Journal of Loss Prevention in the Process Industries 40 (2016) 554–562

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Petri-net based simulation analysis for emergency response to multiple simultaneous large-scale fires

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ARTICLE INFO

Article history:
Received 26 December 2015
Received in revised form
29 January 2016
Accepted 30 January 2016
Available online 4 February 2016

Keywords:
Simultaneous fires
Simulation analysis
Emergency response strategy
Counter-terrorism emergency

ABSTRACT

In the field of hazardous chemicals, there are many flammable materials located in different places within an industrial area. It is possible that major fires occur at the same time due to terrorism or vandalism (i.e. a security point of view). These fires might lead to domino effects at different locations around. Whether the fire emergency response preparedness, which is organized to fight against one of the fires, can handle the multiple fires, is studied in this article and a Petri-net based simulation approach is proposed. Through Petri-net based simulation, the process of fire-fighting can be revealed. A model of fighting against three fires is established, and the strategies of fire fighters staffing arrangements are analyzed. The results show that in most cases the distribution according to fire severity is better than the average distribution, but in some conditions the average distribution strategy prevails. Different backup staffing strategies are also compared, and the results indicate that the improvement by increasing staffing backups also depends on the fire conditions.

1. Introduction

In the chemical industry, there are many flammable materials located in production and storage areas. It is possible that major fires occur simultaneously due to terrorism or vandalism (multiple simultaneous fires may also occur due to safety-related reasons (by coincidence), but the probability is extremely low). General preparedness of fire emergency response is mainly organized to allocate personnel and emergency resources for one of the fires. Whether the emergency preparedness is able to handle multiple fires has not been studied yet, although there were a few studies on simultaneous multiple fires (Liu et al., 2007; Liu et al., 2013).

In the production or storage area of a petrochemical area, the thermal radiation of a fire might damage the neighboring equipment or tanks and cause secondary accidents. This is usually called "domino effect". Simultaneous fires in different places within an isolated area might lead to domino effects at several locations around. Although there are many studies on domino effects triggered by fire, involving the topics such as escalation thresholds (Cozzani et al., 2006; Landucci et al., 2009), prevention approaches (Cozzani et al., 2009; Landucci et al., 2015; Reniers et al., 2005), cross-plant prevention investments (Reniers, 2010), anti-terrorist attack (Reniers and Audenaert, 2014), and so on, how to deal, from a fire-fighting arrangement perspective, with the threat of possible multiple simultaneous large-scale fires is seldom involved. Nevertheless, although from a safety point of view this may be a situation characterized with an extremely low probability (perceived as impossible), from a security point of view (terrorist attack), this could be a possible threat scenario. A simulation analysis method is therefore proposed in this paper to model and analyze the process of emergency response to multiple fires. Through simulation, the defects in preventing multiple domino effects in an emergency response can be revealed, and the preparedness can be improved.

There are many actions in an emergency response process, especially under multiple simultaneous fires circumstances. Petri-net is a powerful modeling and analysis tool for these actions, for example, it can define under which conditions an action is enabled and what happens when it occurs. Petri-net is a graphical modeling and analysis tool, mainly composed of places, transitions and

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http://dx.doi.org/10.1016/j.jlp.2016.01.026
0950-4230/

directed arcs. Such a Petri-net approach may reveal the behavior of a system not only concerning occurrences of single transitions but also sets of occurring transitions which can be in different relationships such as causal relationship (Lorenz et al., 2009), concurrency (Auer et al., 2014), choice (Jiao et al., 2004), or total ordering. There are many extensions to Petri nets. Some of them are completely backwards-compatible with the original Petri net (e.g. colored Petri nets), some add properties that cannot be modeled in the original Petri net formalism (e.g. timed Petri nets). Various Petri nets are widely used in various fields, including process industries (Angeli et al., 2007; Grunt and Bris, 2015; Wu et al., 2010) and emergency responses (Karmakar and Dasgupta, 2011; Meng et al., 2011; Zhong et al., 2010).

In a previous study (Zhou, 2013), a hybrid Petri-net modeling and analysis approach for emergency response was proposed, considering discrete actions and continuous actions according to the characteristics of emergency response. In this paper, the approach is improved to model and analyze the emergency response to multiple simultaneous fires. Section 2 of this paper gives the definition of the timed colored hybrid Petri-net, based on which a model and an illustrative analysis example of emergency response to multiple fires is presented in Section 3. The conclusions from this work are discussed in Section 4.

2. Timed colored hybrid Petri-net

The time characteristic is very important in the process of emergency response. Petri-net can deal with time in several ways, including timed transition (Aybar and İftar, 2008), timed place (Mejia and Odrey, 2005) and timed arc (Valero et al., 1999). In this paper, timed transition is utilized according to the need of the analysis. Based on the definition of colored hybrid Petri-net (CHPN) in Zhou (2013), the timed colored hybrid Petri-net (TCHPN) is defined as follows by introducing the time factor:

A Timed Colored Hybrid Petri Net (TCHPN) is an eleven-tuple

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

Where, definitions of $P, T, A, \sum, V, N, C, G, E, IN$ are the same as the CHPN defined in Zhou (2013). A new tuple τ_{Td} is added.

(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. A token in a discrete place represents a type of message or a command. It is associated with a color such that different messages and commands can be identified. A token's color determines which transition is enabled by the token. A token in a continuous place represents a state, which is time-variant so that it is measured by a real number and can be a vector.

(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; the sets P and T are disjointed. A continuous transition must have at least one output continuous place which indicates the status of the transition, like the relationship between the fire-fighting action and the fire status. The continuous transition and this continuous place form a self-loop. That is, the state of the continuous place can not only influence the occurring of the continuous transition, but also be influenced by the executing of the transition.

(3) $A \subseteq P \times T \cup T \times P$, represents the sets of arcs connecting 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 a guard function that assigns a guard which is to filter and restrict possible events to each transition t so that

$$\forall t \in T : \left[Type(G(t)) = Bool \wedge Type(Var(G(t))) \subseteq \sum\right]$$

(9) E: represents the function of arch expression which assigns an arc expression to each arch so that

$$\forall a \in A : \left[Type(E(a)) = C(p(a))_{MS} \wedge Type(Var(E(a))) \subseteq \sum\right]$$

Where, $p(a)$ is the place of $N(a)$ and C_{MS} denotes the set of all multi-sets over C.

(10) IN: is an initialization function. It is defined from P into expressions such that

$$\forall p \in P : \left[Type(E(p)) = C(p(s))_{MS} \wedge (Var(IN(p))) \subseteq \varnothing\right]$$
where:

Type(expr) denotes the type of an expression,
Var(expr) denotes the set of variables in an expression,
$C(p)_{MS}$ denotes a multi-set over $C(p)$.

(11) τ_{Td}: $T_d \rightarrow R+$ is a function that associates discrete transitions with deterministic time delays.

R+: The set of nonnegative real numbers.

τ_{Td} indicates the executing time of a discrete transition. For a continuous transition, it can keep executing continuously after it is enabled, its executing time depends on some other conditions. Thus, the executing time of a continuous transition is not defined here. Transitions represent the actions in emergency response, the delay time of a transition indicates the executing time of the corresponding emergency response action.

A token element is a pair (p, c) where $p \in P$ and $c \in C(p)$. A binding element is a pair (t, b) where $t \in T$ and $b \in B(t)$. By $B(t)$ the set of all bindings for t is denoted. The set of all token elements is denoted by *TE* while the set of all binding elements is denoted by *BE*.

A marking M is a multi-set over *TE* while a step is a non-empty and finite multi-set over *BE*. The initial marking M_0 is the marking which is obtained by evaluating the initialization expressions.

Let $\bullet t$ ($\bullet p$) and $t\bullet$ ($p\bullet$) denote the set of input places of transition t (the set of input transitions of place p) and the set of output places of transition t (the set of output transitions of place p), respectively.

A transition is enabled if each of its input places contains the multi-set specified by the input arc inscription (possibly in conjunction with the guard), and the guard evaluates to true.

If a discrete transition is enabled, and its delay time is satisfied, it can occur. Occurring of an enabled discrete transition t_{dj} at marking M changes the marking into M'. For the discrete places p_{id} with color u_{id} and p_{kd} with color u_{kd}, the continuous places p_{ic} with color u_{ic} and p_{kc} with color u_{kc},

$$M'(p_{id}, u_{id}) = M(p_{id}, u_{id}) - 1 \ for \ p_{id} \in \ \bullet t_{dj} \wedge G_i(\bullet t_j) = True \quad (1)$$