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Petri-net based evaluation of emergency response actions for preventing domino effects triggered by fire

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ABSTRACT

In industrial chemistry, many flammable materials are handled and/or stored in various facilities. It is possible that major fires occur at these facilities possibly leading to domino effects due to the failure of neighboring facilities caused by thermal radiation. It will take a certain time that thermal radiation causes nearby facilities to fail and that a domino effect occurs. The time needed for escalation to take place allows emergency actions as a response to the primary fire to prevent the propagation of the fire. In the present study, a Timed Colored Hybrid Petri-net (TCHPN) based methodology is introduced to evaluate different emergency response actions based on their efficiency in preventing or delaying the propagation of domino effects. A TCHPN model of emergency response to flammable liquid tank fire is established, and a time based analysis of emergency response actions for preventing domino effects is performed. Based on the simulation analysis, the probability of domino effects is calculated and response actions are compared.

1. Introduction

In the (petro-)chemical industry, a large number of hazardous materials are used in production or for storage purposes. Once an accident happens caused by these materials, devastation may follow. An accident involving large amounts of these hazardous materials usually has a large area of impact, and has an important effect on the surrounding facilities eventually even leading to domino effects.

A domino effect has several characteristics (Reniers and Cozzani, 2013): (i) a primary accident, which triggers other accidents to form an accident chain; (ii) a propagation effect, resulting from the effect of escalation vectors caused by the primary event on secondary targets; (iii) one or more secondary accidents. Many studies have been performed on domino effects in the process industries, involving topics such as risk assessment, escalation thresholds, prevention approaches, cross-plant prevention measurements, and anti-terrorism research.

For example, regarding risk assessment with respect to domino effects, Antonioni et al. (2009) developed a methodology for the quantitative assessment of risk due to a domino effect and applied it to the analysis of an extended industrial area. They applied recently developed equipment damage probability models for the identification of the final scenarios and for escalation probability assessment. Khakzad et al. (2013) introduced a methodology based on Bayesian network both to model domino effect propagation patterns and to estimate the domino effect probability at different levels. The probabilities of events can be updated in the light of new information, and the most probable path of the domino effect can be determined on the basis of the new data gathered. Based on the probabilistic models and the physical equations, Kadri et al. (2013) presented a methodology for quantitative assessment of domino effects caused by fire and explosion on storage areas. A human vulnerability model to the effects of over pressure and heat radiation were developed to estimate the individual and societal risk. Khakzad et al. (2014) provided a dynamic consequence analysis approach for risk assessment and management of domino effects and presented the application of Bayesian networks and conflict analysis to risk-based allocation of chemical inventories to minimize the consequences and to reduce the escalation probability.

For the escalation thresholds, Cozzani and Salzano (2004) studied the definition and assessment of overpressure threshold values for the damage to equipment caused by blast waves which are originated by primary accidental scenarios, and they proposed threshold values for different categories of process equipment, taking into account either damage levels or release intensities following the loss of containment. Cozzani et al.(2006) further studied the revision and the improvement

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of criteria for escalation credibility, based on the modeling of fire and explosion damage to process equipment due to different escalation vectors (heat radiation, overpressure and fragment projection), and proposed revised threshold values. Landucci et al. (2009) developed an approach for the quantitative assessment of the risk caused by escalation scenarios triggered by fire. Simplified models for the estimation of the vessel time to failure (ttf) with respect to the radiation intensity on the vessel shell were obtained using a multi-level approach to the analysis of vessel wall failure under different fire conditions.

In the (petro-)chemical industry, chemical plants are often physically located in groups and are rarely located separately. A plant's accident may thus affect other plants in the neighborhood through escalation. Khan and Abbasi (2001) illustrated the application of DEA (domino effect analysis) and the software DOMIFFECT (DOMIno eFFECT) to four closely spaced petrochemical facilities in an industrial complex. The studies revealed that major accidents—some involving the entire industrial park—can occur. Reniers et al. (2009) proposed a game-theoretic approach to interpret and model behavior of chemical plants within chemical clusters while negotiating and deciding on domino effects prevention investments. Cozzani et al. (2014) presented methodologies developed for the quantitative assessment of risk due to domino and NaTech scenarios in the case of industrial clusters or complex industrial areas. A specific effort was dedicated to the improvement of models for the calculation of equipment damage probability in these accident scenarios.

After the events of 11 September 2001, the risk of terrorist attacks in chemical plants has aroused people's attention. Reniers et al. (2008) provided a theoretical conceptualization on how to manage the prevention and the mitigation of intentionally induced domino effects in a possibly very complex industrial cluster. Reniers et al. (2014) further proved by case-study that chemical industrial areas may follow a power-law distribution, through representing such areas as mathematical 'danger networks'. Landucci et al. (2015b) carried out the analysis of industrial accidents induced by intentional acts of interference, focusing on accident chains triggered by attacks with home-made explosives. The effects of blast waves caused by improvised explosive devices were compared with those expected from a net equivalent charge of TNT by using a specific methodology for the assessment of stand-off distances.

Domino effects can cause great losses, so how to prevent domino effects has also been studied by some researchers. Reniers and Dullaert (2008) developed a simple and user-friendly software named "DomPrevPlanning" to support decision making on safety barriers to prevent/mitigate domino effects in a complex surrounding of chemical installations, and thereby considering multiple domino scenarios. Janssens et al. (2015) presented a decision model to support practitioners about where to locate safety barriers and mitigate the consequences of an accident triggering domino effects, based on the features of an industrial area that may be affected by domino accidents, and knowing the characteristics of the safety barriers that can be installed to stall the fire propagation between installations. Landucci et al. (2015a) developed a LOPA (layer of protection analysis) based quantitative assessment methodology, aimed at the definition and quantification of safety barrier performance in the prevention of escalation of domino events induced by fire.

In addition to safety barriers, emergency response can play an important role in preventing domino effects, but it has seldom been studied. The main escalation vectors that can trigger domino effects are thermal radiation, overpressure, and fragments of explosion (Cozzani et al., 2005). As the duration of nearby facilities being influenced by overpressure or fragments is very short, the role of emergency response in preventing the domino effect in these cases is limited. However, the development of domino effects triggered by thermal radiation is often characterized by a longer duration. In such case, after the occurrence of a primary fire, effective emergency response which is carried out in time can prevent domino effects. Zhou et al. (2016) proposed a methodology based on Event Sequence Diagram (ESD) to evaluate and prioritize different emergency response actions based on their efficiency in preventing or delaying the propagation of domino effects triggered by fire. Owing to the advantages of Petri-nets in modeling and analysis of discrete events (and even continuous events), this paper uses Petri-net to analyze the role of emergency response actions in case of domino effect.

The concept of the Petri-net was proposed by Petri (1966). From then on, Petri-nets are widely used to model and analyze discrete event systems such as communication, manufacturing, and transportation systems. Petri-nets are a graphical and mathematical modeling tool applicable to many systems. They constitute a promising tool for describing and studying systems that are characterized as being concurrent, asynchronous, distributed, parallel, nondeterministic, and/or stochastic (Murata, 1989). In addition to the modeling of systems, tokens are used in Petri nets to simulate the dynamic and concurrent activities of the systems. A variety of high level Petri-nets are proposed to solve various problems. Hybrid Petri-net can be used to model a system if one part is discrete and another part is continuous David and Alla, 2001. Timed Petri-net (TPN) augments PNs with time, such as firing durations, or time delays. In timed Petri-nets, the transitions fire in "real-time", i.e., there is a (deterministic or random) firing/executing time associated with each transition, the tokens are removed from input places at the beginning of firing, and are deposited into output places when the firing terminates (Zuberek, 1991). Colored Petri net (CPN) is a formalism which extends ordinary Petri nets by adding data types and modularity (Jensen, 1990).

In literature, Petri-nets have also been applied to the modeling and analysis of emergency response (Aye and Ni, 2011; Meng et al., 2011; Zhong et al., 2010; Zhou, 2013; Zhou and Reniers, 2016). In Zhou (2013), the emergency response process is considered as a hybrid system, and the emergency actions are divided into discrete actions and continuous actions according to their durations. During an emergency response, in addition to discrete events which can be completed quickly, there are some actions which have a 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. As a colored Petri Net can use colors to distinguish tokens, the hybrid Petri net model will be more compact and concise by integrating with colored Petri net. Because this study analyzes the actions of the emergency response process based on the time analysis, the Timed Colored Hybrid Petri-Net (TCHPN) is adopted to model the process.

This paper is structured as follows. Section 2 provides the definition of TCHPN and discusses its operating mechanism. Section 3 models the emergency response process based on TCHPN. Section 4 discusses the evaluation of emergency response actions, and Section 5 concludes this article.

2. Timed Colored Hybrid Petri-net

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

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

(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) Σ represents a finite set of non-empty types, called color sets.

(5) V is a finite set of variable types, so that $Type[v] \in \Sigma$ for all $v \in V$ variables.