Emergency response actions modeling and time analysis
Considering priority of actions

Zhou, Jianfeng; Reniers, Genserik

DOI
10.1016/j.psep.2024.04.062

Publication date
2024

Document Version
Final published version

Published in
Process Safety and Environmental Protection

Process Safety and Environmental Protection 186 (2024) 1066–1075

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.journals.elsevier.com/process-safety-and-environmental-protection

Emergency response actions modeling and time analysis: Considering priority of actions

Jianfeng Zhou [a,*], Genserik Reniers [b,c,d]

[a] School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou 510006, China
[b] Faculty of Technology, Policy and Management, Safety and Security Science Group (S3G), TU Delft, Delft, BX 2628, the Netherlands
[c] Faculty of Applied Economics, Antwerp Research Group on Safety and Security (ARGoSS), Universiteit Antwerpen, Antwerp 2000, Belgium
[d] CEDON, KULeuven, Brussels 1000, Belgium

ARTICLE INFO

Keywords:
Emergency response
Dynamic relationship
Modeling of actions
Time analysis
Probability analysis
Petri-net

ABSTRACT

When a major chemical accident occurs, emergency response is an important measure to reduce accident losses. Some actions in an emergency response may be more important than others in reducing accident losses, so they need to be carried out as a matter of priority. The impact of the number of emergency personnel on the relationship between emergency response actions and time of emergency response process is analyzed in this paper in the circumstance that the number of responders is not enough to carry out emergency actions with priority at the same time, and a Petri-net based approach is proposed to model and analyze the actions. An emergency response action that needs to consider its priority is divided into two stages, one is to determine the personnel for executing the action, the other is the execution of the action. This division facilitates the handling of dynamic changes in the relationship between actions and differences in start time of the actions. The approach is illustrated by taking the emergency response of on-site emergency personnel of a chemical plant to a fire as an example. The efficiency of the emergency process is analyzed, and for the action of rescuing the wounded, which has the highest priority in the example, the time and the probability when considering the priority of emergency response actions are compared with those when not considering the priority.

1. Introduction

In petrochemical and other process industries, a large number of flammable, explosive or toxic substances often need to be handled or stored. If these substances catch accidents, they are easy to impact a large area, resulting in great losses. Risk management requires the control of the risk of these facilities, mainly from two aspects: (i) reducing the occurring likelihood of accidents, such as managing equipment to keep a safe state and training personnel to avoid unsafe actions; and (ii) reducing the losses caused by an accident, such as using the safety barriers to prevent the accidents from escalating (Khakzad et al., 2014; Misuri et al., 2021).

The main purpose of risk management is to identify potential hazards in a system and to determine safety measures to reduce the likelihood and consequence of hazards (Rasmussen, 1997). In ISO 17,776 (ISO, 2000), safety measures are divided into five categories: prevention, detection, control, mitigation and emergency response. Emergency response is an important measure to reduce accident losses. Effective emergency response can timely shutdown the system operation, rescue the injured, transport the threatened materials, and prevent the spread of accidents (Landucci et al., 2015; Chen et al., 2020; Jiang et al., 2022; Li et al., 2022). A reasonable arrangement and efficient operation of the emergency response system can greatly reduce an accident loss after the occurrence of the accident. Therefore, in the safety assessment or risk analysis of a system, the corresponding emergency response system is also an important factor to evaluate the risk.

An emergency response process is composed of a series of actions, and each action may also require certain emergency resources, which are arranged in advance of a potential accident, and if the actions are improperly arranged, it may have serious consequences at the time of responding to the accident. Therefore, it is necessary to analyze the emergency actions before the occurring of the accident, evaluate the efficiency of the actions and optimize the actions reasonably.

The execution of emergency response actions has a great impact on the efficiency of an emergency response process. If the actions are not correct, they may even cause serious consequences, such as unstructured

* Corresponding author.
E-mail address: jf.zhou@gdut.edu.cn (J. Zhou).

https://doi.org/10.1016/j.psep.2024.04.062
Received 16 November 2023; Received in revised form 27 February 2024; Accepted 14 April 2024
Available online 16 April 2024

emergency operations responding to the fire occurred at the West Fertilizer Company in West, Texas, USA in 2013, and the improper actions in the emergency response to the fire which occurred in the hazardous chemicals warehouse located in Tianjin Port of China in 2015 (MAH-Bulletin, 2017). Many researchers have studied the efficiency of emergency response, using many different methods. Jackson et al. (2011) employed the failure mode effects and critically analysis (FMECA) method to analyze the bottleneck of the emergency response system and the input and output ratio of failure modes. Zhou et al. (2011) adopted a fuzzy DEMATEL (decision making trial and evaluation laboratory) approach to identify critical success factors (CSFs) in emergency response process. Dhingra and Roy (2015) proposed an optimization model to reflect the impact of evacuation delay, availability of limited resource, and costs related to resource allocation in emergency response. Ping et al. (2018) used the task network mapping approach to improve emergency response collaboration and resource allocation. Song et al. (2021) combined the Multilevel Flow Modeling (MFM) method and the Go-Flow method to strengthen emergency response planning. Khan et al. (2023) developed a smart model using machine learning to predict the motion of smoke, so as to improve the fire design and support firefighting.

The efficiency of an emergency response process is mainly reflected in time. After an accident occurs, it is necessary to take emergency response actions as soon as possible, to save the wounded and properties, to prevent the accident from spreading and to put out the accident. In practice, time is often used to assess emergency responses. Many researches also concern the time nature of the emergency response. Kang (2007) provided the analysis of emergency evacuation of the middle-platform train fire in a subway station, and the time-based evacuation was discussed in view of the inability of the stairway access due to the blockage of the smoke. Chow and Ng (2008) studied the evacuation waiting time in crowded transport terminals, and proposed a waiting time index (WTI) to measure the congestion at exits. Chu and Wang (2011) analyzed the time uncertainty of the evacuation of the occupants in emergency situations. Palazzi et al. (2015) provided an approach to evaluate the effectiveness of safety system and developed a framework to identify response actions and intervention times and how to implement these measures. Park et al. (2016) used Geographic Information Systems to analyze fire responders' response times. Bandyopadhyay and Singh (2016) used an agent based approach to predict the emergency response time by analyzing the spatial trajectories determined from GPS data. Chai et al. (2018) proposed an emergency resource scheduling approach for traffic incidents according to travel time estimation of rescue route. Liu et al. (2022) performed an analysis using a Hierarchical Timed Color Petri Nets (HTCPN) model to minimize the emergency response time and the number of firefighters.

The previous studies on emergency response analyzed the response efficiency or emergency time from many different aspects, such as the allocation and use of emergency resources, the cooperation of emergency response agencies, emergency decision-making efficiency, and the uncertainty of emergency evacuation, but the possible priority of emergency response actions was not considered. During an emergency response, losses may be more reduced if some actions are performed first. Therefore, after the occurrence of an accident, some emergency response actions should be performed according to the priorities of the action objectives, so that some emergency response actions have priorities among them. For example, when rescuing people and property, we should save people first and then save the property. When rescuing the wounded, we should first save the seriously wounded and then save the lightly wounded. The priority of emergency actions has an impact on the implementation of emergency actions, and then influences the efficiency of emergency response progress. It brings new problems to the time analysis of emergency response, which has not been paid attention to in previous studies.

An emergency response process often involves a lot of people and substances, and consists of a series of actions. Some graphical methods are used to model and analyze the emergency response process. For example, Bayesian network is a probabilistic graph model that describes random variables and their conditional dependence with directed acyclic graphs, and some researchers used it to analyze emergency response. Khakzad et al. (2017) utilized the Bayesian network to assess the performance of the fire protection system, including emergency response measures. An et al. (2023) used it for the resilience assessment of the emergency response system.

Petri-net is also a powerful graph modeling tool. There are usually sequence, parallelism and other relationships between emergency response actions, and Petri net is suitable to model and analyze these relationships. The concept of Petri-net was first proposed by Carl Adam Petri in 1962 (David and Alla, 1994). Petri-net is a graphical modeling and analysis tool which is composed of elements including places, transitions, arcs and tokens. Petri-net has become a common mathematical and graphic tool for the modeling of parallel systems (Peterson, 1981). In order to facilitate the modeling of different problems, the basic Petri net has some extensions. Timed Petri-net (TPN) allocates times to the transitions or places of a Petri-net so that the activity duration can be considered and incorporated into the model specification (Zuberek, 1991). Thus, it has an advantage over time or performance analysis of a system and is widely used in many fields (Peng et al., 2015; Komenda et al., 2016; Pelz, 2018; Lisboa et al., 2019).

Petri-net and its various extensions have been used to model and analyze emergency response processes. Zhong et al. (2010) adopted the stochastic Petri-net model to study the performance of an urban emergency response system. Zhou (2013) studied emergency response actions using a colored hybrid Petri net (CHPN), and discussed the liveness of the Petri-net model and the conflict possibly existing between emergency actions. Liu et al. (2015) presented a Petri net-based model to model which is called E-Net to analyze an emergency response process, focusing on the key activities analysis. Li et al. (2016) utilized a Petri-net approach to model and analyze the key-tasks of subway fire emergency response processes. Zhou and Reniers (2016) used a Timed Colored Hybrid Petri-net (TCHPN) approach to model cooperation modes of emergency actions on using resources, they further proposed a TCHPN approach to analyze different emergency response actions according to their efficiency in preventing or delaying the domino effect (Zhou and Reniers, 2018). In this work, timed Petri-net (TPN) is utilized to analyze emergency response process considering priority of emergency response actions due to its advantages in modeling and time analysis.

The rest of this paper is organized as follows. Section 2 discusses the influence of the priority of emergency response actions on relationships between actions and the time analysis. In Section 3, the definition of Petri-net is presented and the modeling of emergency response actions with priority is discussed. How to use the proposed modeling approach is illustrated by an example in Section 4. Finally, Section 5 draws the conclusions of this work.

2. Priority of emergency response actions and time analysis

An emergency response process consists of many actions, and there is a certain relationship between the actions, which has been discussed in previous studies. The basic relationship is:

Sequential: When one action is over, another action begins.

Parallel: Two or more actions can be executed simultaneously and their execution does not influence each other.

However, in an emergency response process, if the priority of an action is taken into account, the relationship between emergency response actions will be influenced accordingly. Since the sequential relationship has determined the order of actions, this work focuses on the impact of priority on parallel actions.

Fig. 1 shows a simple example of the relationship between emergency actions a_1, a_2, and a_3. These three actions have a parallel relationship that they can be executed simultaneously without influencing each other.

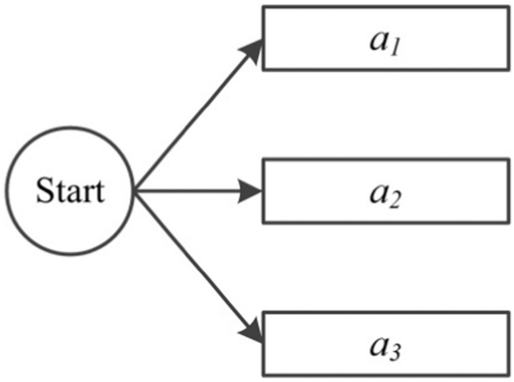

Fig. 1. Parallel relationship between emergency response actions a_1, a_2, and a_3.

According to the role of emergency response actions in reducing accident loss, the actions often have certain priorities. Emergency response actions are constrained by certain resources, for example, emergency actions are carried out by corresponding emergency response personnel, and a certain number of the personnel are usually required to complete an emergency action. In considering the priority of an action, different numbers of emergency personnel may lead to different relationships between the same emergency response actions. Fig. 2 and Fig. 3 reflect different relationships of the emergency response actions shown in Fig. 1 with different resources (number of personnel). It is assumed that actions a_1, a_2 and a_3 all require only one person to execute, a_1 has higher priority than a_2, and a_2 has higher priority than a_3. When there are three emergency responders, actions a_1, a_2 and a_3 can be executed in parallel at the same time; when the emergency responders are not sufficient to execute a_1, a_2 and a_3 at the same time, a_1 should be executed first, then a_2, and finally a_3. This will form many different relationships. Fig. 2 shows the order of execution when there is only one emergency response personnel. At this time, the emergency response actions a_1, a_2 and a_3 show a sequential relationship.

When there are two emergency responders, the relationship of a_1, a_2 and a_3 is shown in Fig. 3. At this time, the emergency actions a_1 and a_2 can be executed in parallel at the same time, and then a_3 is performed. Fig. 3(a) shows that the execution time of the action a_2 is shorter than that of a_1, so that the corresponding person goes to perform a_3 after the execution of a_2, and a_2 and a_3 are in the sequential relationship. Fig. 3(b) shows that the execution time of the action $a_1$is shorter than that of the a_2, so that the corresponding person goes to perform a_3 after the execution of a_1, where a_1 and a_3 show the sequential relationship.

2.1. Dynamics of time

In the emergency response to an accident, the emergency personnel needs to take measures as soon as possible to control the accident and reduce the loss, so the time of the emergency response process plays an important role in the success of the emergency response. The priority of emergency response actions also have an impact on the time performance of an emergency response process, because the relationship between emergency actions may change dynamically with the change of

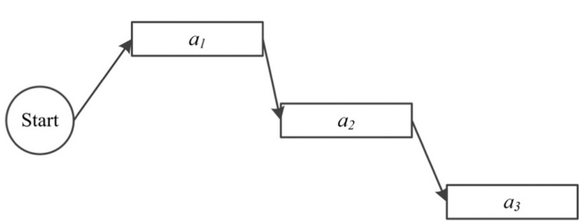

Fig. 2. The relationship between a_1, a_2 and a_3 shown in Fig. 1 for only one emergency responder.

emergency resources (such as the number of personnel), so that the time of emergency response also changes dynamically. Take the emergency response actions shown in Fig. 1 to Fig. 3 as an example, and the execution time of actions a_1, a_2 and a_3 is denoted as τ_1, τ_2 and τ_3, respectively. The time of emergency response process (with three people) in Fig. 1 is max (τ_1, τ_2, τ_3). In the case shown in Fig. 2 (with 1 person), the emergency response time is $\tau_1+\tau_2+\tau_3$; for the case with 2 emergency responders, the emergency response time is $\tau_2+\tau_3$ as shown in Fig. 3(a), where $\tau_2>\tau_1$; for the case shown in Fig. 3(b), the time of the emergency response process is $\tau_1+\tau_3$, where $\tau_1>\tau_2$.

This simple example only discusses the changes in the relationship between three actions when their priorities are considered. If there are more actions (e.g., K actions), the relationship between them will be more complex. In addition, emergency personnel (or other resources) often do not arrive at the same time, hence the arrival at different times will also have an impact on the implementation of the actions, and impacts on the time of the emergency response process. Therefore, it is very difficult to use the analytical expression to express the time of the emergency response process, and the use of Petri-net simulation method can solve this problem well.

3. Petri-net modeling and analysis approach

3.1. Timed Petri-net

Petri-net is a special kind of directed graph composed of nodes and directed arcs. A Petri-net has two kinds of nodes, which are places and transitions. Each arc connects from a place to a transition or from a transition to a place, and is assigned a weight which reflects the number of tokens to be consumed for the execution of a transition or the number of tokens assigned to a place after the execution of a transition. However, the original Petri-net does not have any mechanism to handle the time of system activities. Timed Petri-net (TPN) was proposed to solve this problem. Well-defined semantics can help TPN clearly model the behavior of a net. In TPN, each transition, position, and / or directed arc can have an execution (firing) time or interval (Zhou and Venkatesh, 1998). In this work, transitions are used to represent emergency response actions with certain duration and thus only transitions have time delays in TPN. It is worth noting that in the set of transitions, there exists two types of transitions, one is immediate transitions which execute without time delay, and the other is timed transitions which execute with temporal delays. Timed transitions can also be divided into two types: 1) random transitions whose execution takes a random delay; 2) deterministic transitions whose execution takes a constant time. Thus, a timed Petri-net can be formally defined as

TPN = (P, T, A, W, H, M)

where:

$P = \{p_1, p_2, \ldots, p_n\}$, is a non-empty and finite set of places which can hold tokens;

$T = \{t_1, t_2, \ldots, t_m\}$, is a non-empty and finite set of transitions. $T = T_e \bigcup T_d$, is divided into two subset T_e and T_d, immediate transitions and timed transitions.

$A \subseteq P \times T \bigcup T \times P$, is the finite set of arcs connecting places to transitions ($P \times T$) and transitions to places ($T \times P$). For a transition t, its input places are denoted as $^\bullet t$, and its output places are denoted as $t^\bullet$.

$W: (P \times T) \bigcup (T \times P) \rightarrow N$, is the function of relating weights to arcs, where N is the set of natural number. A weight of an arc means the multiplicity of the arc. W(p, t) is a natural number indicating the arc multiplicity if an arc going from p to t, indicating the number of tokens in place p required by the execution of transition t; and W(t, p) is a natural number indicating the arc multiplicity if an arc going from t to p, indicating the number of tokens created in place p after the execution of transition t. The default value of the weight of an arc is one.

$H: T \rightarrow R^+$, is the time related to transitions, R^+ is a set of non-

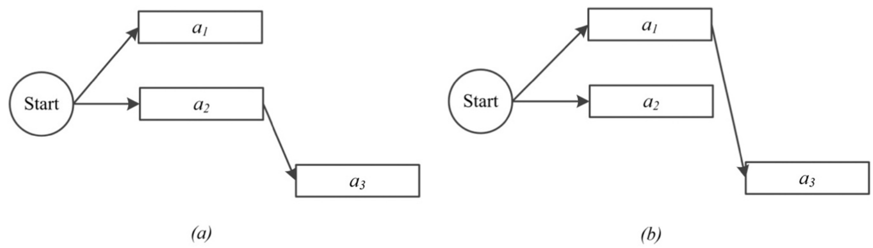

Fig. 3. The relationship of a_1, a_2 and a_3 shown in Fig. 1 with two emergency responders.

negative real numbers.

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

A transition t ($t \in T$) is enabled at marking M if and only if for each $p \in {}^\bullet t$:

$$M(p) \geq W(p, t) \quad (1)$$

Transition t can fire/be executed if it is enabled. As transition t may have a executing duration, the execution of the transition lasts for a certain time. The execution of transition t changes the marking of the Petri-net to M'. At the beginning of its execution,

$$M'(p_i) = M(p_i) - W(p_i, t),\ p_i \in {}^\bullet t \quad (2)$$

and after t executes,

$$M'(p_i) = M(p_i) + W(t, p_i),\ p_i \in t^\bullet \quad (3)$$

The Petri-net is a graphical modeling method that represents the system evolution with icons and directed arcs. In TPN modeling, circles are used to represent places and rectangles are used to represent transitions. The icons are shown in Fig. 4.

3.2. Modeling of the relationship between emergency response actions

For modeling of an emergency response process, we can usually use places to represent states or resources, and transitions to represent actions. Fig. 5 is a basic mode of emergency response action modeling, where transition *t* represents the execution of emergency response action *a*, place p_1 represents the state before action *a* is executed, and place p_2 represents the state after action *a* is executed. Moreover, place p_1 may also represent a condition for the execution of action *a*, and p_2 may represent a condition for subsequent action execution. The duration of the transition *t* corresponds to the execution time of action *a*.

When considering the priority of an action, the action can be modeled in the way shown in Fig. 6. Place p_r represents available emergency response personnel and the personnel number is denoted by tokens in it. The number of emergency personnel required by the execution of action a_i is em_i. Taking into account that multiple actions with priorities can also be performed in parallel, the implementation of emergency response action a_i is divided into two phases: the first phase is the allocation of personnel, which is to assign required number of personnel to an action in accordance with the priority order, and the second is the implementation of the emergency response action, to achieve the corresponding action target. The execution of these two stages of action a_i is represented by transition t_{i_1} and t_{i_2} respectively. Transition t_{i_1} completes the personnel allocation of action a_i, and its execution time can be regarded as zero, thus t_{i_1} can be expressed by an immediate transition. Place p_{i_1} represents the emergency response personnel who carry out action a_i. Transition t_{i_2} completes the task of action a_i, its execution time corresponds to the execution time of action a_i, and place p_{i_2} indicates the state after the execution of emergency action a_i.

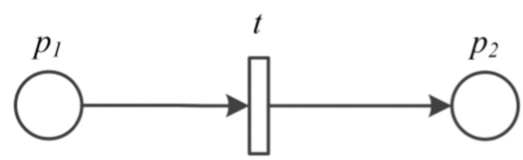

Fig. 5. Modeling of emergency response action with Petri-net.

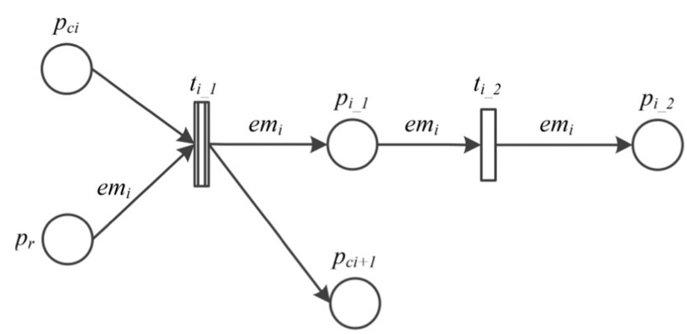

Fig. 6. Modeling of emergency response action considering priority.

In these two phases of an emergency action, priority is reflected only in the allocation of personnel, namely in the first phase. In order to control the priority of an emergency response action a_i, a control place p_{ci} is added for transition t_{i_1}. When there is a token in place p_{ci}, transition t_{i_1} can be executed (the execution of transition t_{i_1} requires at least one token in place p_{ci}), so that the execution of action a_i can be controlled through tokens in place p_{ci}. Accordingly, transition t_{i_1} has an output place p_{ci+1}, and after transition t_{i_1} is executed, it generates a token in p_{ci+1} to control the lower priority action, that is, personnel of action a_i must be satisfied before satisfying the need of lower priority action a_{i+1}.

On this basis, the Petri-net model for *K* emergency response actions (a_1, a_2, …, a_K) whose priorities need to be considered during their execution is shown in Fig. 7, assuming that the priority of these *K* actions

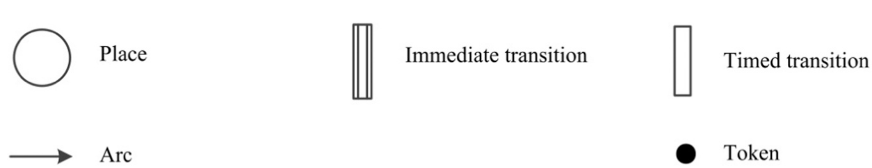

Fig. 4. Icons used by TPN.

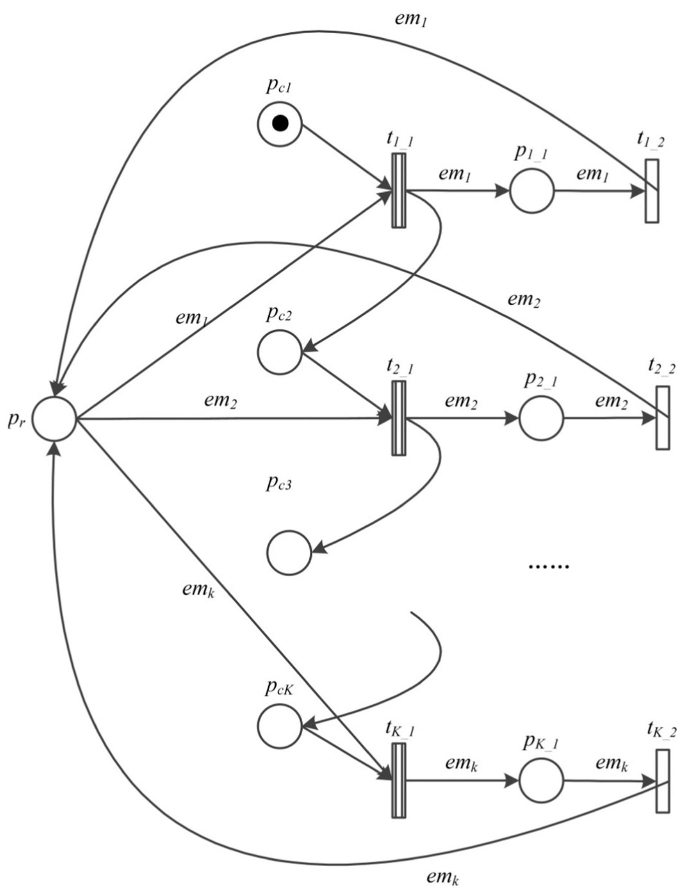

Fig. 7. Petri-net model for *K* emergency response actions (a_1, a_2, …, a_K) whose priorities need to be considered.

is $a_1 > a_2 > \ldots > a_K$. At the beginning, place p_{c1} which controls the personnel allocation of the action with the highest priority (a_1) has a token, and other places from p_{c2} to p_{cK} has no token, so only personnel for action a_1 can be assigned. When the personnel performing action a_1 has been determined (after the execution of t_{1_1}), one token is created in place p_{c2}, at this time personnel allocation of action a_2 can be performed (enabling and executing of t_{2_1}). In this way, it is possible to assign personnel to each action according to the priority order. Place pr represents the personnel that can be used for allocation. It is also used here as an output place for transitions t_{i_2} (i=1, 2, …, K) which represent the execution of corresponding actions. This means that after the completion of action a_i (after the execution of t_{i_2}), the emergency response personnel performing it may in turn be reassigned to other actions.

Because of the complexity of the relationship between *K* emergency response actions with priority, it is difficult to express the emergency response time with a fixed formula. However, using the execution mechanism of Petri net, the time analysis can be carried out by simulation. Token in the Petri-net is given a time attribute to record the time of generating the token. When the transitions are executed, the time of the tokens in the output places is determined according to the time of the token in the input places and the execution time of the transition. In this way, the time of the emergency response process in different situations can be obtained through the execution of the Petri-net and the time of the tokens.

3.3. Analysis of emergency response

Under the condition that emergency response actions need to be considered in a certain priority, and considering the uncertainties in the execution of each action, the success or failure probability of an entire emergency response process can be analyzed by analyzing the time of the emergency response process. The uncertainties in the emergency response process mainly include the following aspects:

(1) Emergency personnel arrive at the scene and join the emergency response at different times. Different emergency personnel have different distances from the scene, and their travel speed is different, so the time to arrive at the scene is generally different.

(2) The execution time of emergency response actions is different. There may be differences in the time for the same person to carry out the same action, and there will be time differences when different people perform the same action.

(3) The priority of emergency response actions makes the relationship between emergency actions uncertain. As mentioned earlier, the relationship between emergency response actions varies with the number of personnel involved in the response and the duration of actions.

These uncertainties make the time of the emergency response process uncertain, and it is difficult to formalize the time with an expression. Although some methods might be used for time analysis, e.g., multi-agent systems and dynamic Bayesian networks, advantages of Petri-net make it very suitable to solve this type of problem. Timed Petri-net has the following advantages (Wang, 1998):

It can intuitively describe the behavior of a system, making the system model and the analysis process easy to understand.

It is easy to develop powerful analysis methods with very few but powerful primitives.

It can clearly describe the interactions between parts within a system and is particularly suitable for modeling discrete event dynamic systems with asynchronous and concurrent properties.

In addition, the characteristic that a Petri-net model can be executed makes it possible to simulate and analyze the emergency response process, revealing the condition and time that an action can be executed, so as to the time of each emergency response process can be obtained.

An emergency response often requires appropriate measures to be taken within the shortest time to rescue the wounded and save properties, and to control and put out the accident. In emergency preparedness or emergency response training, time is also often used to measure the efficiency of an emergency response, e.g., a given time is used to judge whether the execution of an action is acceptable. This work also uses a given time to evaluate the efficiency of emergency response processes with priority.

4. An illustrative example

A petrochemical company is mainly engaged in the sale of oil products. Its storage area is divided into three parts: tank area, loading area and auxiliary production area. The tank area includes two parts, namely, 1# tank area (8 tanks of 3000 m^3 each, including 6 gasoline tanks and 2 diesel tanks) and 2# tank area (6 tanks of 6000 m^3 each, including 3 gasoline tanks and 3 diesel tanks). The oil products of the company are transported by ship through a 3000-ton wharf attached to the storage area, and then sent to the tanks through the above-ground oil pipeline. Oil products can be transported out through ships or tank trucks.

The storage area is subject to the risk of fire, explosion and other accidents, and the corresponding emergency plan was established. For the oil tank fire, the main emergency response actions of field personnel after a fire occurring are as follows:

R1. If any person is injured, rescue the wounded to a safe place.

R2. Close input valve(s) of the firing tank.

R3. Switch on the fire cooling water pump and open the water supply valves of the cooling spray system of neighboring tanks.

R4. Start the foam pump, open the fire-extinguishing foam valve of the tank on fire, supply foam for extinguishing fire.

According to the rules of “Saving life is prior to saving properties”, “Control first, then put out”, these actions have the priority order R1>R2>R3>R4. The rescue of the wounded has a higher priority than other actions.

For the sake of analysis, the following assumptions are made:

(1) The responders at the scene are familiar with the emergency process and know the priority of each task;

(2) Only one person is needed to carry out each task;

(3) The average time for responders to arrive at the fire scene is 3 minutes

(4) The implementation time of emergency operations satisfies the exponential distribution.

The model of emergency response process established using Petri net is shown in Fig. 8, and the meanings of places and transitions are shown in Table 1. The scenario discussed here is that a deflagration of a tank causes an employee to coma and the tank to catch fire. After the occurrence of the accident, the emergency response personnel of the company rush to the scene, and when they arrived at the fire scene, they carried out the emergency response actions according to their priority.

Initially, place p_1 has a token, indicating the occurrence of the accident. Place pc1 also has a token representing that the action of rescuing the wounded should be satisfied first. According to the number (i) of emergency response personnel, places from p_{w_1} to p_{w_i} and transitions from t_{w_1} to t_{w_i} should be determined, and then the model can be executed to simulate the emergency response process. Tokens in places p_1, p_{w_1}, p_{w_2}, p_{w_3}, p_2, p_{c1}, p_{c2}, p_{c3}, p_{c4}, p_{1_1}, p_{2_1}, p_{3_1}, p_{4_1}, p_{1_2}, p_{2_2}, p_{3_2} and p_{4_2} are taken as the marking of the model, which reflects the state of the system. The average time for rescuing the wounded is 5 minutes, the average time for closing input valve(s) of the firing tank is 3 minutes, the average time for starting the cooling pump and opening the water spraying valves is 4 minutes, and the average time for starting the foam pump and opening the foam supply valves is 4 minutes. Suppose the average arrival times of responder 1, responder 2, responder 3,… are 3, 4, 5, … minutes, respectively. Table 2 shows an example illustrating the emergency response process under three responders, and the times of transitions sampled for this simulation are shown in Table 3.

In this case, after the tank fire is discovered, three responders (responder 1, 2 and 3, respectively) rush to the fire scene. Responder 2 arrives at the scene first and contributes to the rescue of the wounded (execution of t_{1_1} and t_{1_2} is started in the 3rd minute). During responder 2 rescuing the wounded, responder 3 arrives and performs the task of closing the input valve of the firing tank (execution of t_{2_1} and t_{2_2} is

Table 1
Meanings of places and transitions.

Place	Meaning	Transition	Meaning
p_1	Occurrence of a tank fire	t_1	Tank fire is discovered
p_2	Responder is at the fire scene and ready for emergency response	t_{w_1}	Responder 1 rushes to the scene of the fire
p_{w_1}	Fire alarm is received by responder 1	t_{w_2}	Responder 2 rushes to the scene of the fire
p_{w_2}	Fire alarm is received by responder 2	t_{w_i}	Responder i rushes to the scene of the fire
p_{w_i}	Fire alarm is received by responder i	t_{1_1}	Assign personnel to rescue the wounded
p_{c1}	Priority control of rescuing the wounded	t_{2_1}	Assign personnel to close input valve(s) of the firing tank
p_{c2}	Priority control of closing input valve(s) of the firing tank	t_{3_1}	Assign personnel to start cooling pump and open the water spraying valves
p_{c3}	Priority control of starting cooling pump and opening the water spraying valves	t_{4_1}	Assign personnel to start foam pump and open the foam supply valves
p_{c4}	Priority control of starting foam pump and opening the foam supply valves	t_{1_2}	Rescue the wounded
p_{1_1}	Personnel is assigned to rescue the wounded	t_{2_2}	Close input valve(s) of the firing tank
p_{2_1}	Personnel is assigned to close input valve(s) of the firing tank	t_{3_2}	Start cooling pump and open the water spraying valves
p_{3_1}	Personnel is assigned to start cooling pump and open the water spraying valves	t_{4_2}	Start foam pump and open the foam supply valves
p_{4_1}	Personnel is assigned to start foam pump and open the foam supply valves		
p_{1_2}	The wounded is rescued		
p_{2_2}	Input valves of the firing tank are closed		
p_{3_2}	The cooling pump is started and cooling water spraying valves are opened		
p_{4_2}	The foam pump is started and the foam supply valves are opened		

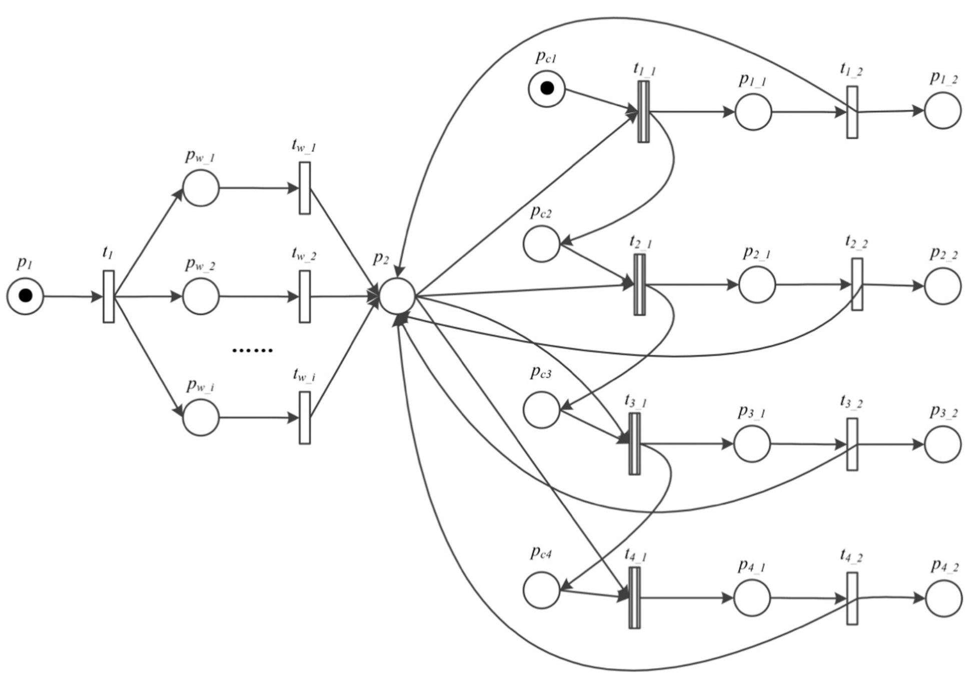

Fig. 8. Emergency response Petri-net model for field responders.

Table 2
Emergency response process under three responders.

Time	Marking	Executed transitions
0	(1,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0)	
1	(0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0)	t1
2	(0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0)	t1, tw_1, tw_2, tw_3
3	(0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0)	tw_1, tw_2, tw_3, t1_1, t1_2
4	(0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0)	tw_1, tw_3, t2_1, t3_1, t1_2, t2_2, t3_2
5	(0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0)	t1_2, t2_2, t3_2
6	(0,0,0,0,1,0,0,0,1,0,0,0,0,0,0,1,0,0)	t1_2, t2_2, t3_2
7	(0,0,0,0,1,0,0,0,0,0,0,0,0,0,1,1,0,0)	t4_1, t1_2, t3_2, t4_2
8	(0,0,0,0,2,0,0,0,0,0,0,0,0,1,1,1,0,0)	t3_2, t4_2
9	(0,0,0,0,2,0,0,0,0,0,0,0,0,0,1,1,1,0)	t4_2
10	(0,0,0,0,2,0,0,0,0,0,0,0,0,0,1,1,1,0)	t4_2
11	(0,0,0,0,3,0,0,0,0,0,0,0,0,0,1,1,1,1)	t4_2

Table 3
Duration (minute) of transitions sampled for the simulation shown in Table 2.

Transition	Duration	Transition	Duration
t_1	1.32	t_{w_1}	2.28
t_{w_2}	1.37	t_{w_3}	1.89
t_{1_2}	4.19	t_{2_2}	2.18
t_{3_2}	3.50	t_{4_2}	4.82

started in the 4th minute). Finally, responder 3 arrives and performs the task of starting the cooling pump and opening the water spraying valves (execution of t_{3_1} and t_{3_2} is started in the 4th minute). In the 6th minute, responder 2 finishes the executed action first and turns to execute the action of starting a foam pump and opening the foam supply valves (execution of t_{4_1} and t_{4_2}). Table 4 shows the start time and the end time of transitions, and the emergency response process finishes at 10.21 minutes.

On the basis of an emergency process simulation, Monte Carlo simulation, which is a simulation based on large number of replications using random sampling values, can be used for emergency response process probability analysis. Fig. 9 shows the process of using the Petri-net model to analyze the success probability of the emergency response process modeled as shown in Fig. 8.

Step 1. Initialize parameters of probability analysis. $C_{s\ im}$ denotes the number of Monte Carlo simulation replications, C_{succ} denotes the number of successful emergency response, and *idx* is the counter of replications. τ_f is the time used to measure the success of an emergency response, which is determined in advance according to the time requirements for the emergency response.

Step 2. Reset parameters of emergency process simulation. Each replication needs to reset the simulation parameters. This includes: sampling and determining the transition execution time according to the distribution function of the duration of corresponding emergency response action; clearing tokens in each place and generating a token in the place p_{c1} that controls the highest priority action; creating a token in place p_1, indicating the occurrence of the fire accident.

Step 3. Simulate an emergency response process. Execute all enabled transitions until places p_{1_2}, p_{2_2}, p_{3_2} and p_{4_2} each has a token, representing the all emergency response actions have been finished.

Step 4. Record simulation data and calculate the failure probability. When each emergency response process simulation represented by Step 3 is completed, the latest time is obtained from the tokens in places p_{1_2}, p_{2_2}, p_{3_2} and p_{4_2}. This time (τ_{er}) represents the end time of the emergency response process and it is compared with the predetermined time of failure (τ_f) of the emergency process. If τ_{er} is smaller than τ_f, it means that the emergency response is successful, and the times of successful emergency response (C_{succ}) plus 1. If the required replications have not

Table 4
Start time and end time of timed transitions.

Transition	Start (minute)	End (minute)	Transition	Start (minute)	End (minute)
t_1	0.00	1.32	t_{1_2}	2.69	6.88
t_{w_1}	1.32	3.60	t_{2_2}	3.21	5.39
t_{w_2}	1.32	2.69	t_{3_2}	3.60	7.10
t_{w_3}	1.32	3.21	t_{4_2}	5.39	10.21

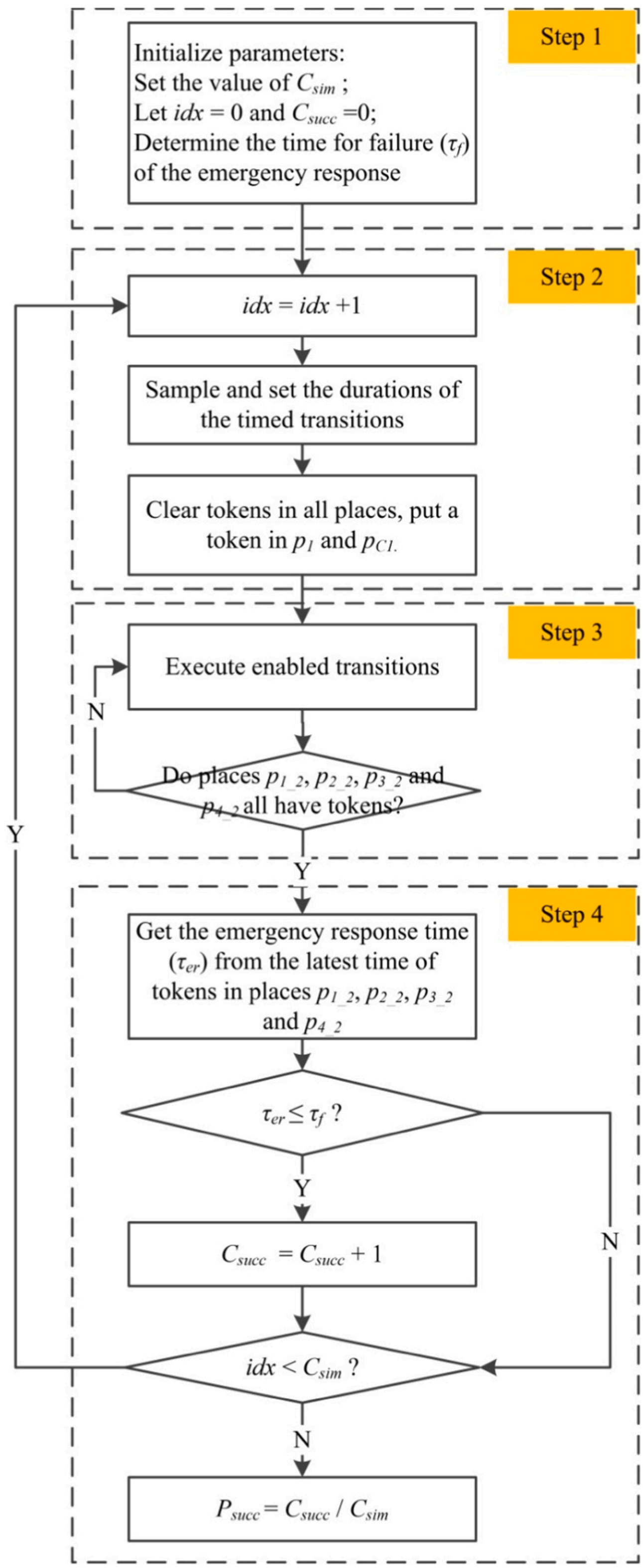

Fig. 9. Process of probability analysis of emergency response.

been finished, then go back to Step 2 to simulate another emergency response process, otherwise, calculate the success probability (P_{succ}):

$P_{succ} = C_{succ} / C_{s\ im}$

In this work, the number of simulation replications is10,000, and the value of τ_f is 15 minutes. For the emergency response process discussed in this example, in the case of three emergency responders, the success probability of emergency response is 0.65, and the average time of the whole process is13.75 minutes.

As discussed in Section 2, the number of responders will impact the time of emergency response. Fig. 10 shows the change in the probability of successful emergency response depending on the number of emergency responders. Since only 4 emergency actions are considered for priority in this example, the probability is increasing as the number increases from 1 to 4. If the number of emergency personnel is more than 4, the probability of success will also increase slowly, because for the fastest four responders, the probability of arriving at the scene within a shorter time is increased.

In the example, rescuing the wounded has the highest priority, which ensures that the wounded can be rescued as much as possible. If priority is not taken into account, the wounded will be rescued in a longer time. Using the Petri-net models, the opportunities for the wounded to be rescued can be quantitatively compared when considering and not considering the priority. Fig. 11 shows the Petri-net model not considering the priority of emergency response actions. Transitions t_{i_1} (i=1, 2, 3, 4) have no arc connecting to other control places, and each of the control places p_{ci} (i=1, 2, 3, 4) have a token initially, indicating the corresponding action has not been assigned a responder. In this situation, transitions t_{i_1} (i=1, 2, 3, 4) may have conflicts with each other in the use of the token in place p_2 when a token is put in p_2. To avoid conflict, transitions t_{i_1} (i=1, 2, 3, 4) are given the right to use tokens in place p_2 in a random way.

Take the time when transition t_{1_2} starts its execution as the time when the wounded get help. For the situation of three responders, the average time for the wounded to get help is 4.9 minutes without regard to the priority of actions. In contrast, when considering the priority of actions, the average time for the wounded to get help is 3.3 minutes. Time is very important for the rescue of the wounded. According to the injury model under thermal radiation, if the thermal radiation received by the wounded in the fire is 2 kW/m^2, the probability of death for a person with clothing protection (20 per cent skin exposure) caused by the duration of 4.9 minutes is 0.04, while the probability of death at 3.3 minutes is 0.003; when the duration under heat radiation decreases from 4.9 minutes to 3.3 minutes, the probability of second-degree burn of a person with clothing protection (20% skin exposure) decreases from 0.35 to 0.06. Therefore, taking into account the priority of actions in emergency response can ensure that important tasks can be implemented as soon as possible in order to minimize losses.

5. Conclusions

Emergency response or emergency rescue is an important safety measure, which can reduce the loss resulting from an accident. The emergency response process is composed of a series of actions, which may have interaction between each other, and how to implement them efficiently has an important impact on the achievement of the objective of an emergency response. Emergency response actions are often arranged before the occurrence of accidents, so how to analyze and optimize emergency actions in advance is a problem worthy of study.

In view of the importance of rescue objectives, or the severity of losses, actions are often performed in a certain order of priority in emergency response, and the implementation of actions usually requires certain resources, which restrict the implementation of actions. Aiming at the fact that the number of emergency responders may be not enough to carry out all priority actions at the same time, this paper analyzes the changes in the relationship between emergency response actions and the impact on emergency response time caused by it.

In order to solve the problems caused by the priority of emergency response actions, this paper proposes a modeling and analysis approach based on Petri-net, which divides an action that needs to consider its priority into two stages: one is to assign the personnel executing the action, the other is the execution of the action. In this way, priority control can be placed at the personnel allocation stage, thus facilitating the handling of relationships between actions. Control places are used to control the execution priority of transitions, and the time and efficiency of an emergency response process can be analyzed on the basis of modeling.

Taking the response actions of the on-site emergency response personnel after the fire accident in a chemical plant as an example, the working of the proposed approach is demonstrated. Emergency response actions such as the rescue of the wounded, the closing of the input valve, the opening of the cooling spray system and the foam fire-extinguishing system are considered, and their implementation is of priority. The emergency response process is discussed and the success probability of the emergency response process is analyzed. The effect of considering and not considering the priority of actions on rescuing the wounded is compared.

In this study the priority issue is considered for emergency response actions with "AND" logic, which means that the actions considered should all be executed in order to achieve the goal. If actions have “OR” logic, that is, the implementation of any of the actions can achieve the

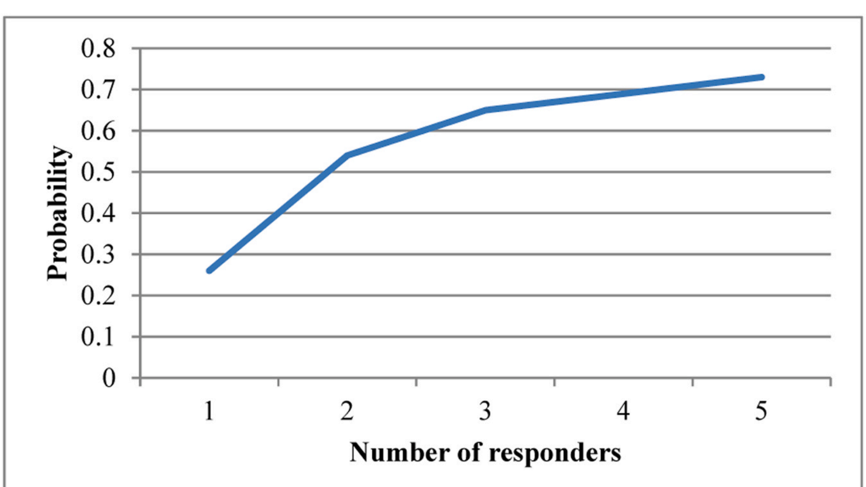

Fig. 10. Relationship between the success probability of emergency response and the number of responders for our illustrative example.

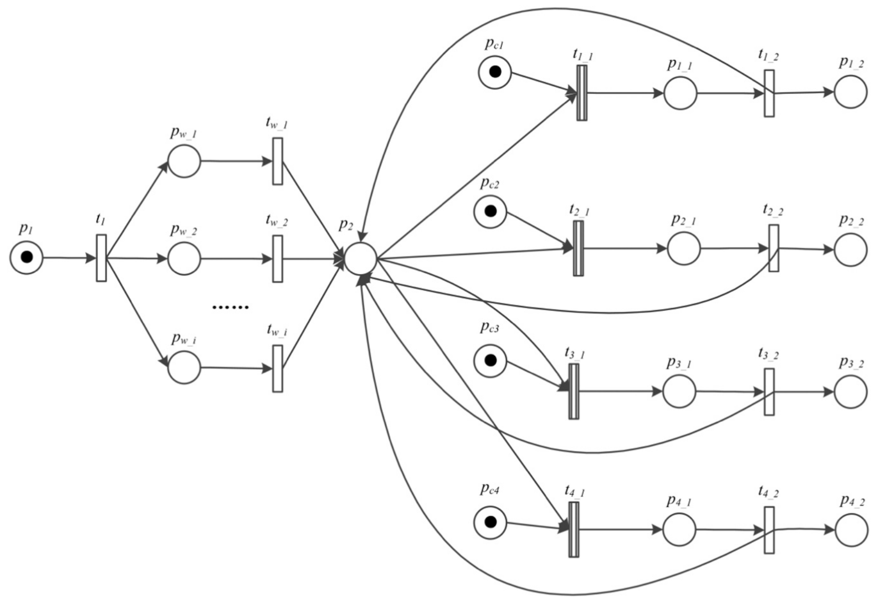

Fig. 11. Petri-net model not considering the priority of emergency response actions.

goal, the priority of actions is usually not considered during the execution, the selection of actions is determined by other important factors, such as the resources needed for an action, the convenience of execution, or the time of execution. Such actions with "OR" logic can be modeled and analyzed using the normal Petri-net modeling approach.

The approach proposed in this paper has the following characteristics: (1) it can reveal the details of an emergency response process. The simulation of the emergency response process shows that this approach can reveal when and under what conditions an action is performed, and what effect it will have after the execution. (2) probability analysis can be carried out. Monte Carlo simulation can be used to analyze the probability of success or failure of emergency response process. (3) it ensures that important actions can be performed first. The modeling of emergency response actions takes into account the priority of actions can ensure that important tasks or tasks that prevent causing greater losses can be carried out first when resources (personnel) are insufficient, so as to minimize the loss.

The limitation of the approach is that the model may be large when the studied problem is complex. In this case, utilizing computer-assisted Petri-net modeling and analysis tools may be needed. There are many actions in an emergency response process, and in addition to prioritization, there may be some action characteristics that need to be considered in modeling, especially those of collaboration between agencies. They can be taken into account in future studies to better reflect various emergency response processes.

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.

Acknowledgments

This work is supported by National Natural Science Foundation of China (No. 71673060).

References

An, X., Yin, Z., Tong, Q., Fang, Y., Yang, M., Yang, Q., Meng, H., 2023. An integrated resilience assessment methodology for emergency response systems based on multi-stage STAMP and dynamic Bayesian networks. Reliab. Eng. Syst. Saf. 238, 109445.
Bandyopadhyay, M., Singh, V., 2016. Development of agent based model for predicting emergency response time. Perspect. Sci. 8, 138–141.
Chai, G., Cao, J., Huang, W., 2018. Optimized traffic emergency resource scheduling using time varying rescue route travel time. Neurocomputing 275, 1567–1575.
Chen, C., Reniersa, G., Khakzad, N., 2020. A thorough classification and discussion of approaches for modeling and managing domino effects in the process industries. Saf. Sci. 125, 104618.
Chow, W.K., Ng, C.M.Y., 2008. Waiting time in emergency evacuation of crowded public transport terminals. Saf. Sci. 46, 844–857.
Chu G., Wang J., 2011. A stochastic analysis on occupant evacuation time under emergency conditions. in 2nd IEEE International Conference on Emergency Management and Management Sciences (ICEMMS), Beijing, China.
David, R., Alla, H., 1994. Petri nets for modeling of dynamic systems – a survey. Automatica 30 (2), 175–202.
Dhingra, V., Roy, D., 2015. Modeling emergency evacuation with time and resource constraints: A case study from Gujarat. Socio-Econ. Plan. Sci. 51, 23–33.
ISO, 2000. Pet. Nat. Gas. Ind. -Offshore Prod. Install. -Guidel. Tools Tech. Hazard Identif. Risk Assess. ISO 17776.
Jackson, B.A., Faith, K.S., Willis, H.H., 2011. Are we prepared? Using reliability analysis to evaluate emergency response system. J. Contingencies Crisis Manag. 9 (3), 147–157.
Jiang, Y., Zhang, R., Wang, B., 2022. Scenario-based approach for emergency operational response: Implications for reservoir management decisions. Int. J. Disaster Risk Reduct. 80, 103192.
Kang, K., 2007. Application of code approach for emergency evacuation in a rail station. Fire Technol. 43, 331–346.
Khakzad, N., Khan, F., Amyotte, P., Cozzani, V., 2014. Risk management of domino effects considering dynamic consequence analysis. Risk Anal. 34, 1128–1138.
Khakzad, N., Landucci, G., Reniers, G., 2017. Application of dynamic Bayesian network to performance assessment of fire protection systems during domino effects. Reliab. Eng. Syst. Saf. 167, 232–247.
Khan, A.A., Zhang, T., Huang, X., Usmani, A., 2023. Machine learning driven smart fire safety design of false ceiling and emergency response. Process Saf. Environ. Prot. 177, 1294–1306.
Komenda, J., Lahaye, S., Boimond, J.-L., 2016. Determinization of timed Petri nets behaviors. Discret. Event Dyn. Syst. 26, 413–437.
Landucci, G., Argenti, F., Tugnoli, A., Cozzani, V., 2015. Quantitative assessment of safety barrier performance in the prevention of domino scenarios triggered by fire. Reliab. Eng. Syst. Saf. 143, 30–43.
Li, Q., Deng, Y., Liu, C., Zeng, Q., Lu, Y., 2016. Modeling and analysis of subway fire emergency response: an empirical study. Saf. Sci. 84, 171–180.
Li, X., Zhu, Y., Abbassi, R., Chen, G., 2022. A probabilistic framework for risk management and emergency decision making of marine oil spill accidents. Process Saf. Environ. Prot. 162, 932–943.
Lisboa, A.C., De Souza, F.H.B., Ribeiro, C.M., Maia, C.A., Saldanha, R.R., Castro, F.L.B., Vieira, D.A.G., 2019. On modelling and simulating open pit mine through stochastic timed petri nets. IEEE Access 7, 112821–112835.
Liu, C., Zeng, Q., Duan, H., Zhou, M., Lu, F., Cheng, J., 2015. E-Net modeling and analysis of emergency response processes constrained by resources and uncertain durations. IEEE Trans. Syst., Man, Cybern.: Syst. 45 (1), 84–96.
Liu, Q., He, R., Zhang, L., 2022. Simulation-based multi-objective optimization for enhanced safety of fire emergency response in metro stations. Reliab. Eng. Syst. Saf. 228, 108820.

MAHBulletin, 2017. Lessons Learned Bulletin No. 11, Chemical Accident Prevention & Preparedness, Learning from emergency response – firefighter preparedness and protection. Available at: https://www.kas-bmu.de/mahb-bulletin-lessons-learned.html?file=files/publikationen/MAHB%20Bulletins%20-%20Lessons%20Learned/mahb-bulletin-no11-emergency-response-part2.pdf&cid=11205.
Misuri, A., Landucci, G., Cozzani, V., 2021. Assessment of safety barrier performance in the mitigation of domino scenarios caused by Natech events. Reliab. Eng. Syst. Saf. 205, 107278.
Palazzi, E., Currò, F., Fabiano, B., 2015. A critical approach to safety equipment and emergency time evaluation based on actual information from the Bhopal gas tragedy. Process Saf. Environ. Prot. 97, 37–48.
Park, P.Y., Jung, W.R., Yeboah, G., Rempel, G., Paulsen, D., Rumpel, D., 2016. First responders' response area and response time analysis with/without grade crossing monitoring system. Fire Saf. J. 79, 100–110.
Pelz, E., 2018. Full axiomatisation of timed processes of interval-timed petri nets. Fundam. Inform. 157, 427–442.
Peng, Y., Yao, S.-Z., Tan, H.-B., 2015. Safety Analysis based on Stochastic Time Petri Nets. In: International Conference on Computer Science and Applications, 2015. Wuhan, China.
Peterson, J.L., 1981. Petri Net Theory and the Modeling of Systems. Prentice Hall, Lebanon, Indiana.
Ping, P., Wang, K., Kong, D., Chen, G., 2018. Estimating probability of success of escape, evacuation, and rescue (EER) on the offshore platform by integrating Bayesian Network and Fuzzy AHP. J. Loss Prev. Process Ind. 54, 57–68.
Rasmussen, J., 1997. Risk management in a dynamic society: a modelling problem. Safefy Sci. 27 (2), 183–213.
Song, M., Lind, M., Yang, J., Gofuku, A., 2021. Integrative decision support for accident emergency response by combining MFM and Go-Flow. Process Saf. Environ. Prot. 155, 131–144.
Wang, J., 1998. Timed Petri Nets Theory and Application. Springer Science+Business Media New York.
Zhong, M., Shi, C., Fu, T., He, L., Shi, J., 2010. Study in performance analysis of China Urban Emergency Response System based on Petri net. Saf. Sci. 48, 755–762.
Zhou, J., 2013. Petri Net Modeling for the Emergency Response to Chemical Accidents. J. Loss Prev. Process Ind. 26, 766–770.
Zhou, J., Reniers, G., 2016. Petri-net based modeling and queuing analysis for resource-oriented cooperation of emergency response actions. Process Saf. Environ. Prot. 102, 567–576.
Zhou, J., Reniers, G., 2018. Petri-net based evaluation of emergency response actions for preventing domino effects triggered by fire. J. Loss Prev. Process Ind. 51, 94–101.
Zhou, M.C., Venkatesh, K., 1998. Modeling, Simulation and Control of Flexible Manufacturing Systems: A Petri Net Approach. World Scientific, Singapore.
Zhou, Q., Huang, W.L., Zhang, Y., 2011. Identify critical success factors in emergency management using a fuzzy DEMATEL method. Saf. Sci. 49 (2), 243–252.
Zuberek, W.M., 1991. Timed Petri nets-definitions, properties and applications. Microelectron. Reliab. 31 (4), 627–644.