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Developing a Petri-net approach for emergency response modeling and time analysis of process accidents considering the execution characteristics of emergency tasks

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ABSTRACT

In the process industry, hazardous chemical accidents can easily cause heavy loss, and emergency response is an important approach to reduce it. In the process of emergency response, many emergency tasks have different characteristics in their execution. This study analyzes the impact of the dynamic changes of emergency response personnel on the emergency tasks, and deduces the relationship between the execution time of an emergency task and the number of people with the time they join the task. Aiming to model the emergency response process under the possible dynamic change of the emergency task execution time, the dynamic timed Petri-net (DTPN) is proposed by improving the timed Petri-net (TPN) on the basis of the execution mechanism of transition, and the corresponding models are established according to several basic execution characteristics of the emergency tasks. The proposed approach is used to model the emergency response of on-site responders to a fire in a storage tank, and the time analysis is carried out. The results show that the approach can well solve the problem of modeling and analysis of emergency tasks with dynamic execution characteristics.

1. Introduction

In the process industry, many installations deal with or store a large number of dangerous substances, and many substances have flammable, explosive, toxic and easy diffusion characteristics. Once an accident occurs, it often has a large range of impact, resulting in heavy casualties and property losses. Emergency response is an important measure or approach to reduce the accident losses. Reasonable arrangement of emergency response personnel, emergency resources and emergency actions play an important role in ensuring efficient emergency response.

The emergency response to major industrial accidents has been studied by many researchers from different aspects. For example, certain emergency resources need to be used in the process of emergency response. Insufficient resources or unreasonable configuration and use will greatly influence the efficiency of emergency response, and even hinder the normal progress of emergency response. Yeboah and Park (2018) used the Kaplan-Meier estimator and Cox hazard model to allocate fire engine for responding to multiple fires. Rebeeh et al. (2019) combined the location hazard index (LHI) and the response time optimization model to establish an index-based emergency response management system, to optimize resources allocation. Zhang et al. (2021) proposed a dynamic multi-objective location-routing model to optimize resource scheduling for emergency response to accidents of marine oil spills. Huang et al. (2025) constructed a dynamic method that incorporates real-time traffic data to assess the spatial accessibility of fire-fighting capabilities in the event of an accident at electric vehicle charging stations. Emergency response usually involves many departments or personnel, and their cooperation also has an important impact on emergency response. Mohammadfam et al. (2015) used social network analysis's cohesion indicators (density, degree centrality, reciprocity, and transitivity) to examine the cohesion status of emergency response teams of a refinery plant. Based on an in-depth case study of marine accident rescue operations in the Arctic highlands, Andreassen et al. (2020) showed that information sharing, coordination mechanisms, and management roles may need to be adjusted during emergency response actions dealing with unstable conditions. In the

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process of emergency response, people are required to take appropriate emergency response actions, which were also studied by some researchers. Ishigami et al. (2004) developed a simplified modelling approach to assist emergency responders in selecting the most effective protective action from alternative actions during emergency response at a nuclear installation. Miguel et al. (2010) studied the effect of training periods on worker behavior in emergency situations (e.g. fire). Vaez and Nourai (2013) used the human reliability analysis method SPAR-H to analyze the reliability of the operation of automatic process control and supervision/intervention of control room operator in emergency situations. Yang et al. (2022) proposed a framework that utilized hazard and reliability indicators for comprehensive operational feasibility analysis, which can be used for operation supervision during emergency response and the identification of potential human error patterns.

The characteristic of emergency response is that it needs to act quickly, that is, response actions need to be taken as soon as possible after an accident occurs. Therefore, the time performance of an emergency response process is an important indicator to measure the efficiency of emergency response. Many studies in the literature also focus on the temporal nature of emergency response. Kang (2007) analyzed the emergency evacuation of a train fire on a platform in a subway station, and discussed time-based evacuation in view of the inability to enter the stairs due to smoke blockage. Palazzi et al. (2015) provided a method for evaluating the effectiveness of safety systems and developed a framework for determining response actions and intervention times, and how to apply these measures. Park et al. (2016) analyzed the service area and response time of fire responders in the case of highway-railway grade crossings with or without monitoring system based on Geographic Information System. Zhou and Reniers (2018) utilized a Timed Colored Hybrid Petri-net (TCHPN) approach to model and evaluate emergency response actions according to their efficiency in preventing or delaying the domino effects in the process industry. Brachner et al. (2019) used a framework of mathematical programming to help plan an emergency response system in the offshore oil and gas industry, considering both response time and response capacity. However, up to present, the research on the time performance of emergency response has not involved the impact of characteristics of emergency response tasks. Different emergency response tasks have their own execution characteristics. The same emergency response task may also show different characteristics due to resources, environmental and other conditions, thus showing differences in the execution time under different conditions. Emergency response tasks are all performed by people, and the competences of the people responsible for emergency response plays an important role. The quality of performance of emergency response not only depends on time, it also depends on the competence of people, the quality of material, etc. Therefore, this paper focuses on the analysis of the impact of changes in the number of people performing emergency tasks on the execution time of the tasks.

As a graphical modeling and analysis tool, Petri-nets have advantages in the modeling and analysis of emergency response processes. It can easily represent the relationship of various parts of a system through elements of place, transition, arc and token. Through the “moving” of tokens in the Petri-net model the evolution of a system can be revealed. Petri-nets have been widely used in many fields since they were proposed. In many researches, Petri-nets are also used to model and analyze emergency response. For example, Zhong et al. (2010) combined Petri net (PN) and Markov chain to study the performance of the typical urban emergency response system in China. Chen et al. (2018) used hybrid Petri nets to model event scenarios and emergency responses, and an oil pipeline leak accident was analyzed. Zhou and Reniers (2018, 2020, 2021) used Petri-nets to model the emergency response process of major accidents in the process industry, and analyzed the use of emergency resources, the relationship between emergency actions, and the cooperation of emergency departments. Sheeba and Jayaparvathy (2019) adopted stochastic Petri-nets to analyze the evacuation scenario on accidental fire, taking into account parameters of human behavior. With the wide application of Petri-nets, many extended Petri-nets have emerged to facilitate the modeling systems with various problems. Among them, Timed Petri Net (TPN) can deal with time in transitions or places, and facilitate the time analysis of a system. Stochastic Petri-net (SPN) is improved on the basis of TPN. The execution time of transition can be a random value that satisfies a certain probability distribution. They are also used in the analysis of safety or security systems (Grunt and Bris, 2015; Kamil et al., 2019; Elusakin and Shafiee, 2020; Taleb-Berrouane et al., 2020).

Regardless of TPN or SPN, once the transition time is determined, it remains unchanged during the execution process. However, during the execution process of an emergency task, as the number of emergency personnel involved in the task changes, the execution time of the task will also change accordingly. There are currently no appropriate modeling tools available to model this process. When making an emergency response plan, it is necessary to evaluate the execution time of emergency response actions, so as to arrange appropriate personnel and allocate reasonable tasks, ensuring prompt and efficient execution of emergency actions. This study proposes an approach to analyze the execution time of emergency response tasks with dynamic characteristics. Based on TPN and SPN, a new type of transition is proposed by modifying the execution mechanism of a transition to dynamically change its execution time according to the number of tokens in the input places of the transition. To distinguish it from other Petri-nets, the modified Petri-net is called dynamic timed Petri-net (DTPN) in this study, thus the emergency response with problems to be studied can be modeled using DTPN and the time performance of the emergency response process can be analyzed.

The remaining parts of this paper are arranged as follows: Section 2 discusses the characteristics of emergency response task execution, and analyzes the relationship between task execution time and changes in the number of executives. Section 3 presents the DTPN based methodology and an example of responding to a fire in a storage tank is illustrated in Section 4. Finally, some conclusions are drawn in Section 5.

2. Problems due to the execution of emergency response tasks

Different emergency response tasks have different time characteristics in the execution, which can influence the performance of the emergency response. Emergency response tasks are performed by emergency personnel (using corresponding emergency resources). Each task requires a certain number of executors. The emergency response tasks may have the following execution characteristics.

(1) There is a minimum number of executors. Almost every task requires a minimum number of people to perform it, and at least one person is required.
(2) There is a maximum number of executors. Generally, there is also an upper limit on the number of people performing a task, e.g., to open or close a valve, too many people may reduce the efficiency.

In general, increasing the number of people will shorten the execution time of most tasks accordingly when the number of executors is between the lower and the upper limits. The execution of many emergency response tasks is related to the number of emergency personnel involved. The more executors, the shorter the execution time of the task, if the responders are well trained.

The execution characteristics of emergency response tasks require that emergency personnel be assigned according to the corresponding characteristics when dispatching emergency response personnel. In addition, the execution of each emergency response task will also undergo dynamic changes during the emergency response process.

(i) Emergency response personnel may not arrive at the same time. The first arriving personnel are in the process of performing a task, and the continuous addition of later arriving personnel will change the execution time of the task.

(ii) After some tasks are finished, the corresponding emergency response personnel can take part in other tasks, and thus change the execution time of other tasks.

The execution characteristics of emergency response tasks can also have an impact on the cooperation between tasks, thus influencing the performance of the entire emergency response process.

Fig. 1 shows the relationship between emergency response tasks a_1, a_2 and a_3. There is a sequential relationship between a_1 and a_2, a_1 and a_3; a_2 and a_3 must be executed after a_1 is executed; and a_2 and a_3 can be executed in parallel.

Fig. 2 shows the relationship between the emergency response tasks shown in Fig. 1 in different situations. Assuming that task a_2 has a higher priority than a_3, when the emergency response personnel arriving at the scene are not sufficient of members to meet the requirements of a_2 and a_3 at the same time, task a_2 should be executed first, and then a_3. This may form two relationships shown in Fig. 2(a) and (b). Fig. 2(a) shows that the number of emergency personnel is less than or equal to the maximum number required by task a_2. At this time, all personnel perform a_2 first, and after task a_2 is completed, they execute a_3. Although a_2 and a_3 can be executed in parallel, they show a relationship of sequential execution in this condition. Fig. 2(b) shows that the number of emergency response personnel exceeds the maximum requirement for a_2 execution, but it is not enough to meet both a_2 and a_3 at the same time. At this time, emergency response personnel will give priority to the execution of a_2 in terms of allocation, and the remaining personnel will execute a_3. When the execution of a_2 is completed, and a_3 has not been finished yet, the personnel performing task a_2 will take part in the execution of task a_3. In this process, a_2 and a_3 are not a simple sequential or parallel relationship, but a mixed relationship.

Speed of action is very important for emergency response. The emergency response process needs to race against time, every minute of emergency work is very critical. Emergency personnel need to take measures as soon as possible to control the accident and reduce losses. Therefore, the time performance of an emergency response needs investigation.

After considering the execution characteristics of emergency response tasks, the relationship between them may change dynamically with the change of the number of personnel who execute the corresponding task, which makes the time of emergency response also dynamically change. Take the emergency response tasks in Figs. 1 and 2 as an example, assuming that the execution time of actions a_1, a_2 and a_3 when there are enough personnel are τ_1, τ_2 and τ_3, respectively, the duration of the emergency response process in Fig. 1 is τ_1+max(τ_2, τ_3). In the case of insufficient personnel as shown in Fig. 2(a), the emergency response duration is $\tau_1+\tau'_2+\tau'_3$, τ'_2 and τ'_3 are the execution time of a_2 and a_3, generally $\tau'_2>\tau_2$, $\tau'_3>\tau_3$; In the case shown in Fig. 2(b), the duration of the emergency response is $\tau_1+\tau_2+\tau''_3$, where τ''_3 is the time to execute task a_3. Generally speaking, $\tau''_3>\tau_3$. Here τ'_2, τ'_3 and τ''_3 may vary with the number of people participating in the emergency task.

Assuming that a certain task requires at least 1 person and at most N people to perform it, the execution time of the task and the number of people performing the task meet a certain relationship:

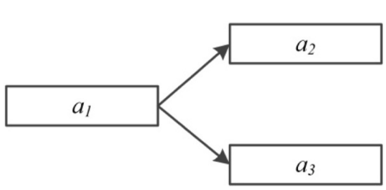

Fig. 1. The relationship between emergency response tasks: a sequential relationship between a_1 and a_2, a_1 and a_3, and a parallel relationship between a_2 and a_3.

$$D_x = f(x)$$

where, x indicates the number of people performing the task, and D_x is the execution time when x people perform the task together.

If the number of personnel participating in the task is $N_0, N_1, N_2, \ldots, N_n$ when the time is $Time_0, Time_1, Time_2, \ldots, Time_n$ respectively, we can obtain that when N_n emergency personnel participate in the task, the task's execution time becomes

$$D = \sum_{k=1}^{n} \Delta Time_k + \left(1 - \sum_{k=1}^{n} \frac{\Delta Time_k}{\tau_k}\right) \times f(N_n) \tag{1}$$

where, $\Delta Time_k = Time_k - Time_{k-1}$

$$\tau_k = \left(1 - \sum_{i=1}^{k} \frac{\Delta Time_i}{\tau_{i-1}}\right) \times f(N_k)$$

and, $\tau_0 = f(N_0)$

3. Methodology

3.1. Dynamic timed Petri-net

In this work, Petri-net is adopted to model an emergency response process. Generally, transitions can be used to express emergency response tasks or actions, places can be used for states or resources of the emergency response process. The execution mechanism of the traditional Petri-net is that the input places of a transition form the execution condition of the transition through tokens, and the token number of the connected places of the transition is changed by the transition after it is executed. In such an execution process, the execution time of the transition is not influenced by the tokens in places. In order to model the problem of emergency personnel affecting the execution of emergency response tasks, some improvements should be made to the traditional Petri-net. Tokens are utilized to represent the personnel who perform emergency response tasks, and the execution time of the transition needs to be changed according to the number of tokens. Therefore, the dynamic timed Petri-net (DTPN) is redefined as follows:

$$DTPN = (P, T, A, W, D, M) \tag{2}$$

(1) P: is a finite set indicating places. In order to distinguish whether a place represents the system state or the resource, P is divided into two subsets P_S and P_R, representing the state and the resource places, respectively. A place can hold tokens which are denoted by dots. When the number of token in a place is large, the number can be also directly used in the place to express tokens. In general, a state place can hold at most one token, indicating that the system is in a certain state, and if the state place has no token, it means the system is not in that state. For resource places, the token number represents the number of resources.

(2) T: is a finite set representing transitions. In this study, in order to facilitate the modeling of the impact of dynamically changing of personnel on emergency response tasks, transitions are divided into two categories. One is the usual timed transition. Once the execution time of these transitions is determined, it will not change during the execution. This includes deterministic execution time and stochastic execution time. The other is the dynamic timed transition. The execution time of such transition is a function of the tokens in the input places. When the token number in the input places changes, the execution time of the transition will change accordingly. Thus, the set T is divided into two subsets T_U and T_D according to their execution time, representing the usual and dynamic transitions, respectively.

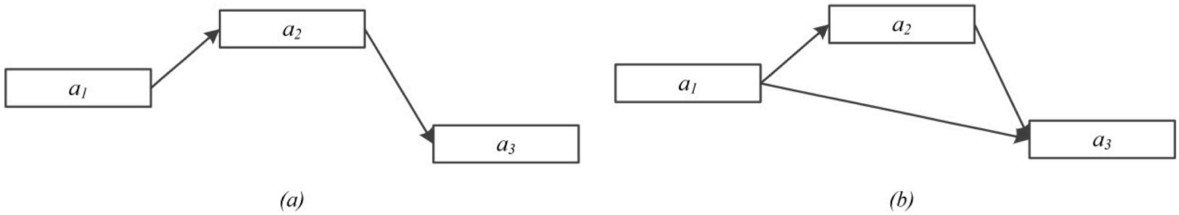

Fig. 2. Influence of execution characteristics of emergency response tasks on the relationship between the tasks.

(3) $A \subseteq P \times T \bigcup T \times P$: is the set of directed arcs connecting from places to transitions or from transitions to places. For a transition *t*, places connecting to it are called its input places and denoted as •t, and places connecting from it are its output places and denoted as t•. There is a special type of arcs called the inhibitor arc, which is used to inhibit the execution of transitions. If the places an inhibitor arc connected from have the required tokens, the execution of the transition it connected to is inhibited.

(4) $W: (P \times T) \bigcup (T \times P) \rightarrow N$, is a function that associates weights with arcs, where N is the natural number set. Each arc has its own weight, which is usually marked on the arc to indicate the token number constraint between the transition and the place. W(p, t) is a natural number, which means that if an arc is connected from p to t, the appropriate number of tokens in p is required to execute the transition t; and W(t, p) is a natural number which means that if an arc going from t to p, the number of tokens will be created in place p when transition t finishes its execution. The default value of the arc weight is one.

(5) $D: T \rightarrow R^+$, is the duration related to transitions, indicating the corresponding execution time. R^+ is a set of non-negative real numbers.

(6) $M: P \rightarrow N$, is the marking of the Petri-net, representing token numbers in places. M is represented by a vector, and its *i*-th element represents the number of tokens in the *i*-th place p_i, $p_i \in P$., which is denoted as $M(p_i)$. The initial marking of a net is usually expressed by M_0.

DTPN is a graphical modeling tool, and its elements are denoted by icons, as shown in Fig. 3.

In this study, in order to model the dynamic changes in the execution time of emergency response tasks, a new type transition is introduced, namely dynamic timed transition. The execution time of the transition is a function of the token number in the input places. The token number changes, and the execution time of the transition also changes. The execution mechanism of such transitions is similar to that of ordinary timed transitions. If there are tokens in the input places that can activate the transition, the transition determine its execution time dynamically according to the change of tokens in the input places using Eq. (1). After a dynamic timed transition is enabled, it can execute, and it removes tokens from its input places when it starts the execution and creates corresponding number of tokens in its output places. It is not restricted by the arc weight.

3.2. Modeling of emergency response tasks

For emergency response processes, we can usually represent states or resources using places and tasks/actions using transitions. Fig. 4 is the basic emergency task modeling mode, where transition *t* represents performing emergency response task *a*, place p_1 represents a resource constraint of the execution of task *a*, and place p_2 represents the resource after performing task *a*. The number of tokens in places represents corresponding number of resources. The execution of transition *t* requires *n* resources in place p_1, therefore, when *m* is greater than or equal to *n*, the transition *t* is enabled to execute. After transition t executes, the number of tokens in place p_1 becomes *m-n*, and *k* tokens are put into place p_2. The execution of transition *t* changes the marking of the Petri net from *M* to *M'*. The execution rule of transition *t* is expressed as Eq. (3).

$$M'(p_1) = M(p_1) - n, p_1 \in {}^*t \quad M'(p_2) = M(p_2) + k, p_2 \in t^* \tag{3}$$

For a state constraint of a task, the modeling is similar. The duration of transition *t* corresponds to the execution time of task *a*.

The execution process of tasks whose execution time varies with the number of people is modeled in Fig. 5. When transition t is enabled or the number of tokens in the input place p_1 changes, it calculates its execution time using Eq. (1), and after the execution time has passed, it removes tokens from the input place p_1 and puts k tokens into the output place p_2. Transition *t* calculates its execution time according to the number of tokens in the input places and the execution time may thus dynamically change. Places p_1 and p_2 can represent available emergency response personnel.

The execution of transition *t* also changes the marking of the Petri net, e.g., from *M* to *M'*. The execution rule of transition *t* shown in Fig. 5 is expressed as Eq. (4).

$$M'(p_1) = M(p_1) - k, p_1 \in {}^*t \quad M'(p_2) = M(p_2) + k, p_2 \in t^* \tag{4}$$

In this work, emergency response personnel are regarded as a kind of emergency resources, which are represented by resource places. If an emergency response task has the requirements of the minimum and the maximum number of executives, the model shown in Fig. 6 can be established to represent it. The two transitions t_{i_1} and t_{i_2} control the allocation of minimum and maximum personnel, respectively, and transition t_{i_3} represents the actual execution of the corresponding emergency task. The two control places p_{ci_1} and p_{ci_2} realize the control of the minimum and the maximum people respectively. The value min of the arc (p, t_{i_1}) represents the minimum number of people required, that is, when the token number *x* in place *p* is greater than or equal to *min*, the transition t_{i_1} will execute. After t_{i_1} is executed, min tokens are created in place p_{i_1}, and *max-min* tokens are generated in p_{ci_2}, so that when there are enough tokens in place *p*, t_{i_2} can execute *max-min* times, and generate *max-min* tokens in p_{i_1} (weights of arcs connecting to and from

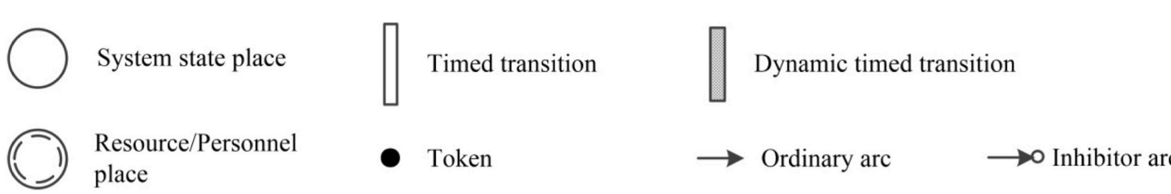

Fig. 3. Elements of DTPN.

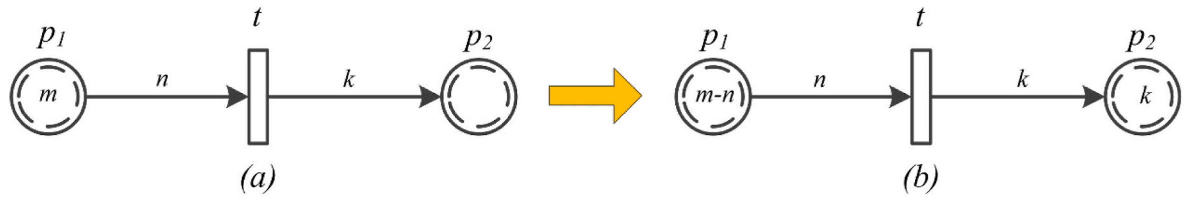

Fig. 4. Transition execution process of emergency tasks with deterministic execution time.

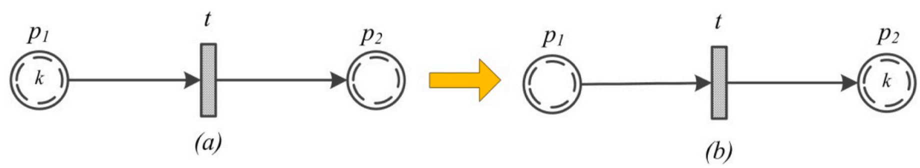

Fig. 5. Modeling of execution process of tasks whose execution time varies with the number of people.

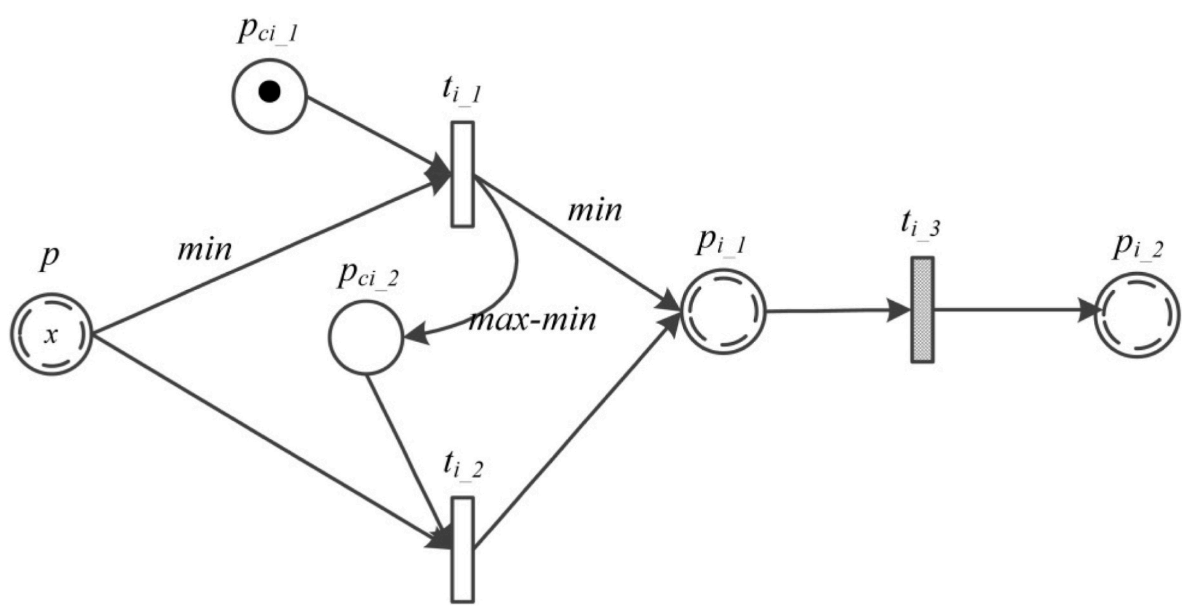

Fig. 6. Petri-net model for the task with minimum and maximum personnel requirements.

t_{i_2} are all 1). When there is another token in p, t_{i_2} cannot be enabled because there is no token in p_{ci_2}, so there are at most max tokens in p_{i_1}. The role of transitions t_{i_1} and t_{i_2} is to control personnel assignment, which does not represent actual emergency task. The execution time can be set to zero. The execution of t_{i_3} is determined by the number of tokens entered into p_{i_1} and the corresponding time.

Fig. 7 is a Petri-net model for some tasks with only lower limit requirement of personnel. Transitions t_{i_1} and t_{i_2} are still used to control

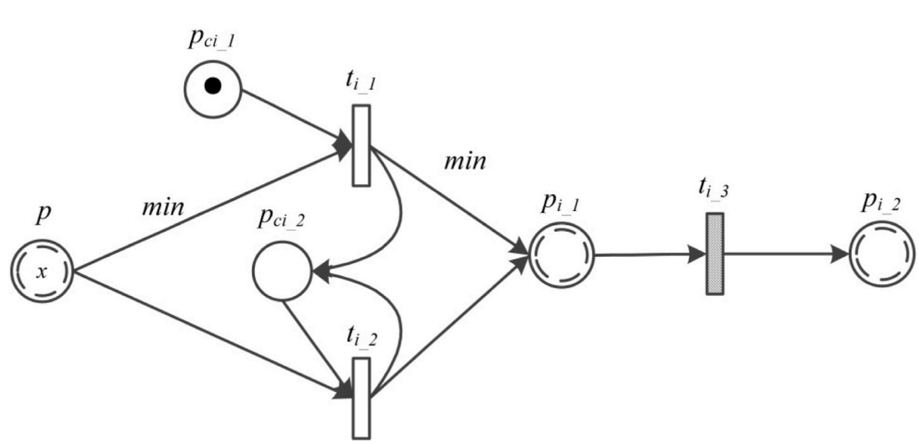

Fig. 7. Petri-net model for task with lower personnel limit.

personnel allocation. Unlike the model in Fig. 5, one token is generated in place p_{ci_2} after transition t_{i_1} executes. The execution of transition t_{i_2} requires a token in p_{ci_2}. Thus, transition t_{i_2} can be executed only after t_{i_1} completes its execution, that is, after the minimum personnel requirement is met. Every time t_{i_2} executes, the token in p_{ci_2} is removed, and another token is generated in p_{ci_2} to enable subsequent execution of t_{i_2}. In this way, as long as there are tokens in place p, transition t_{i_2} will continue to execute, and a token will be generated in place p_{i_1} every time t_{i_2} executes.

4. An illustrative example

A petrochemical company is an environmental-friendly enterprise specializing in the storage of commercial liquid chemical products and the treatment of sewage oil and water, including four areas: loading and unloading operation area, storage tank area, wharf operation area, and office area. The company currently has a wharf with a docking capacity of 20,000 tons and 35 vault storage tanks, including 25 carbon steel tanks and 10 stainless steel tanks, with a storage capacity of 100,000 cubic meters. The company mainly provides customers with liquid bulk storage, distribution and transit services such as alcohols, benzenes and aromatic hydrocarbons. Every department and every employee has the obligation to participate in accident rescue and relief. In order to actively respond to potential accidents, take effective measures in a timely manner, organize accident rescue and relief work in an efficient and orderly way, and minimize casualties and property losses, the company has formulated emergency response plans for accidents.

The requirements in the event of a fire in the cargo in a storage tank are as follows.

(i) Report to emergency response department (only 1 person required)
(ii) Rescue the wounded to a safe area (maximum 2 persons per wounded)
(iii) Close the valves of corresponding storage tank and pipelines (1–3 people are required)
(iv) Open the valves of water deluge system and fire-fighting pipeline of the fire tank and adjacent tanks, to cool the fire tank and adjacent storage tanks for protection (1-3persons); Open the valves of fire-fighting foam pipelines of the fire tank, start the 1#

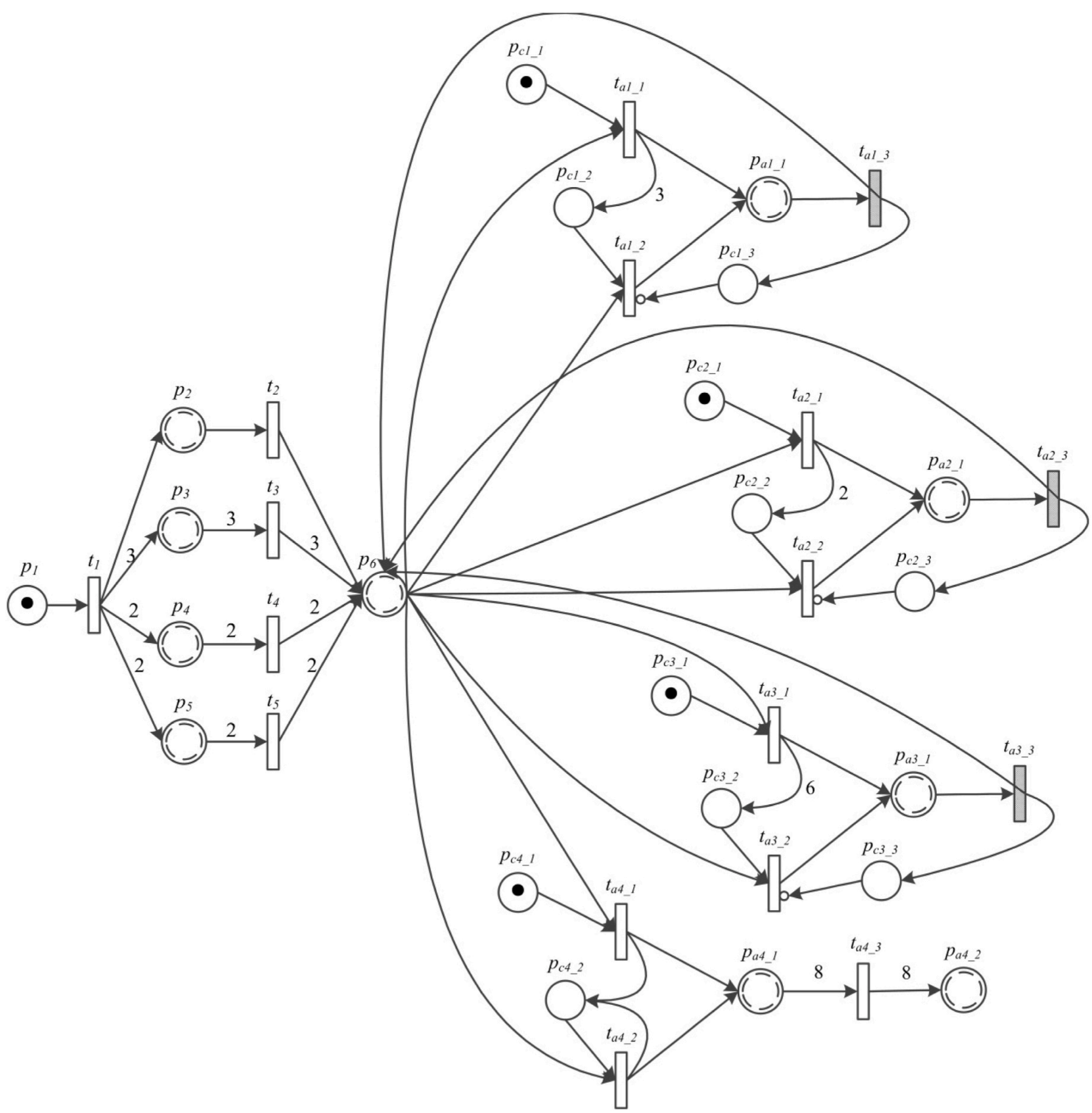

Fig. 8. Petri-net model of emergency response process of on-site employees.

and 2# fire-fighting pumps, start the fire-fighting foam system, and open the main liquid outlet valve of the foam pipeline, the water inlet valve and the liquid outlet valve of the foam tank (1–4 people).

(v) Use cart-type or portable fire extinguishers to put out the fire, and dredge the roads to facilitate the fire brigades to enter the scene (unlimited).

In the previous study of Zhou and Reniers (2016), a timed colored hybrid Petri-net tool was developed with Java language, it is adjusted in this work to achieve dynamic timed Petri-net modeling, mainly to adapt to the dynamic changes in transition times. A Petri-net model is established for the emergency response process of on-site employees, as shown in Fig. 8, here it is assumed that there are two injured persons. The model shows the emergency response process of the company's 3 departments and a person responsible for reporting the fire to emergency response agencies. They all can perform emergency tasks (ii) to (v). Place p_6 indicates that emergency response personnel are waiting for emergency tasks, and it is connected to multiple transitions as an input place, representing a number of different tasks that personnel can perform. Places p_{ci_3} ($i = 1, 2, 3$) can inhibit the execution of the transition to which it connects. Their function is to avoid continuing to assign personnel to execute the task when the corresponding task has not reached the upper limit of executors, but the task has been finished.

In order to avoid conflicts, there is usually a priority order between tasks. In an accident, the emergency response follows the principles such as saving people is prior to saving things, preventing a fire from spreading is prior to extinguishing the fire. Therefore, for the emergency response tasks, task (ii) has higher priority than task (iii), task (iii) has higher priority than task (iv), and task (iv) has higher priority than task (v). In order to simplify the model, the priority of the tasks is not modeled, and it is only distinguished by the execution order of the transitions. The meanings of places and transitions are shown in Tables 1 and 2, respectively.

A Petri-net model is executable. It makes tokens move from place to place through the execution of transitions, thereby revealing the evolution of the system. On the basis of the established model, the specific emergency response process can be analyzed. For usual timed transitions, the transition time can be determined according to the execution of emergency response actions, and the execution time from t1 to t5 is set to satisfy a certain log-normal distribution. The execution time of transitions t_{a1_1}, t_{a1_2}, t_{a2_1}, t_{a2_2}, t_{a3_1}, t_{a3_2}, t_{a4_1} and t_{a4_2} is 0. Transition t_{a4_3} satisfies an exponential distribution. In this work, it is assumed that the execution time of dynamic timed transitions is linear with the number of tokens in the input places. The marking of the Petri-net consists of tokens in places p_1, p_2, p_3, p_4, p_5, p_6, p_{c1_1}, p_{c1_2}, p_{c1_3}, p_{a1_1}, p_{c2_1}, p_{c2_2}, p_{c2_3}, p_{a2_1}, p_{c3_1}, p_{c3_2}, p_{c3_3}, p_{a3_1}, p_{c4_1}, p_{c4_2}, p_{a4_1} and p_{a4_2}, reflecting the system state.

Case 1. Personnel from Department 1, Department 2, and Department 3 arrive the fire scene in chronological order.

The execution time of stochastic transitions is sampled to obtain the following sampling values (minute):

t_1:2.45 t_2:1.7 t_3:2.3 t_4:3.6 t_5:5.2 t_{a4_3}:1.6.

The emergency response process in this case is analyzed, and Table 3 shows the execution process of the model.

In the 3rd minute (2.45 min), transition t_1 completes its execution, and then t_2, t_3, t_4 and t_5 begin to execute. The execution time of t_2 is the smallest among them, the execution completes in the 5th minute (4.15 min), and a token is generated in p_6, indicating that the person has reported the accident to emergency agencies and he is free to perform other tasks. At this time, t_{a1_1} is enabled and executed, one token in p_{c1_1} is removed, 3 tokens are generated in p_{c1_2} meaning that 3 more people can come to rescue the wounded, and one token is generated in p_{a1_1} so that t_{a1_3} is executed, which means that the person reporting the accident to emergency agencies now goes to rescue the wounded. Since the execution time of t_{a1_1} is zero, the start time of t_{a1_3} is 4.15 min, and the

Table 1
Meanings of places of the Petri-net model in Fig. 8.

Place	Meaning	Place	Meaning
p_1	Occurrence of fire	p_2	Fire alarm is received by the person responsible for reporting to emergency agencies
p_3	Fire alarm is received by personnel of department 1	p_4	Fire alarm is received by personnel of department 2
p_5	Fire alarm is received by personnel of department 3	p_6	Emergency responders had no task at the scene of the fire
p_{c1_1}	Control of the minimum personnel requirement of rescuing the wounded	p_{c1_2}	Control of the maximum personnel requirement of rescuing the wounded
p_{c1_3}	Inhibition of the execution of transition t_{a1_2}	p_{a1_1}	Responders rescuing the wounded
p_{c2_1}	Control of the minimum personnel requirement of closing valves of tanks and pipelines	p_{c2_2}	Control of the maximum personnel requirement of closing valves of tanks and pipelines
p_{c2_3}	Inhibition of the execution of transition t_{a2_2}	p_{a2_1}	Responders closing valves of tanks and pipelines
p_{c3_1}	Control of the minimum personnel requirement of opening the water deluge system valves and the fire-fighting foam pipeline valves	p_{c3_2}	Control of the maximum personnel requirement of opening the water deluge system valves and the fire-fighting foam pipeline valves
p_{c3_3}	Inhibition of the execution of transition t_{a3_2}	p_{a3_1}	Responders opening the water deluge system valves and the fire-fighting foam pipeline valves
p_{c4_1}	Control of the minimum personnel requirement of fire-fighting and dredging roads	p_{c4_2}	Continuous control of responders required to fight fire and dredge roads
p_{a4_1}	Responders fighting fire and dredging roads	p_{a4_2}	Emergency response personnel completing tasks

Table 2
Meanings of transitions in the Petri-net model in Fig. 8.

Transition	Meaning	Transition	Meaning
t_1	Discover the fire and sound the alarm	t_2	Report the fire to emergency agencies
t_3	Personnel of department 1 rush to the fire scene	t_4	Personnel of department 2 rush to the fire scene
t_5	Personnel of department 3 rush to the fire scene	t_{a1_1}	Control the minimum personnel required for rescuing the wounded
t_{a1_2}	Control the maximum personnel required for rescuing the wounded	t_{a1_3}	Rescue the wounded to a safe area
t_{a2_1}	Control the minimum personnel required for closing valves of tanks and pipelines	t_{a2_2}	Control the maximum personnel required for closing valves of tanks and pipelines
t_{a2_3}	Close valves of tanks and pipelines	t_{a3_1}	Control the minimum personnel required for opening the water deluge system valves and the fire-fighting foam pipeline valves
t_{a3_2}	Control the maximum personnel required for opening the water deluge system valves and the fire-fighting foam pipeline valves	t_{a3_3}	Open the water deluge system valves and the fire-fighting foam pipeline valves
t_{a4_1}	Control the minimum personnel required for fire-fighting and dredging roads	t_{a4_2}	Continuously control personnel required for fire-fighting and dredging roads
t_{a4_3}	Fight fire and dredge roads		

Table 3
Simulation of the emergency response process of Case 1.

Time	Marking	Executed transitions
0	(1,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	
1	(0,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t1
2	(0,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t1
3	(0,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t1, t2, t3, t4, t5
4	(0,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t2, t3, t4, t5
5	(0,0,0,0,0,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t2, t3, t4, t5, ta1_1, ta1_2, ta1_3
6	(0,0,0,0,0,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t4, t5, ta1_3
7	(0,0,0,0,0,0,0,0,0,0,0,1,0,0,1,0,0,0,1,0,0,0)	t4, t5, ta1_3, ta2_1, ta2_2, ta2_3
8	(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,6,0,0,1,0,0,0)	t5, ta1_3, ta2_2, ta2_3, ta3_1, ta3_3
9	(0,0,0,0,0,0,0,0,4,0,0,0,3,0,0,0,0,0,0,1,1,0)	ta1_3, ta2_3, ta3_2, ta3_3, ta4_1
10	(0,0,0,0,0,0,0,0,4,0,0,0,3,0,0,0,0,0,0,1,1,0)	ta3_3
11	(0,0,0,0,0,0,0,0,4,0,0,0,3,0,0,0,7,0,0,1,0,0)	ta3_3, ta4_2, ta4_3
12	(0,0,0,0,0,0,0,0,4,0,0,0,3,0,0,0,7,0,0,1,0,0)	ta4_3
13	(0,0,0,0,0,0,0,0,4,0,0,0,3,0,0,0,7,0,0,1,0,8)	ta4_3

execution time of t_{a1_3} is determined to be 10 min according to one person rescuing the wounded. At 4.75 min, the execution of t_3 ends, and 3 tokens are generated in p_6, indicating that 3 emergency personnel from Department 1 arrive at the scene. At this time, t_{a1_1} cannot be enabled because there is no token in p_{c1_1}, and t_{a1_2} can be executed 3 times in a row, thus 3 more tokens are generated in p_{a1_3}, which means that 3 more people join the task of rescuing the wounded. At this time, the execution time of transition t_{a1_3} becomes 4.36 min according to the change of tokens in input places, and the t_{a1_3} execution ends at 8.51 min.

At 6.05 min, the execution of transition t_4 ends with 2 tokens generated in p_6, indicating that 2 people from Department 2 arrive at the scene. Since transition t_{a1_2} executes 3 times at 4.75 min, all 3 tokens in place p_{c1_2} have been removed. At 6.05 min, t_{a1_2} can no longer be enabled to execute. At this time, transition t_{a2_1} is enabled and start to execute, removing one token in p_6, generating 1 token in p_{a2_1} indicating that there is a person doing the work of closing the working valves of the tank, and creating 2 tokens in p_{c2_2} indicating that another 2 people can join to perform the task of closing the valves of the tank. Since there is a token in p_6, t_{a2_1} cannot be enabled because there is no token in p_{c2_1}. At this time, t_{a2_2} can be enabled. After the execution of t_{a2_2}, a token is removed from p_6 and p_{c2_2} respectively, and a token is generated in p_{a2_1} at the same time. As the execution time of t_{a2_1} and t_{a2_2} is zero, so at 6.05 min, there are 2 people to close the valves, transition t_{a2_3} starts to execute, and the execution time is determined to be 4 min. However, at 7.65 min, the execution of transition t_5 finishes, and two tokens are generated in p_6, indicating that two personnel from Department 3 arrive at the fire scene. Because there is still a token in p_{c2_2}, transition t_{a2_2} can execute again, thereby generating another token in p_{a2_1}, so that 3 people are closing the valves from 7.65 min, and the execution time is reduced to 2.8 min, so the task ends at 8.85 min.

The execution process of opening the valves of water deluge system pipelines and the fire-fighting foam pipelines is similar. The task starts at 7.65 min, at this time there is 1 person performing the task, at 8.51 min there are 5 people, and at 8.85 min there are 7 people. The final execution time is 2.96 min and the task ends at 10.6 min.

Case 2. Personnel of Department 2 arrive the fire scene first.

The personnel of Department 2 do not meet the maximum personnel requirements for rescuing the wounded, so the personnel from other departments must support the rescue of the wounded when they arrive. The execution times of stochastic transitions are sampled as follows:

t_1:1.76 t_2:4.13 t_3:3.35 t_4:2.16 t_5:5.63 t_{a4_3}:2.81.

The emergency response process is simulated as shown in Table 4.

The changes in the execution time of each emergency response task are shown in Table 5. At time 3.92 min, there are two persons engaging in rescuing the wounded, and at time 5.11 min, there are 4 persons rescuing the wounded. The execution time of the task correspondingly changes from 8 min to 4.6 min. The execution duration of transitions t_{a2_3} and t_{a2_3} changes similarly according to the change of persons and the time when the change occurs.

Table 4
Simulation of the emergency response process of Case 2.

Time	Marking	Executed transitions
0	(1,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	
1	(0,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t1
2	(0,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t1, t2, t3, t4, t5
3	(0,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t2, t3, t4, t5
4	(0,0,0,0,0,0,0,2,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t2, t3, t4, t5, ta1_1, ta1_2, ta1_3
5	(0,0,0,0,0,0,0,2,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t2, t3, t5, ta1_3
6	(0,0,0,0,0,0,0,0,0,0,0,1,0,0,1,0,0,0,1,0,0,0)	t2, t3, t5, ta1_2, ta1_3, ta2_1, ta2_2, ta2_3
7	(0,0,0,0,0,0,0,0,0,0,0,1,0,0,1,0,0,0,1,0,0,0)	t5, ta1_3, ta2_3
8	(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,6,0,0,1,0,0,0)	t5, ta1_3, ta2_2, ta2_3, ta3_1, ta3_3
9	(0,0,0,0,0,0,0,0,4,0,0,0,3,0,0,0,0,0,0,1,1,0)	ta1_3, ta2_3, ta3_2, ta3_3, ta4_1
10	(0,0,0,0,0,0,0,0,4,0,0,0,3,0,0,0,0,0,0,1,1,0)	ta3_3
11	(0,0,0,0,0,0,0,0,4,0,0,0,3,0,0,0,7,0,0,1,0,0)	ta3_3, ta4_2, ta4_3
12	(0,0,0,0,0,0,0,0,4,0,0,0,3,0,0,0,7,0,0,1,0,0)	ta4_3
13	(0,0,0,0,0,0,0,0,4,0,0,0,3,0,0,0,7,0,0,1,0,0)	ta4_3
14	(0,0,0,0,0,0,0,0,4,0,0,0,3,0,0,0,7,0,0,1,0,8)	ta4_3

Table 5
Changes of execution time of tasks of Case 2.

Transition(task)	Time(minute)	Persons	Execution duration (minute)
t_{a1_3}	3.92	2	8.0
	5.11	4	4.6
t_{a2_3}	5.11	1	6.0
	5.89	2	4.26
	7.39	3	3.16
t_{a3_3}	7.39	1	14.0
	8.27	4	
	8.52	7	2.93

Case 3. The maximum number of people required for a task is not reached, and the task completes before the new personnel arrive.

The execution times of stochastic transitions are sampled as follows: t_1:1.23 t_2:1.37 t_3:8.43 t_4:2.25 t_5:9.58 t_{a4_3}:1.76.

The execution of emergency response tasks are shown in Table 6. During the task of rescuing the wounded, the person reporting the accident to emergency agencies and the personnel of Department 2 arrive

Table 6
Simulation of the emergency response process of Case 3.

Time	Marking	Executed transitions
0	(1,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	
1	(0,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t1
2	(0,0,0,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t1, t2, t3, t4, t5
3	(0,0,0,0,0,0,0,3,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t2, t3, t4, t5, ta1_1, ta1_3
4	(0,0,0,0,0,0,0,1,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t3, t4, t5, ta1_2, ta1_3
5	(0,0,0,0,0,0,0,1,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t3, t5, ta1_3
6	(0,0,0,0,0,0,0,1,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t3, t5, ta1_3
7	(0,0,0,0,0,0,0,1,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t3, t5, ta1_3
8	(0,0,0,0,0,0,0,1,0,0,1,0,0,0,1,0,0,0,1,0,0,0)	t3, t5, ta1_3
9	(0,0,0,0,0,0,0,1,3,0,0,0,0,0,1,0,0,0,1,0,0,0)	t3, t5, ta1_3, ta2_1, ta2_2, ta2_3
10	(0,0,0,0,0,0,0,1,3,0,0,0,0,0,0,4,0,0,1,0,0,0)	t3, t5, ta2_3, ta3_1, ta3_2, ta3_3
11	(0,0,0,0,0,0,0,1,3,0,0,0,3,0,0,0,0,0,0,1,1,0)	t5, ta2_3, ta3_2, ta3_3, ta4_1
12	(0,0,0,0,0,0,0,1,3,0,0,0,3,0,0,0,0,0,0,1,1,0)	ta3_3
13	(0,0,0,0,0,0,0,1,3,0,0,0,3,0,0,0,7,0,0,1,0,0)	ta3_3, ta4_2, ta4_3
14	(0,0,0,0,0,0,0,1,3,0,0,0,3,0,0,0,7,0,0,1,0,0)	ta4_3
15	(0,0,0,0,0,0,0,1,3,0,0,0,3,0,0,0,7,0,0,1,0,8)	ta4_3

first. A total of 3 people finish the task of rescuing the wounded in 8.95 min, and transition t_{a1_3} creates 3 tokens in place p_6 after the execution. At this time, although place p_{c1_2} still has a token, there are already tokens in place p_{c1_3}, so that transition t_{a1_2} cannot be enabled. Therefore, t_{a2_1} is enabled to execute, and then transition t_{a2_2} executes. Three tokens are generated in place p_{a2_1}, and t_{a2_3} starts to execute. This shows that after rescuing the wounded, the three people continue to perform the task of closing the working valves of the tank, rather than waiting for other personnel to finish the task of rescuing the wounded. The changes in the execution time of each emergency response task are shown in Table 7.

From the above discussion, it can be seen that the time and number of emergency personnel arriving at the fire scene are different, and the emergency response is a dynamic process. Using Monte Carlo simulation to conduct a large number of replications or trials to simulate various situations, the performance of the emergency response process can be analyzed.

For a given emergency response time standard, assuming that SimC replications of Monte Carlo simulation are performed, and the number of emergency tasks completed within the given time is counted as *SimS*, the success probability Pr of the emergency response process can be obtained:

$$\mathrm{Pr} = \frac{SimS}{SimC}$$

Taking the 15 min required for the fire brigade nearby to arrive at the fire scene as a measure, through 10^5 simulation replications we can obtain that in the scenario determined in this example, the success probability of the emergency response process of the on-site personnel is 92 %, that is, in the studied scenario, there is a 92 % chance that emergency response personnel will be able to complete emergency tasks within 15 min. Increasing the number of trials, the results obtained have no difference.

5. Conclusions

A large number of hazardous chemicals are often produced or stored in the process industry, which can easily cause heavy losses in the event of an accident. Emergency response is an important measure to reduce accident losses. An important feature of emergency response is to respond quickly, to implement and complete corresponding actions or tasks as soon as possible. Emergency response is composed of many actions or tasks with different characteristics in execution, and analyzing the impact of these characteristics on execution time is helpful in arranging appropriate actions and resources.

Emergency response actions or tasks are performed by emergency personnel, such that this study focuses on the characteristics of different numbers of personnel in performing emergency tasks. The execution time of some tasks varies with the number of personnel, while others cannot. Moreover, different emergency personnel may join the corresponding task at different times, thus influence the execution of the task at different times. These factors make the execution time of emergency tasks have dynamic characteristics. The relationship between the task execution time and the number of personnel and the joining time of the personnel is deduced in this work.

In order to solve the modeling and analysis problem of emergency response tasks with dynamic execution time, on the basis of TPN, the execution mechanism of transition is improved to establish the dynamic timed Petri-net (DTPN). The execution process of a task is divided into two stages: personnel assignment and actual execution, which well solves the modeling of tasks with different execution characteristics.

The proposed approach is illustrated by taking the emergency response to a storage tank fire in a chemical plant. The emergency tasks such as rescuing the wounded, closing the fire storage tank and pipeline valves, and opening the valves of fire-fighting pipelines are considered. Time of emergency response processes that the emergency personnel arrive at different times is analyzed, and the success probability of the emergency response is obtained.

Table 7
Changes of execution time of tasks of Case 3.

Transition(task)	Time(minute)	Persons	Execution duration (minute)
t_{a1_3}	2.6	1	10.0
	3.48	3	6.35
t_{a2_3}	8.95	3	2.0
t_{a3_3}	9.66	3	10.0
	10.81	5	
	10.95	7	3.0

The proposed approach has the following advantages: it can model and analyze emergency response tasks or actions whose execution time may change dynamically, thus it can better reflect the real emergency response process; it can analyze the specific emergency response processes to reflect the states at different conditions and times; the probabilistic analysis of the emergency response process can be carried out through Monte Carlo simulation to evaluate the performance of the emergency response system. The limitations of the approach may be the Petri-net modeling is not easy to master and use by ordinary emergency personnel, and the approach will need to be integrated into easy-to-use software tools. In addition, it is necessary to improve the generality of the modeling and improve the adaptability of the model to different emergency response actions.

CRediT authorship contribution statement

Jianfeng Zhou: Writing – original draft, Methodology. **Genserik Reniers:** Writing – review & editing, Validation.

Declaration of competing interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Data availability

Data will be made available on request.

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