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Modeling and analysis of subway fire emergency response: An empirical study

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ABSTRACT

Modeling and analysis of a subway fire emergency response processes are extremely important in metro operation. In this study, a Petri net based approach is proposed to model and analyze the time and resource issues of subway fire emergency response processes. More specifically, the formal specification of subway fire emergency response process is first defined and a real subway fire response process is given to validate our methodologies. Next, resource conflict detection methods along with corresponding algorithms are proposed to detect potential resource conflicts. In addition, a priority criterion which constitutes of key-task priority strategy and waiting-short priority strategy is proposed to resolve the detected resource conflicts and optimize the whole process execution time. By experiment comparison, it is proved that our resolution strategies could effectively resolve resource conflicts as well as achieving high time performance. The proposed approach can be effectively used to simulate and train an emergency response plan to detect potential conflicts in time, sequence, and resources, before its real application. In this way, the reliability and validity of emergency response plan can be improved greatly.

1. Introduction

With the rapid development of subway in China, it has become an increasingly important form of public transportation. Subway safety is directly related to the healthy development and stability of big metropolis. Therefore, subway emergency management plays a key role in the immediate response, control and reduction of subway accidents. Because of the special spatial structure of the subway, fire accidents usually results in serious consequences, and poses serious threats to the safety of passengers, properties and infrastructures. According to a subway accident statistics from 1903 to 2004, it is discovered that fire is one of the most harmful accidents in daily subway operation (Dai et al., 2005). It happens frequently and results in relatively large numbers of causalities, such as the Baku subway fire in the Azerbaijan Republic (in 1995, more than 340 casualties) and the arson fire in Daegu, Korea (in 2003, more than 189 casualties). Due to the heavy casualties and tremendous economic loss of a fire accident, it is of extreme importance to apply effective and efficient emergency rescue for reducing casualties and property damage as soon as possible after the accident.

Generally speaking, a subway fire emergency is a situation that poses immediate risks to human health, life and property (Zeng et al., 2013a; Liu et al., 2015a). Therefore, urgent responses to prevent its worsening are greatly needed in subway operation management. These interventions are usually organized as a process that is usually described in an emergency plan, by which all individuals, groups and communities manage hazards in an effort to avoid or ameliorate the impact of disasters (Perry and Lindell, 2003). During an emergency response process, a set of tasks are issued and executed based on specified order of seniority. Obviously, modeling and optimization of an emergency response process which is derived from an emergency plans is indispensable in dealing with the contingent accidents in subway emergency response management (Zhong et al., 2010). Traditionally, an emergency response process can be seen as an execution sequence of emergency tasks, but the total rescue time is full of uncertainty because of the stochastic environment and unaware characteristics of accidents. Meanwhile, the performance of emergency management may be affected by various different factors and it is always difficult for commanders or practitioners to improve all aspects at the same time. A recent study paid close attention to the factors that may affect an emergency management and 20 influencing factors were identified by combination of fuzzy logic and decision

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making trial evaluation laboratory (Zhou et al., 2011). The influencing factors make it impossible to predict the execution time of the rescue tasks, and increase the indeterminacy of an emergency rescue.

During an emergency response process, emergency resources that refer to all kinds of resources needed in emergency management have huge influence on rescue time and rescue effort (Minciardi et al., 2009). They are the material basis of an emergency rescue, and the management consists of resource reserve under normal circumstances and resource mobilization in the event of an emergency response process. In the fire emergency rescue phase, resource demands would rise to an unprecedented scale in a very short time, and the efficiency of the emergency system can be deeply affected by a reasonable allocation of the available resources. Even worse, if contradictions come up among resources demands, some key tasks may have to be put off, which will greatly reduce the efficiency of rescue, delay the rescue time, and result in greater property loss and casualties (Mendonca et al., 2001).

In real subway operation, accidents usually happen unpredictably and randomly. It is very difficult to predict the time, site, intensity, and damage degree of emergencies (Lu et al., 2013). Therefore, whether an emergency response plan is feasible or not is not known, and cannot be entirely judged by conventional emergency drillings. In fact, it is always practically difficult to implement emergency exercise in a subway station or in a tunnel. The performance of emergency plan can hardly be evaluated before putting into application. How to assess the emergency response plan and improve its scientificity and operability becomes a big intractable problem. Meanwhile, it is also very important to optimize the uncertain rescue time and detect the emergency resources contradictions.

The evaluation of emergency response plan has been researched in many industries and fields, such as chemical industry (Zhou, 2013; Tseng et al., 2008; Wang et al., 2000; Zeng et al., 2013a; Liu et al., 2015a), nuclear industry (Ford and Schmidt, 2000; Lee and Seong, 2004), water pollution emergency (Cheng and Qian, 2010; He et al., 2011), earthquake emergency (Fiedrich et al., 2000; Bisri, 2013), and so on (Chen and Zhang, 2009; Karagiannis et al., 2010; Lumbroso et al., 2011; Piatyszek and Karagiannis, 2012), but there is little attention paid to subway fire emergency response plan. With the progress of research, a number of formal modeling techniques have been proposed in the past few decades, such as unified modeling language (UML), event-driven process chain (EPC), business process execution language (BPEL), business process modeling language (BPML), web service flow language (WSFL), workflow intuitive formal approach (WIFA), and Petri net. According to the different object of research, these tools have different advantages and disadvantages in different aspects (Karagiannis et al., 2010). Because of its formal semantics as well as graphical characteristics (Van Der Aalst, 1998), Petri net is one of the most widely used approaches in discrete manufacturing systems, information systems for their simulation and performance analysis (Girault and Valk, 2003; Hrúz and Zhou, 2007; Liu et al., 2015b; Hua et al., 2014; Cheng et al., 2015; Zeng et al., 2015, 2013b). In addition, it has also been used to analyze the emergency response systems (Karmakar and Dasgupta, 2011; Zhong et al., 2010) in recent years. According to the characteristics of subway fire emergency response process, it would be very suitable to select Petri net as the modeling and analysis tool in this paper.

In this study, Petri net is selected as the modeling tool to analyze emergency response process. More specifically, a kind of Petri net extended with time and resource is used to model the emergency response process. The rest of this paper was organized as follows: Section 2 introduces the formal definition of subway fire emergency response process and then a real subway fire disposal process to validate the methodologies mentioned in the paper. Section 3 discusses the detailed modeling of subway fire emergency response processes with SFERP-Net. In Section 4, resource conflict detection approaches are fully investigated. Section 5 presents the priority criteria to resolve resource conflicts as well as optimizing time performance. Section 6 draws concluding remarks.

2. Formal definition of subway fire emergency response process

In this section, we first introduce the formal definition for a kind of subway fire emergency response process, and then a real subway fire disposal process, as typical scenario, is introduced to validate the proposed approach in the paper.

2.1. Formal definition of subway fire emergency response process

Let $Z = \{0, 1, 2, \ldots\}$, $Z_n = \{1, 2, \ldots n\}$ where n is a positive integer and R^+ be the set of non-negative real numbers.

Definition 1. A *subway fire emergency response process* is a seven-tuple SFERP = $\langle$Task, Resource, Time, Relation, f_{AR}, f_l, $f_u\rangle$, where

(1) $Task = \{task_i | i \in Z_n\}$ is the task set;
(2) $Resource = \{resource_i | i \in Z_m\}$ is the resource set;
(3) $Time = \{time_i | i \in Z_l\}$is the time set, where $time_i \geqslant 0$;
(4) $Relation \subseteq Task \times Task$ is the relation set, representing the connection relations between tasks;
(5) f_{AR}: $Task \to f_{AR}(Resource)$ is the resource function; and
(6) Given $task \in Task$, $f_l(task) \in R^+$ is the minimum time required to execute a task while $f_u(x) \in R^+$ is the maximum one, satisfying $f_l(x) \leqslant f_u(x)$.

Definition 1 presents the formal specification of a subway fire emergency response process, where: (1) The set *Task* defines all tasks in the process; (2) The set *Resource* defines all required resources; (3) For $task_1 \in Task$ and $resource_1 \in Resource$, if $f_{AR}(task_1) = \{resource_1\}$, it means that $task_1$ requires $resource_1$ to initialize. $\forall task_1 \in Task$, if $f_{AR}(task_1) = \varnothing$, it means that $task_1$ does not require any resource. It is assumed that resources are occupied exclusively by tasks in our subway fire emergency response process, i.e. if the execution of $task_1$ requires $resource_1$, $resource_1$ is locked while $task_1$ is executing; (4) For $task_1$, $task_2 \in Task$, if $f_{AR}(task_1) \cap f_{AR}(task_2) \neq \varnothing$, we say that $task_1$ and $task_2$ share same resources. If $resource_1 \in Resource$ is shared by $task_1$ and $task_2$, $resource_1$ will be locked while is $task_1$ executing and $task_2$ has to wait until $task_1$ is finished and $resource_1$ is released; (5) *Relation* defines the connection relations among tasks. $\forall task_i$, $task_j \in Task$, if $(task_i, task_j) \in Relation$, it means that $task_j$ cannot start before $task_i$; and (6) The set *Time* defines time constraints of tasks. For each task, there are two timing functions f_l and f_u, representing the minimum and maximum execution time respectively.

2.2. A running example

In this subsection, we consider a subway fire emergency response process. The data was collected by a two-stage process. In the first stage, interviews were carried out to gain further information about the subway fire emergency response process. By doing this, more data was generated from 12 face-to-face interviews at the interviewee's offices, meeting rooms and tea bars. From July 2014 to September 2014, we met with a high ranking senior officer of *the Shanghai Metro Operation Company*, five high or middle ranked managers and officers in five departments and two station staff. In order to maximize interviewee freedom, the interviews involved mostly open-ended questions. The interviews