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Reference:
Zhou Jianfeng, Reniers Genserik.- Modeling and analysis of vapour cloud explosions knock-on events by using a Petri-net approach
Safety science - ISSN 0925-7535 - 108(2018), p. 188-195
Full text (Publisher's DOI): https://doi.org/10.1016/J.SSCI.2018.04.019
To cite this reference: https://hdl.handle.net/10067/1514110151162165141

Modeling and analysis of Vapour Cloud Explosions knock-on events by using a Petri-net approach

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Abstract: If flammable gas is mixed with air, and the mixture is ignited, it is possible to form a vapor cloud explosion (VCE) which may be very destructive, and easy to trigger a domino effect of accidents because of its large extent of impact. A VCE accident may induce secondary VCE accidents, then tertiary VCE accidents, and so on. This is called the cascading effect of VCE accidents, which requires an understanding of probabilities and propagation patterns to prevent and mitigate the potential damages. In this work, a methodology based on Petri-net is proposed to model the cascading effect of VCE accidents and perform probability analysis, taking the mutual influence between the accidents into account. The deficiency in probability analysis of VCE accidents is discussed. According to the limits of states and their changes which reflect characteristics of VCE propagation, an improved Petri-net approach is provided for modeling and analysis of VCE cascading effect, and the modeling approach and analysis process of VCE cascading effect are presented. The application and efficacy of the methodology are demonstrated via an example of VCE accidents occurring in a gasoline tank storage area. The results show that the developed methodology can effectively reveal the propagation patterns of VCEs cascading and calculate the respective probabilities of VCE accidents.

Keywords: vapor cloud explosion; cascading effect; Petri-net; probability analysis; propagation patterns

1. Introduction

In the petrochemical industry, it is often necessary to process or store flammable gases or liquids with high volatility. If an accident occurs at one unit containing such materials, it may have an impact on other units nearby. A domino effect, which refers to a series of accidents triggered by an initial event/accident, might be induced. Domino effects will cause much more human and asset losses than a mere primary accident (Reniers and Cozzani, 2013). Domino effects or chains of accidents in which an accident in a unit propagates into nearby units, have been recognized as an important matter in safety management of chemical industrial areas, e.g., the requirements of the EU Seveso-III Directive (Directive 2012/18/EU). In process plants, there may be a large number of major hazardous installations (MHIs) containing large inventories of flammable and explosive substances, a primary accident caused by these substances may possibly escalate to a domino effect, and the safety measures

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like safety distances between the installations cannot completely avoid the possible domino effects due to certain restrictions, for instance limited available land.

Among all accidents, vapor cloud explosions (VCEs) are among the most destructive. Predicting damage from vapor cloud explosions has been studied in previous works (Pritchard, 1989; Alonso et al., 2008; Salzano & Basco, 2015). A VCE accident usually has a large extent of impact, and it is easy to trigger a domino effect. Abdolhamidzadeh et al. (2011) studied past domino accidents and found that explosions most frequently cause domino effects (57%), and among the explosions, VCE (vapor cloud explosion) has been the most frequent one (84%). In literature, there are some studies about domino effects of VCEs. For example, Cozzani and Salzano (2004a, 2004b) revised data on process equipment damage caused by blast waves, and derived specific probit models for several categories of process equipment. Cozzani and Salzano (2004c) proposed threshold values of overpressure for the damage to equipment caused by blast waves. Salzano and Cozzani (2005) revised available quantitative assessment models of damage probability to plant equipment caused by pressure waves generated by a vapor cloud explosion. Zhang & Jiang (2008) revised more reliable data to build a quantitative relationship between damage probability and damage degrees of equipment caused by overpressure, and developed reliable probit models. Antonioni et al. (2009) used a methodology developed for the quantitative assessment of risk due to domino effect, and applied it to the analysis of an extended industrial area. Equipment damage probability models including the probit models of VCE were applied for the identification of the final scenarios and for escalation probability assessment. Kadri et al. (2013) developed a methodology, which is based on probabilistic models and physical equations, for quantitative assessment of domino effects caused by fire and explosion in industrial sites. Mukhim et al. (2017) present a probit method to estimate the probability of accident escalation in chemical process industries due to domino effect triggered by overpressure, based on a larger data set, a finer level of classification of the equipment and a different method of linking the qualitative description of the damage to the quantitative probability.

A VCE accident may result in damage to nearby units and lead to secondary VCEs. The overpressures generated by secondary VCE accidents may in turn trigger other VCEs. This propagation of VCEs is called the cascading effect of VCE. This cascading effect of VCE accidents has happened in reality. For example, on 23 October 1989, a vapor cloud explosion occurred at the Phillips 66 Company polyethylene production plant near Pasadena, Texas (U.S. Fire Administration, 2011; Meyer and Reniers, 2016). The accident resulted in 23 deaths, 1 missing and more than 130 injured. The vapor cloud resulted as a sudden gas release of an estimated 85,000 lbs of a flammable gas mixture through an 8-inch open valve. The vapor cloud plus additional flammable gas inside tanks at the valve source exploded with a force equivalent to 2.4 tons of TNT based on blast damage. Two isobutene storage tanks exploded 10 to 15 minutes later. A third explosion occurred 15 to 30 minutes later when a polyethylene plant reactor failed catastrophically. The two polyethylene production plants covering 16 acres near the source of the blast were destroyed. On 27 June 1997, a catastrophic accident happened in Beijing Dongfang Chemical plant of China (China Academy of Safety Science, 2005). A great deal of naphtha spilled over from a tank roof, as an operator opened the wrong valve. The explosive gas mixed with volatilized naphtha and air was ignited to form a severe vapor cloud explosion, which resulted in successive explosions of a nearby ethylene tank A and an ethylene tank B (thousands of cubic meters of ethylene are stored in each tank). This accident killed 9 people and injured 39 others, 20 tanks were destroyed.

In the past studies, there are few attempts made to model and assess the cascading effect of VCE, especially the total probability of each unit with mutual influences in the situation of domino effect, Nevertheless, several researchers have studied the propagation of accidents, for example, Abdolhamidzadeh et al. (2010) and Rad et al. (2014) proposed a Monte Carlo simulation based approach, which is named FREEDOM, to assess the frequency of domino accidents. Khakzad et al. (2013) provided a Bayesian network based approach to model domino effect propagation patterns and to estimate the domino effect probability and Yuan et al. (2016) developed a methodology for the probability estimation of a series of dust explosions based on Bayesian network. Zhou and Reniers (2017) proposed a probabilistic Petri-net (PPN) based approach to model the cascading effect and estimate the probabilities of escalation VCEs.

The present study aims to develop a novel methodology using Petri-net (PN) for modeling the propagation of VCEs and estimating the probabilities of VCE accidents. Petri-net was originally proposed in Carl Adam Petri's dissertation (Petri, 1966), and from then on it is widely used to model and analyze various systems such as communication, manufacturing, and transportation systems. Petri-nets are a graphical and mathematical modeling tool composed of places, transitions, and arcs. This is a promising tool for describing and studying relationships between parts of a system which are characterized as being concurrent, asynchronous, distributed, parallel, nondeterministic, and/or stochastic (Murata, 1989). In addition to modeling of systems, tokens are used in Petri-nets to simulate the dynamic and concurrent activities of a system. Petri-net is utilized to model the impacts of one unit on another under VCE accidents in this study. To model and analyze the states and their changes of VCE propagation among many units, an improved Petri-net is proposed based on the basic Petri-net.

This paper is organized as follows: Section 2 introduces the domino effect of VCE, and problems in probability analysis of VCE cascading effects. In Section 3, the definition and the improving of Petri-net as well as the modeling and analysis process of a VCE cascading effect are provided. In Section 4, an example illustrates the proposed approach. Finally, the conclusions drawn from this work are presented in Section 5.

2. Cascading effect of VCE

2.1 Models of domino effect of VCE

As already mentioned, if an explosive mixture of flammable gas and air is ignited, it is likely to form a VCE accident. If equipment nearby is in the impact extent of the overpressure that goes together with the explosion, it may fail and a secondary accident may occur. To determine whether a nearby unit may fail, the overpressures exerted by the primary VCE event on the nearby units are compared with predefined threshold values. The overpressures above the relevant thresholds are high enough to cause credible damage to the nearby units, resulting in secondary accidents, e.g. other VCE accidents. To simplify the problem, wind direction and wind speed are not considered in this study, and the gas cloud is thus considered around the unit in a circular shape after a unit is damaged.

In literature, several researchers proposed probit models to assess the damage probability of process equipment as a consequence of a blast wave (Eisenberg et al., 1975; Khan and Abbasi, 1998; Cozzani and Salzano, 2004a; Zhang and Jiang, 2008; Mukhim et al., 2017). Generally, the probit value Pr can be obtained using Eq. (1):

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

Where, a and b are probit coefficients determined using experimental data and regression methods, and ΔP is overpressure (Pa) in the case of explosion.

After Y is determined, the escalation probability, P_{esc}, could be calculated as Eq. (2):

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

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

In this study, the probit methods proposed by Cozzani and Salzano (2004a) are used to obtain the probit value for overpressure. For atmospheric equipment, Pr can be determined according to Eq. (3).

$$Pr = -18.96 + 2.44\ln(\Delta P) \tag{3}$$

And for pressurized equipment, Pr can be determined according to Eq. (4).

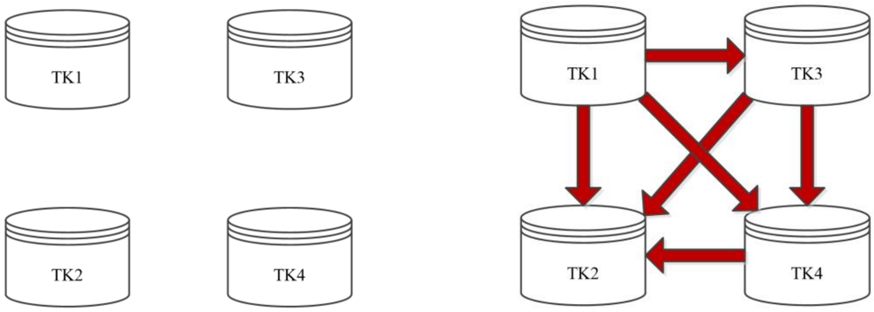
$$Pr = -42.44 + 4.33\ln(\Delta P) \tag{4}$$

VCE accidents may propagate from one unit to another. The VCE accidents of secondary units in the domino effect not only intensify the accident, but also help the domino effect escalate to tertiary units. The overpressures originating from secondary VCE accidents in turn trigger other accidents. The propagation of VCEs may form a cascading effect.

2.2 Deficiency in probability analysis of domino effect

As already mentioned, during the propagation of VCE accidents, one unit may be in the impact extent of the VCE accident of another unit, and the VCE accident of this unit may also impact that unit. Hence, correlations exist in probability calculations of domino effects. These characteristics of VCE propagation lead to the fact that the probit methods cannot be used directly for probability analysis of VCE cascading. In previous studies (e.g. Khakzad et al., 2013; Zhou and Reniers, 2017), only the most possible propagation patterns are considered during the analysis of domino effects. However, for total probability analysis, any possible propagation should be considered. In the tank farm shown in Fig. 1 (a), if a VCE accident occurs at TK1, TK2 is most likely to be damaged under the overpressure from the VCE accident of TK1 according to the overpressure between the tanks and the propagation paths. But to determine the probability of VCE at TK2, the probabilities of other propagation paths which are shown in Fig. 1(b), including TK1→TK3→TK2, TK1→TK4→TK2, and TK1→TK3→TK4→TK2, should be calculated, although the probabilities of some propagation paths are very small. It should be noted that the VCE probability of TK2 should be also taken into account in calculating the probabilities of VCE accidents at TK3 or TK4.

Abdolhamidzadeh et al. (2010) also noticed and studied the mutual impacts in the situation of domino effect. If there are many units that may influence each other under the overpressure of VCE accidents in an area, the total probability analysis of domino effect will be very complex.



(a) (b)

Fig. 1 Layout of four tanks (a) and possible propagations from TK1 to TK2 (b)

The main aim of this work is to introduce a new methodology based on Petri-net to analyze this cascading effect of VCE accidents. Although there are mutual influences between the units on probability calculation, there is no interaction between them during a propagation process. Thus, the probabilities can be obtained through the simulation of propagation processes.

3. Petri-net based analysis approach

3.1 Definitions and rules of Petri-net

(i) Definition of Petri-net

Petri-nets are mathematical modeling tools used to analyze and simulate concurrent systems (Murata, 1989). The system is modeled as a directed graph with two sets of nodes: the set of places representing the state or system objects and the set of events or transitions determining the dynamics of the system.

A Petri net (PN) is a 5-tuple:

$$PN = (P, T, I, O, M)$$

Where:

$P = \{p_1, p_2, \ldots, p_n\}$ is a finite set of places.

$T = \{t_1, t_2, \ldots, t_m\}$ is a finite set of transitions.

I: an input function, $(P\times T) \rightarrow N$, where N is the set of non-negative integer numbers. The value $I(p, t)$ is the number of (directed) arcs from the place p to the transition t.

O: an output function, $(T\times P) \rightarrow N$, where the value $O(t, p)$ is the number of arcs from the transition t to the place p.

$M: P \rightarrow N$ is the marking of a Petri-net. A marking M of a Petri net with n places is a $(1 \times n)$ vector and associates with each place a certain number of tokens which are usually represented by means of dots inside the circles. The initial marking M_0 represents the initial state of the system. The marking at place p_i can also be denoted as $M(p_i)$.

Usually, places are represented with circles, and transitions are represented with rectangles on PN graphs. The arcs (input and output functions) are represented with directed lines, and the tokens in a place are denoted as dots or a number.

A Petri net is executable. The execution of a Petri-net depends on the number and distribution of tokens in the Petri-net (Peterson, 1981). 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. The following two rules control the execution of a Petri-net:

(a) Enabling rule: A transition is enabled if each of its input places has at least as many tokens in it as arcs from the place to the transition.

(b) Execution/firing rule: If a transition is enabled, it can fire/execute. Execution of an enabled transition t at marking M changes the marking into M'.

$$M'(p_i) = M(p_i) + x \quad for\ p_i \in t^{\bullet} \tag{5}$$

$$M'(p_j) = M(p_j) - y \quad for\ p_j \in {}^{\bullet}t \tag{6}$$

Where, x is the number of arcs from transition t to the place p_i, and y is the number of arcs from the place p_j to the transition t.

(ii) Improving of Petri-net

Petri-net can be used for modeling the state transition system. Usually the states of a system can be represented by the places and the changing of the states can be represented by the transitions of a Petri-net. For the VCE cascading analysis, there are some special requirements for modeling the states and their changing, as the units containing flammable gas may interact with each other during the cascading of VCE accidents.

If the state of a VCE accident of a unit is represented by a place, and the impact of overpressure from one unit to another is represented by a transition, at most the place can only contain one token to indicate the unit is in the corresponding state, because the state (e.g. a VCE accident) of this unit can only occur once. In addition, after the VCE accident of a unit has occurred, this unit can not be influenced anymore by the VCE accidents from other units. Thirdly, the impact of one unit on any other unit must meet certain conditions, e.g. the overpressure discussed in Section 2. To model this type of state-constrained system, the Petri-net is improved in the following areas:

- Input function. I: $(P \times T) \rightarrow \{0, 1\}$, there is at most one arc from a place p to a transition t.
- Output function. O: $(T \times P) \rightarrow \{0, 1\}$, there is at most one arc from a transition t to a place p.
- Marking. M: $P \rightarrow \{0, 1\}$ is the marking of a Petri-net. A place p can have zero or one token.
- Enabling function f_{en} of a transition t. This function is introduced to represent the fact that a transition is enabled and can be executed, it needs to meet certain conditions in addition to the tokens in its input places.
- Enabling rule: A transition t of a Petri-net is enabled in a marking M if

  $M(p_i)>0 \quad for\ p_i \in {}^{\bullet}t,\ and$

  $f_{en}(t) = true,\ and$

  $M(p_j)=0 \quad for\ p_j \in t^{\bullet}$
- Execution/firing rule: After transition t fires, the marking of the Petri-net changes to M', where M' is given by

  $M'(p_i)= M(p_i) \quad for\ p_i \in {}^{\bullet}t$

  $M'(p_j)=1 \qquad for\ p_j \in t^{\bullet}$

The execution rule of a transition t can be represented as Fig. 2. After the execution, unlike ordinary Petri-net that removes tokens from its input places, the improved Petri-net does not remove the tokens in its input places, as the tokens indicate the states of occurring of events.

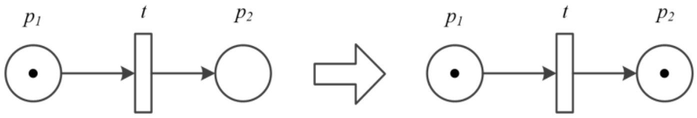


Fig. 2 Execution rule of transition *t*

3.2 Modeling and analysis of VCE cascading effect

Based on the improved Petri-net approach, the domino effect and the cascading effect of VCE accidents can be modeled. Take two units as an example. A VCE accident occurs at Unit1, the overpressure causes the failure of Unit2, and therefore results in a VCE accident at Unit2. This process is expressed in Fig. 3 (a), and is modeled by Petri-net as in Fig. 3 (b). Place p1 indicates the VCE accident at Unit1, p2 represents the failure of Unit2, and p3 indicates the VCE accident at Unit2. A token in p1 indicates that a VCE accident has occurred at Unit1. Transition t1 indicates the impact of VCE accident at Unit1 on Unit2, and t2 represents the damage of Unit2 leads to VCE accident at Unit2. As this study focuses on VCE accidents, the Petri-net model can be simplified as shown in Fig. 3 (c), where p3 indicates the VCE accident at Unit2, and t' which combines t1 and t2 (and p2) in Fig. 3 (b) represents that overpressure from Unit1 leads to VCE accident at Unit2.

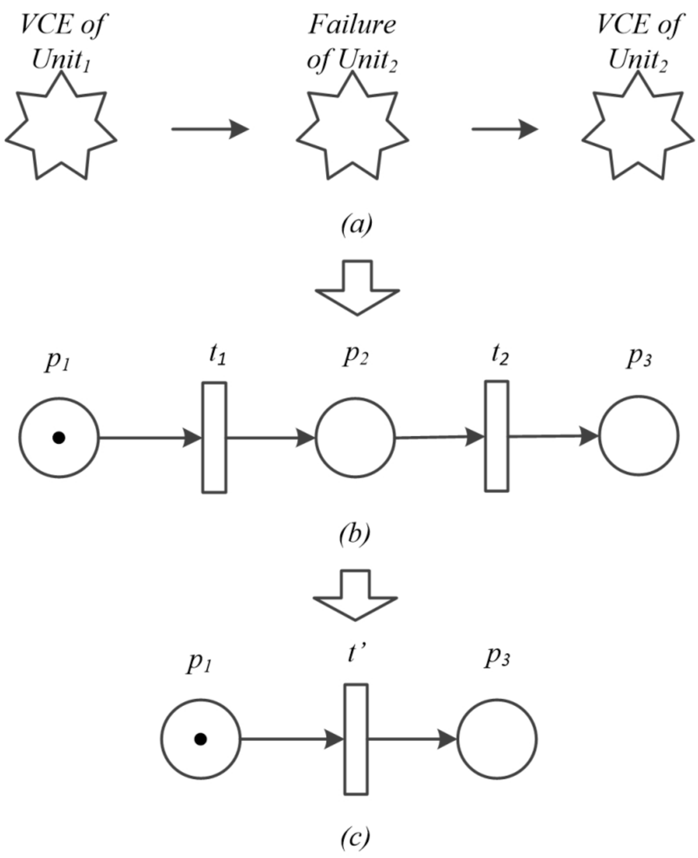


Fig. 3 Modeling of VCE domino effect based on Petri-net

Based on the modeling of a VCE domino effect, the probabilities of the cascading effect of VCE accidents can be analyzed through simulation. The flowchart of the analysis process is shown in Fig. 4.

Step 1: Establish the Petri-net model for VCE cascading effect analysis. Estimate the overpressure of VCE accident between any two units, and model the impact of overpressure by Petri-net if it exceeds the threshold of VCE domino effect.

Step 2: Initialize variables of the simulation analysis of the VCE cascading effect, e.g. set the number of simulation analysis *SimCnt*, let the trial index *idx*=0, and set the number of VCE accident at any unit to zero, etc..

Step 3: Perform a trial of VCE cascading. This includes the following sub-steps:

Step 3.1: Initialize the trial states. Add the value of the trial index *idx* by one. Clear tokens of all places and put a token in the place indicating the primary VCE accident.

Step 3.2: Sample and determine the values of the enabling function f_{en} of the transitions. In this study, function f_{en} is determined as follows,

$$f_{en} = f_1 \text{ and } f_2 \tag{7}$$

$$f_1 = \begin{cases} \text{true} & \text{if normalnum}(0,\ 1) < Pr\text{-}5, \\ \text{false} & \text{otherwise;} \end{cases} \tag{8}$$

$$f_2 = \begin{cases} \text{true} & \text{if random}() < P_{vce}, \\ \text{false} & \text{otherwise.} \end{cases} \tag{9}$$

where, normalnum(x, y) is a function to generate a random number satisfying normal distribution with a mean value of x and a variance of y, and random() is a function that randomly generates a number between 0 and 1.

Function f_1 is utilized to meet the requirement of Eq. (2), and function f_2 is adopted to satisfy the requirement of VCE accident likelihood/probability P_{vce} after a unit is damaged.

Step 3.3: Execute the Petri-net model until no transition is enabled any more. Execute the model according to the enabling rule and the execution rule of the Petri-net. Tokens are put into corresponding places according to the execution to indicate the occurrence of VCE accidents. If on transition is enabled, it means that the VCE cascading process ends.

Step 3.4: Record the results of the trial. The final marking of the Petri-net model which indicates VCE accidents at different units needs to be recorded, and the number of VCE accidents at any unit should be counted according to the final marking. In addition, to analyze the mutual influence between the units, the source of the VCE accident at a unit can also be recorded.

Step 4: If the number of trials is less than the given number of simulation analysis *SimCnt*, go back to the beginning of Step 3 (Step 3.1) to perform the next trial, otherwise, calculate the probabilities of VCE accidents at all units, and analyze the impacts between the units.

4. An example

In the study of Cozzani and Salzano (2004b), domino effects in atmospheric tanks containing fuels with high volatility (gasoline) are analyzed. This case is utilized to illustrate the VCE cascading analysis approach proposed in this study.

To simplify the problem, only 6 of the 8 tanks are considered in this study. The layout of the tanks is shown in Fig. 5.

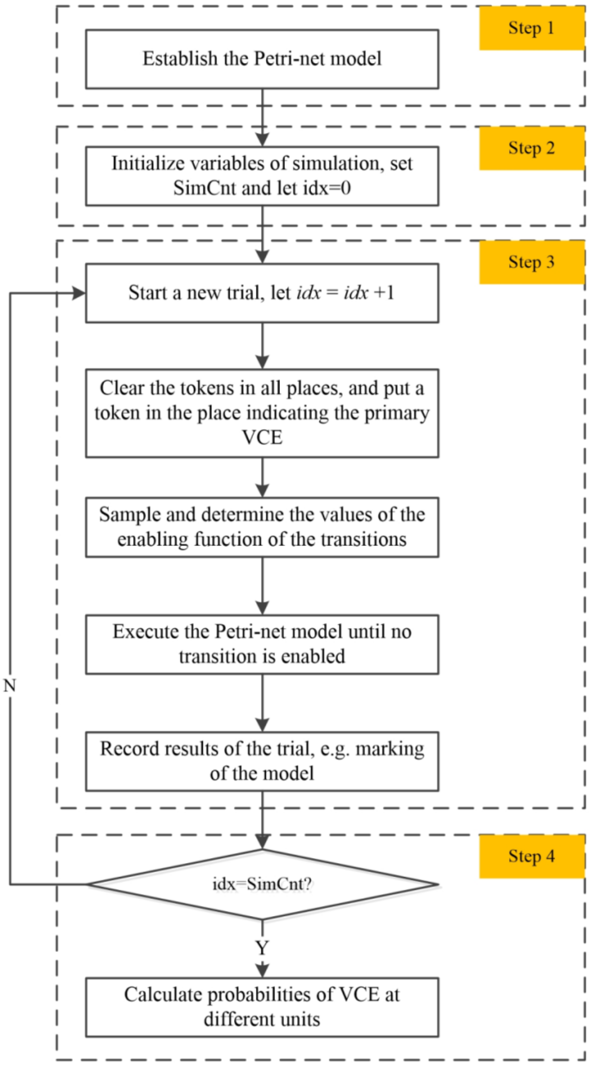


Fig. 4 Flowchart of VCE cascading effect analysis

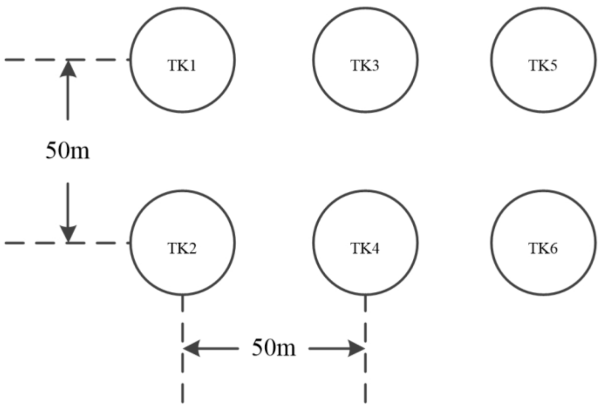


Fig. 5 Layout of the gasoline tanks

Each tank contains gasoline with the capacity of 2,000 metric tons. After a storage tank is damaged, it may result in a secondary accident such as pool fire and VCE. Assume that the VCE probability is 0.50 after a tank is damaged. In this study, only VCE accidents are considered, and the threshold value of overpressure is selected as ΔP_{th} = 7kPa (Khakzad et al., 2013). The overpressure escalation vectors are calculated and illustrated in Table 1 (Cozzani and Salzano, 2004b).

Table 1 Overpressure escalation vectors (kPa) (Cozzani and Salzano,2004b)

	TK1	TK2	TK3	TK4	TK5	TK6
TK1	–	10	10	8	4	4
TK2	10	–	8	10	4	4
TK3	10	8	–	10	10	8
TK4	8	10	10	–	8	10
TK5	4	4	10	8	–	10
TK6	4	4	8	10	10	–

Suppose a VCE accident occurs at TK1, the VCE cascading effect Petri-net model which is shown in Fig. 6 is established according to overpressure escalation vectors between the tanks. The meanings of places and transitions of the model are listed in Table 2.

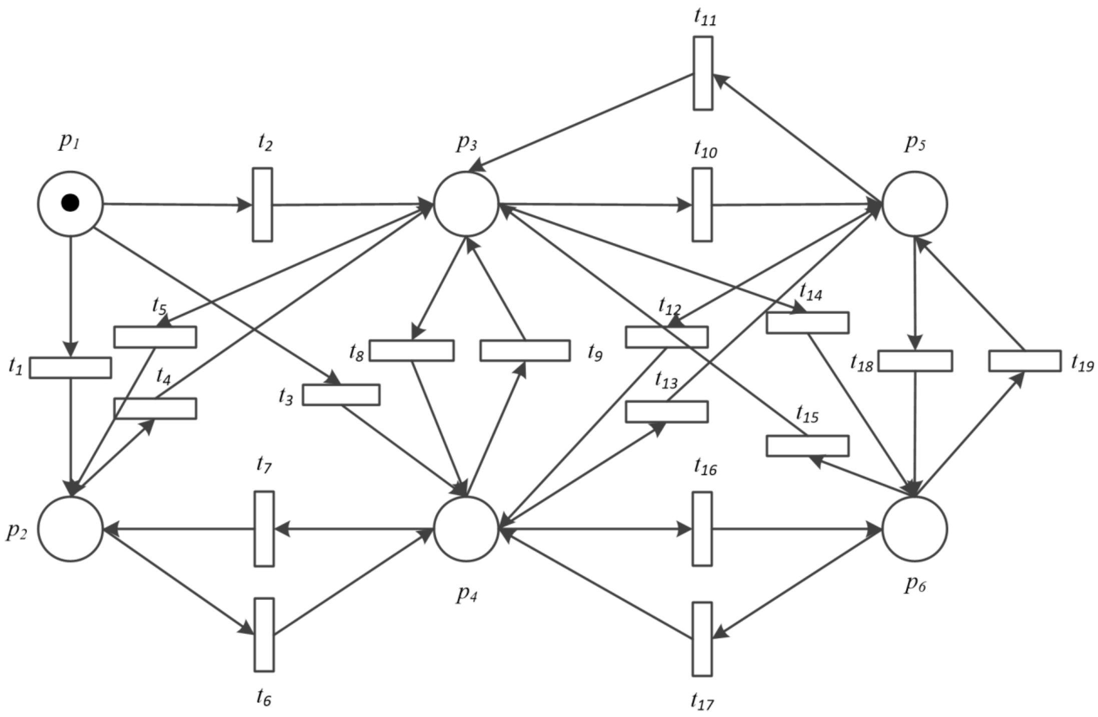


Fig. 6 Petri-net model for VCE cascading effect analysis

Table 2 Meanings of places and transitions of the Petri-net model

Place/ Transition	Meanings	Place/ Transition	Meanings
p_1	VCE at TK1	t_8	Overpressure from TK3 impacts TK4
p_2	VCE at TK2	t_9	Overpressure from TK4 impacts TK3
p_3	VCE at TK3	t_{10}	Overpressure from TK3 impacts TK5
p_4	VCE at TK4	t_{11}	Overpressure from TK5 impacts TK3
p_5	VCE at TK5	t_{12}	Overpressure from TK5 impacts TK4
p_6	VCE at TK6	t_{13}	Overpressure from TK4 impacts TK5

t_1	Overpressure from TK1 impacts TK2	t_{14}	Overpressure from TK3 impacts TK6
t_2	Overpressure from TK1 impacts TK3	t_{15}	Overpressure from TK6 impacts TK3
t_3	Overpressure from TK1 impacts TK4	t_{16}	Overpressure from TK4 impacts TK6
t_4	Overpressure from TK2 impacts TK3	t_{17}	Overpressure from TK6 impacts TK4
t_5	Overpressure from TK3 impacts TK2	t_{18}	Overpressure from TK5 impacts TK6
t_6	Overpressure from TK2 impacts TK4	t_{19}	Overpressure from TK6 impacts TK5
t_7	Overpressure from TK4 impacts TK2		

Let's trace the propagation of VCE accidents to illustrate the analysis approach. According to the overpressure escalation vectors shown in Table 1, and the probit method shown in Eq. (3), the probits between the tanks are calculated and listed in Table 3. They are important to determine the enabling of a transition in the following study.

Table 3 Probits between the tanks

Pr	TK1	TK2	TK3	TK4	TK5	TK6
TK1	–	3.513	3.513	2.969	–	–
TK2	3.513	–	2.969	3.513	–	–
TK3	3.513	2.969	–	3.513	3.513	2.969
TK4	2.969	3.513	3.513	–	2.969	3.513
TK5	–	–	3.513	2.969	–	3.513
TK6	–	–	2.969	3.513	3.513	–

According to the enabling rule of the Petri-net discussed in analysis Step 3.2, a sample of the normal distribution random numbers and the uniform distribution random numbers of the transitions are obtained and listed in Table 4. The values of *Pr*-5 are also listed in Table 4 in order to facilitate the comparison with the normal distribution random numbers.

Table 4 A sample of the random numbers for enabling the transitions

Transition	Normal distribution number	Pr-5	Uniform distribution number
t1	-1.827	-1.487	0.225
t2	-2.420	-1.487	0.718
t3	-0.063	-2.031	0.984
t4	-0.088	-2.031	0.280
t5	1.239	-2.031	0.981
t6	-1.869	-1.487	0.066
t7	-0.364	-1.487	0.741
t8	0.111	-1.487	0.852
t9	0.004	-1.487	0.040
t10	1.162	-1.487	0.604
t11	-1.507	-1.487	0.349
t12	0.362	-2.031	0.257
t13	0.759	-2.031	0.839

t14	-0.762	-2.031	0.766
t15	-1.890	-2.031	0.352
t16	-1.580	-1.487	0.182
t17	1.216	-1.487	0.547
t18	1.903	-1.487	0.348
t19	0.198	-1.487	0.231

Put a token in place p1, and execute the Petri-net model. A transition will be enabled when its normal distribution number is less than the corresponding value of Pr-5, the uniform distribution number is less than 0.5, and each of its input places has a token. Thus, we obtain the execution process as shown in Table 5:

Table 5 Execution process of the Petri-net model

No.	Marking	Executed transition
0	(1,0,0,0,0,0)	
1	(1,1,0,0,0,0)	t1
2	(1,1,0,1,0,0)	t6
3	(1,1,0,1,0,1)	t16

From the execution process we can obtain the propagation pattern of the VCE accidents that the VCE accident at TK1 propagates to TK2, then to TK4, and finally to TK6. It should be noticed that the VCE accident at TK4 is caused by the VCE at TK2 as the executed transition is t6. The tank TK3 is damaged but there is no VCE at TK3 (when p1 has a token, the normal distribution number of t2 is less than the value of Pr-5, this means that TK3 is damaged; but the uniform distribution number of t2 is greater than 0.5, this means the damage of TK3 does not lead to a VCE).

Similarly, other propagation patterns of the VCE accidents can also be obtained. For example, if the sample of the normal distribution random number and the uniform distribution random number of the transitions are obtained as listed in Table 6, we can obtain the process shown in Table 7.

Table 6 Another sample of the random numbers for enabling the transitions

Transition	Normal distribution number	Pr-5	Uniform distribution number
t1	0.622	-1.487	0.526
t2	-0.560	-1.487	0.323
t3	-2.545	-2.031	0.090
t4	-0.229	-2.031	0.279
t5	0.267	-2.031	0.448
t6	1.854	-1.487	0.079
t7	-1.549	-1.487	0.361
t8	-0.167	-1.487	0.415
t9	-1.366	-1.487	0.522
t10	0.341	-1.487	0.334
t11	2.363	-1.487	0.531

t12	0.704	-2.031	0.016
t13	-0.153	-2.031	0.257
t14	-1.899	-2.031	0.568
t15	-1.014	-2.031	0.975
t16	0.672	-1.487	0.150
t17	2.508	-1.487	0.606
t18	0.824	-1.487	0.812
t19	1.680	-1.487	0.371

Table 7 Another execution process of the Petri-net model

No.	Marking	Executed transition
0	(1,0,0,0,0,0)	
1	(1,0,0,1,0,0)	t3
2	(1,1,0,1,0,0)	t7

In this condition, the VCE accidents propagate from TK1 to TK4, and then to TK2. There is no VCE accident occurring at other tanks.

Through single propagation process analysis, the proposed approach which is based on the probit models can be validated. On this basis, the probability analysis of domino effect is carried out using Monte Carlo Simulation (MCS) of propagation processes.

The number of replications or trials of MCS is important to obtain an accurate result. If too few replications are used, the obtained results from a Monte Carlo study might be invalid, whereas time and resources may have been wasted if more replications are used than are necessary. Over the years, several rules have been proposed such as 5-10 observations per parameter, 50 observations per variable, no less than 100, and so on. In reality there is no rule that applies to all situations (Muthén and Muthén, 2002). Muthén and Muthén (2002) studied a confirmatory factor analysis (CFA) model and a growth model and demonstrated that sample size requirements depend strongly on many factors. Mundform et al. (2011) analyzed 22 studies of MCS from various fields to determine empirically-based recommendations of replications. They concluded that 7,500 to 8,000 replications are sufficient to produce stable results, and in a number of situations, depending upon what characteristic is being estimated, 5,000 replications may be enough. Schönbrodt and Perugini (2013) used Monte-Carlo simulations to determine the critical sample size from which on the magnitude of a correlation can be expected to be stable, and their results indicated that in typical scenarios the sample size should approach 250.

In literature, the choice of the number of replications used in most MCS studies appears to be made solely by the judgment of the researchers. In this study, 10^4 is taken as the minimum number of trials as the execution time of simulation is short (it costs the Petri-net model developed in Java language less than two seconds to complete the simulation on a portable computer with 1.70GHz CPU and 4.0GB RAM). If the simulation time is acceptable, the number is increased to obtain more accurate results and the results in different trial number are compared to determine whether the results are stable.

In this way, 10^5 trials are finally adopted for a simulation.

Because there are still differences between different simulations, the average of 5 simulations (each contains 10^5 trials) is utilized as the final result. The VCE number of times and the VCE probabilities of all tanks are obtained and shown in Table 8. Under the circumstance that a VCE accident occurs at TK1, the probability of VCE accident at TK2 is 0.03524, with 0.03447 resulting from TK1, 3.5×10^{-4} caused by TK3, and 4.2×10^{-4} from TK4. Similarly, the probability of VCE accident at any tank and the source of the accident are obtained.

Table 8 VCE probability of all tanks given a primary VCE at TK1

	Probability	Times	Source (Times in 10^5 trials)					
			TK1	TK2	TK3	TK4	TK5	TK6
TK2	0.03524	3524	3447	–	35	42	0	0
TK3	0.03514	3514	3435	39	–	39	0	1
TK4	0.01296	1296	1068	110	114	–	2	2
TK5	0.00148	148	0	0	132	13	–	3
TK6	0.00084	84	0	0	37	42	5	–

5. Conclusions

The Vapor Cloud Explosion phenomenon in the petrochemical industry is a highly destructive one, and has an impact on the surrounding equipment to a large extent. Domino effects are relatively easy to trigger. If an area has many units containing flammable gases or liquids with high volatility, one VCE accident may escalate to a secondary VCE accident, and the secondary VCE accident may also lead to a tertiary VCE accident, and so on. This is a cascading effect of VCE accidents, which has not been paid much attention in the past academic literature.

During the propagation of VCE accidents, the units may have impacts on each other. This brings some difficulties to probabilistic analysis of the VCE accidents. In this study, a Petri-net based approach is proposed to analyze the cascading effect of VCE accidents, as the Petri-net method has advantages on modeling and analysis of various relationships among parts of a system. According to the requirements of VCE cascading effect analysis, the Petri-net is improved in the fields including marking, enabling rule, execution rule, and so on, to model the event states and their changes. The heuristic process of VCE cascading effect analysis is provided.

An example about VCE accidents among six tanks is utilized to illustrate the proposed VCE cascading effect analysis approach. The cascading processes representing different propagation patterns of VCE accidents are discussed and probabilities of VCE accidents at all tanks are obtained based on simulation analysis.

Acknowledgments

This work is supported by National Natural Science Foundation of China (No. 71673060).

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