This item is the archived peer-reviewed author-version of:

Petri-net based cascading effect analysis of vapor cloud explosions

Reference:

Zhou Jianfeng, Reniers Genserik.- Petri-net based cascading effect analysis of vapor cloud explosions
Journal of loss prevention in the process industries - ISSN 0950-4230 - 48(2017), p. 118-125
Full text (Publisher's DOI): <https://doi.org/10.1016/J.JLP.2017.04.017>
To cite this reference: <https://hdl.handle.net/10067/1427110151162165141>

A Petri-net based simulation analysis approach for cascading effect of vapor cloud explosions

Jianfeng Zhou ^{a,*}, Genserik Reniers ^{b, c, d}

a. School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou 510006, China

b. Faculty of Technology, Policy and Management, Safety and Security Science Group (S3G), TU Delft, 2628 BX Delft, The Netherlands

c. Faculty of Applied Economics, Antwerp Research Group on Safety and Security (ARGoSS), Universiteit Antwerpen, 2000 Antwerp, Belgium

d. CEDON, KULeuven, 1000 Brussels, Belgium

Abstract: If flammable gas is mixed with air and ignited, it is easy to form vapor cloud explosion (VCE) which is destructive, and easy to trigger the domino effect 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 is capable of causing severe damages to human, assets, and the environment, thus requiring an understanding of probabilities and propagation patterns thereof to prevent and mitigate the potential damages. In this work, a novel methodology for probability analysis of VCE cascading effect based on Petri-net is proposed. According to the limits of states and their changes which reflect characteristics of VCE propagation, the improvement of Petri-net is provided. The modeling approach and analysis process of VCE cascading effect are discussed. The application and efficacy of the methodology are demonstrated via an example of VCE accidents occurring in a gasoline tanks area. The results show that the developed methodology can effectively reveal the propagation patterns of VCE cascading and calculate the respective probabilities of VCE accidents.

Keywords: vapor cloud explosion; domino effect; cascading effect; Petri-net; escalation probability; propagation pattern

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 to induce a domino effect, which refers to a series of accidents triggered by an initial event/accident. Domino effects will cause more significant human and asset losses than a 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 a priority issue among the risk and safety management, 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 is likely to escalate to a domino effect, and the safety measures like safety distances between the installations cannot completely avoid the domino effects due to restrictions such as limited

*Corresponding author.

available land.

Among all accidents, vapor cloud explosion (VCE) is 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 the domino effect. Abdolhamidzadeh et al. (2010) studied the past domino accidents and found that explosions are the most frequent cause of domino effect (57%), and among the explosions VCE (vapor cloud explosion) has been the most frequent cause (84%). In literature, there are some studies about the domino effect of VCE. 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 thresholds 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 develop reliable probit models. Antonioni et al. (2009) applied a methodology developed for the quantitative assessment of risk due to domino effect 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 the probabilistic models and the physical equations, for quantitative assessment of domino effects caused by fire and explosion in industrial sites. Mukhim et al. (2017) presented 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 VCE. The overpressures generated by secondary VCE accidents may in turn trigger other VCEs. This propagation of VCEs is called the cascading effect of VCE, which is capable of causing severe damages to human, assets, and the environment. 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). 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

nearby ethylene tank A and 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 under the domino effect, although several researchers have studied the propagation of accidents, for example, 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.

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. They are a promising tool for describing and studying relationships between parts of a systems 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 effect. In Section 3, the definition and the improving of Petri-net as well as the modeling and analysis process of 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

If an explosive mixture of flammable gas and air is ignited, it is likely to form a VCE accident. If an equipment nearby is in the impact extent of VCE overpressure, 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 strong 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, the gas cloud is considered around the unit after a unit is damaged.

In the 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):

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

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):

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

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).

$$Pr = -18.96 + 2.44 \ln(\Delta P) \quad (3)$$

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

$$Pr = -42.44 + 4.33 \ln(\Delta P) \quad (4)$$

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

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, that is, correlation exists in probability calculation of domino effect. These characteristics of VCE propagation make the probit methods cannot be directly used for probability analysis of VCE cascading. In previous studies (e.g. Khakzad et al., 2013), only most possible propagation patterns are considered during the analysis of domino effect. 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.

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

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.

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 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 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:

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

$T = \{t_1, t_2, \dots, t_m\}$ 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 *t (*p) and t^* (p^*) 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' .

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

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

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 the state transition system modeling. 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 each other during the cascading of VCE accidents.

If the state of 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. VCE accident) of this unit can only occur once. In addition, after the VCE accident of a unit has occurred, this unit will not be influenced 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

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

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

$$M(p_j) = 0 \quad \text{for } p_j \in t^*$$

- Execution/firing rule: After transition t fires, the marking of the Petri-net changes to M' , where M' is given by

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

$$M'(p_j) = 1 \quad \text{for } p_j \in t^*$$

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 improvement of Petri-net, 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 Fig. 3 (b). Place p_1 indicates the VCE accident at Unit1, p_2 represents the failure of Unit2, and p_3 indicates the VCE accident at Unit2. A token in p_1 indicates that a VCE accident has occurred at Unit1. Transition t_1 indicates the impact of VCE accident at Unit1 on Unit2, and t_2 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 p_2 indicates the VCE accident at Unit2, and t_1 which combines t_1 and t_2 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 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 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,

$$f_{en} = f_1 \text{ and } f_2 \quad (7)$$

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

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

where, $\text{normalnum}(x, y)$ is a function to generate a random number satisfying normal distribution with a mean value of x and a variance of y , and $\text{random}()$ 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. 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 accident 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.

Fig. 4 Flowchart of VCE cascading effect analysis

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. 5 Layout of the gasoline tanks

Each tank contains gasoline with the capacity of 2,000 metric tons. After a storage tank is damaged through the domino effect, 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 $\Delta P_{th} = 7\text{kPa}$ (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 can be obtained as shown in Table 3.

Table 3 Probits between the tanks

	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.

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

Transition	Normal distribution number	Uniform distribution number
t1	-1.827	0.225
t2	-2.420	0.718
t3	-0.063	0.984
t4	-0.088	0.280
t5	1.239	0.981
t6	-1.869	0.066
t7	-0.364	0.741
t8	0.111	0.852
t9	0.004	0.040
t10	1.162	0.604
t11	-1.507	0.349
t12	0.362	0.257
t13	0.759	0.839
t14	-0.762	0.766
t15	-1.890	0.352
t16	-1.580	0.182
t17	1.216	0.547
t18	1.903	0.348
t19	0.198	0.231

Put a token in place p1, and execute the Petri-net model, we can get 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.

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	Uniform distribution number
t1	0.622	0.526
t2	-0.560	0.323
t3	-2.545	0.090
t4	-0.229	0.279
t5	0.267	0.448
t6	1.854	0.079
t7	-1.549	0.361
t8	-0.167	0.415
t9	-1.366	0.522
t10	0.341	0.334
t11	2.363	0.531
t12	0.704	0.016
t13	-0.153	0.257
t14	-1.899	0.568
t15	-1.014	0.975
t16	0.672	0.150
t17	2.508	0.606
t18	0.824	0.812
t19	1.680	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.

After 10^5 trials, the VCE number of times and the VCE probabilities of all tanks are determined and shown in Table 8. Under the circumstance that a VCE accident occurs at TK1, the probability of

VCE accident at TK2 is 0.03497, with 0.03430 resulting from TK1, 2.6×10^{-4} caused by TK3, and 4.1×10^{-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	0.03497	3497	3430	–	26	41	0	0
TK3	0.03531	3531	3439	44	–	47	0	1
TK4	0.0129	1290	1086	107	94	–	1	2
TK5	0.00145	145	0	0	128	16	–	1
TK6	0.00109	109	0	0	41	59	9	–

5. Conclusions

Vapor cloud explosion in the petrochemical industry is highly destructive, and has an impact on the surrounding equipment in a large extent, so that it is easy to trigger the domino effect. 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 enough attention in the past studies.

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 Petri-net 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 process of VCE cascading effect analysis is provided.

An example about VCE accidents among four 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).

References

- Abdolhamidzadeh B., Abbasi T., Rashtchian D., Abbasi S. A., (2010). Domino effect in process-industry—an inventory of past events and identification of some patterns. *Journal of Loss Prevention in Process Industries* 24 (5), 575-593.
- Alonso F. D., Ferradas E. G., Sanchez T. de Jesus J., et al. (2008). Consequence analysis to determine the damage to humans from vapour cloud explosions using characteristic curves. *Journal of*

- Hazardous Materials 150, 146-152.
- Antonioni G., Spadoni G., Cozzani V., (2009). Application of domino effect quantitative risk assessment to an extended industrial area. *Journal of Loss Prevention in the Process Industries* 22, 614-624.
- China Academy of Safety Science. (2005). Hazardous chemical accident cases (in Chinese). Chemical Industry Press, Beijing, China.
- Cozzani V., Gubinelli G., Salzano E., (2006). Escalation thresholds in the assessment of domino accidental events. *Journal of Hazardous Materials A* 129, 1-21.
- Cozzani V., Salzano E., (2004a). The quantitative assessment of domino effects caused by overpressure Part I. Probit models. *Journal of Hazardous Materials A* 107, 67-80.
- Cozzani V., Salzano E., (2004b). The quantitative assessment of domino effects caused by overpressure Part II. Case studies. *Journal of Hazardous Materials A* 107, 81-94.
- Cozzani V., Salzano E., (2004c). Threshold values for domino effects caused by blast wave interaction with process equipment. *Journal of Loss Prevention in the Process Industries* 17, 437-447.
- Eisenberg N. A., Lynch C. J., Breeding R. J., (1975). Vulnerability model: a simulation system for assessing damage resulting from marine spills. In: Rep. CG-D-136-75, Enviro Control Inc Rockville MD.
- Kadri F., Châtelet E., Chen G., (2013). Method for quantitative assessment of the domino effect in industrial sites. *Process Safety and Environmental Protection* 91, 452-462.
- Khakzad N., Khan F., Amyotte P., Cozzani V., (2013). Domino Effect Analysis Using Bayesian Networks. *Risk Analysis* 33(2), 292-306.
- Khan F. I., Abbasi S. A., (1998). Models for domino analysis in chemical process industries, *Process Safety Progress* 17, 107-123.
- Mukhim E. D., Abbasi T., Tauseef S. M., Abbasi S. A., (2017). Domino effect in chemical process industries triggered by overpressure-Formulation of equipment-specific probits. *Process Safety and Environmental Protection* 106, 263-273.
- Murata T., (1989). Petri nets: Properties, analysis and applications. *Proceedings of the IEEE* 77(4), 541-580.
- Peterson J. L., (1981). Petri net theory and the modeling of systems. Prentice-Hall, Inc., Englewood Cliffs, N. J., USA.
- Petri C. A., (1966). Communication with Automata. New York: Griffiss Air Force Base. Technical Report No. RADC- TR-65-377, Volume 1, Supplement 1.
- Pritchard D. K., (1989). A review of methods for predicting blast damage from vapour cloud explosions. *Journal of Loss Prevention in Process Industries* 2, 187-193.
- Reniers G., Cozzani V., (2013). Domino Effects in the Process Industries: Modeling, Prevention and Managing. Elsevier, Amsterdam, The Netherlands.
- Salzano E., Basco A., (2015). Simplified model for the evaluation of the effects of explosions on industrial target. *Journal of Loss Prevention in the Process Industries* 37, 119-123.
- Salzano E., Cozzani V., (2005). The analysis of domino accidents triggered by vapor cloud explosions. *Reliability Engineering and System Safety* 90, 271-284.

- U.S. Fire Administration. (2011). Phillips Petroleum Chemical Plant Explosion and Fire. Technical Report Series USFA-TR-035. Available at: <http://www.usfa.dhs.gov/>.
- Yuan Z., Khakzad N., Khan F., Amyotte P., (2016). Domino effect analysis of dust explosions using Bayesian networks. *Process Safety and Environmental Protection* 100, 108-116.
- Zhang M., Jiang J., (2008). An improved probit method for assessment of domino effect to chemical process equipment caused by overpressure. *Journal of Hazardous Materials* 158, 280-286.