CHEMICAL ENGINEERING TRANSACTIONS
VOL. 82, 2020
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Bruno Fabiano, Valerio Cozzani, Genserik Reniers

ISBN 978-88-95608-80-8; **ISSN** 2283-9216
DOI: 10.3303/CET2082012

A Method for Assessing Propagation Paths and Probabilities of Domino Effects Triggered by Natech Events

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Earthquakes, floods and other natural disasters can lead to serious fires, explosions and other technical disasters, called Natech events, possibly triggering domino effects in chemical industrial parks. However, current studies only look at Natech events or domino effects separately, and don't consider domino effects triggered by Natech events with multiple primary accidents and with higher order accidents. This paper presents a method aiming to obtain all possible paths and probabilities of domino effects triggered by Natech events. Firstly, our suggested method is obtained by integrating conventional assessment frameworks for Natech events and domino effects. Secondly, the method is solved by a Matlab program based on (i) the scenario matrix, (ii) the scenario escalation matrix, and (iii) the path cell array. Finally, the method is illustrated and its availability is verified by a real chemical tank farm which suffered from a flood. The results show that this method can obtain and rank all the possible paths and their probabilities. Furthermore, the cumulative probabilities of each higher order level of domino effect and each tank can be obtained for a subsequent quantitative risk assessment considering both Natech events and their resulting domino effects.

1. Introduction

Natural disasters, such as earthquakes, floods and lightning, have the potential to destroy installations storing hazardous materials, causing serious technical disasters such as fires and explosions, which are known as Natech events. In addition, if the fires and explosions are not effectively controlled, they are easy to cause the failure of surrounding equipment, and then trigger subsequent domino effects, resulting in more serious consequences. Natural hazards can cause multiple and simultaneous releases of hazardous materials over extended areas, destroying safety barriers and lifelines. Therefore, domino effects caused by Natech events have the characteristics of multiple primary accidents and failure of accident mitigation measures, which means that such accidents are catastrophic and difficult to control once they happen.
At present, the research on Natech events mainly focuses on risk assessment and fragility models with respect to different natural disasters. Antonioni et al. (2009) developed a framework for the risk assessment of Natech events, and the framework has been applied to flood (Antonioni et al., 2015) and earthquake scenarios (Antonioni et al., 2007). Landucci et al. (2012) proposed damage models for atmospheric storage tanks and horizontal cylindrical vessels in flood events (Landucci et al., 2014). On the study of domino effects, Cozzani et al. (2005) proposed the framework of quantitative risk assessment of domino effects, and the relevant models and thresholds. Khakzad et al. (2013) analysed domino effects using Bayesian networks and graph theory (Khakzad and Reniers, 2015). Chen et al. (2018) studied the spatial-temporal evolution of domino accidents by a methodology involving a Domino Evolution Graph model and a Minimum Evolution Time algorithm. However, the above studies only look at Natech events or domino effects separately, and don't consider domino effects triggered by Natech events. Furthermore, Yang et al. (2018) proposed a method for predicting the probabilities of domino effects triggered by lightning, and Misuri et al. (2020) developed a Quantitative risk assessment (QRA) method of domino effect triggered by lightning. However, lightning usually causes only one primary accident, and these methods cannot be adapted to the case of multiple primary

Paper Received: 27 January 2020; Revised: 17 April 2020; Accepted: 4 August 2020
Please cite this article as: Yang Y., Chen G., Reniers G., 2020, A Method for Assessing Propagation Paths and Probabilities of Domino Effects Triggered by Natech Events, Chemical Engineering Transactions, 82, 67-72 DOI:10.3303/CET2082012

accidents such as floods and earthquakes. Nevertheless, comprehensive methodologies for the study of domino effects triggered by Natech events with multiple primary accidents are still lacking.
This paper presents a method aiming to obtain all possible paths and probabilities of domino effects of vapour cloud explosions (VCEs) triggered by floods. Floods are among the most frequent regional natural hazards triggering technological accidents, and VCEs are among the most destructive accidents. Therefore, for the sake of simplification, this paper mainly considers the domino effects of VCEs caused by floods, but it could be extended to fire-induced domino effects in other Natech scenarios.

2. Methodology

In a chemical plant, usually a flood event may be able to damage more than one critical installations. Therefore, if n critical installations are possible damaged by floods and other technological accidents, the number of possible accident scenarios, m, given by a generic combination of k failure units (k⩽n) is shown in Eq(1). If the primary accident is determined, other installations not damaged by the flood may be damaged by the overpressure of VCEs caused by the primary failure installations, that is, extend to other accident scenarios, triggering domino effects. As shown in Figure 1, the accident scenarios of T1 and T2 installations simultaneous damaged by a flood is S1, which may escalate to scenario 2, scenario 3, or scenario 4 through different propagation paths, where S2 and S3 can be regarded as the intermediate accident scenarios (S1→S2→S4, S1→S3→S4) or the final accident scenarios (S1→S2, S1→S3). In order to identify all propagation paths and provide a basis for accident prevention and QRA, a method flowchart that can calculate all paths and their probabilities are introduced in the following sections.

$$m = \sum_{k=1}^{n} C_n^k = \sum_{k=1}^{n} \frac{n!}{(n-k)!k!} = 2^n - 1 \tag{1}$$

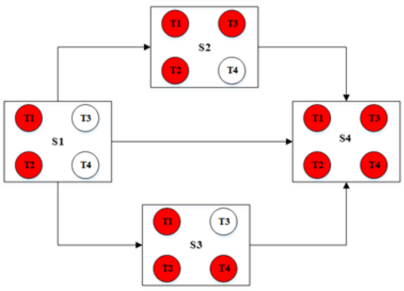

Figure 1: The example for possible propagation paths of domino effects triggered by Natech events

2.1 Step 1 Collect plant information and installation data

Step 1 collects all necessary information and data for different steps of this methodology. The plant information mainly includes the plant layout, environmental parameters (temperature, wind direction, speed, humidity, etc), intensities and return periods of floods. The main installation data include (i) installations types, shapes, sizes and (ii) information about hazardous materials in installations (types, quantities and filling ratios, states).

2.2 Step 2 Assessment of primary scenarios induced by Natech events

The following matrices must be calculated or collected in this step.
S: is an n×m dimensional matrix denoting the accident scenarios of each unit in each failure state combination, where n is the number of units, and m is the total number of possible accident scenarios calculated by Eq(1). The element S_{ij} represents the failure state of *i*th unit in accident scenario *j* (*i*,*j*=1, 2, . . ., n).
PN: is an n×1 dimensional matrix, where PN_i denotes the failure probability of unit *i* caused by flood. It can be calculated by the fragility model or fragility curve (Landucci et al., 2012). For atmospheric storage tanks suffering floods, the fragility model developed by Yang et al (2020) is used in this paper, as shown in Table 1.
PP: is an m×1 dimensional matrix, where PP_i represents the probability of accident scenario *i* as the primary accident scenario triggered by a given flood event, and it can be calculated using Eq(2) and Eq(3),

$$PP_i = f\prod_{j}^{n}[1 - PN_j + 2\delta(j, J_i)(PN_j - 1)] \tag{2}$$

$$\delta(j,J_i)=\begin{cases}1, if\ S_{ij}=1\\0, if\ S_{ij}=0\end{cases} \quad (3)$$

where *f* (1/y) denotes the frequency of a given flood, $\delta(j,J_i)$ represents if unit j belongs to scenario i or not.

Table 1: Fragility model and input parameters for atmospheric tanks involved in flooding events

Item	Definition	Equation
P_{System}	Overall failure probability	$P_{System}=1-(1-P_{Displacement})(1-P_{Buckling})$
$P(x)$	Sigmoid function for transferring the logit function to probability	$P(x)=\dfrac{1}{1+e^{-(\Phi(x))}}$
$\Phi_{Displacement}$	Logit function for displacement failure	$\Phi(D,\ H,\ \varphi,\rho_l,\ V,\ h)_{Displacement}$=0.7895$H-0.05644D$+0.2072$V$+4.803$h$ $+1.429\varphi-0.0009406\rho_l+0.001802Dh-4.33H\varphi-0.001084H\rho_l+$ $0.6349Vh-0.001602\varphi\rho_l-5.925\times10^{-5}D^2H+0.0003153D^2h$ $-0.001349D^2\varphi-7.899\times10^{-7}D^2\rho_l+0.001512D^2+0.0003177DV$ $-0.00878DVh+1.269$
$\Phi_{Buckling}$	Logit function for buckling failure	$\Phi(D,\ H,\ \phi,\ \rho_l,\ V,\ h)_{Buckling}$=0.009675$D$ + 0.3826H + 1.57V + 3.456h + 0.6819φ − 0.003678ρ_l − 2.611$H\varphi$ − 0.0005206$H\rho_l$ − 0.003489$\varphi\rho_l$ + 0.4639

D: Tank diameter; H: Tank height; φ: filling ratio; ρ_l *: storaged liquid density; V: flood velocity; h:flood height*

2.3 Step 3 Assessment of domino effects triggered by primary Natech accidents

Overpressure of installations can be seen as an evaluation index of the domino escalation capability for VCEs, and it can be obtained using the ALOHA or PHAST software based on the necessary information and data collected in step 1. *O*: is an n×n dimensional matrix, the element O_{ij} represents the overpressure of unit *i* on unit *j*, where n is the number of units. A threshold-based approach may then be applied to identify the possible escalation targets, and a number of threshold values suitable to carry out this step of the analysis are proposed in the technical literature (Cozzani et al, 2005), TD_i denotes the escalation threshold of unit *i*.
OE: is an n×n dimensional matrix, OE_{ij} denotes the escalation capability of unit *i* on target unit *j*, where n is the number of units. If the element O_{ij} is above the overpressure threshold TD_j, OE_{ij}=1, otherwise OE_{ij}=0, as shown in Eq(4).

$$OE_{ij}=\begin{cases}1, if\ O_{ij}\geq TD_j\\0, otherwise\end{cases} \quad (4)$$

OP: is an n×n dimensional matrix, OP_{ij} denotes the escalation probability of unit *i* on target unit *j*, and it can be calculated by Eq(5) based on the overpressure intensity and probit model (Cozzani et al, 2005), where Pr represents the Probit model.

$$OP_{ij}=\begin{cases}\Pr(O_{ij}), if\ O_{ij}\geq TD_j\\0, otherwise\end{cases} \quad (5)$$

After the primary accident scenario and escalation matrix are determined, the mxm dimensional scenario escalation matrix *G* can be determined to indicate the escalation capability of one scenario rounds to other scenarios. The scenario escalation matrix can be regarded as the adjacency matrix of digraph. If scenario *i* can escalate to scenario *j*, G_{ij}=1, otherwise, G_{ij}=0. The scenario escalation capability can be determined based on the unit escalation capability matrix *OE*. For the sake of simplicity, it is assumed that a VCE must occur when the unit is damaged.
PG: is an m×n dimensional matrix, PG_{ij} denotes the escalation probability of scenario *i* to scenario *j*, and PG_{ij} can be calculated by Eq(6),

$$PG_{ij}=(1-\prod_{v\in V(i)}\prod_{u\in U(ij)}(1-OP_{vu}))\prod_{v\in V(i)}\prod_{w\in w(ij)}(1-OP_{vw}) \quad (6)$$

where $v \in V(i)$, represents the set of failure units in scenario i, and $u \in U(ij)$ represents the set of new failure units in scenario j compared to scenario i, and $w \in W(ij)$ represents the set of units that can be damaged by the failure units in scenario i, but not damaged in scenario j.

2.4 Algorithm for calculating all the possible paths and probabilities

The possible paths and probabilities of domino effects triggered by Natech events can be calculated by the developed depth-first path search algorithm in Figure 2 based on the adjacent matrix *G* and the scenario escalation probability matrix *PG* as defined in Section 2.3, and the algorithm is developed by a Matlab program.

First, the accident scenario *i*=1 is selected as the primary scenario and the path cell array *RA* is used to store the path sets, and its elements are the set of propagation scenarios for each path, which is initialized to a null set. The primary scenario node is stored on the main path matrix *MP*, and its adjacent node set matrix *AP* is obtained using the function *successors* (*G*, *MP*(end)), which means all the possible adjacent scenarios for the last scenario in the main path *MP* will be obtained. If the main path is not empty, the last element of *MP* will be put in *AT*, which represents the set of non-visited adjacent scenarios, otherwise, the primary scenario will be updated. Next, if *AT* is an empty set, that is, all the adjacent scenarios have been visited or there is no adjacent scenarios, the main path *MP* will be stored in the path cell array *RA*, and the corresponding path probability will be calculated and stored in *PR*, then the last elements of the main path *MP* and auxiliary path *AP* will be deleted, and the evolution will continue. Third, if *AT* is not an empty set, the last element of *AT* will be the new element of the main path *MP*, and other elements of *AT* will be stored in the auxiliary path *AP*, then the adjacent scenarios of the new elements of the main path *MP* will be stored in the new element of the auxiliary path *AP*. If all the primary scenarios have been selected, the algorithm will terminate, and all the possible paths and their probabilities can be obtained in the cell arrays *RA* and *PR*.

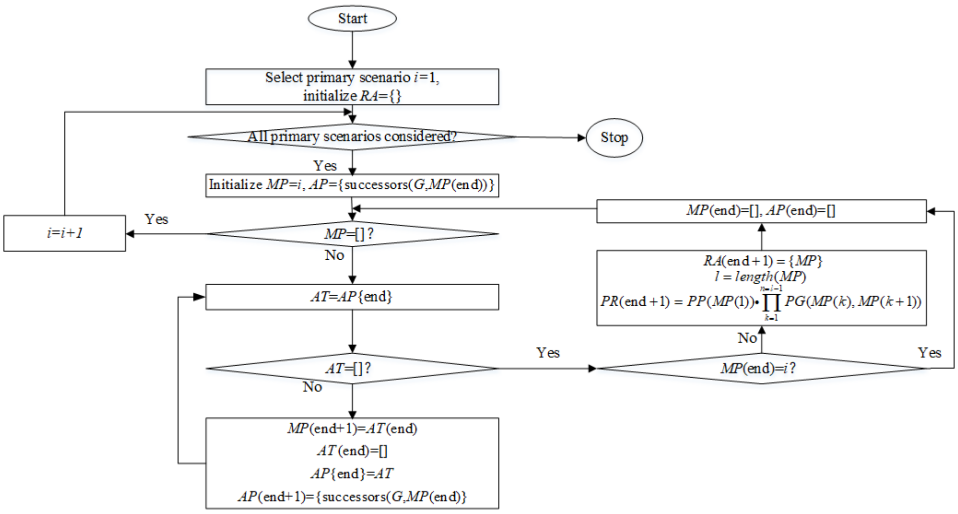

Figure 2: Algorithm flowchart for calculating all the possible paths and probabilities

3. Illustrative case study

3.1 Definition of the case studies

For illustrative purposes, the methodology is demonstrated by an illustrative tank storage area, adapted from the case in Zhou and Reniers (2018). Figure 3 shows the layout of a tank farm comprised of six atmospheric storage tanks with fixed roofs (TK1-TK6). Each tank contains gasoline with the capacity of 2,000 metric tons. The diameter of each tank D is 12.5 m, the height of each tank H is 7.2 m, the filling ratio is assumed as 0.75, and the density of gasoline is 750 kg/m^3. The flood inundation height is assumed to be 3.5 m, flood velocity is 0.5 m/s, and the return period is 200 year, that is, the flood frequency is 0.005/year. Therefore, the failure probability of each tank caused by the flood is 0.0114 calculated by the equations in Table 1.

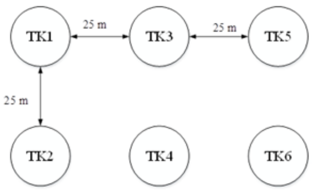

Figure 3: Layout of the gasoline tanks

After a storage tank is damaged, it may result in a secondary accident such as pool fire and VCE. In this study, only VCE accidents are considered, and the threshold value of overpressure is selected as 7 kPa. The overpressure escalation vectors are calculated and illustrated in Table 2.

Table 2: Overpressure escalation vectors (kPa)

	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	/

3.2 Results and discussion

There are 63 accident scenarios and 6,568 propagation paths for the tank farms with six tanks. Table 3 shows the primary accident scenario probabilities with different number of tanks, and it can be concluded that the probability of the primary accident scenario will be reduced by 1-2 orders of magnitude for each additional failure tank. The probability of four tanks is damaged by flood simultaneously is 8.25×10^{-11}, so it can be considered more than four primary units failures have an extremely low probability to happen. It can also be seen from Table 3 that the cumulative primary failure probability of each tank is of the same order of magnitude as the cumulative failure probability of domino effects, so it can be concluded that ignoring the occurrence of domino effect will lead to underestimation of probability and risk. Furthermore, TK3 and TK4 located in the center of the tank farm, and their cumulative domino effect probabilities are higher than other tanks, indicating that tanks located in the center of the tank farm are most possible damaged.

Table 3: Primary accident and domino effect probabilities depending on the number of primary accident tanks

	1 PT	2 PTs	3 PTs	4 PTs	5 PTs	6PT
Primary accident scenario probability	5.38×10^{-5}	6.21×10^{-7}	7.16×10^{-9}	8.25×10^{-11}	9.52×10^{-13}	1.10×10^{-14}
	TK1	TK 2	TK3	TK4	TK5	TK6
CDP	2.72×10^{-5}	2.72×10^{-5}	4.15×10^{-5}	4.15×10^{-5}	2.72×10^{-5}	2.72×10^{-5}
CPP	5.70×10^{-5}	5.70×10^{-5}	5.70×10^{-5}	5.70×10^{-5}	5.70×10^{-5}	5.70×10^{-5}

PT: primary accident tank; CDP: Cumulative domino effect probability; CPP: Cumulative primary accident probability

Table 4: Distribution of domino effects at each level

	Number of paths	Cumulative probability	Maximum probability	Minimum probability
Level 1	482	5.92×10^{-5}	3.36×10^{-6}	1.43×10^{-13}
Level 2	1542	1.44×10^{-5}	2.70×10^{-7}	9.99×10^{-13}
Level 3	2354	3.69×10^{-6}	3.71×10^{-8}	2.82×10^{-12}
Level 4	1712	7.51×10^{-7}	2.98×10^{-9}	1.56×10^{-11}
Level 5	480	9.12×10^{-8}	4.49×10^{-10}	2.91×10^{-11}

Table 4 shows the probability distribution of domino effect at different propagation levels. As can be seen from Table 4, the number of paths at different propagation levels is normal distributed. Although the number of first-level accidents is small, the cumulative probability is the largest. As the accident level increases by one level, their cumulative probability decreases by about one order of magnitude, and their maximum probability also decreases by about one order of magnitude. Furthermore, this method can also record all the propagation paths with different primary Natech scenarios, so as to facilitate the observation of the propagation process of domino effects, and propose targeted prevention and control measures. Figure 4 shows some typical propagation paths. Figure 4 (a) represents one of the most possible propagation paths (S1→S7) and Figure 4 (b) represents one of the least possible propagation paths (S61→S63) as shown in Table 4. Figure 4 (c) denotes the most possible paths involving three order domino effects (S5→S21→S41→S56)

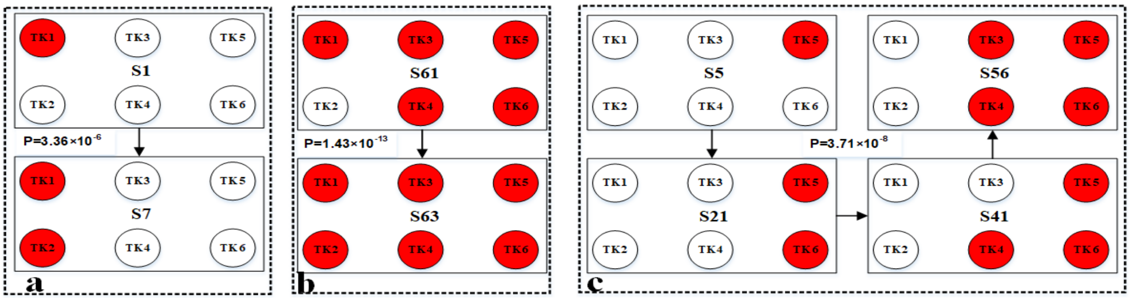

Figure 4: Typical propagation path of domino effects triggered by flood. (a) one of the most possible paths;(b) one of the least possible paths; (c) one of the most possible paths involving three order domino effects

4. Conclusions

In this paper, a method for calculating all the possible paths of domino effects triggered by Natech events with multiple primary accidents and with higher order accidents is proposed. The results showed that ignoring the domino effects caused by Natech events would lead to underestimation of accident probability and risk. Although only the VCEs caused by floods are considered in this case, this method can be extended to fire accidents caused by other natural disasters. The results can be used in a subsequent QRA and accident prevention considering both Natech events and their resulting domino effects.

Acknowledgments

This study was supported by the National Key R&D Program of China (2017YFC0804700), the National Natural Science Foundation of China (21878102).

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