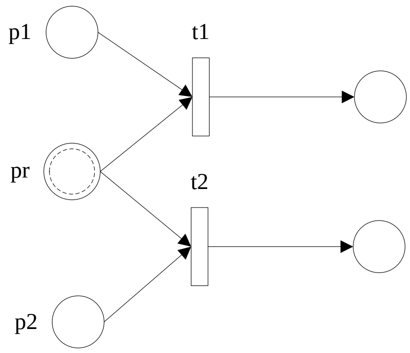

Fig. 5 Petri-net model of two emergency actions sharing one resource

(3) Supplementing

During an emergency response process, some consumptive emergency resources need to be supplemented or refilled, so that the emergency process continues. For example, during a fire fighting process, after a fire truck runs out of water, it must be refilled to continue the firefighting. The supplementing mode is usually composed of two emergency actions, one consumes resources, and the other refills/reloads them. The corresponding Petri-net model is shown in Fig. 6. There are three types of emergency resources in this process. Pr1 indicates a container filled with a firefighting media, pr2 indicates the empty container (its firefighting media has been consumed), and pr3 indicates the firefighting media which is also an emergency resource. Transition t1 represents the emergency response action which consumes emergency resources (the firefighting media represented by pr3), and t2 is the refilling action. This consuming-refilling process constitutes a loop. Each time this loop is executed, certain amount of emergency resource indicated by pr3 is consumed.

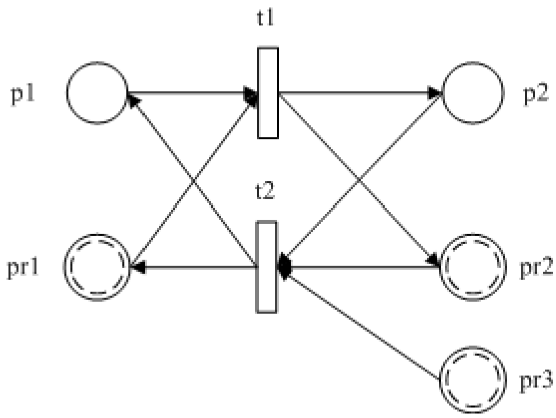

Fig. 6 Petri-net model of emergency resource supplement

(4) Continuous action and continuous resources

During an emergency response process, there may exist continuous emergency actions which last a long time and impact the accident state continuously. The execution of a continuous emergency action usually needs some continuous emergency resources. For example, the continuous action of cooling tanks in a fire accident requires continuous water. The continuous emergency action and corresponding continuous resource are shown in Fig. 7. T is a continuous transition representing a continuous emergency action, the place pr indicates the continuous resource, and the place p2 is the state influenced by the continuous action.

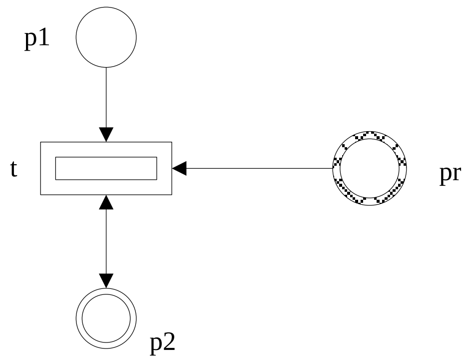

Fig. 7 Petri-net model for a continuous emergency action using continuous resource

4. Conflict detection and conflict avoidance approach

4.1 Conflict detection

In the above-mentioned four modes describing the possible synchronization of emergency actions with respect to the consumption of resources, the sequential relationship can delay or block the execution of succeeding actions, but this is not considered as a conflict of emergency actions in this study. Both the sharing and the supplementing relationships can result in emergency action conflicts due to simultaneously using the same resource. For the continuous actions' use of continuous resources, whether there is a conflict between the actions depends on the specific usage of resources. In most conditions, continuous resources can be considered sufficient, but in some cases, the sharing of continuous resources may still result in conflicts.

Based on the graphical Petri-net model of emergency response, the potential emergency action conflicts can be detected.

Denote that transition t_i of a Petri-net *Net* is enabled under the marking M as (Net, M)[t_i>. Thus, the resource conflict can be defined as follows:

(1) IF $({}^\bullet t_i \cap {}^\bullet t_j \cap P_{DR}) \neq \varnothing$ or $({}^\bullet t_i \cap {}^\bullet t_j \cap P_{CR}) \neq \varnothing$ THEN there is resource-sharing between t_i and t_j, denoted as t_i Ʉ t_j.

(2) For any transitions $t_i, t_j \in T$ $(t_i \neq t_j)$, t_i and t_j are in a resource conflict, if (i) (Net, M)[t_i> and (Net, M)[t_j>; (ii) $pr \in t_i$Ʉt_j ; and (iii) $w(pr, t_i) + w(pr, t_j) > M(pr)$.

Where, $w(pr, t_i)$ represents the weight of the arc from place *pr* to transition t_i. This weight which actually means the tokens required by transition t_i is a kind of arch expression E. The condition (iii) indicates that the tokens provided by resource place *pr* can not satisfy the needs of all transitions connecting from *pr*.

4.2 Conflict avoidance

It can be seen that 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. To avoid conflict, one approach is to provide sufficient resources so that multiple emergency actions can be performed concurrently. However, many emergency resources are limited in reality. There must be an appropriate approach to manage emergency actions using shared resources.

The queuing method may be considered well-known and common in dealing with the use of limited resources. To avoid emergency resource conflict in the emergency response system, queuing systems should be integrated into the Petri-net model. Although some researchers have studied the specific Queuing Petri Nets (QPN) (Bause, 1993; Chiang et al., 2006; Kounev, 2006; Rak, 2014), an ordinal Colored Petri-net based model is utilized in this paper to model the queuing problems for future simulation analysis.

A queue is a waiting line of "customers" requiring service from one or more servers. A queue forms whenever existing demand exceeds the existing capacity of the service facility, that is, whenever arriving customers cannot receive immediate service due to busy servers.

When a "customer" enters the queue, he must wait until a server is idle, after which he can obtain the service. A queuing process can be considered to be a two-stage process: the first is a customer waiting to obtain the right of service; the second is a server providing the customer service. Thus, the process using one resource in a queue can be modeled by a Petri-net shown in Fig. 8. The meanings of the transitions and places are shown in Table 3.

Table 3 Meanings of transitions and places of the Petri-net model shown in Fig. 8

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
		pr	Emergency resource

The model in Fig. 8 is a single queue and single server queuing system. The place qp1 indicates the queue buffer, when an action needs the emergency resource represented by pr, a token is put into qp1; qp3 and qp4 indicate the resource (server) is idle and busy, respectively. Initially, there is a token in qp3, which means the resource is idle. If there are actions waiting for the resource (that is, there are tokens in qp1), and the resource is idle (a token is in qp3), the action will obtain the using right, qt1 fires and puts a token into qp2 (at the same time, the token in qp3 is removed and the token in qp1 is subtracted by 1). At this time, the resource-use process (qt2) can be executed. After qt2 executes, the token in qp2 is removed and a token is put into qp3 indicating the resource is idle again. Thus, the next action can get the right to use the resource.

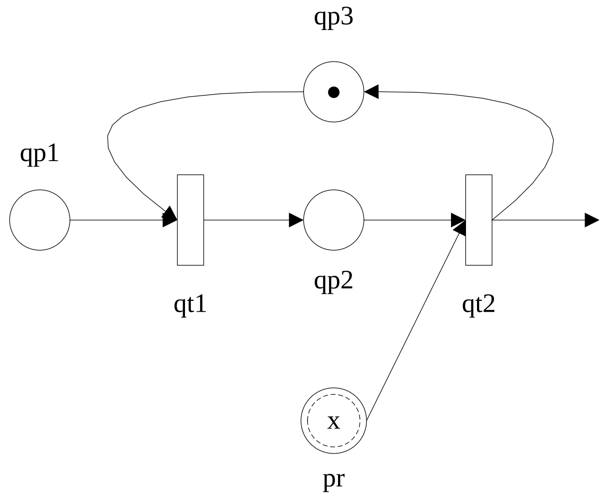

Fig. 8 Petri-net model of using one resource in a queue

5. An illustrative example and discussion

5.1 The RO-TCHPN based model

In (Zhou & Reniers, 2016), an example is provided to analyze the emergency response to multiple simultaneous fires. The example is adopted to analyze the using of emergency resources in this study. Assume the accident is an oil fire so that firefighting foam is necessary. The focus of research is changed from scheduling responders to synchronizing the use of resources. To simplify the model, suppose the emergency response activity deals with one or two fires that have to be tackled with two fire trucks, and the modeling using the approach elaborated in this paper considers the use of the two fire trucks and firefighting foam for fire extinguishing, and does not consider resource allocation for multiple fires.

The resource-oriented Petri-net model is shown in Fig. 9. The transitions and places and their meanings are shown in Table 1. Main colors defined for this model are shown in Table 2. In this model there are two refilling processes of the two fire trucks during their extinguishing processes.

Table 1 Transitions and places of the Petri-net model shown in Fig. 9

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	refill fire truck 1
P6	fire truck 1 is ready for firefighting	T6	try to extinguish fire with fire truck 1
P7	foam of fire truck 1 is exhausted	T7	refill fire truck 2
P8	fire truck 2 is ready for firefighting	T8	try to extinguish fire with fire truck 2
P9	foam of fire truck 2 is exhausted	T9	measure fire states
P10	fire state	T10	evacuate
P11	end of emergency response	T11	terminate emergency response

P12	under fire fighting
Pr1	fire trucks
Pr2	fire truck 1 filled with foam
Pr3	fire truck 1 without foam
Pr4	fire truck 2 filled with foam
Pr5	fire truck 2 without foam
Pr6	thermal radiation detection equipment
Pr7	firefighting foam

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
PN		Person Number
FS		Compound color of TR and FL
EL		Compound color of SL and FS
TK*	Tk1	Fire truck 1
	Tk2	Fire truck 2
FF*		Firefighting Foam
TF*		A fire truck of foam
TD*		Thermal detection equipment

* This color is introduced in the present study.

5.2 Qualitative analysis and model improvement

Analyzing the Petri-net model shown in Fig. 9 shows that there is a resource sharing between T_5 and T_7, T_5 Ʉ T_7= {Pr7}. If the fire-fighting actions of fire truck 1 and fire truck 2 represented by T_6 and T_8, respectively, run out of firefighting foam at the same time, the fire is still not extinguished (the SL color of P10 is still '*f*'), then both T_5 and T_7 are enabled, namely, fire truck 1 and fire truck 2 need to be refilled with firefighting foam at the same time. In such case, there may be a potential resource conflict. If the amount of refilling foam required by both emergency actions represented by T_5 and T_7 is greater than the amount of the foam resource represented by Pr7, transition T_5 will conflict with transition T_7. This conflict can even cause deadlock of the system, which means no transition can be executed in a certain marking. In the model, the number of tokens in Pr7 is x, representing the resource amount. If x is great enough (e.g. infinite), that is, the emergency resource of firefighting foam is sufficient, T_5 and T_7 can be executed in parallel and there will be no resource conflict between them.

In practice however, the use of the emergency resources like firefighting foam and water is usually limited by the refilling equipment. For example, suppose the firefighting water is infinite, but the fire hydrants or water pumps are limited, the fire trucks may still conflict with each other when they need refilling simultaneously.

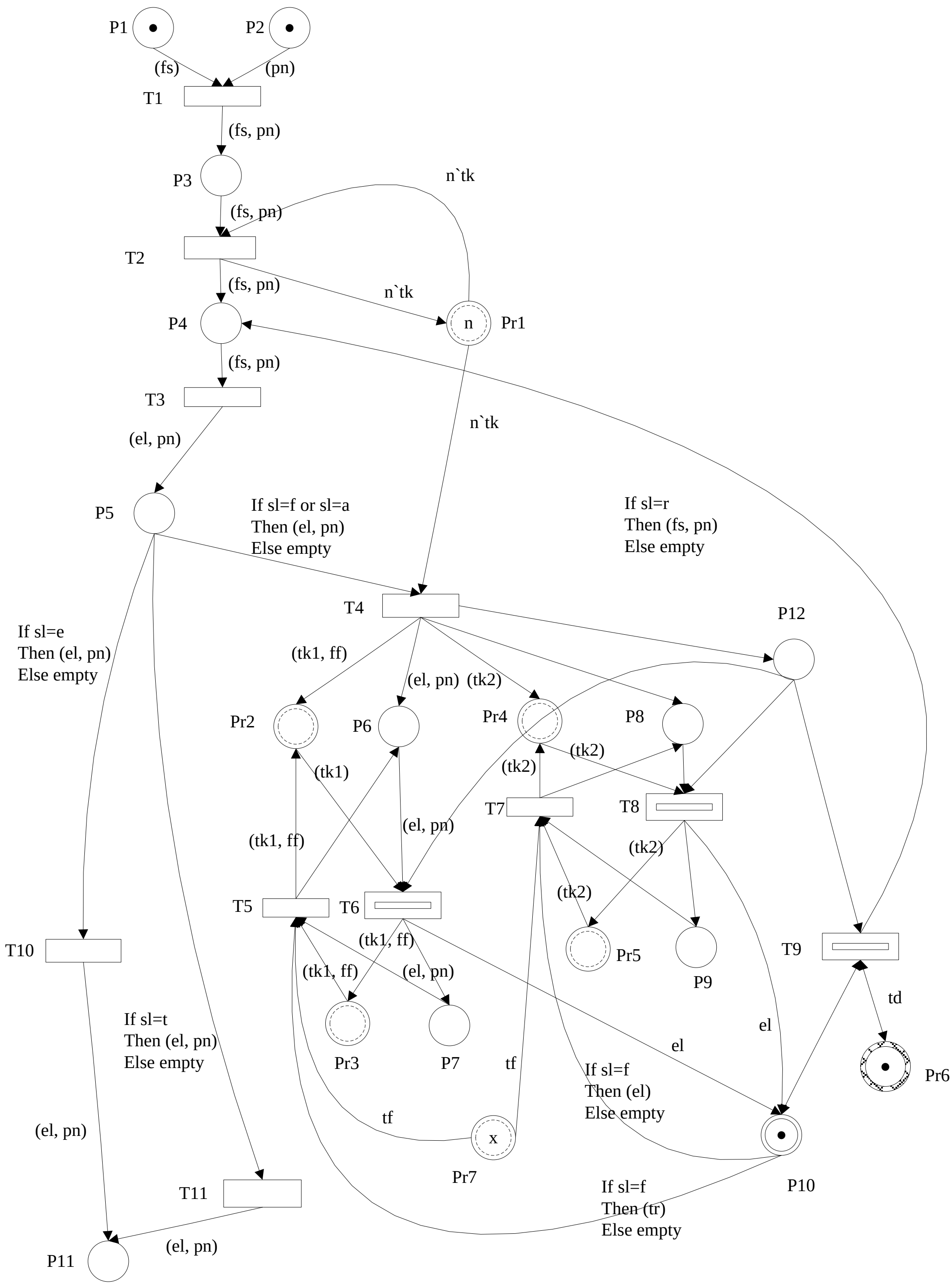

Fig. 9 Petri net model of emergency response to an oil fire

In the model shown in Fig. 9, let Pr7 represent foam refilling equipment, and its token number is 1, that is, there is only one foam refilling equipment. If fire truck 1 and fire truck 2 need to supplement fire foam at the same time, there is a conflict due to the competition of using the refilling equipment. Obviously, if the fire trucks are not organized in proper order, the conflicts will impact on the efficiency of the emergency response. There are many different methods that can be used to deal with these resource conflicts. For example, we can set priorities to the fire trucks according to their tasks, thus the fire truck with higher priority will use the refilling equipment when multiple fire trucks need refilling simultaneously. Another solution is the queuing method. When multiple fire trucks need refilling, they enter a queue and use the refilling equipment according to the principle of first-come first-served.

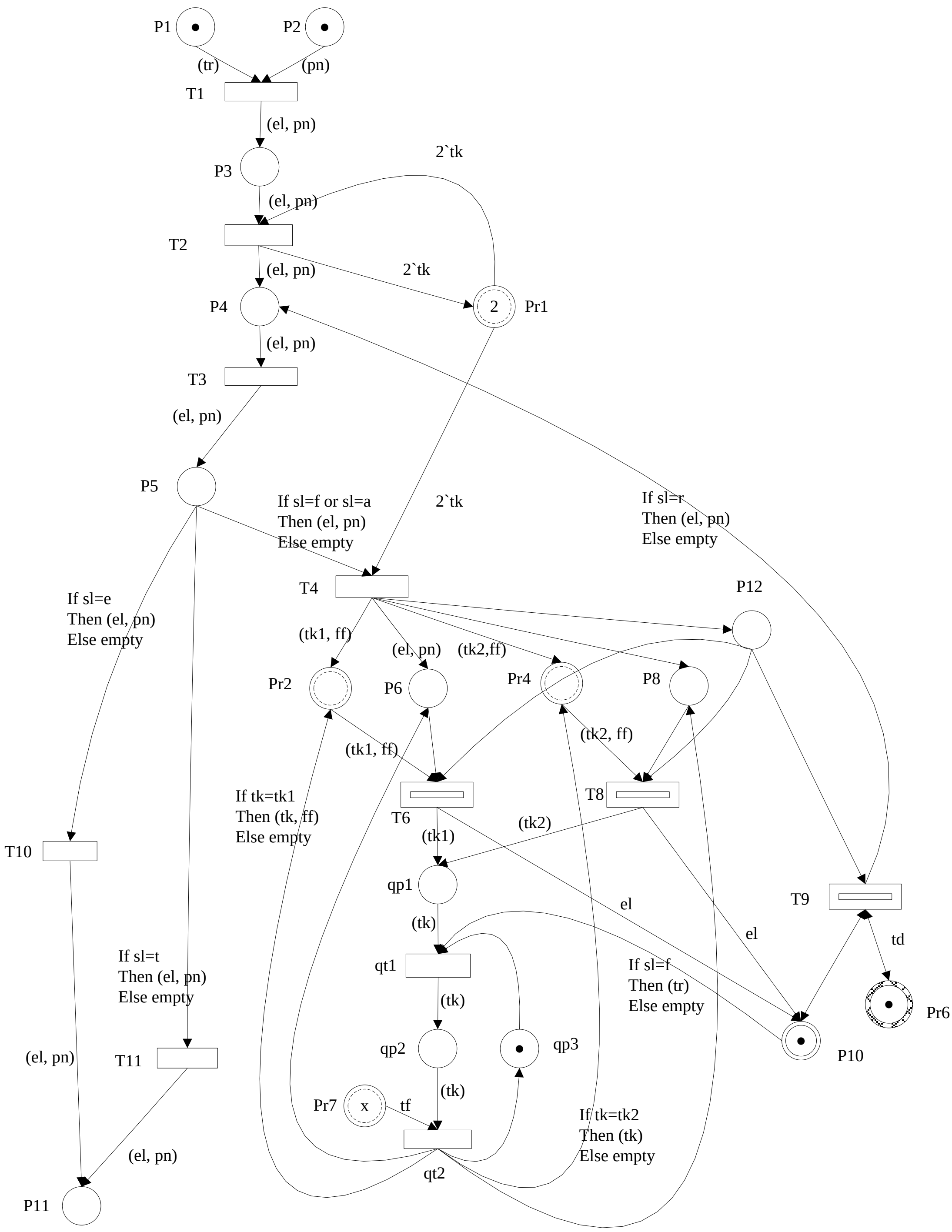

Fig. 10 Improved Petri-net model of emergency response to an oil fire

Based on the Petri-net model of queuing system, the model of emergency response to a fire accident discussed in Fig. 9 is improved and shown in Fig. 10. From the structure of the model, there is no longer a resource conflict. Similarly, if there are many fire trucks which want to use one fire hydrant to fill water at the same time, a queuing Petri-net sub-model can be used to model it. Each fire hydrant or foam filling equipment can be modeled as a single queue and single server queuing system. In addition, multiple filling equipment sharing one queue can also be modeled as a single queue multi-server system, which can easily be represented as the model in Fig. 8 by adding tokens to qp3.

5.3 Simulation analysis

A Petri-net model can be executed. Through the execution of transitions, tokens (with certain colors) move from place to place. This mechanism can help to reveal the evolution process of a system and determine under which conditions a transition is enabled and what will happen after it occurs.

A TCHPN software was developed with Java language for the study in Zhou and Reniers (2016), it is also used to perform the analysis in this study. This paper only performs a simple quantitative analysis due to the combination of the legibility and length of the paper. A more detailed quantitative analysis and discussion will be provided in a follow-up paper. Thus, the determination of simulation parameters is not discussed in depth here. Just assume a fire truck can store 3 tons of water and 1 ton of foam concentrate (but the use of water is the bottleneck and as such, it is considered in this simplified simulation analysis). Increase or decrease a fighting fire-truck will change about 0.2kW/m^2 thermal radiation (30 meters away from the fire center). 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 $V \sim N(500, 20^2)$. Thus, to perform this simulation analysis, the model established above is expanded to simulate the process of three fire-trucks fighting against a 3 kW/m^2 thermal radiation fire, and the results are shown in Table 3. The velocities of water consumption (L/min) of the three fire-trucks are 478, 503 and 532, respectively. The durations (in minutes) of the discrete transitions are as follows: T1: 1; T2: 3; T3: 2; T4: 2; T5 (T7 or other refilling transitions): 1; T10:4; T11: 1. Assume that only one fire hydrant can be used for water refilling and it can only serve one fire-truck at the same time.

Table 3 Simulation of three fire-trucks fighting against a 3 kW/m^2 thermal radiation fire

Time	Marking	Fighting fire-trucks	Waiting for refilling	Refilling	Thermal radiation
0	(1,1,0,0,0,0,0,3)	0	0	0	3
1	(0,0,1,0,0,0,0,3)	0	0	0	3
2	(0,0,1,0,0,0,0,3)	0	0	0	3
3	(0,0,1,0,0,0,0,3)	0	0	0	3
4	(0,0,1,0,0,0,0,3)	0	0	0	3

5	(0,0,0,1,0,0,0,3)	0	0	0	3
6	(0,0,0,1,0,0,0,3)	0	0	0	3
7	(0,0,0,0,1,0,0,3)	0	0	0	3
8	(0,0,0,0,1,0,0,3)	0	0	0	3
9	(0,0,0,0,0,0,1,0)	0	0	0	3
10	(0,0,0,0,0,0,1,0)	3	0	0	2.7
11	(0,0,0,0,0,0,1,0)	3	0	0	2.37
12	(0,0,0,0,0,0,1,0)	3	0	0	2.01
13	(0,0,0,0,0,0,1,0)	3	0	0	1.61
14	(0,0,0,0,0,0,1,0)	3	0	0	1.17
15	(0,0,0,0,0,0,1,0)	1	1	1	1.09
16	(0,0,0,0,0,0,1,0)	0	2	0	1.19
17	(0,0,0,0,0,0,1,0)	1	2	0	1.11
18	(0,0,0,0,0,0,1,0)	1	2	0	1.02
19	(0,0,0,0,0,0,1,0)	1	2	0	0.93
20	(0,0,0,0,0,0,1,0)	1	2	0	0.82
21	(0,0,0,0,0,0,1,0)	1	2	0	0.7
22	(0,0,0,0,0,0,1,0)	0	3	0	0.77
	……				
56	(0,0,0,0,1,0,0,0)	0	3	0	14.82
57	(0,0,0,0,1,0,0,0)	0	3	0	14.82
58	(0,0,0,0,1,0,0,0)	0	3	0	14.82
59	(0,0,0,0,0,1,0,0)	0	3	0	14.82

In Table 3, ‘time’ represents the system evolution in time (minutes). Marking indicates the tokens in places P1, P2, P3, P4, P5, P11, P12, Pr1, respectively. From table 3, it can be seen that the three fire-trucks start to put out the fire at the 10th minute, and at the 15th minute only one fire-truck is fighting against the fire and the other two fire-trucks run out of water, among which one fire-truck is refilling and the other is waiting (due to the time difference in water consuming). But at the 16th minute, the fighting fire-truck also exhausts its water and needs to be refilled. At this time there are two fire-trucks waiting for water refilling, so that a conflict occurs because there is only one fire hydrant. After the refilled fire-truck exhausts its water (at the 22nd minute), it needs to be refilled again and its refilling action conflicts with other two fire-trucks’ refilling. At last, the fire-fighting fails, and all fire-trucks have to evacuate.

Similarly, the conflict avoidance approach which integrates the queuing method into the Petri-net model can also be simulated. The three fire-trucks run out of water successively, and need to be refilled at the 15th and the 16th minute. They enter the queue and get refilled one after another. The fire is successfully extinguished and the emergency response process is terminated at the 22nd minute.

6. Conclusions

During an emergency response to an accident in the process industry, there are many emergency resources needed by various emergency actions. There may be conflicts among these emergency actions when they use the resources. In the preparedness for an accident, the potential conflicts among the emergency actions should be analyzed and detected, and the actions should be properly arranged to avoid the potential conflicts.

There exist some cooperation modes of emergency actions on using emergency resources, such as sequential execution, sharing the same resource, and loop execution of resource consuming and resource reloading/refilling. On the basis of formal description of emergency resources and emergency actions, the modeling approach for cooperation modes of emergency actions is provided based on resource-oriented timed colored hybrid Petri-net. A detection approach for emergency action conflict resulting from resource-using is proposed. Aiming for the conflicts caused by sharing of limited resources, the queuing system is introduced to avoid the conflicts. The Petri-net model of a queuing system is integrated into the model of emergency response.

The approaches are illustrated by an emergency response to a fire accident. During this emergency response process, there is a resource-sharing in the process of firefighting foam refilling. Two types of Petri-net model are established: one is to use shared emergency resources directly, and the other is to use the shared resources through the queuing system. The former can potentially result in conflicts according the analysis of conflict detection. The latter effectively avoids the situation of limited resources for shared use, and thus avoids conflicts.

This paper focuses on the Petri-net based modeling and the conflict detection approach. In addition to the conflict detection according to the structure of the model, to detect emergency response action conflicts for a given schedule, we should run the system (or do simulations based on the model) and check if there are conflicts and evaluate the efficiency of the emergency system according to the markings reached. A simple simulation example is provided in this paper. Detailed simulation and analysis including the influences among the number of fire-trucks, refilling equipment, and fire severity (thermal radiation) will be performed in the following study.

In this study, the emergency response to an oil fire is taken as an example to illustrate the approach, and only the use of fire-trucks (and corresponding refilling equipment) is analyzed. An emergency response process is a complex system, among which there are many different resources, such as PPE (Personal Protective Equipment), fire-fighting equipment, casualty rescue equipment, evacuation equipment, and so on. Besides, the emergency response to different types of accidents/disasters may have different requirements for the use of emergency resources. So, the presented modeling and conflicts detecting/avoiding approach is necessary to ensure the smooth progress of the emergency response. It is believed that this approach can be applied to analyze the use of emergency resources in other emergency response fields, for example, the crowd evacuation through limited passages / gates, but in general, in case of conflict between time and means at the disposal during emergency operations.

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