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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.

Keywords: domino effect; probability analysis; matrix modeling; process industry

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

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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 (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 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 (Abdolhamizadeh 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):

$$Pr = a + b\ln(x) \tag{1}$$

Where, a and b are probit coefficients.

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

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

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.

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

$$Pr = 9.25 - 1.85\times\ln(ttf/60) \tag{3}$$

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):

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

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.

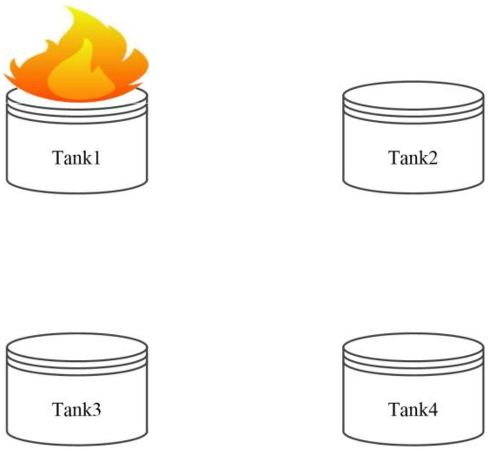

Fig.1 Layout of four tanks

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	-

2.3 Problem in probability analysis of fire-induced domino effect

When calculating the fire probabilities of all tanks under domino effects according to Eq.(2), Eq. (3) and Eq. (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.

Table 2 Conditional probabilities of Tank4 on fire given Tank1, Tank2, and Tank3 on fire (Y) or not (N)

Tank1	Tank2	Tank3	Tank4 (Fire)
Y	Y	Y	0.9603
Y	Y	N	0.7544
Y	N	Y	0.7544
Y	N	N	0

Table 3 Conditional probabilities of Tank 3 on fire given Tank1, Tank2, and Tank4 on fire (Y) or not (N)

Tank1	Tank2	Tank4	Tank3 (Fire)
Y	Y	Y	0.9603
Y	Y	N	0.7544
Y	N	N	0.4374

It can be seen that the fire probability of Tank3 is influenced not only by the fire of Tank1, but also by the fire of Tank4 (also influenced by Tank2). On the contrary, the fire probability of Tank4 is also influenced by the fire of Tank3 (also influenced by Tank1 and Tank2). Similarly, there are mutual influences between Tank2 and Tank3, and Tank2 and Tank4 when computing probabilities. That is, the fire probability of any tank given a primary tank fire occurring in this tank farm is not independent. If there are a lot of tanks, the relationship of impacts on fire propagation among the tanks is quite complex. The complex relationship of influences among the tanks makes it difficult to determine the fire probability of each tank.

Nevertheless, for a specific fire propagation process, the impact of one tank on another is deterministic, there is no mutual influence between the tanks. For example, if the fire propagates from Tank1 to Tank3, then the fire of Tank3 will impact Tank4, and cannot be influenced by the fire of Tank4. Each propagation process can be looked as a pattern of the domino effect. If we simulate the patterns of the fire propagation according to the rule of escalation, we can obtain the fire probability of each tank.

3. Matrix-based analysis approach

3.1 Modeling approach

For a fire accident (e.g. pool fire), the escalation vector is the thermal radiation (Cozzani et al., 2006). Suppose there are n units containing flammable liquids in an area, the fire in each unit will emit thermal radiation to all other n-1 units. These impacts of one unit on other units can be modeled by a matrix.

In order to analyze the propagation of fires in an area, the following matrices are introduced to model the relationship between units in an area that may be influenced by a fire-induced domino effect and the state of fires:

- O: is an n×n dimensional matrix denoting heat radiation of one unit on each target unit. Where, n is the number of units which may be influenced by fires in the area. The element O_{ij} means the heat radiation of unit *i* on unit *j* (i=1, 2, …, n; j=1, 2, …, n).
- M: →{0, 1}, is a 1×n dimensional matrix indicating the fire states of the units. If the value of element *i* (*i*=1, 2, …, n) equals 1, it means the unit *i* is on fire; otherwise, the unit *i* is not on fire. The initial states of the units are denoted by M_0.
- B: is a 1×n dimensional matrix denoting thresholds of fire escalation of the units. The value of element *i* is the threshold of unit *i*, *i*=1, 2, …, n.
- V: is a 1×n dimensional matrix, the element v_i represents the volume of unit *i* (*i*=1, 2, …, n).

3.2 Simulation approach of fire propagation

In order to represent the fire propagation formally, and perform the analysis process automatically in parallel (the propagation of fires may be in parallel), the following operators are used:

(1) $\oplus$: $A \oplus B = C$, where, *A, B* and *C* are all m×n matrices, a_{ij}, b_{ij}, c_{ij} are their elements, respectively, such that

$$c_{ij}=\max\{a_{ij},\ b_{ij}\},\ i = 1,2,...,m;\ j = 1,2,...,n \tag{5}$$

(2) ©: A © $B = C$, where, *A, B* and *C* are all m×n matrices, a_{ij}, b_{ij}, c_{ij} are their elements, respectively, such that

$$c_{ij} = \begin{cases} a_{ij}, & if\ \ a_{ij} > b_{ij} \\ 0, & otherwise \end{cases} \tag{6}$$

To satisfy the escalation rule of fire escalation, a sampling function *ff()* is utilized to determine whether a unit is on fire or not under heat radiation:

$$D = ff(R, V)$$

Where, D, R and V are 1×n matrices, d_i, r_i and v_i are their elements, respectively, $i = 1,2,...,n$; r_i indicates the received total heat radiation of unit *i*, and v_i is the volume of unit *i*, such that

$$g = -1.128\times\ln(r_i) - 2.667 \times 10^{-5}\times v_i + 9.877;$$

$ttf = e^g/60$;

$Pr = 9.25 - 1.85 \times \ln(ttf)$;

and

$$d_i = \begin{cases} 1, & if \ \ (normrnd(0,1) - (Pr - 5) < 0) and \ \ (rand() < 0.5) \\ 0, & \end{cases}$$

Where, *normrnd(x, y)* is a function to generate a random number from the normal distribution with mean parameter x and standard deviation parameter y, and function rand() generates a random number that is uniformly distributed in [0, 1].

If one unit storing flammable liquid (with high volatility) is damaged due to a domino effect, it may result in a fire, fireball, VCE, or just leakage. In this study, if a unit is damaged, it is assumed that it will be on fire with a probability of 0.5 after the damage of the unit (Khakzad et al., 2013), and the probability is considered through the function rand().

The process of simulating the propagation of a fire is shown in Fig. 2.

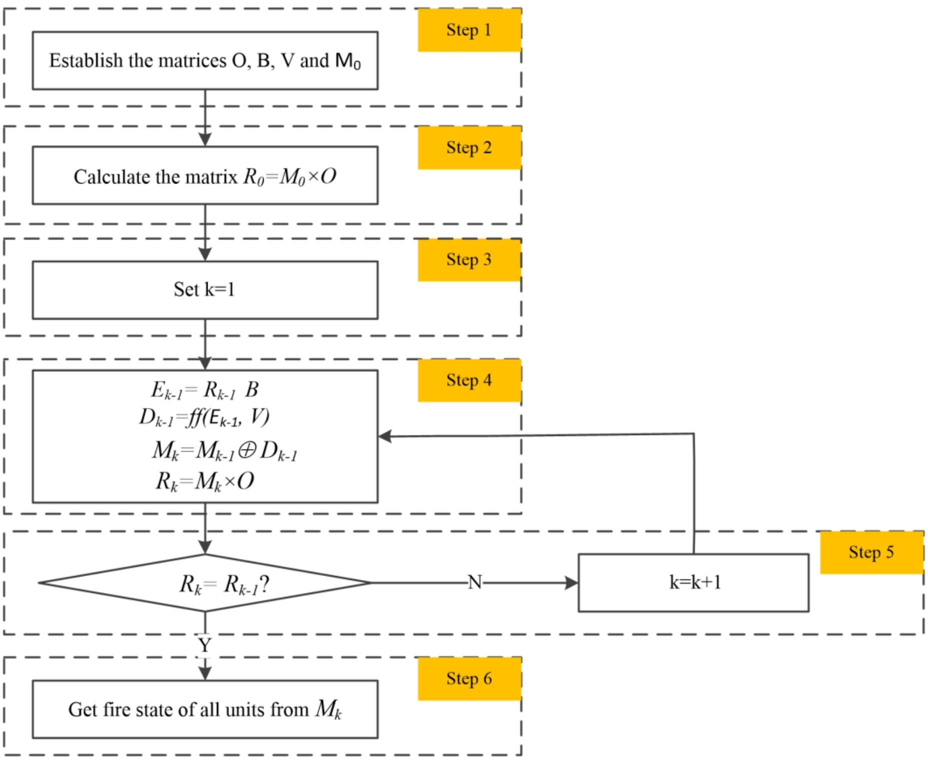

Fig. 2 Simulation analysis flowchart of a fire propagation process

Step 1: Establish the matrices O, B, V and M_0. These matrices should be established according to the environment and the fire state.

Step 2: Calculate the matrix R_0:

$$R_0 = M_0 \times O \tag{7}$$

R_0 indicates the received total heat radiation of the units under the primary fire(s). The heat radiation received by the unit which has been on fire is usually not concerned, and it is determined by the matrix O.

Step 3: Initialize the variable k, set its value to 1.

Step 4: Calculate the matrices E_{k-1}, D_{k-1}, M_k, and R_k.

$$E_{k-1} = R_{k-1} \copyright B \tag{8}$$

$$D_{k-1} = ff(E_{k-1}, V) \tag{9}$$

$$M_k = M_{k-1} \oplus D_{k-1} \tag{10}$$

$$R_k = M_k \times O \tag{11}$$

If the total heat radiation received by a unit exceeds the threshold of escalation, the vessel of the unit may be damaged and this unit may catch fire. Even if the received heat radiation of a unit exceeds the threshold, the unit will not necessarily be damaged, and whether the unit will be on fire or not, characterized with certain probability. The function $ff()$ determines the fire state of the units according to corresponding probability distributions. On the other hand, if the total heat radiation received by a unit has changed (e.g. a new unit catches fire), the fire probability of the unit needs to be re-evaluated.

M_k is the new fire state of the units, and R_k is the received total heat radiation of the units under M_k.

Step 5: Evaluate whether R_k equals R_{k-1}. If no additional unit catches fire, the received heat radiation of any unit will not change (supposing the fires remain in their states). Thus, the matrix R is utilized to evaluate whether the fire propagation is over. If R_k is not equal to R_{k-1}, it indicates the propagation does not end, so add variable k by 1 and go back to Step 4 to calculate the new fire state and the received heat radiations of all units.

Step 6: If the fire propagation ends, obtain the fire states of all units from the matrix M_k.

Under the primary fire(s) condition, if we perform enough trials of propagation simulation, we can obtain the probability of catching fire of each unit. Assume the number of trials is SimCnt, and FC_i indicates the number of catching fire of unit i in the SimCnt trials, $i = 1,2,...,n$.

Initially, set $FC_i = 0$.

After each trial, let $FC_i = FC_i + M_{ki}$, where, M_{ki} is the i-th element value of M_k.

When the SimCnt trails are completed, the fire probabilities of the units can be obtained according to Eq. (12).

$$Prob_i = FC_i \ / \ SimCnt \tag{12}$$

Where, $Prob_i$ indicates the fire probability of unit i, $i = 1,2,...,n$.

4. Illustrative examples

4.1 Example 1

A simple example is utilized to validate the approach proposed in this study. Fig. 3 shows a tank farm consisting of three atmospheric storage tanks. The heat radiations caused by a pool fire following the ignition of flammable material contained in the storage tanks are analyzed and the results of the consequence assessment are reported in Table 4.

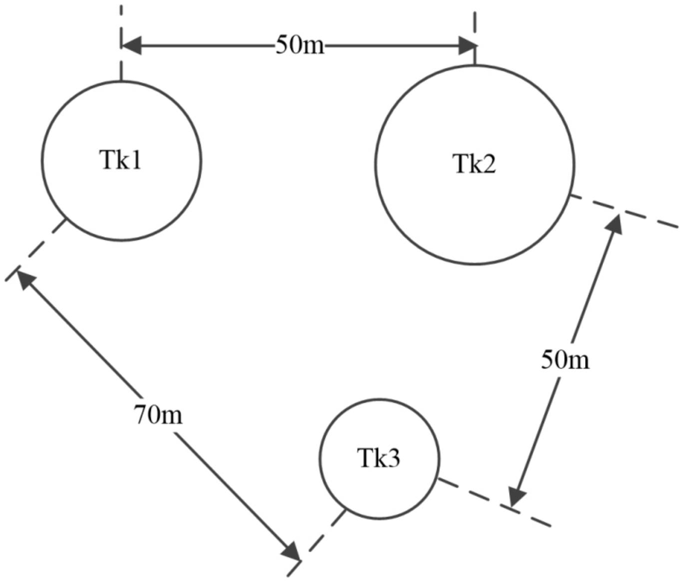

Fig. 3 Layout of atmospheric storage tanks in a tank farm (example 1)

Table 4 Features of the tanks of example 1 and radiation on each target

ID	Subst.	Diameter (m)	Height (m)	Radiation on each target (kW/m^2)		
				Tk1	Tk2	Tk3
Tk1	Gasoline	30	10	-	25.90	9.02
Tk2	Benzene	40	15	26.95	-	22.57
Tk3	Benzene	20	8	3.90	11.60	-

The threshold value for the radiation effect on atmospheric vessels is selected as Q_{th} = 15 kW/m^2 (Cozzani et al., 2005). For this simple example, we can manually calculate the probabilities of the tanks on fire according the equations from Eq. (2) to Eq. (4). If Tk1 primarily catches fire, Tk2 may be damaged because the thermal radiation received by it exceeds the threshold value and Tk3 cannot be damaged. Assume a tank will be on fire with the probability of 0.5 after it is damaged, thus, according to the equations from Eq. (2) to Eq. (4), the fire probability of Tk2 is 0.4493. After Tk2 is on fire, Tk3 would receive heat radiation from both Tk1 and Tk2 (the total received radiation is 31.59 kW/m^2). Thus, Tk3 would be physically damaged and ignited, with a probability 0.1800 in the case of a pool fire in Tk1.

The possible fire propagation path is from Tk1 to Tk2, and then to Tk3 given a primary fire in Tk1. During this process, there is only one direction effect and no mutual influence on the occurrence of fire. Therefore, these results can be compared with those of the proposed approach in this study.

According to the thermal radiation of one tank on each target, the matrix O is determined:

$$O = \begin{pmatrix} 0 & 25.90 & 9.02 \\ 26.95 & 0 & 22.57 \\ 3.90 & 11.60 & 0 \end{pmatrix}$$

And the following matrices can be obtained:

B = (15 15 15)

V=(7065 18840 2512)

M_0=(1 0 0)

Based on the simulation approach, we perform 10^5 trials, Tk2 is on fire in 45190 trials, and Tk3 is on fire in 18382 trials, and hence, the fire occurrence probabilities of Tk2 and Tk3 are about 0.4519 and 0.1838, respectively, given a primary pool fire in Tk1. The results are in agreement with the results directly calculated according to the equations from Eq. (2) to Eq. (4). It can be seen that the results of the matrix-based approach are consistent with the results of manual calculations using equations from Eq. (2) to Eq. (4).

If the primary pool fire occurs in Tk2, the situation is more complex. In this case, both Tk1 and Tk3 may be damaged under the thermal radiation from Tk1 as the radiations received by them exceed the escalation threshold value. The fire of each of these two tanks will have an influence on the fire occurrence of the other tank. Even if the Bayesian method can be used to calculate the fire probabilities of these two tanks, the conditional probabilities should be carefully determined. Using the matrix-based method proposed in this paper, we can easily obtain the probabilities by only changing the matrix M_0 to (0 1 0). It is drawn from the simulation analysis that the fire occurrence probabilities of Tk1 and Tk3 are about 0.4649 and 0.3971, respectively, given a primary pool fire in Tk2.

4.2 Example 2

A case study from Paltrinieri et al. (2011) and Khakzad et al. (2013) is adapted and modeled in this section to illustrate the proposed approach in a wider range. Fig. 4 shows the ground plan of a tank farm comprised of eight atmospheric storage tanks with fixed roofs (D1-D8). Each tank contains gasoline with the capacity of 2,000 metric tons.

The thermal radiation escalation vectors are listed in Table 5.

Table 5 Thermal Radiation Escalation Vectors (kW/m^2)

	D1	D2	D3	D4	D5	D6	D7	D8

D1	-	19.3	4.6	19.3	9.3	3.6	4.6	3.6
D2	19.3	-	19.3	9.3	19.3	9.3	3.6	4.6
D3	4.6	19.3	-	3.6	9.3	19.3	2.2	3.6
D4	19.3	9.3	3.6	-	19.3	4.6	19.3	9.3
D5	9.3	19.3	9.3	19.3	-	19.3	9.3	19.3
D6	3.6	9.3	19.3	4.6	19.3	-	3.6	9.3
D7	4.6	3.6	2.2	19.3	9.3	3.6	-	19.3
D8	3.6	4.6	3.6	9.3	19.3	9.3	19.3	-

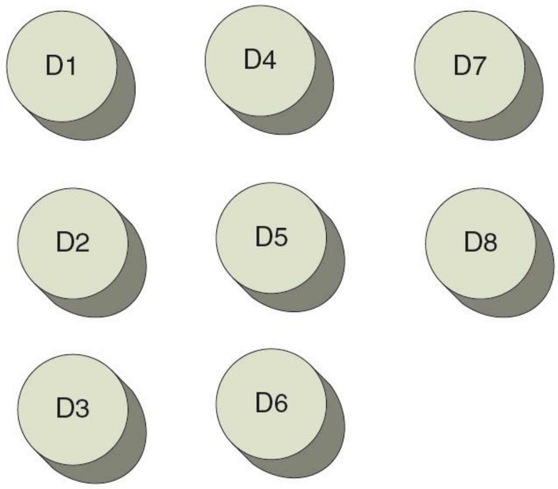

Fig. 4 Layout of atmospheric storage tanks in a tank farm (example 2)

(i) Simulation analysis of the single propagation process

Supposing a primary tank fire occurred at D1, we first analyze a propagation process of the fire. According to the thermal radiation escalation vectors, the matrix O can be obtained:

$$O = \begin{pmatrix} 0.0 & 19.3 & 4.6 & 19.3 & 9.3 & 3.6 & 4.6 & 3.6 \\ 19.3 & 0.0 & 19.3 & 9.3 & 19.3 & 9.3 & 3.6 & 4.6 \\ 4.6 & 19.3 & 0.0 & 3.6 & 9.3 & 19.3 & 2.2 & 3.6 \\ 19.3 & 9.3 & 3.6 & 0.0 & 19.3 & 4.6 & 19.3 & 9.3 \\ 9.3 & 19.3 & 9.3 & 19.3 & 0.0 & 19.3 & 9.3 & 19.3 \\ 3.6 & 9.3 & 19.3 & 4.6 & 19.3 & 0.0 & 3.6 & 9.3 \\ 4.6 & 3.6 & 2.2 & 19.3 & 9.3 & 3.6 & 0.0 & 19.3 \\ 3.6 & 4.6 & 3.6 & 9.3 & 19.3 & 9.3 & 19.3 & 0.0 \end{pmatrix}$$

The matrix B can be determined according to the threshold value for radiation effects on atmospheric vessels :

$$B = (15\ 15\ 15\ 15\ 15\ 15\ 15\ 15)$$

And the matrix V is:

$$V=(\ 785.4\ 785.4\ 785.4\ 785.4\ 785.4\ 785.4\ 785.4\ 785.4)$$

The matrix M_0 is determined according to the initial fire state:

$$M_0= (1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0)$$

Based on matrices M_0 and O, the matrix R_0 can be obtained:

R_0=(0 19.3 4.6 19.3 9.3 3.6 4.6 3.6)

R_0 is the matrix indicating the received thermal radiation of each tank given the fire of D1.

Based on the simulation approach of fire propagation, the propagation of the fire is revealed through iteration analysis. After the first iteration, the following matrices can be obtained:

E_0=(0 19.3 0 19.3 0 0 0 0)

C_0=(Inf -0.2404 Inf 0.4589 Inf Inf Inf Inf)

U_0=(0.9595 0.3335 0.7499 0.6606 0.3846 0.9808 0.4807 0.4537)

M_1=(1 1 0 0 0 0 0 0)

R_1=(19.3 19.3 23.9 28.6 28.6 12.9 8.2 8.2)

E_0 shows that D2 and D4 may be damaged because their received thermal radiations are higher than the threshold value. There is a certain probability whether D2 and/or D4 will fail under the thermal radiation, and this is simulated by sampling according to the function *ff*() discussed above.

In this example, the matrix C_k is utilized to show the sampling results which indicate whether a tank is damaged when its received thermal radiation is higher than the threshold. The matrix U_k is adopted to show the sampling results which indicate whether a tank is on fire after it is damaged.

From the matrix C_0, it can be seen that the tank D2 is damaged (the corresponding value is less than zero) and the tank D4 is not damaged. In the matrix C_0, the symbol Inf indicates an infinite value, which means the time to failure of the corresponding tank is very large (infinite) because the received heat radiation is very small (zero). The matrix U_0 shows that D2 is on fire after its damage (the sample value of the uniform distribution function is less than 0.5). Thus, the matrix M_1 reflects the new fire state of the tanks. D1 and D2 are on fire now.

As a new fire arises at D2, the thermal radiations received by other tanks (indicating by R_1) have changed due to the synergistic effect. So the iteration process continues. After the second iteration, we can obtain:

E_1=(19.3 19.3 23.9 28.6 28.6 0 0 0)

C_1=(1.2708 0.1951 -1.6355 -0.6124 -1.1134 Inf Inf Inf)

U_1=(0.9833 0.6883 0.1035 0.4955 0.6690 0.6516 0.3537 0.1050)

M_2=(1 1 1 1 0 0 0 0)

R_2=(43.2 47.9 27.5 32.2 57.2 36.8 29.7 21.1)

From M_2 we can see, the fire has propagated to D3 and D4.

Similarly, after the third iteration, we obtain:

E_2=(43.2 47.9 27.5 32.2 57.2 36.8 29.7 21.1)

C_2=(-0.0062 -2.7938 -0.1472 -1.0093 -2.1911 0.5478 -1.3459 0.9243)

U_2=(0.5673 0.2359 0.1920 0.8689 0.9292 0.8999 0.9126 0.0772)

M_3=(1 1 1 1 0 0 0 0)

R_3=(43.2 47.9 27.5 32.2 57.2 36.8 29.7 21.1)

It is shown from C_2 and U_2 that D5 and D7 are damaged but they are not on fire at this time, and the tanks D6 and D8 are still not damaged.

As R_3=R_2, the propagation analysis process ends.

From the results, we can see that in this process the fire of D1 propagates to tanks D2, D3 and D4 at last. The levels of the domino effect of the tanks are shown in Table 6.

Table 6 Level of domino effect of the tanks

Primary	Secondary	Tertiary
D1	D2	D3, D4

(ii) Probability analysis of the catching fire of each tank

When a sufficient number of simulations of the single propagation process are carried out, and fire times of each tank are recorded, the probability of the catching fire of each tank after the primary fire(s) can be obtained.

After 10^5 trials of fire propagation simulation, the fire probability of each tank in the case of a primary fire of D1 is shown in Table 7.

Table 7 Fire probabilities of the tanks given a primary fire in D1

Tank	D2	D3	D4	D5	D6	D7	D8
Probability	0.3021	0.1969	0.3021	0.2274	0.1796	0.1972	0.1804

The results indicate that when the tank D1 catches fire, there is little difference in the probabilities of catching fire for the other tanks due to the domino effect except that the probabilities of D2 and D4 are larger.

Utilizing the proposed approach, we can easily analyze the domino effect under other conditions. For example, let M_0=(0 0 0 0 0 0 0 1), which means the tank D8 primarily catches fire, the fire probabilities of other tanks are obtained as shown in Table 8.

Table 8 Fire probabilities of the tanks given a primary fire in D8

Tank	D1	D2	D3	D4	D5	D6	D7
Probability	0.1805	0.2006	0.1678	0.2317	0.2869	0.2053	0.3178

Similarly, assume two or more tanks catching fire simultaneously (e.g. due to terrorism or vandalism), the domino effect can be also evaluated. Let M_0=(1 0 0 0 0 0 0 1), which means the tanks D1 and D8 simultaneously catch fire at first, the fire probabilities of other tanks are shown in Table 9.

Table 9 Fire probabilities of the tanks given primary fires in D1 and D8

Tank	D2	D3	D4	D5	D6	D7

Probability	0.6590	0.4960	0.6946	0.6852	0.5405	0.6692

5. Conclusions

In the process industries, fire or explosions of flammable or/and explosive materials may cause damage to the surrounding equipment, possibly resulting in domino effects. The secondary fire or explosion event may still trigger other events and cause even greater losses due to the large extent of heat radiation influence. The accident may continue to propagate from one equipment (or unit) to another equipment (or unit) when several are located in the area.

Domino effects which occur in chemical facilities usually lead to great losses. Analyzing the probability of accidents resulting from a domino effect is therefore very important for risk assessment, since the weakness of a system can be revealed and risk mitigation measures can be better arranged.

As there may be mutual influences for the occurrence of an accident between equipment (or units), making the calculation of accident probabilities difficult, a matrix-based approach is proposed to model the influences between equipment (units) in an area that may be influenced by a fire-induced domino effect. Furthermore, an analysis approach for accident propagation as well as a simulation based algorithm of probability calculation of accidents is provided. The synergistic effect of thermal radiation is taken into account during the propagation of a fire accident. This modeling and analysis approach is much simpler than existing approaches based on Bayesian networks or Petri-nets, but effective and flexible. Through the matrix operation, we can easily analyze the accident propagation process, and calculate the fire probability of each equipment (or unit).

The proposed approach is illustrated by an example for analyzing the fire propagation among tanks in a tank farm. The propagation of a specific process is demonstrated, and the fire probabilities at the tanks are calculated. The results show that there is little difference in the probabilities of catching fire for the tanks due to a domino effect, and the probabilities under different primary fire conditions can be obtained by setting the initial matrix indicating the fire states (M_0 in this study).

In this study, the discussed probabilities of domino effects are those conditioned by the occurrence of a primary fire (or primary fires). If the probability of the initial events (fires) is taken into consideration, the fire probability of a facility is equal to the probability of the corresponding conditional probability of a domino effect multiplied by the probability of the initial fire. Multiple simultaneous fires may also occur due to safety-related reasons (by coincidence), but the probability is extremely low. But in the case of security (e.g., a terrorist attack), this is much more likely and may be realistic. The propagation possibility under the condition of multiple simultaneous primary fires can also easily be analyzed by using the proposed approach.

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