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Towards limiting potential domino effects from single flammable substance release in chemical complexes by risk-based shut down of critical nearby process units

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ABSTRACT

The explosion load is a significant escalation factor possibly influencing the potential occurrence of domino accidents in chemical plants. It is not economical to install explosion isolation systems (e.g., extinguishing barrier) for all equipment or process units across a chemical plant. Although shutting down all equipment or process unit can prevent an explosion, it may also cause further economic losses. To prevent domino accidents, the process unit that needs to be shut down accurately should be selected, and the normal operation of other units needs to be ensured. A method to select the process unit to be isolated based on the Dimensioning Accidental Load (DAL) is proposed. By calculating the occurrence probability and consequences of the accident scenarios, the DAL of the surrounding units is determined. DAL is used as the impact intensity of the accident unit on the surrounding units. The probit model is used to calculate the damage probability of surrounding units. The case analysis results show that the method of selecting the process unit to be isolated based on DAL quantifies the impact intensity of the exploded unit on surrounding units from probability and consequence. Under the premise of meeting the acceptable risk criteria, the method can determine which units should be shut down and which units can operate normally when a release accident occurs. While preventing domino accidents, economic losses caused by the shutdown of all process units are reduced and a theoretical basis for accident prevention and safe operation of the plant is provided.

1. Introduction

A chemical plant usually has an extensive storage and use of hazardous materials and a compact equipment layout. Once an accident occurs, it may cause severe casualties, property losses, and environmental damage (Vianello et al., 2019; Zhou and Reniers, 2018; Yang et al., 2015; Khan et al., 2016). When a flammable gas release accident occurs, an explosion accident may occur in the presence of the ignition source. The explosion at one process unit may severely impact the surrounding units and then escalate to a catastrophe through domino effects (Birk Michael, 2017). However, not all accidental releases of flammable gas and vapors create explosions. Most of the explosion accidents generate low or medium overpressure only (Chamberlian et al., 2019). When a release accident occurs in a plant, the shutdown of all process units are generally taken to prevent explosion accidents. However, shut down all process units may obviously cause significant economic losses. Therefore, the process unit that must be stopped and isolated during an accident should be reasonably determined to effectively terminate the accident propagation route and ensure the normal operation of other units.

It is a challenging task to select the process unit to be isolated to prevent domino accidents. The traditional method is generally based on experience, from the perspective of product process safety, determining which units should be shut down and isolated and which units can continue to operate according to the mini-

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mization of the influence between processes. However, the impact of specific physical location and explosion risk is not considered.

Domino accidents take place when an accident in a unit (primary unit) propagates to other units (secondary units) through the impact of escalation vectors (Kamil et al., 2019). Escalation vectors are physical effects such as overpressure in an explosion (Khakzad et al., 2013). Many scholars have studied domino accidents from the occurrence probability perspective and made outstanding contributions (Bagster and Pitblado, 1991; Necci et al., 2015; Khan and Abbasi, 1998; Cozzani and Salzano, 2004). Cozzani et al. (2005) developed a systematic procedure for the quantitative assessment of domino effect risks. Reniers et al. (2009) used a game-theoretic approach to interpret and model behavior of chemical plants within chemical clusters while negotiating and deciding on domino effects prevention investments. A quantitative risk assessment method for chemical domino accidents based on field theory and Monte Carlo simulation is proposed by He and Weng (2020). This method aims to obtain the dynamic distribution of individual risk caused by the domino accident. Zeng et al. (2020) developed a new method to provide more accurate probabilities related to domino effects, by considering the temporal evolution of escalation vectors caused by time-dependent factors. Naderpour and Khakzad (2018) proposed a Natech (natural hazard triggering technological disasters) risk assessment methodology that relies upon Bayesian network capabilities and takes into account the potential Natech domino effects. Ding et al. (2020) proposed a novel approach to model the spatial-temporal evolution and performed a risk analysis of fire-induced domino effects based on synergistic effect and accident evidence. These studies focus on finding out the development path of Domino accidents and probability, which lays a foundation for accident prevention and control and emergency decision-making in a chemical plant. However, in consequence analysis, only the consequences of accidents under the worst conditions are generally analyzed, leading to excessive risk assessment (Paik et al., 2011). From the perspective of the accident consequences and corresponding probability, this study investigates how to select the process unit to be isolated to prevent a domino accident based on its predicted probability and consequence.

Risk is determined by the probability and the consequence of an accident. Only considering the consequence of the accident may lead to excessive measures, such as the shutdown of all process units. When the explosion load and probability of a unit affected by the initial unit exceed the threshold, the unit is selected as an process unit to be isolated. NORSOK Z-013 (2010) provides a framework for explosion risk analysis but does not provide specific analysis methods and cases. There are many methods to assess the impact of an explosion, such as the Multi-energy method, the TNT equivalent method, the Baker-Strehlow method, and CFD simulations. (van den Berg and Lannoy, 1993; Qiao and Zhang, 2010; Qi et al., 2019; Chen et al., 2020; Zhang et al., 2020; Horvat, 2018; Moen et al., 2019). The multi-energy method is widely used in the two-dimensional model, which comprehensively considers the turbulence acceleration and gas activity. However, it is difficult for the two-dimensional model to consider the impact of the complex equipment and piping system of the plant on the explosion overpressure. In recent years, computational fluid dynamics (CFD) software has developed rapidly, such as AutoReaGas, FLUENT and FLACS. Since the CFD model can well represent the real physical environment, it has increasingly become the mainstream of explosion risk analysis (Huang et al., 2019; Shen et al., 2020). Hansen et al. (2016) used FLACS to evaluate the explosion overpressure of equipment, pipelines, and critical buildings and convert the overpressure into actual forces, guiding the design strength of the equipment. Baalisampang et al. (2019) used FLACS to analyze the integrated consequence of hydrocarbon release, fire, explosion, and dispersion of combustion products. Rui et al. (2021) investigated the effect of low vent burst pressure on the overpressure buildup and flame evolution during the vented methane-air deflagrations in a 1 m^3 rectangular vessel, and used FLACS to validated the experimental data. Li and Hao (2018) proposed a combined CFD approach on far-field pressure prediction based on experiments and FLACS. Dadashzadeh et al. (2014) proposed a new method to quantify the risk of combustion products dispersion phenomenon in a confined or semi-confined facility. Li and Hao (2019) investigated the explosion pressure and impulse from large-scale explosions by using experiments and FLACS.

The explosion load is affected by the gas cloud volume and position, and ignition position. The volume and position of the gas cloud are affected by factors such as wind speed, wind direction, leak rate, release location, release direction, etc. The combination of these factors results in a large number of accident scenarios. Although the CFD model can represent the real physical environment well, the existing study is limited to the worst-case simulation or some selected hypothetical scenarios for analysis due to the computer resources and time limitations. This increases the uncertainty of the scenario selection and thus makes the results not representative.

The present study aims to propose a method to a) select representative scenarios and reduce the uncertainty of scenario selection, and b) to comprehensively analyze the risk of the affected units from the perspectives of accident consequence and probability. The dimensioning accidental load (DAL) of each unit under the influence of accident units is calculated, and DAL is used as the input of the probit model to calculate the potential damage probability of each affected unit. When the risk is high, the unit is selected as an process unit to be isolated.

The remaining parts of this paper are organized as follows. The isolation idea in the process industry is presented in Section 2. A brief description of the proposed method, including scenario development, explosion risk analysis, and how to select process unit to be isolated, is shown in Section 3. The case study is presented in Section 4. The assumptions and limitations are discussed in Section 5. Finally, conclusions are drawn in Section 6.

2. Process unit to be isolated

The process industry contains a large number of flammable substances. When the gas cloud within the explosion limit is under an ignition source condition, an explosion accident will occur. When a release accident occurs in a plant, the shutdown of all process units are often taken to prevent domino accident. However, a plant-wide shutdown evidently will lead to economic losses since the daily production of the chemical plant is very large. To overcome this shortcoming, it is necessary to investigate for which units need to be isolated or normal operation needs to be maintained when a release accident occurs.

When a release incident occurs in a chemical plant, some units should be stopped to prevent accident escalation and keep others running. However, selecting the units that need to be isolated is a challenging task. When release occurs in a plant, an explosion accident caused by a delayed ignition will affect the surrounding units. In order to prevent a domino accident, the process unit to be isolated should be reasonably selected to form an isolation area to ensure that other units are not affected by the accident.

For instance, there are 5 units in a plant, namely units 1, 2, 3, 4, and 5, as shown in Fig. 1. When an explosion accident occurs at unit 1 (the solid red arrows indicate the impact on other units when the explosion accident occurs in unit 1, and the black dotted line indicates the secondary accident caused by the affected unit), other units will be affected. The direction of the red line indicates the direction of the accident, and the weight of the red line indicates the impact intensity, which is represented by DAL

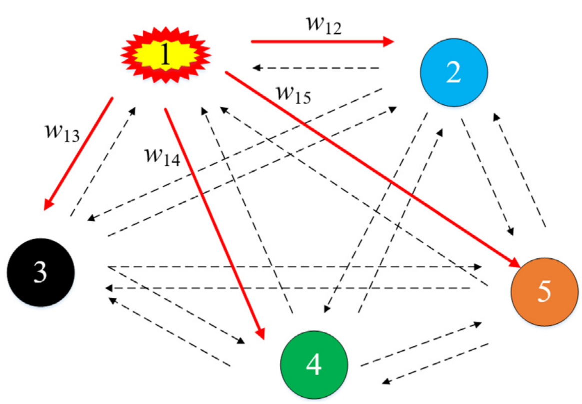

Fig. 1. The overpressure propagation route.

in this study, as shown in Fig. 1. Due to the severe consequence of explosion accidents, explosion overpressure is selected as the escalation vector. To prevent accidents from escalating, decision-makers must effectively judge the possible consequences of the accident and take measures to prevent accident escalation. However, the overpressure is affected by factors such as the position and volume of the gas cloud. It is difficult to determine which unit should be selected as the process unit to be isolated. Therefore, it is necessary to comprehensively analyze the risk of affected units from accident consequence and probability perspectives. When the unit's DAL being affected by the initial unit exceeds the threshold, the unit should be selected as a process unit to be isolated.

Fig. 1 is abstracted as a graph composed of discrete points and connected edges, which is represented by a sparse matrix connected graph *G=(N, E, W)* with weighted acyclicity. $N=(n_1,n_2,n_3,...,n_i)$ is the units set affected by the explosion accident. $E=(e_1,e_2,e_3,...,e_i)$ represents the connection edge set of nodes. $W=(w_1,w_2,w_3,...,w_i)$ is the impact intensity set of each connecting edge, and represented by DAL in this study. Different from general models, the edge connection strength of this model is determined by overpressure and probability. As shown in Fig. 1, there are 5 independent units, and the accident impact intensity is represented as W_{ij} by a sparse matrix:w_{13} w_{14} w_{15} w_{12}

$$W_{ij} = \left\{ \begin{matrix} w_{11} & w_{12} & w_{13} & w_{14} & w_{15} \\ w_{21} & w_{22} & w_{23} & w_{24} & w_{25} \\ w_{31} & w_{32} & w_{33} & w_{34} & w_{35} \\ w_{41} & w_{42} & w_{43} & w_{44} & w_{45} \\ w_{51} & w_{52} & w_{53} & w_{54} & w_{55} \end{matrix} \right\} \quad (1)$$

where *i* is the accident unit; *j* is the unit affected by *i*; W_{ij} represents DAL generated in unit *j* when an explosion accident occurs in unit *i*.

3. The proposed methodology

To effectively evaluate the impact of each unit's explosion accident on other units, a DAL-based method is proposed to select the process unit to be isolated. The DAL generated by the accident unit at each affected unit is calculated. DAL is used as input of the probit model to calculate the damage probability of each unit. The unit whose probability is higher than the threshold is selected as a process unit to be isolated to prevent the domino accident. The method is divided into three parts: scenario development, calculating the probability and consequence of the scenarios and determination of DAL, and selecting the process unit to be isolated. The specific process as shown in Fig. 2. The first step is to develop the accident scenarios and calculate their occurrence probability. We then calculate accident consequence and combine the explosion overpressure and probability to determine the DAL of each unit. The final step is to calculate the damage probability of each unit and select the process unit to be isolated. The specific procedure is shown in Fig. 2.

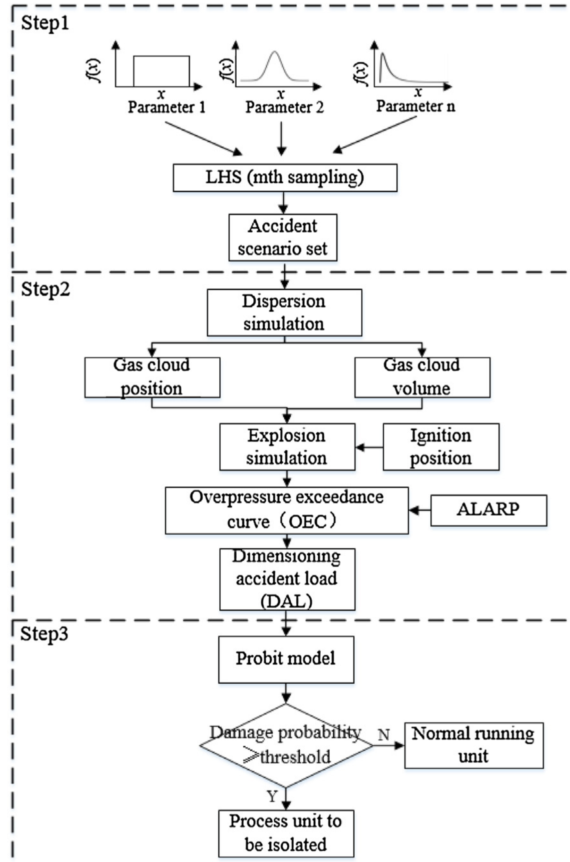

Fig. 2. The process of determine the process unit to be isolated.

3.1. Scenario development

Latin Hypercube Sampling (LHS) is a random sampling method from multivariate parameter distribution, which belongs to stratified sampling. Compared with the Monte Carlo sampling method, the LHS method has fewer sampling times, and the sampling times will not increase with the increase of variables. The LHS method divides the probability distribution into *n* intervals with equal probabilities, where *n* is the number of sampling. The technique can well describe the characteristics of the input distribution with a few iterations (Abrahamsson, 2002). The sampled points from the probability distributions of each parameter compose representative scenarios. In this paper, the LHS method is introduced to develop accident scenarios to reduce the uncertainty of scenario selection.

3.1.1. Dispersion scenarios

(1) Wind field

The wind field is composed of wind speed and direction. Wind speed affects the dispersion velocity and concentration of the gas cloud. Wind direction determines the gas cloud dispersion direction, and the change of wind direction will lead to the change of the gas cloud position.

Table 1
The interval of release direction.

	+X	-X	+Y	-Y	+Z	-Z
A	0–10	10–20	20–30	30–40	40–50	50–60

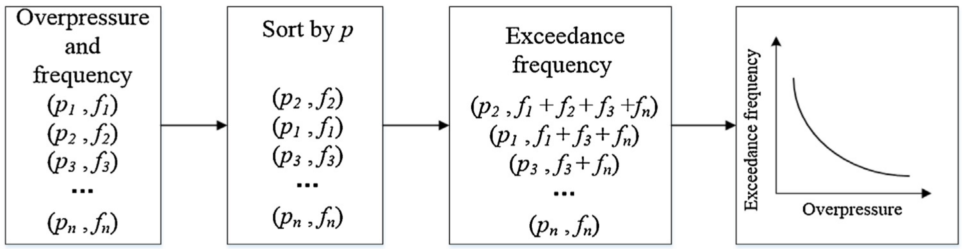

Fig. 3. Procedure to determine the DAL.

The probability density function of wind speed and direction is determined according to the wind field data of the plant area. The wind field data of accident scenarios is extracted by the LHS method.

(2) Leak rate

The release of hazardous materials may cause fire, explosion, and poisoning accidents in the process industry. When the leak rate is low, the gas cloud is greatly affected by the wind field. The smaller the gas cloud, the smaller the explosive overpressure. When the leak rate is high, it reflects a pipeline rupture, and these scenarios are generally very transient.

(3) Release position and direction

To obtain a representative distribution, each leak point has 4–6 leak directions (NORSOK Z-013, 2010). There should be at least three release directions, i.e., the same as the wind direction, opposite to the wind direction, and perpendicular to the wind direction (NORSOK Z-013, 2010). In this study, the release direction is divided into 6 categories, which are + x, -x, +y, -y, +z and -z, respectively. Since the release direction is random, it is assumed to follow a uniform distribution, and the release direction is equivalent to interval A, as shown in Table 1. For instance, when the corresponding value of the sampling result is 6.6, it means that the release direction is + X.

The specific release location and direction should be determined according to the specific layout of the plant. Geometry and symmetry can be used to simplify the distribution of leak locations and directions to balance the representativeness and quantity of the scenario.

3.1.2. Explosion scenario

(1) Ignition probability

After the release of hazardous materials, fire and explosion accidents are prone to occur with ignition sources. The study of ignition probability is one of the critical elements of quantitative risk assessment. The present study focuses on the explosion overpressure in critical areas; thus, the delayed ignition probability is analyzed.

(2) Gas cloud volume and position

The overpressure value is affected by the location and volume of the flammable gas cloud. The different volume of gas clouds produces different explosion overpressures. The change of gas cloud location will result in a significant change in spatial pressure distribution. According to the release scenario set, the gas cloud position and volume of each of the scenarios are calculated by CFD software.

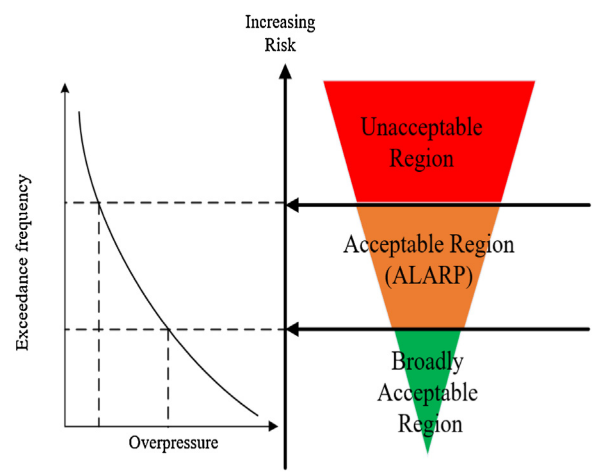

Fig. 4. Application of the ALARP to determine the DAL.

3.2. Determination of DAL

Once the overpressure and the corresponding frequencies from all possible scenarios are determined, the DAL calculation is carried out. Fig. 3 shows how to obtain the exceedance curve of overpressure. Overpressure values are arranged in ascending order and cumulative frequency in descending order. According to the acceptable frequency, we can determine the overpressure, called DAL.

The ALARP (As low as reasonably practical) method is used as a risk calibration method to determine the acceptance of explosion accident (Li et al., 2016b). In the unacceptable region, measures are necessary to be taken to reduce the risk. The risk is acceptable when it is in the tolerable region (the ALARP region). Measures to reduce risks in this region are needed, but if the cost-benefit analysis shows that the cost is not proportional to the benefits obtained, no measures are required. In the broadly acceptable region, the risk is acceptable, and there is no need to take measures to reduce the risk. The specific process is shown in Fig. 4.

3.3. The selection of the process unit to be isolated

Probability models were used to assess the damage probability of installations to quantify the damage probability of installations

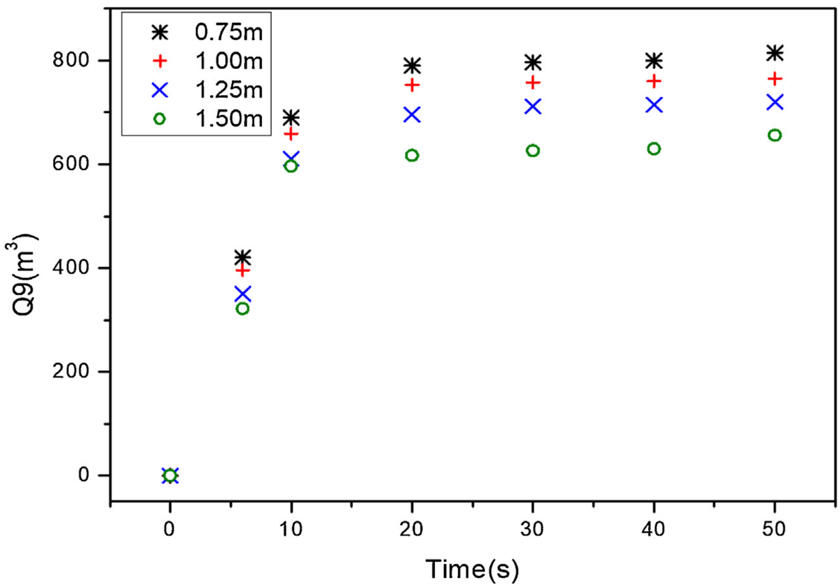

Fig. 5. Q9 at different time generated by three grids.

Table 2
Probit coefficients of Eq. (2) for different equipment.

Equipment	*a*	*b*
Atmospheric vessels	−18.96	2.44
Pressurised vessels	−42.44	4.33
Elongated equipment	−28.07	3.16
Small equipment	−17.79	2.18

in the unit subject to overpressure effects. The probit function was firstly developed by Eisenberg et al. (1975), as shown in Eq. (2).

$$Y = a + b \cdot \ln(\Delta P) \tag{2}$$

where $\triangle P$ (Pa) is the peak overpressure; Y is the probit value; a and b are constants, as shown in Table 2. Then the damage probability Pr can be calculated using the cumulative standard normal distribution (Φ), as shown in Eq. (3).

$$P_r = \Phi(Y - 5) \tag{3}$$

Cozzani and Salzano (2004) developed different probit models for different equipment types, as shown in Table 2. A probit model is used to calculate the damage probability of surrounding units when an explosion accident occurs in the initial unit. The high damage probability corresponds to the process unit to be isolated.

4. Case study

The propylene production process area, as an example, is used to illustrate the proposed method. There are four units in this process area, the size of each unit is 40 m × 30 m×25 m, and the distance between the units is 30 m. Based on a large number of experimentally calibrated grid models, it has been widely verified that the cell size range of large-scale vented fields was between 1 m and 1.5 m (GexCon, 2015). In order to study the influence of grid size on the simulation results, the grid sensitivity analysis is conducted using four different grid sizes. The Q9 at different time(s) under these four grid sizes are compared in Fig. 5. It can be seen that the Q9 under 1 m grid is closer to that under 0.75 m compared to that under 1.3 m and 1.5 m, which means that the Q9 decreases as the grid size increases. Considering the computational accuracy and cost, the 1 m is used to calculate the rest of the scenarios, which can meet the criteria of FLACS and the extensively validated cell size (usually around 1 m) (Gexcon, 2015; Li et al., 2016b). The simulation volume is set as 150 m × 150 m × 40 m.

In the process, the density of liquid propylene is 516 kg/m^3, the operating pressure is 1.4 mPa, and the temperature is 20°C. The maximum release amount of propylene in the unit is 3260 kg. The specific layout is shown in Fig. 6.

To demonstrate the proposed method, unit 1 is selected as the accident unit to study the accident influence of unit 1 on units 2, 3, and 4. The red arrow represents the release directions, and the blue arrow represents the wind directions, as shown in Fig. 7.

4.1. Scenario development

According to the wind field data in the plant region, the probability density functions of wind speed and wind direction are calculated. The data and fitting curves of wind speed and direction are shown in Figs. 8 and 9.

Due to the large distance between process units, gas clouds formed by small leak rate are not threaten adjacent units. According to the simulation results, the 16 kg/s is used to represent the low boundary of leak rate. According to the equipment size and Eq. (7), 96 kg/s represent the full-bore rupture. Finally, 16 kg/s - 96 kg/s is selected as the interval of the release rate.

The leak rate is random, and different leak rates have a significant influence on the results. Therefore, the sampling results must cover an extensive range of leak rates to deal with the uncertainties in the generation of representative scenarios. According to IOGP (2019), the release frequency is different in different leak hole diameter. The data from LRC (2018) can be used to calculate the probability density in each leak rate interval, and its probability density function and cumulative probability function are shown in Eqs. (4) and (5).

$$f(x) = \begin{cases} 0.03125, 16 \le x \le 32 \\ 0.0104, 32 \le x \le 64 \\ 0.0052, 64 \le x \le 96 \end{cases} \tag{4}$$

$$F(x) = \begin{cases} 0.03125(x - 16), 16 \le x \le 32 \\ 0.0104(x - 32) + 0.5, 32 \le x \le 64 \\ 0.0052(x - 64) + 0.8333, 64 \le x \le 96 \end{cases} \tag{5}$$

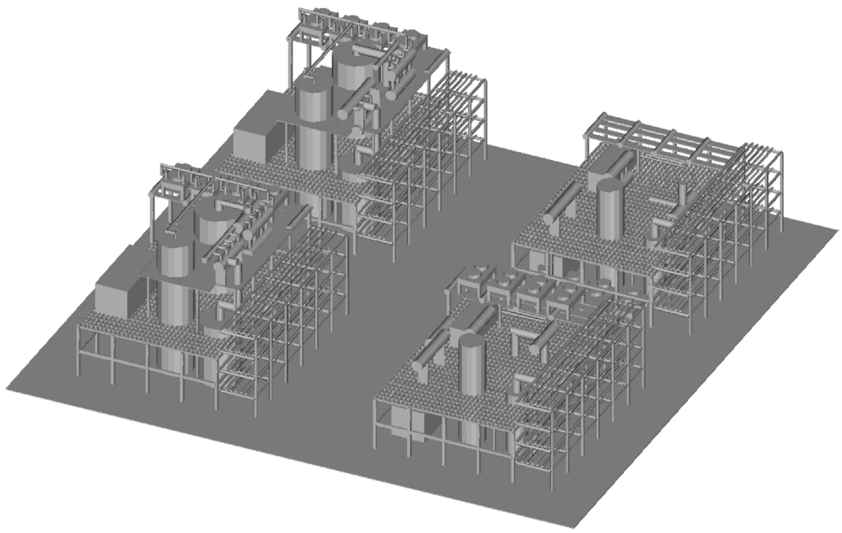

Fig. 6. Propylene process area.

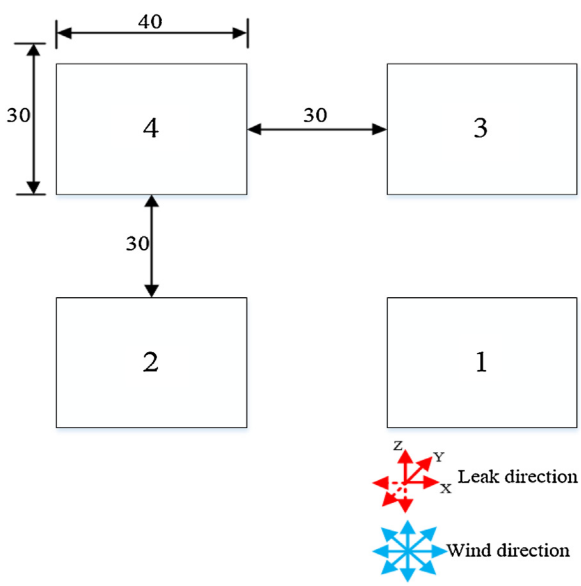

Fig. 7. Simplified diagram of propylene production process area.

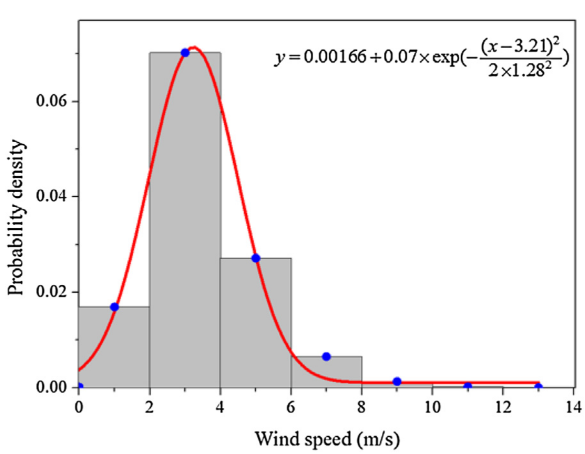

Fig. 8. Region data and probability density function of wind speed.

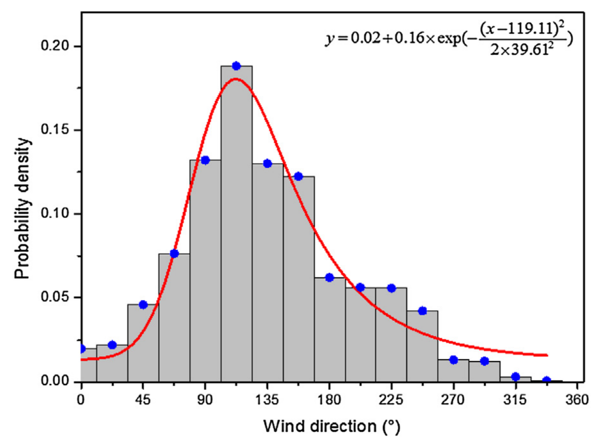

Fig. 9. Region data and probability density function of wind direction.

According to the selected leak rate, the outlet cross-sectional area in FLACS can be obtained using Eq. (6). The probability of different leak sizes can be obtained by referring to relevant data (Spouge, 2005; IOGP, 2019).

$$A = \frac{q}{\rho \cdot u} \tag{6}$$

where q is the leak rate, kg/s; A denotes the cross-sectional area of the leak size, m^2; ρ is the gas density, kg/m^3; u is the velocity at the outlet, m/s. The jet leak with a high momentum can result in a gas velocity at the outlet of up to subsonic speed, which was near the 300 m/s (Li et al., 2016b).Due to the complexity of the equipment and pipeline at the bottom of the unit, the release accident will cause serious consequences. In this paper, the pipeline at the bottom of the unit is selected as the release source. According to Eq. (5), Fig. 7, Fig. 8 and Table 1, the LHS method is introduced to develop the accident scenarios, and the specific results are shown in Appendix A.

The leak size corresponding to each leak rate is calculated according to Eq. (6). The release frequency of release hole size is obtained according to Spouge (2005). The ignition probability is positively correlated with the leak rate (Rew et al., 1997).

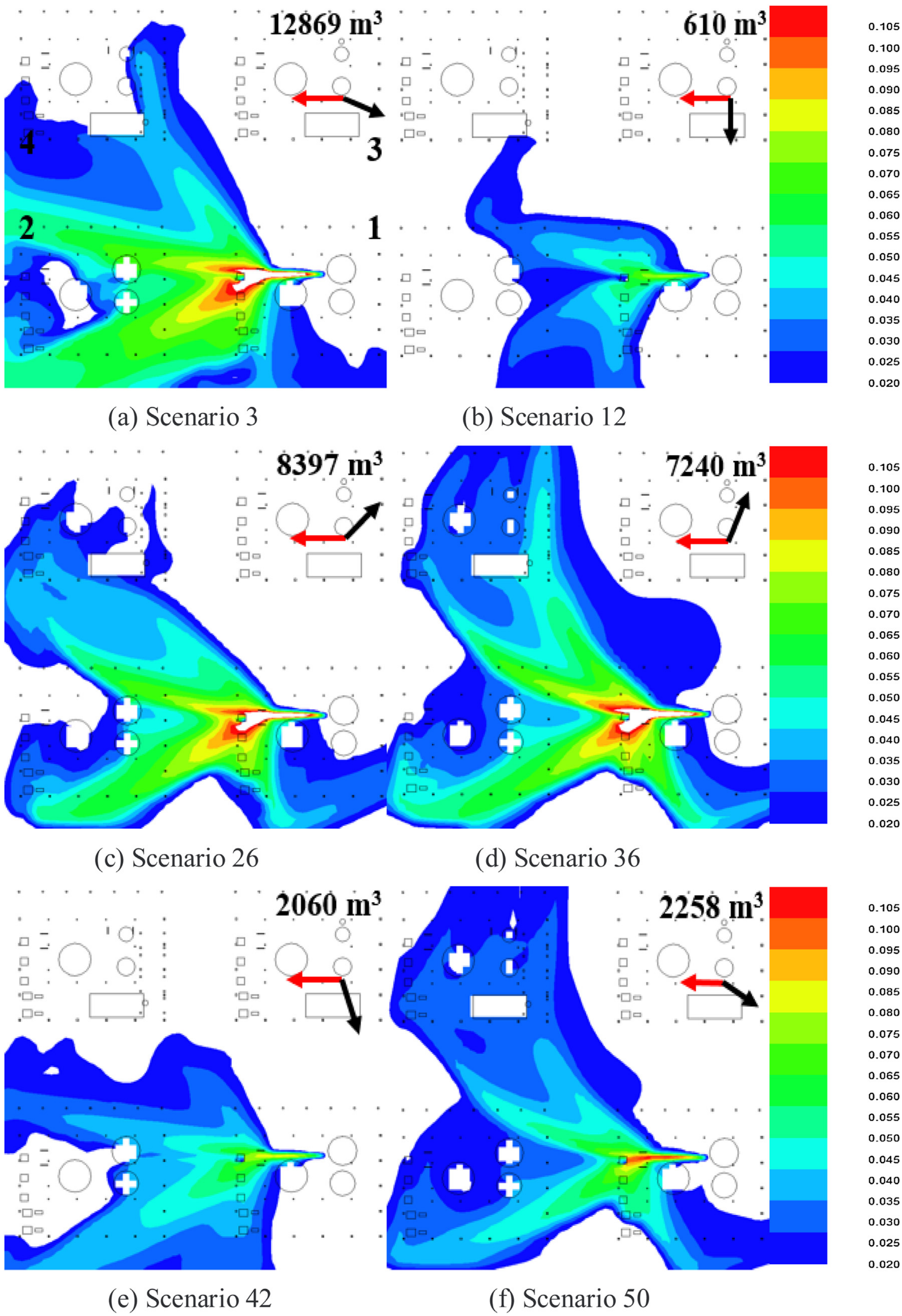

Fig. 10. Gas dispersion simulations with leak direction of -X.

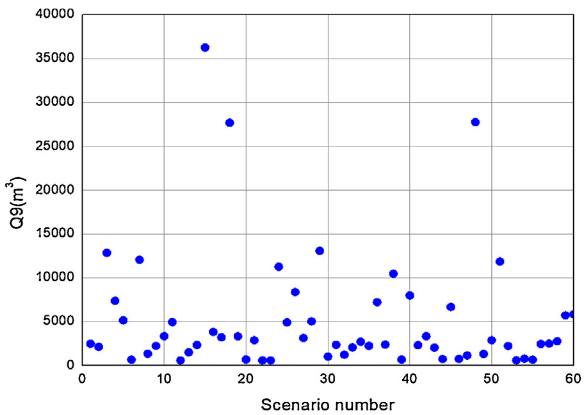

Fig. 11. Gas cloud volume (Q9) generated in each scenario.

4.2. Determine the DAL

The dispersion and explosion simulation is carried out for 60 scenarios to explore the gas cloud position, gas cloud volume, and overpressure generated by the explosion accident at each unit in different scenarios.

4.2.1. Dispersion analysis

The dispersion analysis of each scenario should be performed first to obtain the distribution of the gas cloud position and volume and then used to assess the impact of the accidental unit on the surrounding units. The gas monitor region for dispersion analysis covers all the units of the process area.

Several examples of dispersion simulation outputs for gas releases with a leak direction of -X are demonstrated in Fig. 10. The red arrow represents the leak direction, and the black arrow indicates the wind direction. The specific parameters of the scenarios are shown in Appendix A. It can be seen from Fig. 10 that different scenario results in different gas cloud volumes and positions under the same leak direction. The gas cloud volume of (a), (b), (c), (d), (e), and (f) is 12,869 m^3, 610 m^3, 8397 m^3, 7240 m^3, 2060 m^3 and 2258 m^3, respectively. Under the same conditions, the larger the gas cloud size, the greater the explosion overpressure. It can be seen that the volume of gas cloud generated by different scenarios varies greatly. In these six scenarios, the maximal gas cloud volume is 12,869 m^3, the average is 5572.33 m^3. The minimum gas cloud volume is 610 m^3 under the wind speed of the 5.82 m/s and vertical wind direction. The maximal volume is 21.09 times the minimum.

It can be seen from Fig. 10 (a) and (b) that when the leak direction is -X, the most affected by the accident is the unit 2; When the wind direction vector has a + Y component, propylene starts to diffuse towards unit 4 and eventually covers the entire unit. In Fig. 10 (a) and (b), when the wind direction vector has a -Y component, propylene cannot diffuse into unit 4, and the impact with respect to unit 4 is small. It can be seen from Fig. 10 (a) that when the wind speed is low (0.56 m/s), even if the component of the wind direction vector is -Y, the wind field does not have an enormous impact on the dispersion. Scenario 3 still has some propylene diffused to unit 4. It can be seen from Fig. 10 (b) that when the wind speed is high (6.04 m/s) and perpendicular to the release direction, the wind field has a large impact on the dispersion. Scenario 12 only generated 610 m^3 of propylene. The results show that the wind direction perpendicular to the release direction influences more on the gas cloud volume than the wind direction parallel to the release direction. The higher the wind speed, the faster the gas cloud spreads. The gas cloud concentration is greatly diluted, which is beneficial to disaster reduction in the plant area.

To analyze the simulation results of the release scenario set, the Q9 of each scenario and the accumulative curve of Q9 in each monitoring area is calculated, as shown in Figs. 11 and 12. It can be seen from Fig. 11 that the Q9 generated by different scenarios varies greatly. The maximal Q9 is 36,276 m^3, the average is 5168 m^3, and the minimum is 610 m^3. The maximum volume is 7.02 times the average volume. The maximum is 35,666 m^3 more than the minimal Q9. This indicates that the volume and location of gas clouds generated by different scenes are very different, resulting in different accident consequences. To evaluate the accident consequences comprehensively, the method proposed in this study can cover the possible values of each parameter, reduce the uncertainty of scenario selection, and improve the accuracy of the calculation results.

In Fig. 12, it can be seen that the proportion of a large volume of gas clouds is small. Scenarios with Q9 cloud model less than 2500 m^3 accounted for 45 % of the total scenario, while scenarios with Q9 cloud model less than 5000 m^3 accounted for 71.67 % of the total scenario. 15 % of the scenarios produced Q9 cloud model greater than 10,000 m^3, and 5% of the scenarios generated Q9 cloud model greater than 15,000 m^3.

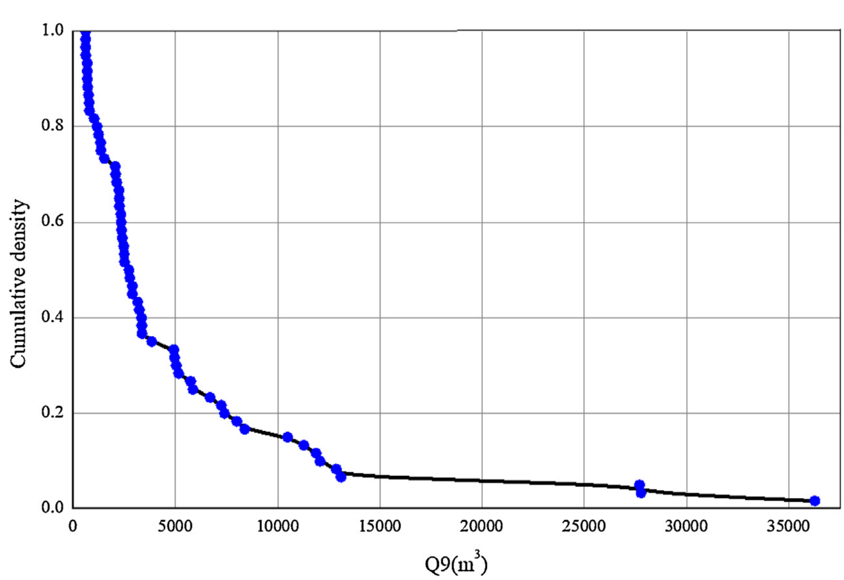

Fig. 12. Cumulative curve of gas cloud sizes for all leak rate scenarios.

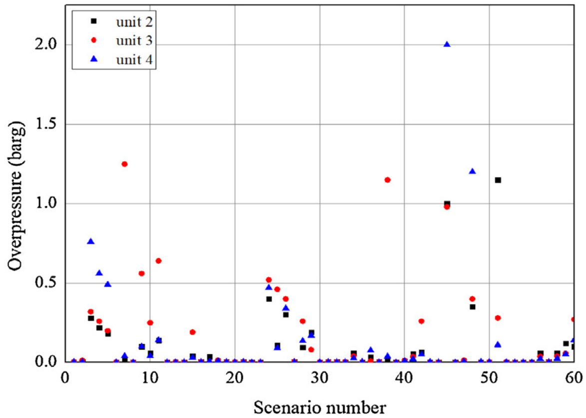

Fig. 13. Exceedance curve of overpressures around the unit 2, 3 and 4.

4.2.2. Explosion analysis

To analyze the influence of the explosion accident caused by the release accident in unit 1 with respect to the unit 2, 3 and 4, explosion simulations are performed by using gas cloud data resulting from dispersion analysis. For each gas explosion simulation, the gas cloud is ignited in the edge of the gas cloud. Since a major interest of this study is to assess the overpressure of units 2, 3 and 4, 24 monitor points are assigned near these units to record the overpressures for each gas explosion scenario. The explosion overpressure values generated by each scenario at units 2, 3 and 4 are shown in Fig. 13. As can be seen from Fig. 13, the explosion overpressure generated in most scenarios is very small. The 30 kPa is used as the overpressure threshold for the unit to be destroyed (Cozzani and Salzano, 2004), the scenarios of destroying unit 2 accounted for 8.33 % of all the scenarios; the scenarios of destroying unit 3 accounted for 18.33 % of the scenarios; and the scenarios of destroying unit 4 accounted for 13.33 % of the scenarios.

To determine the DAL of units 2, 3 and 4 in case of an explosion accident in unit 1, an exceedance curve is drawn in combination with the explosion overpressure and its corresponding occurrence frequency, as shown in Fig. 14. 1×10^{-4}/year is selected as acceptable frequency for each process unit (NORSOK Z-013, 2010), and the DAL of unit 2, 3 and 4 are 6.42 kPa, 26 kPa and 3.6 kPa, respectively.

4.3. The selection of process unit to be isolated

The probit model is used to calculate the potential damage probability of surrounding units when a release accident occurs in the initial unit. The unit with high damage probability is selected as the process unit to be isolated. DAL is used as the input of the probit model to calculate the damage probability of units 2, 3, and 4.

Units 2, 3, and 4 are composed of pipelines, pressure vessels, and various small equipment. According to Eq. (2),(3) and the parameters in Table 2, when a release accident occurs in unit 1, the damage probability of other units is calculated. The results are shown in Table 3.

As shown in Table 3, when the accident occurs in unit 1, the potential damage probability of unit 4 is minimal, the damage probability of small equipment, pipelines, and the pressurized container is 0. The equipment in unit 3 is more likely to be damaged due to the accident. When the release accident occurs in unit 1, the small equipment of unit 3 has an 26 % chance of being damaged. To prevent accidents from escalating, unit 3 should be selected as a process unit to be isolated.

Similarly, when an accident occurs in units 2, 3, and 4, the DAL generated in the surrounding units can be calculated separately, and the process unit to be isolated can be determined. In the case study, only unit 1 is used to demonstrate the proposed method.

5. Discussion

There remain some issues to be addressed in the proposed approach. Firstly, we ignored the difference in the results of sampling in scenario development. Although each sampling follows the same probability density function, there will still be slight differences in the sampling results. Secondly, a domino effect can be viewed as a result of a combination of deterministic and uncertain events. Given real-time data, the deterministic methods should be applied to model the domino evolution process, while the proposed approach will be used to assess the damage probability of the surrounding process units. Though not perfect yet, the proposed approach has made an attempt to provide decision support to minimizing potential domino effects through risk-based shutdown in chemical complexes.

The proposed approach is designed to handle the scenarios in which explosive material releases already occur in a chemical plant. For instance, when an operator finds there is a release incident in the plant. On that occasion, there is no other information about the release incident (such as wind speed, leak size). It is challenging for operators to decide how to prevent the potential domino effects without shutting down all process units. In this situation, the proposed method can support operators' decision on which unit should be isolated based on the available information at that time. With new information available, the proposed approach can further update its results. Besides, this approach can also be used for plant design at early stage. When designing a chemical plant, the results of this method can be used to define design parameters, such as the distance between the process units, the arrangement of process units in the P&ID, etc.

The scope of this study is limited to probabilistic explosion analysis through a CFD approach. FLACS has been proved to be a very mature and reliable software, widely used in the simulation of release and explosion analysis in the process industries (Qiao and Zhang, 2010; Shi et al., 2018; Zhang et al., 2020). The accuracy and reliability of FLACS have been validated against numerous experiments with different scales and different scenarios (Middha et al., 2009; Hansen et al., 2010; Bleyer et al., 2012). Middha et al. (2009) carried out a range of different experiments to validate the accuracy of FLACS, and the results show that the experiment results are in good agreement with the simulation results. Hansen et al. (2010) simulated 33 groups of experiments. The results indicate that FLACS is a reliable simulation tool. Therefore, the dispersion and explosion simulation results presented in this study should be considered accurate and reliable.

Once an overpressure exceedance curve has been determined, the process units' risk can be evaluated. This process often involves the application of a risk acceptance or risk tolerance criterion. Risk acceptance or tolerance criteria may vary from different plants. Risk acceptance criteria (RAC) can be divided into three categories: RAC related to safety function (facility integrity), RAC related to loss of life, and environmental RAC. In this study, the primary aim is to prevent escalating accidents. We only consider the damaged probability of equipment under the influence of overpressure, that is, only RAC related to safety functions is considered. The acceptable frequency of the whole site is 4×10^{-4}/year. As the site is composed of four identical propylene units, we assume that the 1×10^{-4}/year is selected as the acceptable frequency for each process units in this study to determine the DAL of different process units. In addition, the engineers could choose another acceptable frequency according to their plant situation and safety requirements.

In this case, the model is composed of four independent propylene production units. Therefore, this study only considers the impact of explosion risk on adjacent units. When this method is used in plants that are closely related to processes, not only the impact of explosion risk should be taken into account, but also the

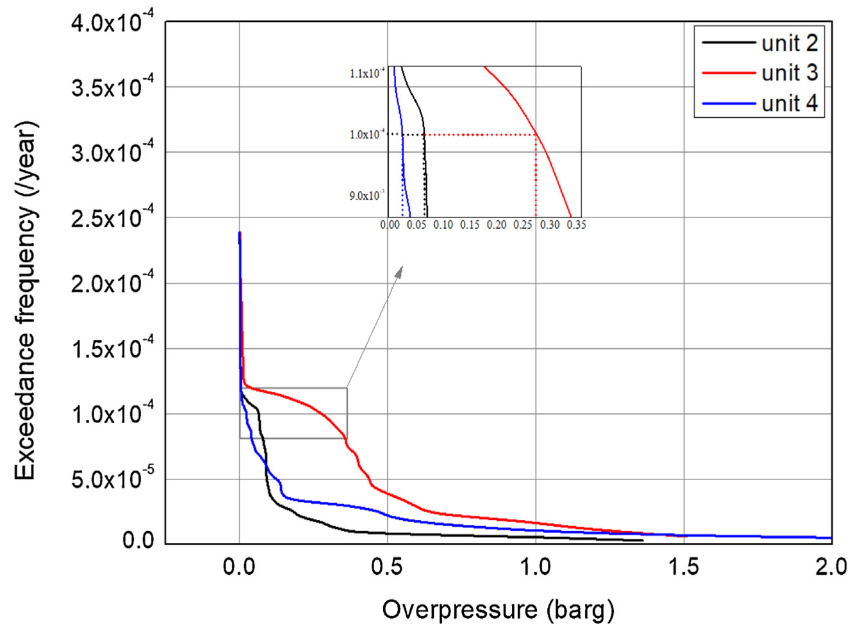

Fig. 14. Exceedance overpressures of the unit 2, 3 and 4.

Table 3
Damage probability of unit 2, 3 and 4.

Accident unit	Equipment type	Model	Affected units		
			Unit 2	Unit 3	Unit 4
1	Small equipment	Probit	1.32	4.37	0.06
		Vulnerability	0%	26 %	0%
	Elongated equipment	Probit	−0.37	4.05	−2.19
		Vulnerability	0%	17 %	0%
	Pressurized vessels	Probit	−4.48	1.58	−6.98
		Vulnerability	0%	0%	0%

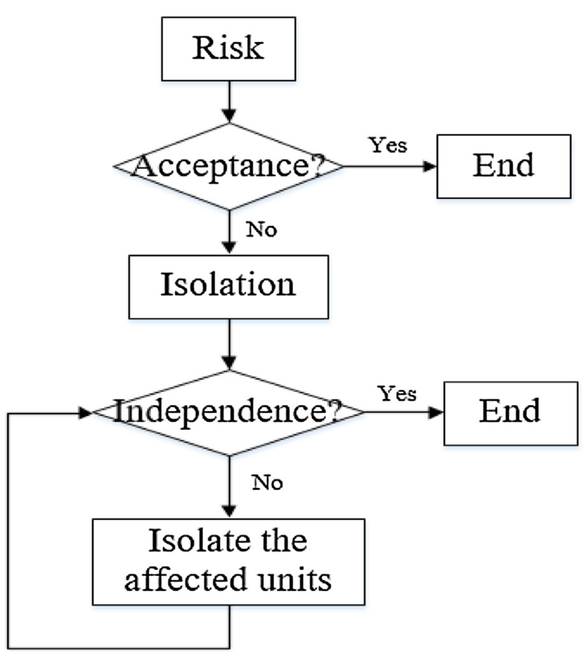

Fig. 15. The process of determining the isolated unit.

interaction between processes. When one unit is shut down, if it affects other process units, the affected unit should also be closed. The specific analysis is shown in Fig. 15. Thus, engineers should consider specific site and process information when the proposed method is applied to real projects.

6. Conclusions

Fire and explosion events will lead to catastrophic scenarios in chemical plants. Explosion accident, in particular, will cause serious impact on people, property and environment once it happens. In this study, we focus on the explosion risk analysis and propose an approach to determine which equipment or units should be shut down and which should keep operating normally when a release accident occurs. The traditional method to select the process unit to be isolated is generally based on experience, from the perspective of the product and process safety, determining: a) which units should be stopped and b) which units continue to operate, to achieve impact minimization between processes. However, the impact of specific physical location and explosion risk is not considered. This paper proposes an approach to support the selection of the process unit to be isolated based on the DAL in the scenarios where explosive material releases occur in a chemical plant. The proposed method can overcome the above pitfalls. Besides, this method can identify the possible scenarios of the explosion accident and reduce the uncertainty of scenario selection, and quantify the probability and the consequence of the accident.

DAL is used as the impact intensity of an explosion accident on surrounding units, which is determined by accident consequence and occurrence probability. The probit model is used to calculate the damage probability of surrounding units. When the damage probability is high, the unit should be selected as the process unit to be isolated to form the isolation zone, which can not only prevent the domino accident but also protect the normal operation of other units. The contribution of this methodology is proposing the selection method of process units to be isolated based on the DAL to reduce the economic loss and prevent the domino accident. This can reduce shutdown time. While ensuring the safety of the plant, it can also reduce the economic losses caused by the shutdown of the entire plant.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. 60 accident scenarios sampled by LHS

Scenario	Leak rate (Kg/s)	Leak direction	Leak duration (s)	Wind speed (m/s)	Wind direction
1	36.79	+Y	88	3.22	106.45
2	32.11	+Z	101	3.15	87.30
3	90.50	-X	36	0.56	109.97
4	59.88	+Z	54	2.41	267.14
5	42.01	+Z	77	3.15	260.52
6	26.43	+Y	120	6.63	168.29
7	65.36	+Y	49	1.75	153.61
8	16.76	-Z	120	3.92	69.34
9	58.79	-Z	55	1.84	97.64
10	90.61	+Z	35	4.52	96.22
11	56.72	-Z	57	3.63	289.56
12	23.76	-X	120	6.04	171.20
13	25.16	-Z	120	2.85	125.92
14	72.17	-Z	45	3.52	107.61
15	87.27	+Z	37	5.09	83.72
16	67.61	+Y	48	0.31	121.71
17	27.37	+Z	119	1.13	167.97
18	84.59	+Y	38	3.74	12.93
19	30.91	-X	105	2.38	26.88
20	24.97	+Y	120	2.83	148.32
21	19.88	-Z	120	1.30	15.33
22	20.71	-X	120	2.06	55.54
23	28.91	+Y	112	2.69	122.26
24	23.45	-X	120	2.28	104.11
25	19.14	+Z	120	2.11	38.50
26	49.95	-X	65	2.67	67.29
27	22.64	-Z	120	2.01	108.44
28	53.33	+Y	61	4.92	305.17
29	21.98	-X	120	1.95	112.14
30	39.53	+Y	82	5.53	132.19
31	33.75	-Z	96	1.49	148.31
32	19.73	+Z	120	2.10	47.30
33	94.33	-Z	34	1.38	122.35
34	16.55	+Z	120	2.54	101.94
35	26.96	-X	120	1.80	28.13
36	37.99	-X	85	2.29	60.51
37	63.06	-Z	51	2.82	106.81
38	51.56	+Y	63	1.65	159.38
39	26.12	-Z	120	3.19	110.97
40	75.43	+Y	43	3.66	133.53
41	27.80	+Z	117	1.96	80.27
42	37.65	-X	52	1.15	125.80
43	78.19	-Z	41	4.47	22.47
44	30.04	+Z	108	2.71	77.83
45	45.28	+Y	71	1.28	175.31
46	21.74	-X	120	2.77	201.13
47	18.61	+Z	120	1.49	104.43
48	80.32	+Y	40	2.47	176.24
49	47.39	-X	68	2.25	165.26
50	28.41	-X	67	0.53	119.16
51	55.85	+Y	55	1.67	56.67
52	17.22	+Y	120	3.95	133.48
53	55.60	-X	58	5.82	179.66
54	24.40	-Z	120	6.11	276.56
55	40.60	+Y	80	2.57	152.45
56	31.33	+Z	104	3.16	273.63
57	20.87	-Z	120	2.61	107.14
58	16.42	+Z	120	3.31	138.90
59	31.48	+Z	103	2.02	18.08
60	29.70	+Y	109	0.72	67.86

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