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Analysis of emergency response actions for preventing fire-induced domino effects based on an approach of reversed fuzzy Petri-net

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Abstract: In the chemical process industry, large quantities of different flammable substances are stored in tank farms. Due to potential mutual impacts among the tanks, severe domino accidents may occur after a tank catches fire. The emergency response to a tank fire may influence the development of the accident and impact the occurring of escalating events or so-called domino effects. In this paper, a fuzzy Petri-net (FPN) based reversed reasoning approach is proposed to analyze emergency response actions impacting domino effects. FPN is utilized to deduce the consequence-antecedent relationship between an accident and the emergency response actions. To analyze and compare the impacts of the actions on a domino effect, the backward reasoning is of special interest and often preferable when the occurrence probability of domino effects is known. As a tank fire accident in an oil depot usually lasts for a certain period of time, and as it may be greatly influenced by emergency response actions, it is taken as an example to illustrate the proposed approach.

Keywords: Chemical process industry; Emergency response; Domino effect; Fuzzy Petri-net; Backward reasoning

1. Introduction

In the chemical and process industries, various hazardous chemicals which have flammable, explosive, toxic or/and corrosive characteristics are handled and/or stored. Once an accident happens where such chemicals are involved, it may have a great impact and lead to huge losses. Such an accident may result in the failure of other equipment around, and become the cause of other accidents. The phenomenon where a primary accident develops into some secondary accidents is usually called the “domino effect”. A domino effect contains the following characteristics (Reniers & Cozzani, 2013):

- (i) An initial accident triggering the domino effect;
- (ii) Escalation effect under the actions of the propagation factors;
- (iii) One or more secondary accidents.

A true domino effect always causes more significant damage than the initial accident. After an accident occurs, we should thus endeavor to prevent the accident from escalating. Safety management therefore requires risk assessment of domino effects. In Europe, the Seveso-III Directive requires the European member states to assess risks of domino effects in hazardous installations (Directive2012/18/EU).

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Since the mid-1990's, there have been an increasing number of domino effect studies related to chemical facilities. For example, Cozzani & Salzano (2004a, 2004b) derived specific probit models for several categories of process equipment aiming at the quantitative assessment of domino effects caused by overpressure, and compared them to other literature approaches for the prediction of probability of damage of equipment loaded by overpressure. Salzano & Cozzani (2005) elaborated several specific probit functions for the quantitative estimation of damage probabilities to plant equipment caused by pressure waves. Cozzani et al. (2006) proposed revised threshold values and specific escalation criteria, based on recent advances. Reniers & Dullaert (2007) designed a new computer-automated tool to support decision-making on preventive and protective measures to alleviate domino effects in a complex surrounding of chemical installations. Reniers et al. (2008) proposed a theoretical conceptualization on how to manage the prevention and the mitigation of intentionally induced domino effects in a possibly very complex industrial cluster. Antonioni et al. (2009) applied a methodology that can be employed for the quantitative assessment of risk related to domino effects within an entire industrial area. Landucci et al. (2009) specifically developed an approach for the quantitative assessment of the risks due to escalation scenarios triggered by fire. They proposed simplified models for the estimation of the vessel time to failure (ttf) with respect to the radiation intensity on the vessel shell, using a multi-level approach for the analysis of vessel wall failure under different fire conditions. Reniers et al. (2009) employed a game-theoretic approach to interpret and model strategic cooperation behavior of chemical plants within chemical clusters while deciding on domino effects prevention investments. Reniers (2010) suggested an approach indicating what information is required to evaluate the available investment options in external domino effects prevention for companies situated within a chemical cluster. To this end, game theory is used as a promising scientific technique to investigate the decision-making process on investments in prevention measures simultaneously involving several plants. Khakzad et al. (2014) provided a dynamic consequence analysis approach for risk assessment and management of domino effects. The application of Bayesian networks and conflict analysis was presented to risk-based allocation of chemical inventories to minimize the consequences.

These researches about domino effects cover topics such as risk analysis, escalation thresholds, domino effect prevention, and so on. After the initial accident, people tend to perform emergency response to control the accident. Correct and effective emergency actions are essential to reduce the possibility of domino effects, and also to mitigate potential consequences and then to reduce accident losses. Therefore, the risk assessment of domino effects should consider the impact of emergency response as well. Nevertheless, this subject has until now seldom been studied.

Emergency actions after an accident would affect the evolution of the accident, and different evolutionary directions can cause different consequences. Analyzing the causes of an accident evolution can help us improve emergency plans, and to take reasonable emergency actions in the accident, and mitigate the accident losses. For instance, domino effects resulted from fire escalation (mainly caused by the thermal radiation) require a certain time to failure. When the thermal radiation received by adjacent tanks exceeds a certain threshold and the duration exceeds a certain time, secondary accidents may occur. Thus, timely emergency response may prevent domino effects triggered by fire.

Petri-net which is a graphical modeling and analysis tool composed of places, transitions and

directed arcs can model the causal relationships of the actions and the events. The uncertainties of the actions and the events can be easily handled by fuzzy Petri-net (FPN), which is an extension of Petri-net. FPN is able to develop specific knowledge, and exhibit structural characteristics among the rules of the knowledge base. The technique has got many applications in fields such as fault diagnosis and knowledge reasoning (Gao et al., 2003; Aziz et al., 2010). It is also used for safety analysis. For example, Lee et al. (1999) proposed a fuzzy Petri net approach to modeling fuzzy rule-based reasoning to bring together the possibilistic entailment and the fuzzy reasoning to handle uncertain and imprecise information, and used it to the damage assessment of bridges. Tao and Lin (2008) developed and applied Fuzzy Petri Nets (FPN) to the safety analysis for three types of level crossing surveillance systems of Taiwan Railway Administration. Tao (2009) presented a two-stage safety analysis model for railway level crossing surveillance systems by using Fuzzy Petri Nets, Fault Tree Analysis and Markov model. Guo et al. (2016) proposed a comprehensive risk evaluation method based on a fuzzy Petri net (FPN) model for long-distance oil and gas transportation pipelines. In addition to being able to model various relationships between parts of a system, like ordinary Petri-nets, FPN can also model and analyze uncertainties. Owing to the advantages of fuzzy Petri-nets in modeling and analysis of uncertainties and their relationships, this paper analyzes the role of emergency response actions in the prevention of fire escalation by using fuzzy Petri-nets.

The remaining parts of this paper are organized as follows. In Section 2, the definition of FPN is provided, together with the backward reasoning approach. Section 3 discusses how to carry out an emergency response actions analysis. Section 4 illustrates this approach by analyzing the actions responding to a fire of a flammable liquid. The conclusions of this work are given in Section 5.

2. Fuzzy Petri-net Analysis approach

2.1 Definition of fuzzy Petri-net and reversed fuzzy Petri-net

The main purpose of fuzzy Petri-net based reasoning is to determine the causal relationship between the propositions of production rules (or so-called IF-THEN rules), and to calculate the probability when causes are true and the effect is also true. In practice, there exist some conditions that the likelihood of an effect is known, while the likelihoods of the causes need to be determined. This can be achieved by using the fuzzy Petri-net and the backward inference.

Fuzzy Petri-net (FPN) can be defined as a 5-tuple (Hu et al., 2011; Liu et al., 2013):

$$FPN=(P, T, \Delta, \Gamma, M, U) \quad (1)$$

Where,

$P = \{p_1, p_2, \dots, p_n\}$ is a set of places;

$T = \{t_1, t_2, \dots, t_m\}$ is a set of transitions;

$\Delta = P \times T \rightarrow \{0, 1\}$ is an $n \times m$ input matrix defining the directed arcs from places to transitions. The element $\delta_{i \times j} = 1$, if there is a directed arc from p_i to t_j , and $\delta_{i \times j} = 0$, if there are no directed arcs from p_i to t_j for $i=1, 2, \dots, n$, and $j=1, 2, \dots, m$. The places connecting to transition t are denoted as t^* .

$\Gamma = P \times T \rightarrow \{0, 1\}$ is an $n \times m$ output matrix defining the directed arcs from transitions to places. The element $\gamma_{i \times j} = 1$, if there is a directed arc from t_j to p_i , and $\gamma_{i \times j} = 0$, if there are no directed arcs from t_j to p_i for $i=1, 2, \dots, n$, and $j=1, 2, \dots, m$. The places connecting from transition t are denoted as t^* .

$M: P \rightarrow [0, 1]$ is a marking vector. $M = (\theta_1, \theta_2, \dots, \theta_n)^T$, θ_i is the “truth value” of place p_i . The initial marking is denoted by M_0 .

$U: T \times T \rightarrow [0, 1]$ is a certainty factor matrix. The elements u_{ij} is the certainty factor (CF) of transition t_j , and $u_{ij}=0 (j \neq i)$, $i=1, 2, \dots, m, j=1, 2, \dots, m$.

$\forall t \in T$, t is enabled if $\forall p_i \in {}^*t, \theta_i > 0$. An enabled transition can fire/execute, and after t is fired, the tokens in input places are copied, and a token with fuzzy truth is put into each of the output places.

In order to analyze the causes according to the effects, the directions of the arcs in a FPN model can be reversed, and the corresponding reversed fuzzy Petri-net can be obtained. Thus, a reversed fuzzy Petri-net (RFPN) can be defined as:

$$RFPN = (P', T', \Delta', \Gamma', M', V) \quad (2)$$

Where,

$$P' = P; T' = T; \Delta' = \Gamma; \Gamma' = \Delta; M' = M;$$

$$V = (v_{ij})_{m \times m}, \text{ and } v_{ij} = 1/u_{ij}, v_{ij} = 0 \text{ for } j \neq i, i=1, 2, \dots, m, j=1, 2, \dots, m..$$

Petri-net and its corresponding reversed Petri-net are illustrated in Fig. 1, where, (a) indicates the reasoning process of FPN, and (b) indicates the reasoning process of RFPN.

Fig. 1 Reasoning process of FPN and RFPN

2.2 RFPN based backward reasoning

In a RFPN model, all enabled transitions can fire/execute in parallel. In order to formally describe the reasoning process of FPN, two operators derived from the max-algebra are introduced in Gao et al. (2000, 2003).

$\oplus : A \oplus B = C$, where A, B and C are $m \times n$ matrices, a_{ij}, b_{ij}, c_{ij} are their elements, respectively, and $c_{ij} = \max \{ a_{ij}, b_{ij} \}$;

$\otimes : A \otimes B = C$, where A, B and C are $m \times p, p \times n$ and $m \times n$ matrices, respectively, $c_{ij} = \max \{ a_{ik} \times b_{kj} \}$, $k = \{ 1, 2, \dots, p \}$, $i = \{ 1, 2, \dots, m \}$, $j = \{ 1, 2, \dots, n \}$.

The backward reasoning algorithm is as follows (Hu et al., 2011; Liu et al., 2013).

Step 1: Let the iteration number $k=0$;

Step 2: Calculate the new truth values of the places according to

$$M(k) = M(k-1) \oplus [\Delta \times V \otimes \rho(k-1)] \quad (3)$$

Where, $\rho(k) = \text{neg}(\Gamma^T \text{neg}(M(k)))$

The operator neg is initially defined in Tzafestas and Caplovic (1997) whose representation

can be described as follows. Let x be an m -dimensional vector, $\text{neg}(x) = 1_m - x$, where $1_m = [1_1, 1_2, \dots, 1_m]^T$, and $x = [x_1, x_2, \dots, x_m]^T$.

Step 3: Let $k = k+1$, repeat Step 2 until $M(k)=M(k-1)$.

From the marking of the reasoning result, the truth values of all places including those indicating the causes, can be obtained.

3. Emergency response actions analysis

In the petrochemical industry, a fire (e.g. a tank fire or a pool fire) can easily affect surrounding equipment (e.g. tanks). In this study, only pool fires are considered.

3.1 Risk assessment of domino effects triggered by a pool fire

In order to analyze the occurrence probability of domino effects induced by a pool fire, it is necessary to estimate the thermal radiation received by nearby equipment. We assume (for sake of simplicity) the nearby equipment to be storage tanks. The commonly used fire thermal radiation model includes a point source model, and a solid flame radiation model. The point source model considers the pool fire flame as a point in the center of the fire, and all the heat radiation is released from this point (Mudan, 1984; McGrattan et al., 2000). The solid flame radiation model is based on the proposition that the entire visible volume of the flame emits thermal radiation and the non-visible part of the flame does not contribute significantly. The fire is idealized as a solid vertical cylinder emitting thermal radiation from its sides (Mudan, 1984; McGrattan et al., 2000). Besides, there are some other models, including the two zone entrainment model (Fay, 2006), the Computational Fluid Dynamics (CFD) based model (Chun et al., 2009), and other models, to estimate the thermal radiation of a pool fire. The solid flame radiation model is relatively simple and is widely used for describing thermal radiation from large hydrocarbon fires (Mudan, 1984; McGrattan et al., 2000), thus it is adopted to estimate the thermal radiation of a pool fire in this work. For the details of the model, we refer to Mudan (1984).

If there is a huge fire, the neighboring equipment (e.g. tanks) may fail due to thermal radiation. Cozzani et al. (2005) summarized the models for the assessment of escalation probability. For atmospheric vertical cylindrical vessels, the time to failure t_{tf} (in second) can be determined as follows:

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

Where, I is the radiation intensity on the target equipment (kW/m^2); V is the equipment volume (m^3).

In the process industry, probit model, which is a nonlinear regression models most widely used in modern statistics, is widely used to analyze the probabilities of damages (Cozzani and Salzano, 2004a; Cozzani et al., 2005; Salzano and Cozzani, 2005). Landucci et al. (2009) discussed a simplified probit model and provided an expression for preliminary assessment of fire-induced escalation probabilities. When the maximum time required to start the emergency operations is equal to 5 min, and the maximum time required to start the mitigation actions equals 20 min, the probit value Pr can be calculated according to the following equation:

$$Pr = 9.25 - 1.85 \ln(t_{tf}) \quad (5)$$

Where, t_{tf} is the time to failure (minute).

The value of the probit variable Pr and the value of the probability of damage and escalation P ($0 \leq P \leq 1$) (which indicates the likelihood of the failure of the neighboring equipment) have the following relationship:

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\text{Pr}-5} e^{-\frac{u^2}{2}} du \quad (6)$$

3.2 Emergency response actions analysis through backward reasoning

After flammable liquid (e.g. oil in tanks) catches fire, the emergency response actions may influence the fire and prevent escalation. If the truth value of a domino effect is known (e.g., by risk assessment), an interesting question can be what are the truth values of the emergency actions? Using FPN, the truth values of emergency actions can be determined.

The steps to analyze the emergency actions are as follows:

(1) Establish the fuzzy Petri-net model according to the rules that the emergency response actions impact on the fire accident. Normally, the propositions of the rules can be converted to places of the FPN model, and the rules are considered as transitions. Directed arcs connect them according to their relationships.

(2) Establish the reversed fuzzy Petri-net model according to the FPN model.

(3) Determine the truth value of the domino effect induced by fire. This can be obtained through the risk assessment discussed in Section 3.1.

(4) Calculate the truth values of all places based on the reasoning algorithm of reversed fuzzy Petri-net.

After the backward reasoning ends, the truth values of emergency response actions can be obtained from the corresponding places. Thus, the influences of the emergency response actions on the domino effect can be estimated.

4. An illustrative example

In a previous study (Zhou et al., 2016), an example is provided to illustrate the evaluation of emergency response actions. This example is adopted (slightly changed) to analyze the impacts of emergency actions on domino effects based on the reversed fuzzy Petri-net approach in this study.

An oil depot storage area has 5 gasoline atmospheric storage tanks (vertical cylindrical tanks). The diameters of the tanks (Tk2-Tk6) are 20m, and their heights are 10m. At the location of the pool fire is assumed, the distance from Tk1 to Tk2 is 30m (center to center), and so is the distance from Tk1 to Tk3. The layout of the tanks is shown in Fig. 2.

If there is a pool fire at Tk1, the fire may be controlled via emergency response actions, or else the fire may escalate to one of the storage tanks, resulting in a domino event. When the pool at Tk1 catches fire, Tk2 and Tk3 will receive the maximum intensity of thermal radiation. Based on Mudan's model (Mudan, 1984), the thermal radiation intensity received by Tk2 and Tk3 is about 12.5 kW/m². These two tanks are most likely to fail, since they are closest to the pool fire. The corresponding *ttf* is about 17min calculated according to Eq. (4). This means that the intensity of thermal radiation received by Tk2 and Tk3 must be decreased in 17min during an emergency response; otherwise, Tk2 and/or Tk3 may fail and a knock-on effect may occur.

During an emergency response, many factors have influence on the development of the accident, such as the quality of personnel, the allocation of resources, the actions taken, and the mutual coordination. In this study, the impacts of two actions on the accident are considered, one is whether the emergency personnel is delayed to arrive at the scene, the other is whether the firefighting measures are correct. The rules are as follows:

Fig. 2 Layout of the tanks

R1: IF arriving at the scene is delayed ($p1$) THEN firefighting is delayed ($p2$) AND cooling adjacent tanks is delayed ($p3$), $CF=0.8$;

R2: IF firefighting is delayed ($p2$) THEN thermal radiation emitted by the fire is not reduced in time ($p5$), $CF=0.9$;

R3: IF cooling adjacent tanks is delayed ($p3$) THEN thermal radiation received by adjacent tank is not reduced in time ($p6$), $CF=0.9$;

R4: IF firefighting measures are not correct ($p4$) THEN thermal radiation emitted by the fire is not reduced in time ($p5$), $CF=0.95$;

R5: IF thermal radiation emitted by the fire is not reduced in time ($p5$) AND thermal radiation received by adjacent tank is not reduced in time ($p6$) THEN domino effect occurs ($p7$), $CF=0.95$.

Based on the rules, the fuzzy Petri-net model is established as shown in Fig. 3. The five rules are converted to transitions $t1$, $t2$, $t3$, $t4$, and $t5$, respectively. The certainty factors of the rules are considered as the certainty factors of the corresponding transitions.

Fig. 3 FPN model for the impact of emergency response on domino effect

By reversing the direction of all directed arcs, the reversed FPN model is established and shown in Fig. 4.

Fig. 4 Reversed FPN model for the impact of emergency response on domino effect

According to formulas (2) and (3), the probability of domino effect induced by a tank pool fire is about 0.16 when the t_{tf} is 17min. Although the concept of probability is not exactly the same as the concept of truth value, in some cases probabilities can be treated as truth values. Generally, in the fuzzy logic, a truth value, sometimes called a logical value, is a value indicating the relation of a proposition to truth. Probability is a measure of the likelihood of a random event. Nevertheless, Zadeh (1988) pointed out that fuzzy logic has three principal modes of qualification, namely truth-qualification, probability-qualification, and possibility-qualification. Nilsson (1986) considered the truth value as a probability and initiated probability logic. Thus, the probability of domino effect is taken as the truth value in this study, that is, the truth value of a place indicates the probability that the proposition represented by the place is true. This way, we can obtain the following matrices:

$$\Delta = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \quad V = \begin{pmatrix} 0 & 0 & \frac{1}{0.9} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{0.95} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{0.95} \end{pmatrix} \quad (7)$$

And,

$$M(0)=[0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0.16]^T, \quad \rho(0)=[0 \ 0 \ 0 \ 0 \ 0.16]^T \quad (8)$$

Through iterative calculation, the following results can be obtained:

$$M(1)=[0 \ 0 \ 0 \ 0 \ 0.1684 \ 0.1684 \ 0.1600]^T \quad (9)$$

$$M(2)=[0 \ 0.1871 \ 0.1871 \ 0.1773 \ 0.1684 \ 0.1684 \ 0.1600]^T \quad (10)$$

$$M(3)=[0.2339 \ 0.1871 \ 0.1871 \ 0.1773 \ 0.1684 \ 0.1684 \ 0.1600]^T \quad (11)$$

$$M(4)=[0.2339 \ 0.1871 \ 0.1871 \ 0.1773 \ 0.1684 \ 0.1684 \ 0.1600]^T \quad (12)$$

As $M(4)=M(3)$, the iteration ends. It can be seen from the results that when the truth value of

domino effect is 0.16, the truth value of “arriving at the scene is delayed” is 0.2339 and the truth value of “firefighting measures are not correct” is 0.1773. It indicates that in this case the action “arriving at the scene is delayed” has a greater likelihood of causing the domino effect and should be improved first.

5. Conclusions

Emergency response actions after the occurrence of an accident can affect the development of the accident. Avoiding fire-induced escalation events is a typical example of the importance of emergency response actions. Analyzing the factors having influence on a possible domino effect therefore may help us to improve emergency preparedness.

In this paper, a reversed fuzzy Petri-net based analysis approach for emergency actions is elaborated and discussed, to analyze the effectiveness of these actions given that the probability of the domino effect is known. A pool fire accident in a tank farm of an oil depot is taken as an example to illustrate the analysis of emergency actions impacting on a potential domino effect.

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