Application of event sequence diagram to evaluate emergency response actions during fire-induced domino effects

Reference:
Zhou Jianfeng, Reniers Genserik, Khakzad Nima.- Application of event sequence diagram to evaluate emergency response actions during fire-induced domino effects
Reliability engineering and system safety - ISSN 0951-8320 - 150(2016), p. 202-209
Full text (Publisher's DOI): https://doi.org/doi:10.1016/J.RESS.2016.02.005
To cite this reference: http://hdl.handle.net/10067/1319140151162165141

Jianfeng Zhou [a], Genserik Reniers [b, c *], Nima Khakzad [b]

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

b. Safety and Security Science Group, Delft University of Technology, Delft, The Netherlands

c. Faculty of Applied Economics, Antwerp Research Group on Safety and Security (ARGoSS), Universiteit Antwerpen, 2000 Antwerp, Belgium; tel.: +32 3 265 4182; e-mail: genserik.reniers@uantwerpen.be

[*]Corresponding author

Application of event sequence diagram to evaluate emergency response actions during fire-induced domino effects

Jianfeng Zhou [a], Genserik Reniers [b, c *], Nima Khakzad [b]

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

b. Safety and Security Science Group, Delft University of Technology, Delft, The Netherlands

c. Faculty of Applied Economics, Antwerp Research Group on Safety and Security (ARGoSS), Universiteit Antwerpen, 2000 Antwerp, Belgium; tel.: +32 3 265 4182; e-mail: genserik.reniers@uantwerpen.be

Abstract: Emergency response actions can significantly influence the propagation of domino effects, particularly those triggered by fires. Thus, the performance and efficiency of devised emergency response actions should be carefully evaluated and taken into account when analyzing the propagation of domino effects and their risk. In the present study, we have introduced a methodology based on Event Sequence Diagram (ESD) to evaluate and prioritize different emergency response actions based on their efficiency in preventing or delaying the propagation of domino effect. Using the developed methodology, the risk of domino effects under emergency response actions can be assessed, while considering factors such as sequence, duration, correctness, and mutual interaction of the emergency response actions. We demonstrated the application of the methodology in analyzing the effect of emergency response actions on fire-induced domino effects in a fuel storage plant; the comparison of the results with previous studies illustrates the efficacy and practicality of the developed methodology.

Keywords: Domino effect; Emergency response; Risk assessment; Event sequence diagram; Process industry.

1. Introduction

Major industrial fires in the chemical and process industry can cause huge losses. In addition to inherent safety and add-on safety measures aimed at preventing or controlling of major fires, effective emergency response plans play a key role in preventing a major fire from causing secondary fires and thus forming a fire-induced domino effect. In order to ensure rapid, orderly and effective implementation of emergency response actions, emergency response plans are usually pre-established in chemical plants. Such plans arrange the structure of the emergency organization, personnel, technology, equipment, materials, actions, commands and coordination beforehand. However, whether these arrangements are reasonable and whether the actions and the coordination actions are effective or not are difficult to assess in the design stage of a plan. Some studies on the evaluation of emergency response plans have been carried out (Cheng and Qian, 2010; Chen and Zhang, 2009; Darren et al., 2011; Karagiannisa et al., 2010; Piatyszek and Karagiannis, 2012); most of these researches aimed to evaluate the emergency plans from robustness and integrity perspectives.

*Corresponding author

However, the relevant studies in the field of emergency response actions are relatively limited. Nevertheless, the evaluation of emergency response actions has become an urgent requirement for improving emergency preparedness as the emergency actions responding to an accident can significantly affect the evolution of the accident. Different patterns of an accident evolution may lead to different consequences. As a result, the efficacy of the emergency response actions and their impact on both the evolution of the accident and the likelihood of the ensuing consequences should be effectively taken into account in the risk analysis of the accident.

Domino effects refer to a series of accidents triggered by an initial event/accident. In petrochemical storage areas, for example, there are many storage tanks containing large quantities of flammable substances. This makes these storage tanks potential sources of severe fires or explosions which could emerge as domino effects. Particularly, the large inventory of flammable chemicals along with the congestion of the storage tank area facilitates the escalation of an initial fire (primary fire) into a series of secondary and tertiary fires in the neighboring storage tanks - a so-called fire-induced domino.

Domino effects will cause more significant losses than a primary accident. Safety management often requires the risk assessment of domino effects; for example, the Seveso-III Directive requires the European member states to assess the risk of domino effects in their hazardous installations (Directive 2012/18/EU). Many researchers have studied the risk of domino effects and developed risk assessment methodologies (Antonioni, et al., 2009; Cozzani, et al., 2014; Cozzani, Gubinelli, & Salzano, 2006; Cozzani & Salzano, 2004; Cozzani, Tugnoli, & Salzano, 2007; Cozzani, Tugnoli, & Salzano, 2009; Khakzad, et al., 2013, 2014; Khakzad, 2015; Khakzad and Reniers, 2015a,b; Khan & Abbasi, 1998; Landucci, et al., 2009; Mingguang & Juncheng, 2008; Necci, et al, 2015; Reniers, 2010; Reniers, et al., 2005; Reniers & Cozzani, 2013; Salzano & Cozzani, 2005; Salzano & Cozzani, 2006). Most of these methods analyze probabilities or consequences of domino events based on the escalation vectors.

For fire-induced domino effects in chemical plants, the major escalation vector is the thermal radiation. If the thermal radiation intensities received by neighboring tanks from a primary tank fire (or pool fire) both exceed a certain threshold and last for at least some specific time lapse, secondary fires or explosions may occur, and so on.

The emergency response actions can impact the propagation of a primary fire, thus affecting the possibilities and patterns of potential domino effects. Although the importance of emergency response actions in either preventing or controlling domino effects has previously been addressed by researchers (Landucci et al, 2009, 2015), the impact of emergency response actions has not given due attention.

2. Emergency response

2.1 Definition

Emergency response is usually looked upon as a factor to mitigate the risk of accidents mainly by reducing the losses. However, actual emergency response actions do not necessarily reduce the losses, especially under wrong circumstances. After an accident occurs, different propagation patterns can be envisaged. The emergency response actions impact both the likelihood of the patterns and the respective consequences. In the present study, an emergency response evaluation methodology is introduced to investigate the foregoing impacts of emergency response actions.

The risk of an accident subject to an emergency response plan (hereafter emergency response risk) can be defined as:

$$ER_j = f\ (P_j,C_j)\ \ for\ \ \ j=1,2,\ \ldots\text{'}M \tag{1}$$

where ER_j is the emergency response risk, that is, the risk resulting from the jth propagation pattern of the accident under the emergency response; P_j is the probability of the j^{th} propagation pattern under the emergency response, and C_j is the consequence of the j^{th} propagation pattern; M is the total number of possible patterns.

Since the emergency response risk is a function of the occurrence of emergency response actions, it can be defined dynamically by considering the influences of each specific emergency action:

$$ER_j^{\ i} = f\,(C_j^i, P_j^i)\quad for\ i = 1,2,\ldots,N\ \ \ and\ \ \ \ j = 1,2,\ldots,M \tag{2}$$

where ER_j^i indicates the emergency response risk of the j^{th} propagation pattern under the i^{th} emergency response action; N is the number of emergency response actions. P^i_j represents the conditional probability of the j^{th} propagation conditioned by the occurrence of the i^{th} emergency response action. Likewise, C^i_j represents the consequence of the j^{th} propagation conditioned by the occurrence of the i^{th} emergency response action.

The conditional probability embedded in Equation (2) can be used to evaluate the efficacy of each emergency response action.

Domino effects are results of accident propagation. So, to assess the risk of domino effects under emergency response, M in Equation (2) can be considered as the total number of domino effects resulted from an initial accident; P^i_j is the conditional probability of the j^{th} domino effect conditioned by the occurrence of the i^{th} emergency action; C^ij is the consequence of the j^{th} domino effect conditioned by the occurrence of the i^{th} emergency action; and ER^i_j is the risk of the j^{th} domino effect conditioned by the occurrence of the i^{th} emergency action after the initial accident occurs.

During the emergency response to an accident, the factors such as the time of each action and the sequence of the actions can influence the propagation of the accident. Thus, to assess the emergency response risk, the following factors should be considered:

(i) Time of emergency response action. An action implemented at different times may lead to different results.

(ii) Sequence of emergency actions. A different sequence of emergency response actions can change the probability of the resulting events, and also influencing the consequences.

(iii) Mutual influence of the actions. Some emergency actions may interact with each other, leading to different results.

(iv) Correctness of the actions. Whether an emergency action is performed correctly will affect the propagation of the accident. The correctness of an emergency response action can be reflected by its states. Although an action may include several states, usually two basic states are considered for an action: correct action which means the action works well and produces the intended results according to the objective of the emergency response; incorrect action which cannot prevent the propagation of the accident or mitigate the losses.

(v) Relations of the process variables. Emergency actions are highly related to process variables.

2.2 ESD modeling of emergency response

2.2.1. ESD modeling approach

Event sequence diagram (ESD) is a graphical method for visualizing the sequence of related events. As an effective risk assessment method, it has been used in many different fields. Swaminathan and Smidts (1999) expanded the ESD framework by introducing dynamic factors, so that it can be used for probability risk assessment of dynamic systems.

Applications of ESD have been reported in Abdolhamidzadeh et al. (2012), Ale et al. (2009), Groth et al. (2010), Luo & Hu (2013), and Mohaghegh et al. (2009). For assessing emergency response risk in the present study, ESD is defined based on the work of Swaminathan & Smidts (1999):

$$ESD = (E, Cd, G, Pr) \tag{3}$$

where E refers to the events, which in turn implies any changes from one state to another. This approach will be employed to describe the event sequence in a domino effect scenario and related emergency actions. Events are divided into four categories: (1) “Initial event” (IE), being the beginning event of an ESD, and starting the potential event sequence. (2) “Delay event” (DE), including ‘deterministic delay event’ and ‘random delay event’. The deterministic delay event indicates that no event occurs within a certain time. It is also used to describe the fixed time, for example, the time to complete a regular job. The random delay event indicates that the delay time is determined by a random number. (3) “Comment event” (CE), describing the development of an event sequence. (4) “Termination event” (TE), indicating the termination event of the ESD.

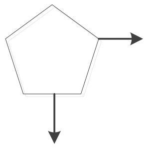
Cd indicates conditions, which represent the rules controlling the development of an event sequence into different branches. The event sequence will develop in different directions according to whether the conditions are satisfied. They can be used to describe the impacts of emergency response actions on the development of an event sequence.

G represents the logic gates, indicating the logical relationships among events. The basic gates are the AND gate and the OR gate, which can be further divided into four types according to event relationships: (1) “Output AND gate”, representing the logical relationship that the occurrence of an event will lead to multiple independent events occurring simultaneously; (2) “Input AND gate”, indicating that one event occurs only if multiple other events have occurred; (3) “Output OR gate”, representing multiple exclusive events occurring when one input event occurs; (4) “Input OR gate”, indicating that if any of the input events occurs, the output event will occur.

Pr is a set of process parameters, indicating the system parameters during an emergency response action. The parameters reflect the states of the system, and may impact the propagation of an accident. For example, the thermal radiation of a fire will damage nearby equipment and may propagate the accident.

In addition to common symbols of ESD, a new event and a new condition are added in this paper to describe the event sequence of accident scenarios and emergency actions. The added event is the action State Event (SE). It is added here to describe the state of an emergency action. The implementation of an emergency action may result in multiple states, whose likelihoods are expressed by probabilities. The action state event is denoted by the following symbol:

The added condition is the emergency action correctness condition. It influences the development direction of an accident according to the states of an emergency action. The condition is denoted by the symbol:



For more details about ESD please see Swaminathan & Smidts (1999). The symbols and their meanings are listed in the Appendix, including the symbols in Swaminathan and Smidts (1999) along with the ones developed in the present study.

2.2.2. Probabilities of termination events

The consequences can be assessed based on corresponding consequence models (i.e., thermal radiation of a fire, overpressure of explosion, and gas dispersion) and surrounding people and properties. The present study, however, only focuses on the probability of domino effects not the consequences. A domino effect is the result of the escalation of a primary accident while considering existing safety barriers including emergency response. The escalation is influenced by many factors, including system parameters (such as temperature and pressure) and emergency response actions. ESD can be adopted to model and analyze the emergency response process, especially the relationship between emergency response actions.

The steps for determining the probability of a domino event which is represented as a termination event in ESD are as follows:

(1) Determine the time requirement (T_{max}) for emergency response according to escalation vectors, for example, the thermal radiation of a fire.

(2) Determine the emergency response time T from the initial event to the termination event.

(3) Determine the probability of timeliness of emergency response $Pt = P\{T \leq T_{max}\}$.

(4) Determine the probability of correctness of emergency response actions (*Pa*) from the initial event to the termination event.

(5) Determine the probability of the termination event based on *Pt* and *Pa*.

The duration of emergency response actions and the probability of the correctness of emergency response actions (*Pa*) are influenced by the structure of the ESD model, especially the relationships between actions. The emergency response time is determined by the delay time of emergency actions. The delay times of the sequentially executed actions can be accumulated. But calculating the emergency time based on the logical gates should obey certain transferring rules:

(i) Output AND gate: The time of each output branch is equal to the input time, as shown in Fig. 1 (a), Time 2 =Time 1 and Time 3 =Time 1;

(ii) Input AND gate: The output time is the maximum time of all input branches, as shown in Fig. 1 (b), Time 3 = max (Time 1, Time 2);

(iii) Output OR gate: The times of all output branches are equal to the input time, as shown in Fig. 1 (c), Time 2 = Time 1 and Time 3 = Time 1;

(iv) Input OR gate: The output time equals the time of the selected input branch, as shown in Fig. 1 (d), Time 3 = Time 1 or Time 3 = Time 2 (depending on which input branch works).

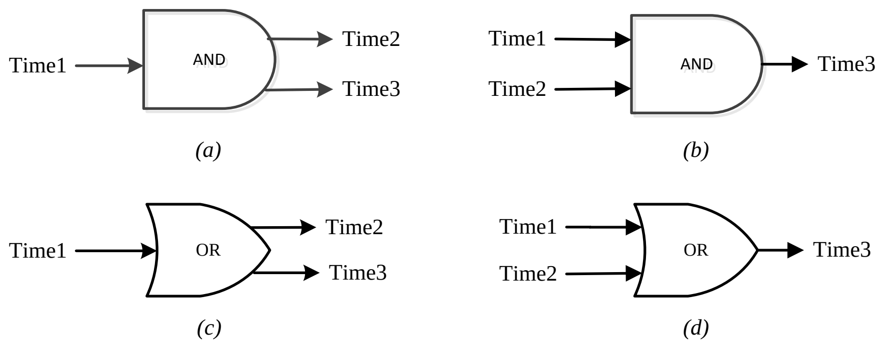


Fig. 1 Time transferring through gates

Events from the initial event to a termination event form an event chain, which is defined as an event path in this paper. A termination event can be reached from multiple event paths. All the events on a path have impacts on the occurrence of the termination event. The impacts can be expressed by using conditional probabilities:

$$P_{ij} = P\{te_j|e_i\} \quad for \quad I = 1,..., N, and\ j = 1,..., M \tag{4}$$

where te_j is the j^{th} termination event; M is the number of termination events; e_i indicates the i^{th} event; N is the number of events; P_{ij} is the conditional probability of the occurrence of the j^{th} termination event conditioned by the occurrence of the i^{th} event.

Emergency actions can be expressed as events, and the domino effects can be expressed as termination events, thus the importance of the emergency actions can be analyzed through the conditional probabilities.

3. An illustrative example

For illustrative purposes, consider a storage plant comprising six atmospheric gasoline tanks. The layout of the plant is shown in Fig. 2. The diameters of the tanks (T1 - T6) are 20 m, and their heights are 10 m. The distance from T1 to T2 is 30 m (center to center), and so is the distance from T1 to T3.

Fig. 2 Layout of the gasoline tanks

3.1 ESD model of the emergency response to a tank fire

If one tank catches fire (e.g., if there is a pool fire at T1), the fire may be controlled[1] via an emergency response plan, or else the fire may escalate to another storage tank, forming a domino event. Two termination events are discussed here: one is “The accident is controlled”, the other is “domino effect occurs”, both shown as diamonds in Figure 3. Based on ESD modeling and the risk assessment approach described previously, the probability of a domino effect occurrence under emergency response circumstances can be analyzed. The ESD model of the emergency response to a tank fire in the gasoline storage plant is shown in Figure 3.

The emergency response actions after a tank fire breaks out include “discover the fire and alarm”, “dispatch emergency teams”, “arrive at the scene of the accident”, “perform correct firefighting action”, “cool adjacent tanks”, and so on. For the sake of brevity, the correctness of the relatively simple actions is not discussed here. Only the correctness of the action “Perform correct firefighting action” is considered. This action has two states: one is “The action is correct”, which will gradually control the blaze and decrease the intensity of thermal radiation; the other is “The action is not correct”, which is not beneficial to reduce the thermal radiation.

[1] In the case of a fully developed pool fire of gasoline, emergency responders will hardly attempt to extinguish the fire due to the high volatility of gasoline as such an attempt may cause the formation of a flammable vapor cloud that given a delayed ignition can result in a vapor cloud explosion.

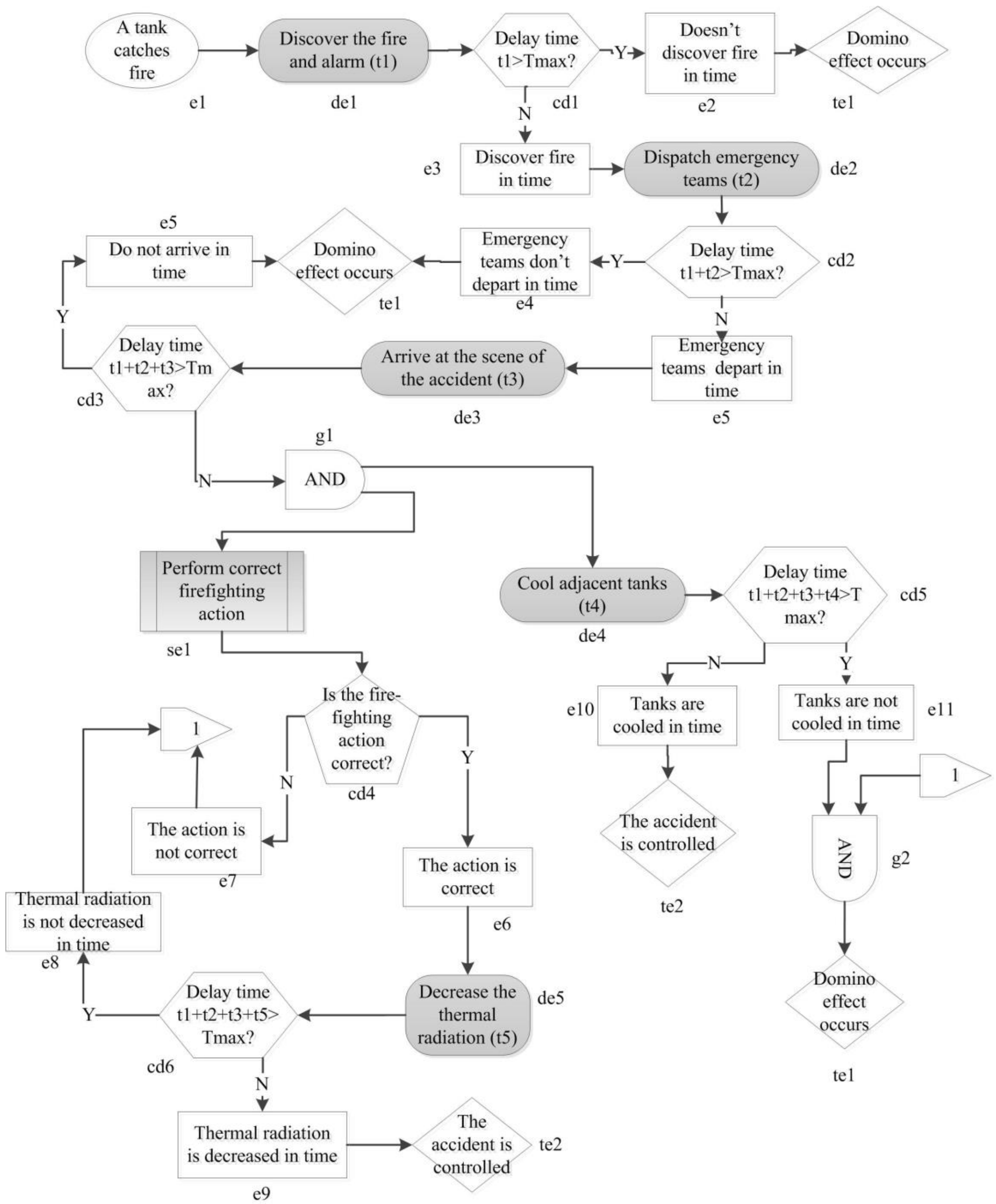


Fig. 3 ESD model of emergency response to a tank fire

To assess the risk of a potential domino effect, the thresholds that might lead to a domino effect should be determined first. After tank T1 catches fire, the thermal radiation will impact the adjacent tanks, possibly leading to a domino effect. Besides the thermal radiation intensity, the duration of the thermal radiation has an impact on the likelihood of the domino effect. Previous studies (Landucci et al., 2009; Cozzani et al., 2006) discuss the thresholds of domino effects and provide relationships between the intensity of the heat radiation and the time to failure (ttf) of target units. To prevent a tank fire from propagating to a domino effect, the thermal radiation intensity received by neighboring tanks should be decreased under the threshold of the domino effect in time (before ttf is reached) during the emergency response to the fire.

3.2 Monte Carlo simulation

Monte Carlo simulation can be employed to analyze the occurrence probability of the ESD termination event. The flowchart of the analysis is shown in Fig. 4.

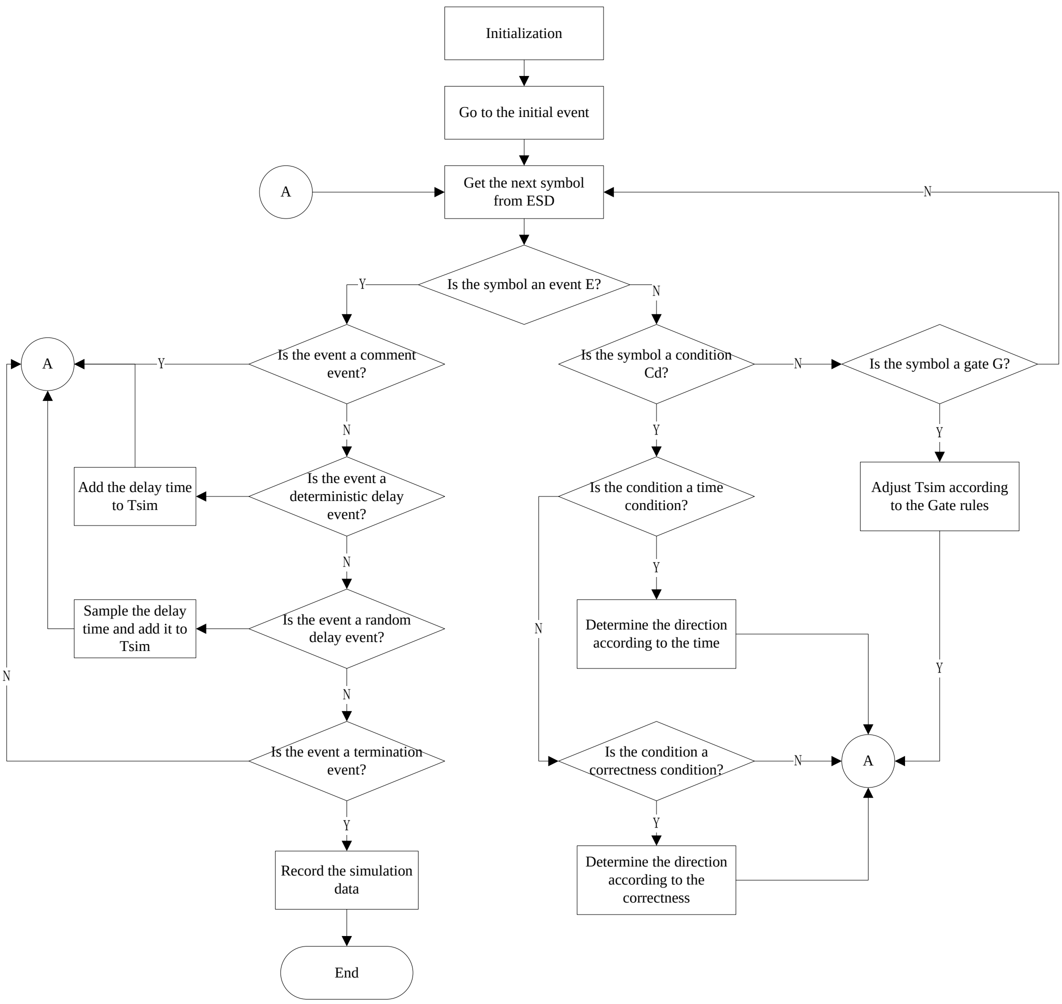


Fig. 4 Flowchart of the ESD based simulation

During the initialization, set the simulation time $T_{sim} = 0$. According to the escalation characteristics of the initial accident, threshold values of domino effect occurrence are determined as well as the time required for emergency response. In case of pool fires, thermal radiation is the escalation vector. The threshold of thermal radiation and the time to failure (*ttf*) of each neighboring tank should be determined.

After a simulation, the time T_{sim} is compared to the *ttf* to determine the possibility of a domino effect.

In order to analyze the escalation probability of an accident and compare the importance of the actions, the following data should be recorded:

(1) Simulation number N: Monte Carlo simulation needs a large number of computer simulations to test the system's dynamic characteristics and summarize the statistical results.

In the present study, 10^5 simulations were performed to capture the very small probabilities of 10^{-5} orders of magnitude.

(2) Delay time: for a delay event: the lasting time should be recorded.

(3) States of the action state event (SE): for an action state event, the state of an action should be sampled and recorded; for example, the correctness of an action should be sampled when this action is denoted by a SE.

(4) Number of event occurrences: in each simulation, if one event occurs, the counter of this event is increased by 1. After N simulations, the times of the occurrence of each event can be obtained. In each simulation, only one termination event arrives. After N simulations, the arrival times of the termination events are also recorded.

Based on the simulation data, the following probabilities can be estimated:

Probability of the occurrence of event e_i:

$$P(e_i) = \frac{N_{e_i}}{N} \tag{5}$$

where N_{ei} is the number of the occurrence of event e_i.

Likewise, the probability of the occurrence of the termination event te_i:

$$P(te_i) = \frac{N_{te_i}}{N} \tag{6}$$

where N_{tei} is the number of the occurrence of the termination event te_i.

Conditional probability of the occurrence of the termination event te_j's:

$$P(te_j \mid e_i) = \frac{N_{te_j|e_i}}{N_{e_i}} \tag{7}$$

where $N_{tej|ei}$ is the number of times the termination event te_j occurs via the occurrence of the event e_i.

3.3 Analysis and discussion

Based on the ESD model and Monte Carlo simulation, the probability of domino effects can be determined, and the adequacy of the emergency response actions can be compared.

In the storage plant shown in Fig. 1, when T1 catches fire, T2 and T3 will receive the maximum intensity of thermal radiation. Based on Mudan's model (Mudan, 1984), the thermal radiation intensity received by T2 and T3 is about 12.5 kW/m^2 while the one received by T4 is about 5 kW/m^2. 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):

$$ln(ttf) = -1.13\, ln(I) - 2.67 \times 10^{-5} V + 9.9 \tag{8}$$

The volume *V* is in m^3. Thus, the *ttf* for T2 and T3 is about 17 minutes, and the *ttf* for T4 is about 49 minutes.

As a result, the intensity of thermal radiation received by T2 and T3 must be decreased in 17 minutes during an emergency response; otherwise, T2 or T3 will fail and a domino effect will occur. Similarly, the radiant flux at T4 must be decreased in 49 minutes. If there is no response to the fire in T1, the fire can last over 2000 minutes (assuming that the gasoline will not spill over), triggering a domino effect.

In the model shown in Fig. 3, there are several delay events corresponding to emergency actions.

Peng (2010) studied the statistic law of fire response time and its correlation with the scale of urban fire (burned area and direct losses) based on the urban fire data of Japan and China. They analyzed 44505 valid fire records from 1995 to 2003 obtained from the Disaster Prevention Research Institute of Japan, and each record containing information about fire beginning time, alarm time, responders arrival time, fighting time, fire reason, weather conditions, and losses, etc. They also analyzed 14391 fire records from 2000 to 2009 of a city in China. Through statistical analysis they found that the response times and the firefighting times follow log-normal distributions.

According to the data of Peng (2010), the expected times of “discover the fire”, “dispatch emergency teams”, “arrive at the scene of the fire”, and “start fire fighting” are about 4, 2.5, 5, and 3.5 minutes, respectively. From NFPA’s report (Flynn, 2009) similar data can be derived. The parameters of log-normal distributions (Equation 9) of the delay events in the ESD model are shown in Table 1.

$$f(x) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma x} e^{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}}, & x > 0 \\ 0, & x \leq 0 \end{cases} \tag{9}$$

Table 1 Parameters of log-normal distributions for emergency action durations (Peng, 2010)

Event	Expected value (min)	μ	σ
de1	4	1.30	0.40
de2	2.5	0.88	0.78
de3	5	1.56	0.31
de4\de5	3.5	1.20	0.34

The correctness of the firefighting action is influenced by some factors such as the knowledge and training of the emergency personnel. Suppose the probability of the state “correct action” of “firefighting” in the ESD model is 50%.

In the ESD model shown as Fig.3, there are two major tasks for the emergency response (other tasks are not discussed here; one task is composed of several events): one is to fight against the fire of tank T1 while the other is to cool the neighboring tanks with water. The former will decrease the thermal radiation emitted by the fire whereas the latter will either decrease the temperature or delay the temperature rise of the neighboring tanks. It is shown through an output AND gate – g1 – that these two tasks are performed simultaneously.

Based on the simulation, the probability of domino effect (T2 or T3 fails) is 0.1563 after T1 catches fire. The failure probability of T4 is about 10^{-5} (among 10^5 Monte Carlo simulation samples, there is only one sample where T_{sim} is greater than 49 minutes). As a result, the protection of T2 and T3 is more important than the protection of T4 in order to prevent a domino effect when T1 catches fire.

Consider only one task is performed (that is, the gate g1 in Fig. 3 is replaced by an output OR gate): if only the task “perform correct firefighting action” (firefighting for tank T1) is performed, the probability of a domino effect (T2 or T3 fails) is 0.6027, and the failure probability of T4 is 0.499. However, if only the task “cool the neighboring tanks” is performed, the probability of domino effect (T2 or T3 fails) is 0.216 while the probability of T4 failure is about 10^{-5}.

If the correctness of “perform correct firefighting action” (firefighting for tank T1) is increased, for example, to 100%, and the tasks are performed simultaneously, the failure probability of T2 or T3 is calculated as 0.14 given a fire in T1. Moreover, the failure probability of T4 is about 10^{-5}.

To validate the results, the following function is built according to the probit model provided by Landucci et al. (2009) and the emergency response conditions previously described:

$$Pr = 14.11 - 3.42 \ln(ttf) \quad (10)$$

where *Pr* is the probit variable, and *ttf* (min) is the time to failure.

When *ttf* is 17 minutes, the value of Pr is 4.42; thus, the probability of escalation (domino effect) is 0.16. Similarly, when *ttf* is 49 minutes, the value of *Pr* is 0.8, corresponding to a probability of escalation of 1.33×10^{-5}.

From the results, it can be seen that the values obtained from the probit model is close to those obtained from the ESD model when the tasks are performed simultaneously. The application of ESD model also facilitates analyzing the possibility of domino effects under various emergency response conditions and different levels of action adequacy.

Employing the model shown in Fig. 3, probabilities of the emergency actions (delay events in Fig. 3) and the conditional probabilities of the domino effect are listed in Table 2. The adequacy of the actions can also be compared based on the conditional probabilities. The results show that the action “cool adjacent tanks” is more effective in preventing domino effects than “Perform correct firefighting action” because the domino effect occurrence probability conditioned by *de4* (cool adjacent tanks) is greater than that conditioned by *de5* (decrease the thermal radiation).

It should be noted that the priority of “cooling adjacent tanks” over “Perform correct firefighting action” is merely based on the assumptions made in the present study (e.g., the numerical values of the log-normal distribution parameters in Table 1, domino effect thresholds, etc.) and according to the characteristics of the specific case study under consideration. Thus, it is likely that by employing the developed methodology to another case study and under different assumptions the latter strategy proves more effective than the former one.

Table 2 Probabilities of the emergency actions and the conditional probabilities of the domino effect

Event	Event occurrence probability	Domino effect occurrence probability conditioned by *dei*
de1	1.0	0.1563
de2	0.9997	0.1561

de3	0.9993	0.1558
de4	0.5667	0.2353
de5	0.4970	0.0999

4. Conclusions

The performance and efficiency of emergency response strategies play a key role in preventing, controlling, delaying, and mitigating potential domino effects in chemical plants. After an initial tank fire occurs, emergency response will be carried out to prevent the propagation of the fire to adjacent tanks and thus forming a domino effect. Effective emergency response strategies may prevent the occurrence of domino effects, while improper emergency response actions not only fail short to prevent the domino effect but also endangers the lives of emergency responders. Thus, to assess the risk of domino effects, the impacts of emergency response actions should be considered.. In order to ensure rapid, orderly, and effective emergency and rescue actions, the emergency response actions should carefully be contemplated and evaluated. In the present study, we demonstrated the application of event sequence diagrams to assess the impact of emergency response actions on fire-induced domino effects in chemical storage plants. In the developed methodology, emergency actions are converted into corresponding events in an event sequence diagram. Based on the dynamic structure of the event sequence diagram and the embedded conditional probabilities, not only the impact of relevant emergency response actions on the risk of potential domino effects can be assessed but also the emergency response actions can be evaluated and prioritized based on their effectiveness.

We exemplified the application of the methodology using a hypothetical tank farm. Comparison of the results with previous established studies indicates a good agreement, validating the efficacy of the proposed methodology.

References

Abdolhamidzadeh B, Rosmani C, Hassan C, et al. Anatomy of a domino accident: Roots, triggers and lessons learnt. Process Safety and Environmental Protection 2012; 90: 424-429.

Ale B J M, Bellamy L J, van der Boom R, et al. Further development of a Causal model for Air Transport Safety (CATS): Building the mathematical heart. Reliability Engineering and System Safety 2009; 94: 1433-1441.

Antonioni G, Spadoni G, Cozzani V. Application of domino effect quantitative risk assessment to an extended industrial area. Journal of Loss Prevention in the Process Industries 2009; 22: 614-624.

Cheng C Y, Qian X. Evaluation of Emergency Planning for Water Pollution Incidents in Reservoir Based on Fuzzy Comprehensive Assessment. Procedia Environmental Sciences 2010; 2: 566-570.

Chen G, Zhang X. Fuzzy-based methodology for performance assessment of emergency planning and its application. Journal of Loss Prevention in the Process Industries 2009; 22: 125-132.

Cozzani V, Antonioni G, Landucci G, et al. Quantitative assessment of domino and NaTech scenarios in complex industrial areas. Journal of Loss Prevention in the Process Industries 2014; 28:10-22.

Cozzani V, Gubinelli G, Antonioni G, et al. The assessment of risk caused by domino effect in quantitative area risk analysis. Journal of Hazardous Materials 2005; A127: 14-30.

Cozzani V, Gubinelli G, Salzano E. Escalation thresholds in the assessment of domino accidental events. Journal of Hazardous Materials 2006; A129: 1-21.

Cozzani V, Salzano E. Threshold values for domino effects caused by blast wave interaction with process equipment. Journal of Loss Prevention in the Process Industries 2004; 17: 437-447.

Cozzani V, Tugnoli A, Salzano E. Prevention of domino effect: from active and passive strategies to inherently safer design. Journal of Hazardous Materials 2007; 139: 209-219.

Cozzani V, Tugnoli A, Salzano E. The development of an inherent safety approach to the prevention of domino accidents. Accident Analysis & Prevention 2009; 41: 1216-1227.

Darren L, Karin S, Freddy V. An assessment of flood emergency plans in England and Wales, France and the Netherlands. Natural Hazards 2011; 58: 341-363.

Flynn J D. Fire service performance measures. National Fire Protection Association 2009.

Groth K, Wang C, Mosleh A. Hybrid causal methodology and software platform for probabilistic risk assessment and safety monitoring of socio-technical systems. Reliability Engineering and System Safety 2010; 95: 1276-1285.

Karagiannisa G-M, Piatyszeka E, Flaus J-M. Industrial emergency planning modeling: A first step toward a robustness analysis tool. Journal of Hazardous Materials 2010; 181: 324-334.

Khakzad N, Khan F, Amyotte P, Cozzani V. Domino effect analysis using Bayesian networks. Risk Analysis 2013; 33(2): 292-306.

Khakzad N, Khan F, Amyotte P, Cozzani V. Risk Management of Domino Effects Considering Dynamic Consequence Analysis. Risk Analysis 2014; 34(6): 1128-1138.

Khakzad N. Application of dynamic Bayesian network to risk analysis of domino effects in chemical infrastructures. Reliability Engineering and System Safety 2015; 138: 263-272.

Khakzad N, Reniers G. Using graph theory to analyze the vulnerability of process plants in the context of cascading effects. Reliability Engineering and System Safety 2015a; 143: 63-73.

Khakzad N, Reniers G. Risk-based design of process plants with regard to domino effects and land use planning. Hazardous Materials 2015b; 299: 289–297.

Khan F I, Abbasi S A. Models for domino effect analysis in chemical process industries. Process Safety Progress 1998; 17: 107-123.

Landucci G, Argenti F, Tugnoli A, Cozzani V. Quantitative Assessment of Safety Barrier Performance in the Prevention of Domino Scenarios Triggered by Fire. Reliability Engineering and System Safety 2015; 143:30-43.

Landucci G, Gubinelli G, Antonioni G, et al. The assessment of the damage probability of storage tanks in domino events triggered by fire. Accident Analysis and Prevention 2009; 41: 1206-1215.

Lopez-Molina A, Vazquez-Roman R, Sam Mannan M, et al. An approach for domino effect reduction based on optimal layouts. Journal of Loss Prevention in the Process Industries 2013; 26: 887-894.

Luo P, Hu Y. System risk evolution analysis and risk critical event identification based on event sequence diagram. Reliability Engineering and System Safety 2013; 114: 36-44.

Mohaghegh Z, Kazemi R, Mosleh A. Incorporating organizational factors into Probabilistic Risk Assessment (PRA) of complex socio-technical systems: A hybrid technique formalization. Reliability Engineering and System Safety 2009; 94: 1000-1018.

Mudan K S. Thermal radiation hazards from hydrocarbon pool fires. Progress Energy Combustion Science 1984; 10: 59-80.Necci A, Cozzani V, Spadoni G, Khan F. Assessment of Domino Effect: State of the Art and Research Needs. Reliability Engineering and System Safety 2015; 143:3-18.

Peng C. The Statistics Law of Fire Response Time and Its Correlation with the Scale of Urban Fire (Thesis for master’s degree). University of Science and Technology of China, 2010.

Piatyszek E, Karagiannis G M. A model-based approach for a systematic risk analysis of local flood emergency operation plans: a first step toward a decision support system. Natural Hazards 2012; 61: 1443-1462.

Reniers G. An external domino effects investment approach to improve cross-plant safety within chemical clusters. Journal of Hazardous Materials 2010; 177(1-3): 167-74.

Reniers G, Cozzani V. Domino Effects in the Process Industries: Modelling, Prevention and Managing. Elsevier: 2013.

Reniers G, Dullaert W, Ale B, Soudan K. The use of current risk analysis tools evaluated towards preventing external domino accidents. Journal of Loss Prevention in the Process Industries 2005; 18: 119-26.

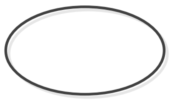
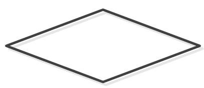
Salzano E, Cozzani V. The analysis of domino accidents triggered by vapor cloud explosions. Reliability Engineering & System Safety 2005; 90: 271-284.

Salzano E, Cozzani V. A fuzzy set analysis to estimate loss intensity following blast wave interaction with process equipment. Journal of Loss Prevention in the Process Industries 2006; 19: 343-352.

Swaminathan S, Smidts C. The Event Sequence Diagram Framework for Dynamic Probabilitic Risk Assessment. Reliability Engineering and System Safety 1999; 63: 73-90.

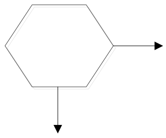
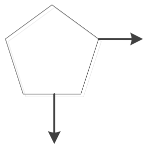
Appendix: Symbols of ESD

Table 3 Categories and symbols of events (Swaminathan and Smith, 1999)

Category	Symbol	Annotation
Initial event		Beginning event of the ESD
Deterministic delay event		The delay time is fixed
Random delay event		The delay time is a random number
Action state event*		The likelihood of each action state is expressed by probability or random number
Comment event		Providing information of the development of event sequence
Termination event		An end state of the ESD

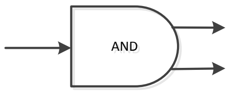
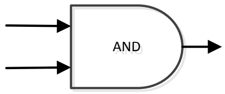
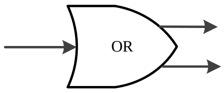
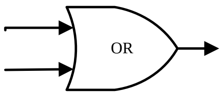
*. This event has been introduced in the present study.

Table 4 Categories and symbols of conditions (Swaminathan and Smith, 1999)

Category	Symbol	Annotation
Time condition		The direction of the event sequence is influenced by event time.
Action correctness condition*		The direction of the event sequence is influenced by event state.

*. This condition has been introduced in the present study.

Table 5 Types and symbols of gates (Swaminathan and Smith, 1999)

Type	Symbol	Annotation
Output AND gate		The occurring of one input event will lead to multiple output events occurring.
Input AND gate		The output event will not occur until all input events occurs.
Output OR gate		The occurring of one input event will lead to multiple exclusive output events occurring.
Input OR gate		Any of the input events occurring will lead to the output event occurring.