Journal of Loss Prevention in the Process Industries 44 (2016) 1–11

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Simulation analysis of the use of emergency resources during the emergency response to a major fire

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, 2628 BX, Delft, The Netherlands
[c] Faculty of Applied Economics, Antwerp Research Group on Safety and Security (ARGoSS), Universiteit Antwerpen, 2000, Antwerp, Belgium
[d] CEDON, KULeuven, 1000, Brussels, Belgium

A R T I C L E I N F O

Article history:
Received 25 May 2016
Received in revised form
15 August 2016
Accepted 15 August 2016
Available online 17 August 2016

Keywords:
Emergency response actions
Emergency resources
Petri nets
Simulation analysis

A B S T R A C T

During an emergency response to an accident or disaster, emergency response actions often need to use various emergency resources. The use of resources plays an important role in the successful implementation of emergency response, but there may be conflicts in the use of resources for emergency actions. According to the emergency response in case of an oil fire, two types of emergency response models with dynamic structure are established by using Resource-Oriented Timed Colored Hybrid Petri-Net (RO-TCHPN). Type 1 model does not establish a special conflict avoidance mechanism for emergency actions, while Type 2 model uses a queuing method to avoid possible conflicts in the use of limited resources by multiple actions. In this paper, the two types of models are simulated and analyzed, including (1) emergency response process simulation, which analyzes and determines the time and the conditions of the potential conflicts occurring; and (2) comparison analysis, analyzing the improvement of the Type 2 model as compared with the Type 1 model. Increasing emergency resources to reduce or avoid conflicts and whether all the fire-trucks should be fully filled at the beginning of an emergency response, are also discussed based on the simulation.

1. Introduction

Various resources are often used in the process of emergency response. Especially with respect to accidents in the process industries, there are special requirements for emergency resources during the emergency response process. For example the treatment of a chemical fire requires the use of appropriate fire extinguishing agents. The use of emergency resources may have great impacts on the emergency response.

In literature, there are many studies about the problem of emergency resources in the emergency response to various accidents or disasters. One is the emergency resources allocation, which focuses on determining the optimal facility/resource location in decision support systems. Most of these methodologies in literature aim at detecting the minimum response time to the disasters so that they can be put into the emergency response at minimum cost (Hawe et al., 2015; Wang et al., 2014; Zhang et al., 2012). Another area of research on emergency resources is the scheduling of resources, which mainly deals with the problems or the optimization of resource dispatching in the process of emergency response (Zhang et al., 2011; Li and Li, 2012; Ren et al., 2012). In addition, in view of the shortage of emergency resources possibly restricting the emergency response, some researchers have also studied the demand forecasting of emergency resources, to determine the minimum requirement of resources for effective emergency response (Liu et al., 2012; Wang et al., 2009). 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. All emergency resources are used by various emergency response actions. Different actions in the use of emergency resources may form different relationships, such as the sequential use of resources, the parallel use of resources, the cyclic use of resources, and so on. The use of emergency resources may also result in conflict between the emergency response actions when carried out, which will affect the smooth progress of the emergency response. Aiming at the use of emergency resources in the emergency response to a major fire accident in the process industry, this paper performs a simulation analyses based on Petri-net models.

* Corresponding author. Faculty of Technology, Policy and Management, Safety and Security Science Group (S3G), TU Delft, 2628 BX, Delft, The Netherlands.
E-mail address: genserik.reniers@ua.ac.be (G. Reniers).

http://dx.doi.org/10.1016/j.jlp.2016.08.007
0950-4230/

Petri-net is a powerful tool for modeling the relationships among emergency response actions. Petri-net was proposed by Dr. Petri in 1962 when he developed the information flow model of the computer operating system (David and Alla, 1994). It is a graphical modeling and analysis tool, including elements like places, transitions, arcs and tokens. Firstly, Petri nets are widely used in modeling and analysis of discrete event systems. In order to model and analyze more complex systems, a number of extensions are formed on the basis of ordinary Petri-net. For example, in order to model and analyze the continuous event system, hybrid Petri-net is proposed by introducing continuous places and continuous transitions to the common Petri-net. In order to analyze the duration of the events, timed Petri-nets are proposed by assigning times to the places or transitions. In order to simplify the common Petri-net model, colored Petri-nets are proposed.

Petri-net is very suitable for modeling the relationship between the various parts of the system, such as sequential, parallel, conflict, etc. Besides, a Petri-net model can be executed. The execution of a transition consumes token(s) from incoming place(s) and produce token(s) to outgoing places. This mechanism can help revealing the evolution process of a system and determining under which conditions a transition is enabled and what will happen after it occurs. Thus, using Petri-nets to model and analyze the process of emergency response can help us to find the problems that may exist in this process. In literature, Petri-net has been applied to the modeling and analysis of emergency response (Aye and Ni, 2011; Karmakar and Dasgupta, 2011; Meng et al., 2011; Zhong et al., 2010; Zhou, 2013; Zhou and Reniers, 2016a).

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.

During the sequential use of reusable resources, one action can delay or block the execution of succeeding actions, but this is not considered as a conflict of emergency actions in this study. This paper focuses on the emergency action conflicts due to simultaneously using the same resource. Some simulation analyses for the emergency response actions constrained by emergency resources based on two types of Petri-net models are performed: one model does not consider conflict avoidance measures, while the other model does so. In Section 2, the two types of Petri-net models are described. The simulation analysis and discussions are performed in Section 3. At last, some conclusions of this study are drawn in Section 4.

2. Petri-net based model

2.1. RO-TCHPN

In Zhou (2013), the emergency response actions are divided into discrete processes and continuous processes according to their durations. During an emergency response, in addition to discrete events which can be completed soon, there are some actions which have long duration and may be affected by the development of the accident. These long duration actions can be looked as continuous processes. Besides, many handled materials in the process industry or some statuses of the emergency response are continuous and should be described as continuous variables. So, the emergency response is a hybrid system. Colored Petri Net (CPN) which uses colors to distinguish tokens is an extension of ordinary Petri net. Based on colored Petri net, the hybrid Petri net model will be more compact and concise. As this study is based on the time to analyze the performance of the emergency response process, the Timed Colored Hybrid Petri-Net (TCHPN) is adopted to model the process.

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

A Timed Colored Hybrid Petri-Net (TCHPN) is an eleven-tuple (Zhou and Reniers, 2016a):

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

(1) P: is a finite set of places. P can be split into two subsets P_D and P_C gathering, respectively, the discrete and the continuous places. (2) T: is a finite set of transitions. T can also be split into two subsets T_D and T_C gathering, respectively, the discrete and continuous transitions. (3) $A \subseteq P \times T \cup T \times P$, represents the sets of arcs connect places with transitions and transitions with places. (4) $\sum$ represents a finite set of non-empty types, called color sets. (5) V is a finite set of variable types, so that $Type[v] \in \sum$ for all $v \in V$ variables. (6) N: $A \rightarrow P \times T \cup T \times P$ is a node function. (7) C: $P \rightarrow \sum$ -represents the color set function that assigns a color set to each place. (8) G: represents guard function that assigns a guard which is to filter and restrict possible events to each transition t. (9) E: represents the function of arch expression assigning an arc expression to each arch. (10) IN: is an initialization function. (11) τ_{Td}: $\text{T}_\text{d} \rightarrow \text{R}^+$ is a function that associates discrete transitions with deterministic time delays.

A TCHPN satisfying the following conditions is called a resource-oriented TCHPN (RO-TCHPN):

(1) The discrete places P_D can be split into two subsets P_{DS} and P_{DR}, the discrete state and the discrete resource places.
(2) The continuous places P_C can be split into two subsets P_{CS} and P_{CR}, the continuous state and the continuous resource places respectively.

The elements in RO-TCHPN are represented as icons, as shown in Fig. 1.

The tokens are usually denoted by dots, and they can also be expressed by a number. The executing rule of a transition in RO-TCHPN is the same as that of a TCHPN. The rules are shown in Figs. 2 and 3, for discrete transitions and continuous transitions, respectively.

In Fig. 2, (a) indicates tokens in the input discrete place is subtracted by 1 (or the number marked on the input arc) after T occurs; and (b) indicates tokens in the output discrete place is added by 1 (or the number marked on the output arc) after T occurs; As a token in a discrete place represents a type of message or a command, (a) and (b) represent the transmission of the message or command, which may be transformed during T occurring.

(c) and (d) in Fig. 2 indicate the tokens in the continuous input places are not changed after T occurs. (e) and (f) in Fig. 2 indicate the tokens in the continuous output places are not changed after T occurs. However, the occurring of the discrete transition may access the color values of the continuous places. The interaction between a discrete resource place or a continuous resource place and the