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

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ABSTRACT

During an emergency response after an accident, emergency actions often require certain emergency resources. The adequate use, or the lack thereof, of emergency resources will affect the efficiency and even the success of emergency response activities or processes. Different emergency actions form certain relationships on using emergency resources. The cooperation modes of emergency actions on using resources are analyzed in this paper, and Petri-net models for these cooperation modes are provided. On this basis, an approach to detect emergency action conflicts resulting from resource-use is proposed. For conflicts caused by limited resources sharing, the queuing system which is modeled by a Petri-net and integrated into the model of emergency actions, is adopted to avoid conflicts. An example of an emergency response activity related with a fire accident is used to demonstrate the modeling method. The conflicts are analyzed and a queuing system is used to avoid simultaneously employing the same resource.

1. Introduction

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

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

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

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

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

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

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

The Petri-net approach represents a powerful modeling and analysis tool. It can formally describe the flow of activities in complex systems. It is particularly suited to represent logical interactions among different parts or activities in a system. Typical situations that can be modeled by Petri-nets are synchronization, sequentiality, concurrency and conflict. Petri-nets have for instance been used to model and analyze emergency responses (Karmakar and Dasgupta, 2011; Meng et al., 2011; Zhong et al., 2010; Zhou, 2013).

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

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

2. Formal specifications

2.1. *Formal specifications of emergency resources and actions*

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

i. Consumptive resources and reusable resources: some emergency resources can be reused (e.g., certain personal protective equipment) and some emergency resources can not be reused (e.g., firefighting foam or water);
ii. Discrete resources and continuous resources. This division is relative. It depends on the condition in which the resource is used. For example, water can be looked as a continuous resource when it is taken through a fire hose connected to a fire hydrant, it can also be considered as a discrete resource when it is used through a fire truck or a bucket for instance.

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

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

$$ER = \langle \text{Resource Name}, \text{Resource property}, \text{Resource Type} \rangle$$

where ResourceName: name of an emergency resource; ResourceProperty = {0, 1}, property of a resource, 0 – reusable, 1 – consumptive; ResourceType = {0, 1}, type of a resource, 0 – discrete, 1 – continuous.

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

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