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A matrix-based modeling and analysis approach for fire-induced domino effects

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ABSTRACT

Knock-on effects or so-called domino effects in the process industries may cause much greater losses than merely a primary event. Probability analysis of accidents resulting from domino effects is important for risk assessment. However, for the accident occurrence of a unit there may be mutual influences between the units in the area influenced by the accidents due to a domino effect, and this makes the calculation of probabilities of the accidents rather difficult. A matrix-based approach is proposed to model the influences between units influenced by a fire-induced domino effects, and the analysis approach for accident propagation as well as a simulation-based algorithm for probability calculation of accidents is provided. The synergistic effect of thermal radiation is taken into account during the accident propagation. The proposed approach is flexible to model and analyze domino effects in various conditions of primary fires by only changing the value of the initial matrix indicating the fire states. Two examples illustrate analyzing the fire propagation among tanks storing flammable liquids. The results show that this approach is simple but effective for offering an insight in the accident propagation process and for knowing the probabilities of equipment getting on fire.

1. Introduction

When a major fire accident occurs in a process plant or a storage area, surrounding equipment may be damaged due to the thermal radiation. In some cases the failure of the affected equipment can lead to loss of containment and an additional accident. The phenomenon that a relatively minor accident initiates a sequence of events causing damage over a much larger area and leading to far more severe consequences than the original event is called ‘domino effect’.

There are many studies on domino effects in scientific literature. Most of them focus either on damage probability or on domino effect frequency estimation. For example, Khan and Abbasi (1998) proposed some specific methods for domino frequency estimation as a part of their DEA (Domino Effect Analysis) procedure. They also demonstrated its application to real-life situations such as an industrial complex comprising 16 different facilities (Khan and Abbasi, 2001). Cozzani et al. (2005) developed a systematic procedure for the quantitative assessment of the risk caused by domino effect. Landucci et al. (2009) proposed a simplified approach for the estimation of escalation thresholds and escalation probabilities triggered by fire scenarios. Reniers et al. (2009) proposed a game-theoretic approach to interpret and model behaviour of chemical plants within chemical clusters while negotiating and deciding on domino effects prevention investments. Bernechea et al. (2013) developed a simple method to include domino effects in QRAs of storage facilities, by estimating the frequency with which new accidents will occur. However, most of these studies focus on the first level of accidents where primary and secondary events are taking place. Furthermore, these works mostly use simplified assumptions, e.g. the synergistic effects and/or the mutual impacts among hazard installations usually are not considered.

Some researchers studied the probability analysis of cascading effects, which refer to the domino effects that a primary accident propagates to higher level accidents. Abdolhamidzadeh et al. (2010) proposed a Monte Carlo Simulation based approach to assess the likely impact of domino effects. Khakzad et al. (2013) provided a new methodology based on Bayesian networks to model domino effect propagation patterns and to estimate the domino effect probability at different levels. Rad et al. (2014) proposed a method named FREEDOM II to assess the frequency of domino accidents. Zhou and Reniers (2017) proposed a Petri-net based approach to

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model the cascading effect and estimate the probabilities of escalation vapor cloud explosions. Some of these studies considered the mutual impacts among hazard installations, however, most of them are not flexible enough to model and analyze cascading effects under different conditions, when primary accident changes, the models often need to be reconstructed, and some data (e.g., Conditional Probability Table) need to be rebuilt.

From previous studies it can be seen that fire is a major primary event in domino effects. Nearly half of the domino effects are caused by fire (Abdolhamidzadeh et al., 2011; Darbra et al., 2010; Hemmatian et al., 2014). When a vessel is subjected to a fire, its damage will depend on the type of fire, more specifically on the thermal radiation released, and on whether there is flame impingement. Fire induced domino effects has been studied in literature (Gomez-Mares et al., 2008; Landucci et al., 2009; Hemmatian et al., 2015). Pool and tank fires can last a long time. If thermal radiation reaches equipment nearby, unless it is adequately protected, such as by thermal insulation and water deluge, the conditions for failure may be reached. In this study, the probability analysis of domino effects is discussed based on the pool fire or tank fire in a tank farm. In this case, the equipment (tank) adjacent to a primary tank fire is exposed only to thermal radiation and there is no flame impingement, as there is a certain distance between any two tanks.

There is a synergistic effect of thermal radiation received by a tank. In literature, to determine which nearby units are impacted, the escalation vectors exerted by the primary event on the nearby units are compared with predefined threshold values (Cozzani et al., 2006). The escalation vectors well above the relevant thresholds are strong enough to cause credible damage to the nearby units. Obviously, if the total thermal radiation received by a tank is above the threshold, it may be damaged even if the thermal radiation received from each of other fired tanks is lower than the threshold. Thus, a matrix is utilized to model the mutual impacts between the tanks, and on this basis, a novel probability analysis approach is provided for determining the fire probability of any tank in a tank farm.

This paper is organized as follows: Section 2 briefly discusses the domino effect of fires, including the models for escalation probability, synergistic effect of fires, and the problem in probability analysis. In Section 3, the matrix-based modeling and analysis approach is provided. An example illustrates the proposed approach in Section 4. Finally, the conclusions drawn from this work are presented in Section 5.

2. Domino effect of fires

2.1. Escalation probability

In literature, probit methods have been widely used to estimate the escalation probability of equipment because of simplicity and flexibility (Cozzani et al., 2005; Antonioni et al., 2009; Landucci et al., 2009).

Generally, the probit value Pr can be obtained using Eq. (1):

$$Pr = a + b\ln(x) \quad (1)$$

Where, a and b are probit coefficients.

After Pr is determined, the escalation probability, P_{esc}, could be calculated as:

$$P_{esc} = \phi(Pr - 5) \quad (2)$$

Where, ϕ is the cumulative density function of standard normal distribution.

Since vessel failure is caused by the vessel wall heat-up and this is a relatively slow process under the thermal radiation, the time to failure (*ttf*) of the vessels exposed to fire is a fundamental parameter in the analysis of domino accidents triggered by fire. The vessel *ttf* expresses the resistance of the target equipment to an external fire.

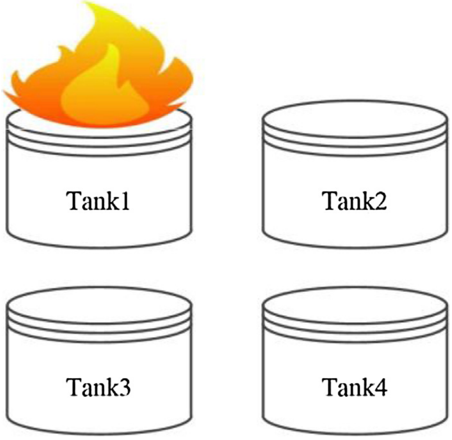

Fig. 1. Layout of four tanks.

Table 1
Thermal radiation on each target (kW/m2).

	Tank1	Tank2	Tank3	Tank4
Tank1	–	20	20	10
Tank2	20	–	10	20
Tank3	20	10	–	20
Tank4	10	20	20	–

In this study, the expression of Pr provided by Landucci et al. (2009) is adopted:

$$Pr = 9.25 - 1.85 \times \ln(ttf/60) \quad (3)$$

The *ttf* can be determined according to the relationship between heat flux I (kW/m^2) and *ttf* (s) provided by Cozzani et al. (2005):

$$\ln(\mathrm{ttf}) = -1.128\ln(\mathrm{I}) - 2.667 \times 10^{-5}\mathrm{V} + 9.877 \quad (4)$$

Where, V is the volume of the vessel (m^3).

2.2. Synergistic effect during the propagation of fires

The thermal radiations emitted from multiple fires have the synergistic effect, that is, if they reach the same equipment, the received thermal radiation is the sum of the thermal radiations from all fire sources. Take four tanks as an example, the layout of them is shown in Fig. 1. The thermal radiations acting on other target tanks of each tank fire are given in Table 1.

If Tank1 is on fire, the thermal radiations received by Tank2, Tank3, and Tank4 are 20 kW/m^2, 20 kW/m^2, and 10 kW/m^2, respectively. If Tank2 catches fire successively, the thermal radiation received by each of Tank3 and Tank4 would become 30 kW/m^2. The changes of received thermal radiation will impact the calculation of fire probabilities of the tanks.

2.3. Problem in probability analysis of fire-induced domino effect

When calculating the fire probabilities of all tanks under domino effects according to Eqs. (2), (3) and (4), there are mutual influences among the tanks. Shaluf et al. (2003) and Abdolhamidzadeh et al. (2010) also noticed and studied the mutual impacts among major hazard installations. The mutual impacts among hazardous installations make the probability calculation quite difficult. For example, the conditional probabilities of Tank4 on fire given Tank1, Tank2, and Tank3 on fire, or not, are calculated and shown in Table 2. Similarly, the conditional probabilities of Tank3 on fire given Tank1, Tank2, and Tank4 on fire, or not, are calculated and shown in Table 3.