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## Article

## A risk-based methodology for the optimal placement of hazardous gas detectors☆

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## ABSTRACT

Hazardous gas detection systems play an important role in preventing catastrophic gas-related accidents in process industries. Even though effective detection technology currently exists for hazardous gas releases and a majority of process installations have a large number of sensitive detectors in place, the actual operating performance of gas detection systems still does not meet the expected requirements. In this paper, a risk-based methodology is proposed to optimize the placement of hazardous gas detectors. The methodology includes three main steps, namely, the establishment of representative leak scenarios, computational fluid dynamics (CFD)-based gas dispersion modeling, and the establishment of an optimized solution. Based on the combination of gas leak probability and joint distribution probability of wind velocity and wind direction, a quantitative filtering approach is presented to select representative leak scenarios from all potential scenarios. The commercial code ANSYS-FLUENT is used to estimate the consequence of hazardous gas dispersions under various leak and environmental conditions. A stochastic mixed-integer linear programming formulation with the objective of minimizing the total leak risk across all representative leak scenarios is proposed, and the greedy dropping heuristic algorithm (GDHA) is used to solve the optimization model. Finally, a practical application of the methodology is performed to validate its effectiveness for the optimal design of a gas detector system in a high-sulfur natural gas purification plant in Chongqing, China. The results show that an appropriate number of gas detectors with optimal cost-effectiveness can be obtained, and the total leak risk across all potential scenarios can be substantially reduced. This methodology provides an effective approach to guide the optimal placement of point-type gas detection systems involved with either single or mixed gas releases.

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## 1. Introduction

Hazardous gas detection is an essential layer of protection in process industries. Its principal function is to effectively detect hazardous gas accumulation before it reaches a specific concentration and size and to initiate proper emergency response procedures. Hazardous gases can be classified into two main categories: flammable and toxic gases. The catalytic and infrared gas detectors are commonly used to detect flammable gas clouds, whereas the electrochemical and semiconductor gas detectors are typically designed to be activated at the tolerable toxicity level of a gas toxic to human health. When there is a possibility of a mixed release of flammable and toxic gases, both types of gas detectors

should be present to protect against catastrophic accidents in terms of human health, structural safety, and surrounding environment [1].

Although effective detection technology currently exists for hazardous gas releases and a majority of process installations may have hundreds of sensitive detectors in place, the actual effectiveness of gas detection systems is still not satisfactory [2]. For example, the Health and Safety Executive (HSE) [3–4] reported that less than 50% of the known releases in offshore facilities were successfully detected by the facility's gas detection system. This failure is due to the wide range of uncertainties that can affect the performance of gas detection systems, including the leak location, process condition, product composition and phase, and surrounding geometry as well as weather conditions [5–7].

General guidelines for the design of gas detection systems have been provided by several existing regulations, standards, and recommended practices [8–16]. However, most of these guidelines focus primarily on type selection, installation, testing, and calibration of gas detectors whereas very little research provides explicit guidance in optimizing

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placement [17]. Due to the generality of existing standards and the inherent uncertainties in gas detection, qualitative placement approaches based on rules-of-thumb and prescriptive procedures are typically adopted in modern process industries. According to the primary intended purposes, the placement strategies can be categorized into five classes, namely, source monitoring, volumetric monitoring, enclosure monitoring, path of travel and target receptor monitoring, and perimeter monitoring [18]. The detection performance metrics, such as the distance from leak sources and the maximum volume uncovered, are widely used to assess the effectiveness of gas detector system.

In recent years, risk concepts and gas dispersion modeling based on computational fluid dynamics (CFD) have been introduced to above qualitative approaches to improve the detection performance. For example, Strøm and Bakke [19] proposed a performance-based algorithm for sensor placement where potential sensor locations are selected according to the ranking of an overall efficiency metric. DeFriend *et al.* [20] presented a five-step procedure based on risk evaluation to determine the maximum gas cloud size that must be detected to maintain a tolerable risk level. ISA-TR84.00.07 [14] developed a coverage-based risk assessment procedure for gas detector placement. If the expected risk threshold is not met, the placement scheme of the gas detectors has to be modified, and the process is repeated. Mariotti *et al.* [21] developed a heuristic approach to allocate flammable gas detectors with the objective of maximizing the detection coverage. Richart *et al.* [22] presented a CFD-based approach to estimate gas dispersion and then to obtain the optimal gas sensor allocation. Wang *et al.* [23] proposed a meta-modeling strategy using Gaussian process regression to reduce the number and required time of CFD simulations by selecting a reduced set that is sufficient to build an approximated model. In the previous studies, commercial packages, such as FLUENT, CFX, FLACS, and PHAST, have often been used to perform gas dispersion modeling.

More recently, Legg *et al.* [6] developed a stochastic mixed-integer linear programming formulation for optimizing the placement of gas detectors. It aims to minimize the detection time for a given set of release scenarios based on a coverage constraint. To improve the tail behavior, Legg *et al.* [24] extended their previous work and added an additional constraint on the conditional-value-at-risk function across the entire set of leak scenarios. Benavides-Serrano *et al.* [25] modified the optimization formulations of Legg *et al.* [6,24] and incorporated detector unavailability and voting logic into the optimization model to consider the possibility that a detector is not able to perform its intended function and the requirement for a voting logic. In addition, four types of placement approaches, namely, the random approach, the volumetric approach, the minimum source distance approach, and the greedy scenario coverage approach, were compared with the formulation developed by Benavides-Serrano *et al.* [5].

Even though significant progress has been made for the placement of hazardous gas detectors, several key issues still need to be addressed. First, a majority of the existing studies and industry practices have typically considered a very limited set of high-impact or worst-case leak scenarios [26]. However, there may be hundreds of thousands of potential leak scenarios due to the wide range of uncertainties resulting from leak conditions and weather parameters. How to reliably identify the important leak scenarios across all potential leak scenarios remains a great challenge. Second, in the existing stochastic programming formulations, the risk value of each leak scenario was assumed to be identical; thus, the objective functions were then simplified to minimize the detection time instead of the leak risk across all of the leak scenarios considered [6,24,25]. Obviously, this hypothesis cannot reflect the real risk generated by various leak scenarios and might result in the designed detection system not meeting the detection performance requirements. In addition, only the placement approach for one type of gas detectors, *i.e.*, either flammable or toxic gas detectors, has been involved in previous studies. In actual applications, however, there may be a mixture of gases released. For example, the gas released from a high-sulfur natural gas purification plant may contain both flammable and toxic gases (*e.g.*,

methane and hydrogen sulfide). In this case, how to allocate the location and number of two types of gas detectors is still an open question.

The aim of this study is to develop a risk-based point-type detector placement methodology suitable for either single or mixed gas release events. To cover the wide range of uncertainties related to leak conditions and weather parameters, a quantitative approach is first presented to identify the representative leak scenarios. Rigorous gas dispersion modeling is implemented using ANSYS-FLUENT. A modified stochastic mixed-integer linear programming formulation with the objective of minimizing the leak risk is proposed for the optimal placement of both flammable and/or toxic gas detectors. The greedy dropping heuristic algorithm (GDHA) is used to solve the optimization model. A case study is performed to illustrate and validate the proposed methodology.

## 2. Methodology

The framework of the proposed methodology is shown in Fig. 1. The major steps are described in detail in the following sections.

### 2.1. Generation of representative leak scenarios

#### 2.1.1. Set of leak sources

In order to fully reflect the actual leak risk of a target installation, all potential leak sources involved in hazardous gas releases should be identified through a hazard identification (HAZID) study, such as the hazard and operability analysis (HAZOP) and/or the preliminary hazard analysis (PHA) [27]. The results of the HAZID should include the main features of a leak accident, such as the leakage location, direction, medium composition and phase, and time duration.

In addition, there may be a continuous distribution of leak hole sizes for various process equipment, making a great difficulty in estimating the leak frequencies based on the generic statistical data. To quantitatively characterize the leak probability, four hole size categories (*i.e.*, the small, medium, large and rupture holes) are adopted in this paper, as shown in Table 1 [28]. In this approach, four diameters (*i.e.*, 6.4 mm, 25 mm, 102 mm,  $\text{Min}[D, 406]$ ) are used to represent the continuous ranges associated with hole sizes, respectively.

With the identification of all possible leak sources for a selected installation, the set of leak sources can be generated using Eq. (1):

$$L = [l_{xy}]_{1 \leq x \leq b, 1 \leq y \leq 4} \quad (1)$$

where,  $L$  denotes the set of leak sources;  $l_{xy}$  represents a leak source located on the  $x$ th process equipment with the  $y$ th hole size; and  $b$  is the total number of process equipment with potential gas releases.

The occurrence probability  $P(l_{xy})$  of a leak source  $l_{xy}$  can be calculated with the commercial software DNV-LEAK [26]. The software is suitable for estimating the leak probability of base elements, equipment, segments, areas and installations used in onshore and offshore process industry. In DNV-LEAK, leaks are differentiated for 17 types of equipment (*e.g.* flanges, pipes, vessels). The generic leak frequencies of each type of equipment with different release hole sizes are obtained based on the historical failure data, which is derived from the Hydrocarbon Release Database (HCRD) compiled by HSE. The occurrence probability  $P(l_{xy})$  can then be calculated based on the corresponding generic leak frequency as well as the actual operating and management conditions.

#### 2.1.2. Set of wind fields

A wind field is typically characterized by two variables: wind direction and wind velocity. The wind direction determines the gas diffusion direction, whereas the wind velocity affects the diffusion and dilution rate of the released gas [2]. In this paper, the wind direction is divided into eight equally distributed groups of  $45^\circ$  each using the eight-orientation method [29]. The occurrence probability in each wind direction is obtained based on a statistical analysis of the local meteorological data. In addition, the wind velocity is divided into  $c$  groups with equal

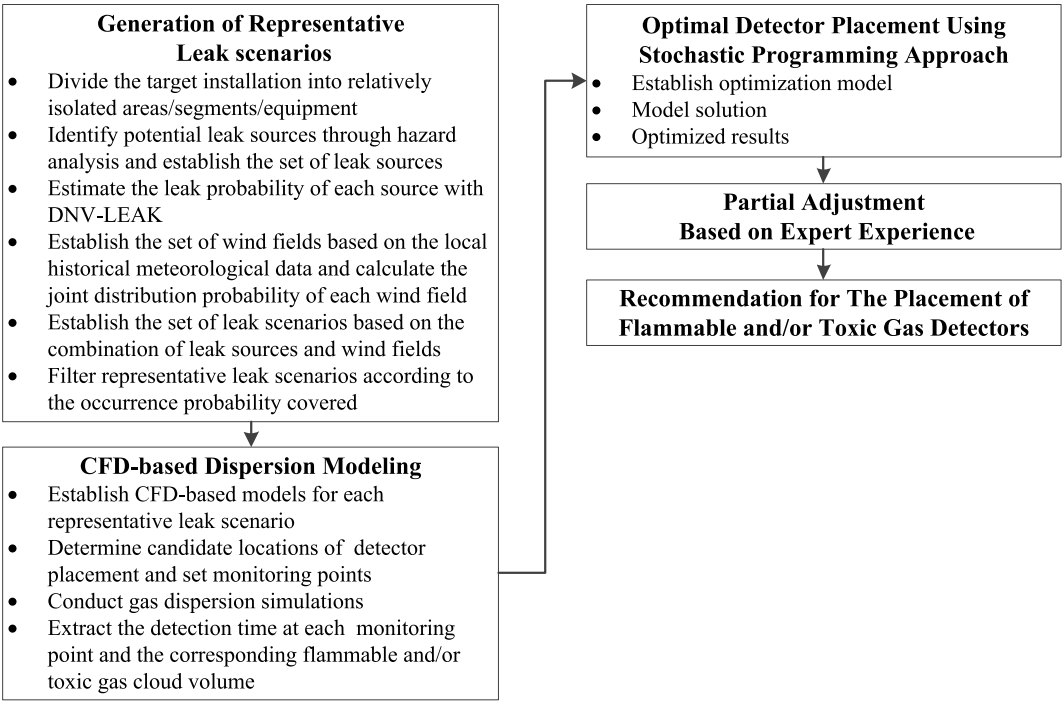


Fig. 1. Framework of the methodology.

intervals in the range of 0 to  $v_{\max}$  (e.g., the maximum local wind velocity over the past ten years). Then, the set of wind fields can be developed by combining various groups of wind directions and wind velocities, as shown with Eq. (2):

$$W = [w_{\theta v}]_{1 \leq \theta \leq 8, 0 \leq v \leq c} \tag{2}$$

where,  $W$  is the set of wind fields;  $w_{\theta v}$  represents a wind field whose wind direction falling in the  $\theta$ th group while wind velocity in the  $v$ th group; and  $c$  is the number of wind velocity groups.

Based on the local historical meteorological data such as the wind-rose diagram, the joint distribution probability  $P(w_{\theta v})$  for each wind field  $w_{\theta v}$  can be obtained by counting the frequencies of those wind velocity groups in eight wind directions.

2.1.3. Filtering representative leak scenarios

A complete set of leak scenarios for the installation is then generated via a random combination of the leak source set and the wind field set, as expressed with Eq. (3):

$$S = \{S_{xy\theta v} | 1 \leq x \leq b, 1 \leq y \leq 4, 1 \leq \theta \leq 8, 0 \leq v \leq c\} \tag{3}$$

where,  $S$  is the set of leak scenarios;  $S_{xy\theta v}$  represents a leak scenario associated with the  $x$ th leak equipment,  $y$ th leak hole size,  $\theta$ th wind direction group, and  $v$ th wind velocity group.

Table 1  
Typical size of leak holes

| No. of leak hole size | Description | Range of leak hole diameters covered/mm | Representative diameter/mm |
|-----------------------|-------------|-----------------------------------------|----------------------------|
| 1                     | Small hole  | 0–6.4                                   | 6.4                        |
| 2                     | Medium hole | 6.4–51                                  | 25                         |
| 3                     | Large hole  | 51–152                                  | 102                        |
| 4                     | Rupture     | > 152                                   | Min[ $D$ , 406]            |

Due to the mutual independence between the leak source set and the wind field set, the occurrence probability  $P(S_{xy\theta v})$  of leak scenario  $S_{xy\theta v}$  is calculated using Eq. (4):

$$P(S_{xy\theta v}) = P(l_{xy}) \times P(w_{\theta v}) \tag{4}$$

where,  $P(S_{xy\theta v})$  represents the occurrence probability of leak scenario  $S_{xy\theta v}$ ;  $P(l_{xy})$  denotes the occurrence probability of leak source  $l_{xy}$ ; and  $P(w_{\theta v})$  is the joint distribution probability of wind field  $w_{\theta v}$ .

Based on above approach, the limited but representative leak scenarios can then be filtered across the entire set of leak scenarios by balancing the potential leak scenarios covered and the computation cost. Compared with the conventional method, the proposed approach in this paper takes all equipment with potential gas releases into consideration rather than just the limited major equipment. In addition, all possible wind directions and wind velocities are considered. As a result, the proposed approach for the generation of representative leak scenarios is much more complete and robust than the conventional method.

2.2. CFD-based dispersion modeling

2.2.1. Modeling approach

Generally, 3D modeling is recommended to guarantee accurate gas dispersion output, especially for installations with intricate geometries. In this study, the ANSYS-FLUENT package is used to model the gas dispersion [30]. The computational domain is typically simplified to be a cuboid, and sufficiently large to simulate the effect of the local wind field [22]. According to the specified wind direction, the wind is typically aligned normal to one or two surfaces of the computational domain, which are defined as the velocity inlet. The downwind boundary is set as the pressure outlet. A mass flow inlet boundary is applied at the leak source. The other surfaces are all defined as solid walls.

Gas concentration monitoring points (i.e., candidate detector locations) should cover all areas where the accumulation of hazardous gases might occur. In general, if the released gas is heavier than air, detectors may be placed at a relatively low elevation (a minimum of 0.6 to 1.0 m above ground out-of-doors and 0.3 m above ground indoors) [11]. In contrast, if the gas is lighter than air, detectors should be placed at a relatively high elevation (0.5–2 m above the release location) [11].

Before modeling a transient release, a converged steady state simulation with the leak source turned off should be performed to initialize the transient simulation. At the time  $t = 0$  s, the leak source is switched on, and a transient simulation for each representative scenario is then performed. A simulation lasting for 4 min is typically suggested for the transient simulations [31].

The  $k$ - $\varepsilon$  turbulence model is widely adopted to account for turbulence during the gas release. The segregated SIMPLE algorithm is used to couple the pressure and velocity. According to the desirable output accuracy, the first- or second-order upwind scheme and the first- or second-order central-differencing scheme can be employed for the convective and diffusion terms, respectively.

### 2.2.2. Data obtained from dispersion modeling

During every transient simulation, the gas concentration with time at each monitoring point (i.e., detecting flammable and/or toxic gas release) should be recorded. Generally, the alarm threshold for flammable gas is set to 20% of the lower explosion limit (LEL), whereas the threshold for toxic gas is 10% of the concentration immediately dangerous to life or health (IDLH) [7].

It is well known that the leak risk is associated with the probability and the relevant accidental consequences. However, a rigorous accidental consequence analysis is extremely time-consuming in a practical project. To simplify the consequence assessment, the flammable or toxic gas cloud size above the threshold resulting from a release is used to approximately represent the possible consequences of a leak scenario in this paper.

Once the gas concentration at a monitoring point reaches the specified alarm threshold at the earliest time, the leak scenario is assumed to be detected by this monitoring point; the maximum value between the flammable and toxic gas cloud sizes above the threshold at this detection time is then taken as the accidental consequence in terms of this monitoring point. Undoubtedly, some monitoring points may not be able to detect a specific leak scenario at all or have a time delay compared to the first detection location. Under these situations, the emergency response procedures cannot be activated in time by the gas detection system, resulting in a large amount of hazardous gas released into the environment. Thus, a large enough size of gas cloud needs to be estimated. In this paper, the volume of the entire computational domain is used to represent the consequences for these situations [32].

## 2.3. Optimization formulation and solution algorithm

### 2.3.1. Objective function

The optimal placement scheme of hazardous gas detectors is typically defined as one with the minimum sum of leak risk across all leak scenarios. The objective function is expressed as follows:

$$\min R(U) = \min \sum_{i \in S} P_i \sum_{j \in \phi} V_{ij} \delta_{ij} \quad (5)$$

where  $U$  is the decisive variable, which represents the set of optimal locations of gas detectors;  $S$  denotes the set of representative leak scenarios,  $S = \{1, 2, \dots, m\}$ , where  $m$  is the number of representative leak scenarios;  $\phi$  is the set of monitoring points,  $\phi = \{1, 2, \dots, q\}$ , where  $q$  is the number of monitoring points;  $P_i$  is the occurrence probability of a representative leak scenario  $i$ , which can be determined using Eq. (4);  $\delta_{ij}$  is a Boolean variable, which denotes whether

the leak scenario  $i$  would be first detected by the monitoring point  $j$  or not,  $\delta_{ij} = 1$  if so and 0 otherwise; and  $V_{ij}$  is the maximum value between the volume of flammable and toxic gas cloud above the threshold, which is associated with the leak scenario  $i$  detected at the monitoring point  $j$ . It can be obtained using Eq. (6):

$$V_{ij} = \max(V_{ijk}) \quad k = 1, 2 \quad (6)$$

where,  $V_{ijk}$  is the  $k$ th hazardous gas cloud size above the threshold released from the scenario  $i$  when detected at the monitoring point  $j$ .

### 2.3.2. Constraints

The constraints for the optimization problem are illustrated as follows.

#### (1) Maximum number of gas detectors allowed

To achieve a balance between the safety and the cost, the maximum number of gas detectors designed for an installation should be limited before optimization. This constraint can be expressed as follows:

$$\sum_{j \in \phi} d_j \leq n, \quad (7)$$

where,  $d_j$  is a binary variable that represents the existence of a detector ( $d_j = 1$ ) or the lack of a detector ( $d_j = 0$ ) at the monitoring point  $j$ ; and  $n$  is the total number of gas detectors.

#### (2) Relationship between monitoring points and gas detectors.

If one monitoring point can detect the release of hazardous gases, there must be a gas detector placed at this position. This constraint can be described as follows:

$$\delta_{ij} \leq d_j \quad \forall i \in S, j \in \phi \quad (8)$$

#### (3) Relationship between leak scenarios and gas detectors.

Each leak scenario needs to be detected by at least one monitoring point. In other words, there must be the presence of a monitoring point which is the first one to detect each leak scenario. To ensure this requirement, the variable  $\delta_{ij}$  should satisfy the following constraint:

$$\sum_{j \in \phi} \delta_{ij} = 1 \quad \forall i \in S \quad (9)$$

If the leak scenario  $i$  cannot be detected by any monitoring points, the dispersion simulation should be ran again after properly resetting the locations of monitoring points.

### 2.3.3. Solution algorithm

The above optimization formulation is a mixed-integer linear programming problem. It can be solved using the drop-heuristics [33], the Lagrangian algorithm [34], or the branch-and-cut approach [35] in simple cases. When the problem size becomes too large, more advanced heuristics, such as genetic algorithms or Tabu Search and its derivatives [36–38], have to be adopted to enhance computational efficiency. Because the number of monitoring points is not prohibitively large in this study, the greedy dropping heuristic algorithm (GDHA) with more robustness is proposed to solve the optimization problem [39]. Based on the GDHA, the optimization model can be solved by the following procedures.

Step 1: Set the number of monitoring points  $q$ . Note that  $q \geq n$ .

Step 2: Input basic data, including the number of representative leak scenarios  $m$ , the total number of gas detectors  $n$ , and all maximum gas cloud sizes  $V_{ij}$  ( $i = 1, 2, \dots, m; j = 1, 2, \dots, q$ ).

Step 3: Initialize the serial number  $g = 1$ .

Step 4: Remove the  $g$ th monitoring point; for each leak scenario, search for the minimum value among the gas cloud volumes associated with the remaining monitoring points,  $\min\{V_{ij}\}$  ( $j = 1, 2, \dots, q; j \neq g$ ); calculate the objective function value  $R(U_g)$  using Eq. (10), which derived from Eq. (5).

$$R(U_g) = P_1 \cdot \min\{V_{1j}\} + P_2 \cdot \min\{V_{2j}\} + \dots + P_m \cdot \min\{V_{mj}\} \quad j = 1, 2, \dots, q; j \neq g \quad (10)$$

Step 5: Set  $g = g + 1$ , and return to Step 4. If  $g > q$ , then continue to Step 6.

Step 6: Rank all the objective function values  $R(U_g)$ ; drop out the monitoring point corresponding to the minimum objective function value,  $\min\{R(U_g)\}_{g=1, 2, \dots, q}$ .

Step 7: Set  $q = q - 1$ , and return to Step 3. If  $q < n$ , then output the remaining monitoring points' IDs, which represent the optimal locations and the corresponding type of detectors (i.e., a flammable or toxic detector).

Above procedures can also be depicted by a flow chart, as shown with Fig. 2.

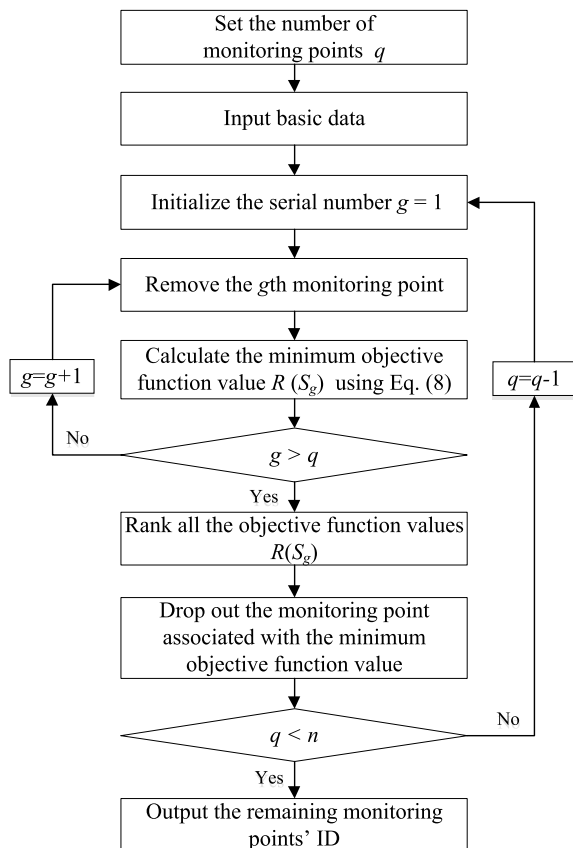


Fig. 2. Solution procedure of the optimization model.

Based on the above optimization formulation and its solution algorithm, a computer program with C# language was developed to obtain the optimal results.

### 3. Case Study

#### 3.1. Description

A high-sulfur natural gas purification plant in Chongqing, China, contains four main process units, namely, separation and filtration, desulfurization, dewatering, and sulfur recovery. The inlet pressure of the raw gas is 4.6–6.3 MPa, and the mole fraction of the hydrate sulfide is 12.31%–17.05%. For the simplified discussion in this study, only the desulfurization unit is selected as the target unit, whose three-dimensional view and primary equipment are depicted in Fig. 3.

#### 3.2. Representative leak scenarios

For the desulfurization unit, a total of 16 potential leak locations were identified via a HAZOP analysis. They were all located at the manholes or flange connections associated with four pressure vessels (i.e., the wet purifying gas separator, the MDEA absorption tower, the MDEA regenerator, and the acid gas separator). The ranges of composition, pressure and temperature of released medium were determined according to the relevant process diagrams. The leak probability of each source was calculated using DNV-LEAK. The release rates were obtained through the gas leak rate formulations [40]. We consider two potential leak sources (No. 1 and No. 2) as examples. Leak source No. 1 is located at the connecting flange of the raw gas inlet pipe associated with the MDEA absorption tower, while No. 2 is located at a manhole of the MDEA regenerator. The hazardous gases released from these two sources and their occurrence probabilities and leak rates are shown in Table 2.

Based on the local wind-rose diagram, the wind velocity can be divided into six groups with intervals of  $2 \text{ m} \cdot \text{s}^{-1}$ . The joint distribution probability  $P(W_{\theta v})$  of wind direction and wind velocity can be obtained using the method proposed in Section 2.1.2, as shown in Table 3.

Based on the leak source and wind field sets, a total of 3072 potential leak scenarios ( $16 \text{ leak equipment} \times 4 \text{ leak hole sizes} \times 8 \text{ wind directions} \times 6 \text{ wind velocities}$ ) were then generated for the unit. Using Eq. (4) and the data presented in Tables 2 and 3, the quantitative occurrence probability for each leak scenario can be calculated using the MATLAB package.

According to the recommended approach in Section 2.1.3, the limited representative leak scenarios could then be filtered from the entire set of leak scenarios. Note that the occurrence probability of a leak scenario is selected as the filtering criterion. The leak scenarios covered under various filtering criteria are shown in Table 4. Only 81 leak scenarios are filtered from 3072 leak scenarios, if the occurrence probability of a scenario is required to be greater than  $10^{-4}$  per year. Meanwhile, the coverage rate for the total occurrence probability of leak scenarios reaches up to 91.83%. These results indicate that the representative leak scenarios can be effectively identified to reduce the computational resources, while still reflecting the real leak risk.

#### 3.3. Gas dispersion simulations

The dimensions of the desulfurization unit are approximately with the length of 47 m, the width of 8 m, and the height of 10 m. The computational domain size is set to  $160 \text{ m} \times 50 \text{ m}$  in area and 30 m in height, and the process unit is placed in the center of the computational domain. The transition of the mesh is slow and smooth. The total number of cells is approximately 3.9 million.

Because both methane and hydrogen sulfide may be released, two layers of gas concentration monitoring points were arranged on a

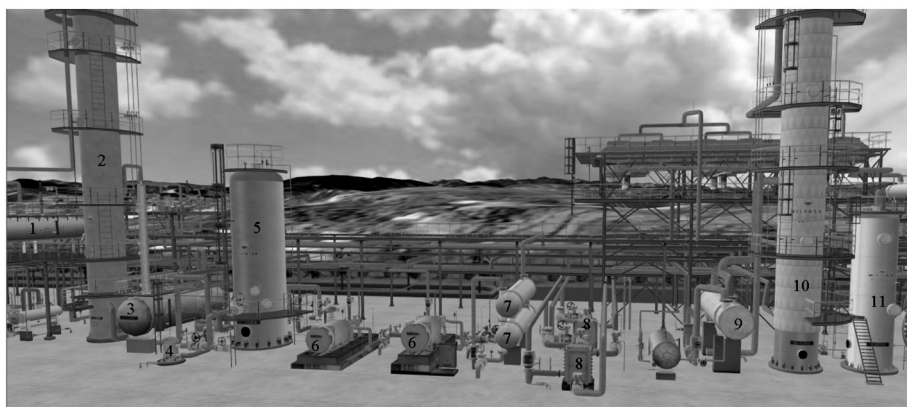


**Fig. 3.** Three-dimensional view of the desulfurization unit. (1—Wet purifying gas separator; 2—Methyl Di Ethanol Amine (MDEA) absorption tower; 3—MDEA flash tower; 4—MDEA filter; 5—MDEA activated carbon separator; 6—MDEA circulating pump; 7—MDEA barren liquor after-cooler; 8—MDEA barren-rich liquor heat exchanger; 9—Reboiler of MDEA regenerator; 10—MDEA regenerator; and 11—Acid gas separator)

**Table 2**

Leak probability ( $\times 10^{-3}$  per year) and release mass rate ( $\text{kg}\cdot\text{s}^{-1}$ ) of two leak sources

| Leak source | Hazardous gases released             | Small hole leak |           | Middle hole leak |           | Large hole leak |           | Rupture leak |           |
|-------------|--------------------------------------|-----------------|-----------|------------------|-----------|-----------------|-----------|--------------|-----------|
|             |                                      | Probability     | Mass rate | Probability      | Mass rate | Probability     | Mass rate | Probability  | Mass rate |
| 1           | $\text{CH}_4$ , $\text{H}_2\text{S}$ | 6.556           | 0.040     | 1.359            | 2.221     | 0.767           | 25.53     | 0.012        | 33.19     |
| 2           | $\text{H}_2\text{S}$                 | 5.695           | 0.011     | 1.912            | 0.167     | 0.774           | 2.772     | 0.126        | 6.402     |

2 m  $\times$  2 m grid at different elevations, as shown in Fig. 4. The height of upper layer used to detect methane is 2 m above the release sources, whereas that of lower layer used to detect hydrogen sulfide is 0.5 m above the ground. The coding rule for monitoring points is as follows:  $F_{x,y}$  and  $T_{x,y}$  represent methane and hydrogen sulfide gas detectors, respectively, and  $(x, y)$  denotes the location coordinates.

The simulations were all performed for 81 leak scenarios identified in Section 3.2 using a HP Z620 Workstation (Intel Xeon E5–2620 v2). Based on the simulation results, the detection time  $t_{ij}$  at the monitoring point  $j$  under the leak scenario  $i$  could be obtained. Furthermore, the monitoring point which first detects the leak scenario  $i$  and the maximum gas cloud volume  $V_{ij}$  could also be determined. For example, the monitoring point  $T_{0,2}$  is the first location to detect a specific leak scenario. The concentration vs. time curve at  $T_{0,2}$  is illustrated in Fig. 5, and the gas cloud volume vs. time curves are shown in Fig. 6. According to the specified thresholds, the detection time at the monitoring point  $T_{0,2}$  is 25.5 s, as shown in Fig. 5. The size of methane and hydrogen sulfide gas cloud corresponding to  $t = 25.5$  s could then be determined to be 36  $\text{m}^3$  and

2030  $\text{m}^3$ , respectively, as illustrated in Fig. 6. Thus, the gas cloud volume associated with the monitoring point  $T_{0,2}$  is 2030  $\text{m}^3$  according to Eq. (6). The hydrogen sulfide dispersion range above 10% IDLH at the detection time is shown in Fig. 7.

### 3.4. Optimal results and discussion

#### 3.4.1. Number of gas detectors

After the total number of gas detectors  $n$  is specified and all maximum gas cloud sizes  $V_{ij}$  are obtained from above gas dispersion simulations, the optimal locations and the corresponding number of flammable and/or toxic gas detectors can then be determined using the optimization formulation and solution algorithm proposed in Section 2.3.

To investigate the effect of the number of gas detectors on the leak risk, the objective function values associated with various number of gas detectors were calculated in sequence, as shown in Fig. 8. It can be seen that the leak risk value will be reduced sharply when the number of gas detectors is less than 20, whereas remaining nearly unchanged when the number of gas detectors exceeds 20. Obviously, further

**Table 3**

Joint distribution probability ( $\times 10^{-3}$  per year) of wind direction and wind velocity

| Wind direction | Wind velocity/ $\text{m}\cdot\text{s}^{-1}$ |        |        |        |        |       |
|----------------|---------------------------------------------|--------|--------|--------|--------|-------|
|                | 0–2                                         | 2–4    | 4–6    | 6–8    | 8–10   | 10–12 |
| N              | 24.367                                      | 26.772 | 17.164 | 11.520 | 6.171  | 3.257 |
| NE             | 41.294                                      | 45.369 | 29.087 | 19.522 | 10.457 | 5.519 |
| E              | 57.676                                      | 63.367 | 40.626 | 27.266 | 14.606 | 7.709 |
| SE             | 36.107                                      | 39.670 | 25.433 | 17.070 | 9.144  | 4.826 |
| S              | 24.367                                      | 26.772 | 17.164 | 11.520 | 6.171  | 3.257 |
| SW             | 47.574                                      | 52.268 | 33.511 | 22.491 | 12.048 | 6.359 |
| W              | 27.916                                      | 30.671 | 19.664 | 13.198 | 7.069  | 3.731 |
| NW             | 13.719                                      | 15.073 | 9.664  | 6.486  | 3.474  | 1.834 |

**Table 4**

Leak scenarios covered under different filtering criteria

| Filtering criterion (per year) | Leak scenarios              |                 | Total occurrence probability                     |                 |
|--------------------------------|-----------------------------|-----------------|--------------------------------------------------|-----------------|
|                                | Number of scenarios covered | Coverage rate/% | Probability covered ( $\times 10^{-3}$ per year) | Coverage rate/% |
| $\geq 10^{-3}$                 | 25                          | 0.81            | 52.01                                            | 65.21           |
| $\geq 10^{-4}$                 | 81                          | 2.64            | 73.25                                            | 91.83           |
| $\geq 10^{-5}$                 | 221                         | 7.19            | 77.78                                            | 97.51           |
| $\geq 10^{-6}$                 | 749                         | 24.38           | 79.28                                            | 99.38           |
| $\geq 10^{-7}$                 | 1980                        | 64.45           | 79.75                                            | 99.97           |
| $\geq 10^{-8}$                 | 2352                        | 76.56           | 79.77                                            | 99.99           |
| $\geq 10^{-9}$                 | 2668                        | 86.85           | 79.77                                            | 99.99           |
| $\geq 10^{-10}$                | 2994                        | 97.46           | 79.77                                            | 99.99           |
| $\geq 10^{-11}$                | 3072                        | 100             | 79.77                                            | 100             |

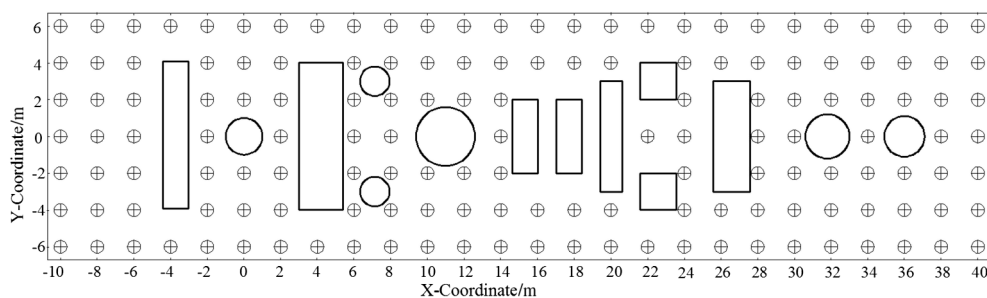


Fig. 4. Top view of the monitoring points. Flammable gas monitoring points are represented by O; toxic gas monitoring points are represented by +.

increasing the number of gas detectors cannot effectively reduce the total leak risk across all 81 representative scenarios. Thus, the optimal number of gas detectors under this situation should be around 20.

### 3.4.2. Location of gas detectors

To verify the effectiveness of the proposed methodology, a comparative analysis of the detection performance was further performed towards various placement schemes. Fig. 9 presents the current placement scheme of gas detectors for the unit, which includes 2 flammable and 11 toxic gas detectors. Note that the gas detectors are all close to four pressure vessels (i.e., the wet purifying gas separator, the MDEA absorption tower, the MDEA regenerator, and the acid gas separator). This placement is selected because the medium released from

the wet purifying gas separator and the MDEA absorption tower primarily contains methane and hydrogen sulfide, whereas the gas leaked from the MDEA regenerator and the acid gas separator is only hydrogen sulfide. For this placement scheme, the coverage rate across all 81 representative release scenarios is only 65.4%, whereas the leak risk value gets up to 618 m<sup>3</sup> per year, as shown in Table 5.

Using the proposed methodology, an optimal placement scheme with 20 gas detectors can be obtained, as illustrated in Fig. 10. There are 6 flammable gas detectors and 14 toxic gas detectors in the modified scheme. Compared to that of the current scheme, the coverage rate across all 81 leak scenarios is as high as 98.8%, whereas the leak risk value substantially drops to 60 m<sup>3</sup> per year, as shown in Table 5. The results illustrate that the methodology proposed in this study can improve

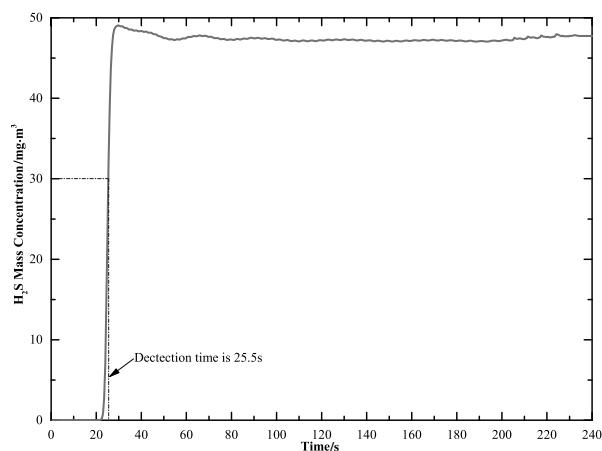


Fig. 5. Concentration vs. time curve at the monitoring point  $T_{02}$ .

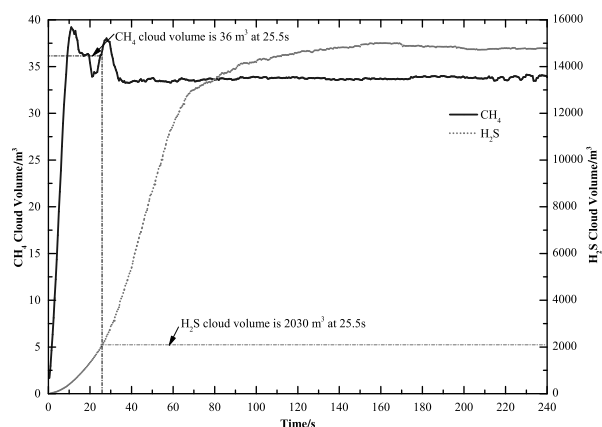


Fig. 6. Gas cloud volume vs. time curves for a leak scenario.

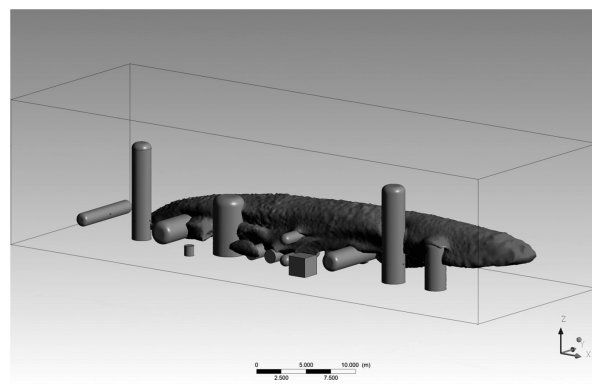


Fig. 7. Dispersed hydrogen sulfide gas cloud above 10% IDLH at  $t = 25.5$  s.

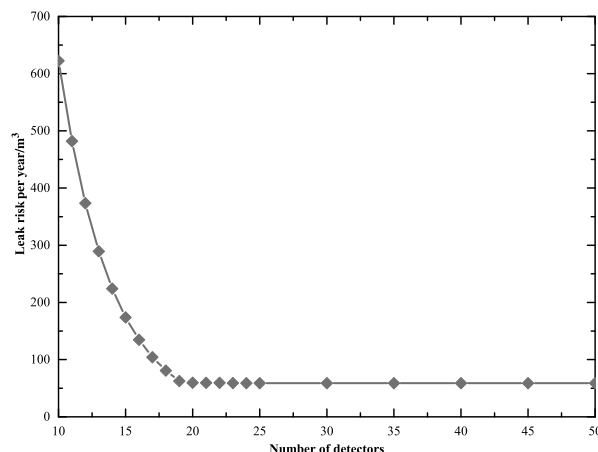


Fig. 8. Effect of the number of gas detectors on the leak risk.

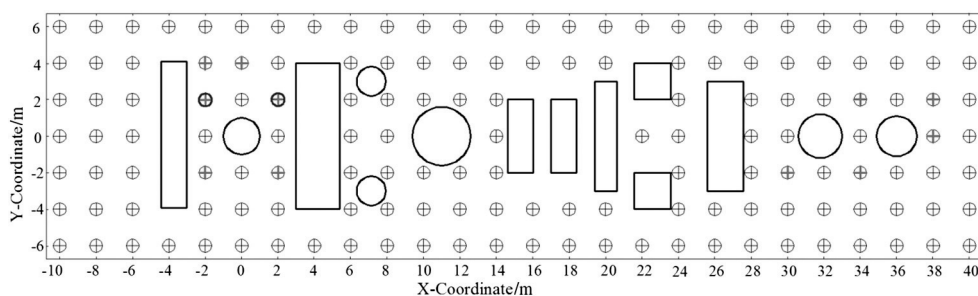


Fig. 9. Current placement of gas detectors. Blue ○ denotes flammable gas detectors, and red + denotes toxic gas detectors.

Table 5

Detection performance for two placement schemes

| Detection performance                                | Current scheme | Optimal scheme |
|------------------------------------------------------|----------------|----------------|
| Number of scenarios covered                          | 53             | 81             |
| Coverage rate across all identified leak scenarios/% | 65.4           | 98.8           |
| Leak risk per year/m <sup>3</sup>                    | 618            | 60             |

the coverage fraction of leak scenarios, and ensure all scenarios detected with the minimum leak risk.

#### 4. Conclusions

This study developed a risk-based methodology to optimize the placement of hazardous gas detectors with the objective of minimizing the total leak risk across all identified leak scenarios. Three main steps were included in the methodology: identifying representative leak scenarios, CFD-based dispersion modeling, establishment and solution of an optimization formulation. A quantitative approach to filter the representative leak scenarios was incorporated into the methodology to cover the wide range of uncertainties related to leak conditions and weather parameters. Three-dimensional CFD modeling was used to estimate the consequences of hazardous gas dispersions. A stochastic mixed-integer linear programming formulation and its solution algorithm were introduced in detail. The proposed methodology can determine the optimal point-type detector placement for either single or mixed gas releases.

This methodology was used to implement the optimal design of gas detector system in a high-sulfur natural gas purification plant in Chongqing, China. The effects of the number and location of gas detectors on the total leak risk was discussed. The results show that the methodology proposed in this study can improve the coverage fraction of leak scenarios, and ensure all scenarios detected with the minimum leak risk.

In this study, only the gas cloud volume was used to assess the consequences of leak scenarios instead of the actual accidental consequences. In addition, detector unavailability and voting logic were not incorporated into the optimization formulation to take into consideration the possibility that a detector might be not capable of performing

its intended function. Therefore, in the future, more appropriate consequence representations and detector unavailability and voting logic should be introduced into the optimization methodology to improve it further.

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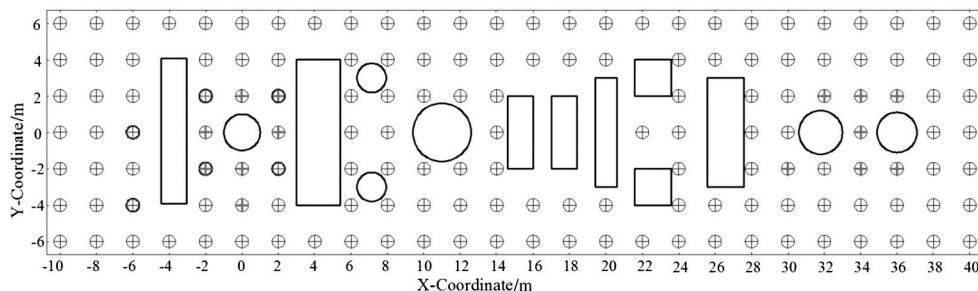


Fig. 10. Optimal placement of gas detectors. Blue ○ denotes flammable gas detectors, and red + denotes toxic gas detectors.

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