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A Risk-based MILP Approach for Optimal Placement of Flammable Gas Detectors

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Gas detectors play an important role in safety of process plants. In-time detection of flammable gas releases may prevent major fire and explosion as well as property loss in process plants. One of the challenges of the gas detection system design is determining the best layout for detectors in order to reduce the risk of gas releases as much as possible. However, current methods do not address the risk concept in placement of detectors quantitatively. A risk-based methodology is proposed for optimal placement of point type flammable gas detectors in which first the risk (defined as a combination of scenario frequency, delayed ignition probability and damage) is estimated for any release scenario. Then, an MILP (Mixed Integer Linear Programming) formulation called MwRR (Maximum weighted Risk Reduction) is proposed for optimal placement. The methodology uses steady-state dispersion results which is an advantage compared to approaches that use dynamic results. The proposed approach is tested on a real petrochemical process unit. For this purpose, the methodology was implemented in MATLAB programming language and the required dispersion data was prepared by means of DNV PHAST software.

1. Introduction

Despite the improvements of preventive measures in process plants, release of flammable material still occurs due to leak events which may lead to severe fire and explosion accident such as Valero Refinery Fire (CSB, 2008) or even worse to domino accidents such the one mentioned by Abdolhamidzadeh et al. (2012). Vapor Cloud Explosion (VCE) and flash fire are reportedly the most serious outcomes of delayed flammable gas release detection, and the ultimate goal of a detection systems is normally set on VCE and flash fire prevention and their destructive effects mitigation.

When a leak occurs, gas detection system as the first mitigative element of protection comes into service and could activate other safety systems such as emergency shut-down (ESD), blow down system (BDS) and alarm. However, the performance of this system majorly depends on number of detectors used and the layout. While required number of detectors is often limited by budget or risk acceptance goals, the layout (or placement) issue remains an open problem which is not addressed specifically in regular standards for open, outdoor process plants. Current standards and regulations give only prescriptions on installation of gas detectors in special points with highest necessity (e.g. HVAC or compressor air intake) and do not provide proper recommendations for the number of detectors required in other monitoring situations (API, 2001). The importance of layout is more highlighted referring that based on HSE UK statistics (HSE, 2008), only 23 out of 36 major releases and 18 out of 58 significant releases have been detected within offshore hydrocarbon releases from 2001 to 2008.

1.1 Previous works

Approaches for placement of detectors could be categorized into non-dispersion based and dispersion based (Benavides, 2014). Volumetric monitoring (BP-Oil, 2009) is an example of non-dispersion based methods which has been in long use by engineering procedure. In volumetric monitoring, the goal is set on detecting a spherical gas volume with a specified radius to prevent occurrence of VCE. Determining this coverage radius has been the subject of some researches. Mariotti et al. (2014) introduced a simple methodology to be applicable in FEED stage where limited data are available. It provides heuristic criteria for risk volume

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definition and spacing of detectors. In summary, non-dispersion based methods rely mostly on expert judgement, heuristics and are easy to use and implement.

In contrast, dispersion based methods which have been developed in recent years use dispersion data for evaluation of the layout. ISA TR84.00 (ISA, 2010) as an example of these methods, proposes a mitigated risk assessment with regard to detectors coverage and availability in which the gas detector layout is modified to obtain the objective risk reduction (without applying optimization techniques). More recently, Legg et al. (2012) proposed a stochastic MILP (Mixed- Integer Linear Programming) formulation called SP using quantitative information provided by dynamic dispersion simulation and expected gas detection time as objective function. Computational bottleneck of this method is dynamic simulation of numerous scenarios which takes the order of CPU hours to days per scenario as reported by the authors.

Although dispersion-based methods require more information and computational effort, a comparison made by Benavides et al. (2014), shows that these methods including: Greedy Coverage (GC), Maximum Coverage Location Problem (MCLP) and SP-U outperform significantly non-dispersion based methods including: Random Approach (RA), Minimum Source Distance Problem (MSDP) and Volumetric Approach (VA). The authors concluded that volumetric approach (VA) (as one of the most common approaches for detector placement) consistently performed poorly because real dispersion clouds are not spherical as this is a basis for this method.

1.2 Proposed approach

In previous published formulations, evaluation of the layout has been carried out by coverage (ISA, 2010) or expected detection time (Legg, 2012) as performance metrics or objective function. The present work utilizes a risk-based objective function which gives the possibility to take into account factors such as probability of wind direction (wind rose), ignition probability and damage potential of gas clouds in selection of the optimal detector layout. In this methodology, steady state dispersion simulation results are required which is an advantage to approaches that use dynamic results because of less time-consuming solution. To address the fact that earlier detection gives more chance to mitigate a scenario, a weight factor is defined as a function of distance to the source of release. Approximately, closer locations to the release source have shorter detection times. The scope of this study is limited to point-type detectors placement within open onshore facilities. The applicability of the methodology is tested in a petrochemical Company. For this purpose, it was implemented in MATLAB programming language and the required dispersion data were provided by means of DNV PHAST RISK software (DNV, 2016).

2. Methodology

The proposed methodology consists of four main steps (see Figure 1). In this methodology, performance of the layout is evaluated against a set of scenarios which are representatives of the whole possible gas release scenarios. In the first step (Input Data), different required data should be provided including frequency of release, weather data and site data. Using these data, two important steps are accomplished: Dispersion Analysis and Risk Analysis. The outputs of these steps would be the risk of each scenario and a matrix called detection matrix. Finally, Risk and detection matrix will be the feeds of the optimization process. The optimization formulation optimizes the layout with regard to an objective function which is defined based on risk of scenarios and the arrangement of detectors.

2.1 Input Data

The required data for optimal placement falls into three categories: Scenario Data, Weather Data and Site Data.In order to design an effective detection system, first a set of release scenarios are defined for the assessment of detection performance. Scenarios originate from sources of release. In process plants these include often places with highest historical probability of release such as connection flanges and valves. After identification of the sources, a set of leak events are defined for each source. Leak events are characterized by the specifications such as location, leak size and leak direction. Since a leak event may occur in different weather conditions, in this work a scenario is defined as the pair of a leak event and a weather condition. Another important data related to the scenarios is frequency of release which is as an essential part of any risk-based study. Frequency of release depends majorly on type of the source (valve, flange, instrument, and equipment), size of connection and leak size range. References such as OGP (2010) provide generic frequency of an individual equipment part based on these factors.

Weather Data includes probability distribution of wind speed and wind directions. Weather is one of the random parameters affecting dispersion behaviour of leak events. Therefore, sufficient number of weather categories should be defined which are representative of yearly condition. The most important parameters of weather are temperature, humidity, stability class, wind speed and wind direction. Distribution of wind speed and wind direction is often given in the form of a diagram called wind rose.

Site data includes set of grid points and location of ignition sources. Set of grid points, L, includes potential locations for installation of detectors which should be checked by an expert to remove infeasible points for detector placement.

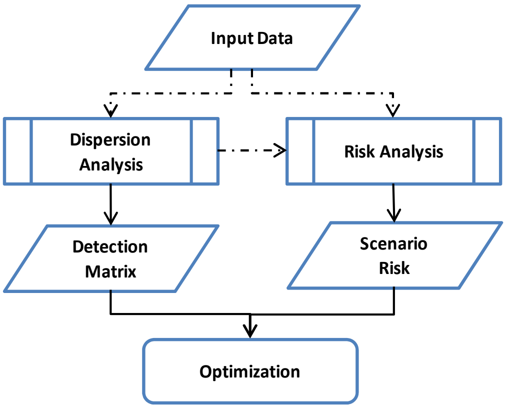

Figure 1: Steps of the risk-based detector placement methodology

2.2 Dispersion Analysis

Release of gas in a leak event results in a flammable gas cloud which is detectable by sensor if gas concentration is above a specified set-point. For instance, it is common to set 20 % LEL (Lower Explosive Limit) for Low Alarm and 50 % for action level (HSE, 2011). In this step, for each defined scenario included in the scenario set, 3D concentration contour or cloud shape is determined via dispersion analysis. In our case study, we used DNV PHAST software for dispersion simulation. Since PHAST gives the results of dispersion modelling in 2D graphs, the results were imported into MATLAB to build 3D surface of the gas cloud. The results of dispersion modelling will be used for two purposes: estimating risk of each scenario and finding the grid points that can detect a specific scenario (detection matrix). Detection matrix (DI) is a binary matrix which indicates the possibility of detecting a scenario in a grid point. It is defined as:

$$DI(s,l) = \begin{cases} 1, & s \text{ is detectable by } l \\ 0, & s \text{ is not detectable by } l \end{cases}, \forall s \in S, \forall l \in L \qquad (1)$$

Where s denotes scenario index and l is grid index. S is set of all scenarios and L is set of all grids. A scenario is detectable by a grid point if the grid point is located inside gas cloud of the scenario or if the concentration of flammable gas resulted from the scenario is greater than or equal to the detection set-point at the grid point. For our case, this matrix was computed by means of computational geometry algorithms which determine the containment of a point within a 3D surface (known as point-in-polyhedron problem (Linhart,1990)).

2.3 Risk Analysis

Risk of an unmitigated flammable release is a function of Damage (D) and frequency (f). Damage itself is a function of gas cloud volume, congestion degree (VCE rather than Flash Fire), occupancy and distance to high-value assets. To address the most important factors involved in risk of a flammable gas release, in the present research, the risk associated with a scenario is defined as the following function:

$$R(s) = f_s P_{d,s} D_s \qquad (2)$$

Where f_s is scenario frequency, $P_{d,s}$ is probability of delayed ignition and D is Damage. Probability of delayed ignition is the chance of a flammable release to become an accident (Flash Fire or VCE). Eq(2) gives the maximum risk of a release (if unmitigated). If detected earlier, there would be lower risk and more chance to prevent the accident. Frequency of a scenario (f_s) in terms of occurrence per year is determined as follows:

$$f_s = f_e P_w \qquad (3)$$

Where f_e is frequency of leak event *e* (given as input data) and P_w is the probability of weather condition *w* found from wind rose diagram. $P_{d,s}$ is computed from distribution of ignition sources and flammable gas cloud area by a risk analysis tool, here PHAST RISK.

Damage is evaluated in terms of fatality number and asset financial loss for each scenario. In our case study, Damage was assessed via consequence modeling and vulnerability models defined in DNV PHAST RISK software. Since money and fatality are inconsistent and could not be summed, a semi quantified categorization method was taken from the company modified risk matrix (which can be different for other companies). According to Table 1, the fatality number and asset loss are converted to the same category level (1-5) and this damage level is used as D_s in risk calculation Eq (2). However, where only one type of consequence is important, the damage could be used directly without converting.

Table 1: Safety and Asset Consequence Categorization

Damage Level	Safety (Number of fatality)	Asset Loss (Million Dollar)
1	0-0.5	<0.5
2	0.5-1	0.5-5
3	1-2	5-10
4	2-10	10-50
5	>10	>50

3. Optimization: problem formulation

The risk based MILP formulation for optimal placement of flammable gas detectors is given by:

$$\min\ f = \sum_{\forall s \in S} \sum_{\forall l \in L_s} r(s,l) x_{s,l} \tag{4}$$

Subject to:

$$\sum_{\forall l \epsilon L} b_l \leq p \tag{5}$$

$$\sum_{\forall l \in L_s} x_{s,l} = 1, \forall s \in S \qquad (6$$

$$x_{s,l} \leq b_l, \forall s \in S, l \in L_s \tag{7}$$

$$b_l \in \{0,1\} \tag{8}$$

$$0 \leq x_{s,l} \leq 1 \tag{9}$$

The formulation is an extension of Legg's work (Legg,2012) called SP formulation. The objective here is to minimize total residue risk by detecting high risk scenarios at the closest possible locations (or alternatively maximize reduced risk). Residue risk , r(s,l), at each point is defined as the risk of scenario *s,* which would still be remained if a detector is placed at location *l*. Residue risk is pre-computed before optimization step and is given by :

$$r(s,l) = w(s,l)R(s), \quad l \in L_s \tag{10}$$

Where L_s is the set of all grids that can detect scenario s (found from Detection Matrix), R(s) is the risk of scenario s, found from Eq(2) and w(s,l) is the distance weight factor defined as a linear function of distance:

$$w(s,l) = w_m + (w_M - w_m).\frac{d(s,l)}{d_M(s)} \tag{11}$$

Where d(s,l) is distance between source of scenario, s, and location *l*. $d_M(s)$ is the maximum distance travelled by gas cloud of scenario s (found from dispersion analysis). w_m and w_M are minimum and maximum weights respectively. Based on this equation, points closer to the source get smaller weight factor and consequently

smaller residue risk. This definition reflects the fact that there is more chance to reduce risk at points closer to the source because of shorter detection time. Decision variables in this formulation are b_l and $x_{s,l}$. b_l is a binary variable which takes values of 1 and 0. Value 1 indicates that a detector is installed at location *l.*
$x_{s,l}$ is a continuous variable indicating the location which first detects s. Although continuous, it takes final value of 1 or 0 with regard to Eq(6) and Eq(9). Value 1 indicates the location that first detects s. Eq(5) limits the maximum number of detectors to be less than *p*. Eq(6) requires each scenario to be detected by at least one detector. To consider cases that scenario *s* is not detected by any detector, a dummy location is added to L for which the weight factor is set to 1 (as a penalty).

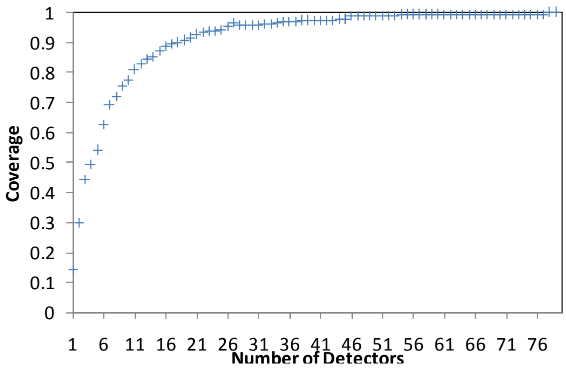

Figure 2: Coverage vs. Number of detectors placed

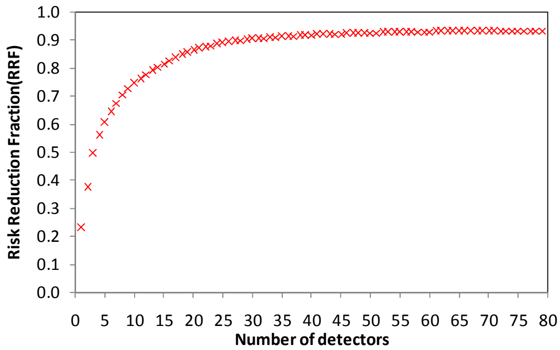

Figure 3: Risk Reduction Fraction (RRF) vs. Number of detectors placed

4. Case-Study

4.1 Description

The proposed methodology was tested on one of the process units of a petrochemical plant located at Asalouyeh, Iran. The monitored process area was a 70 m ×100 m x 3 m volume. From a previous QRA (Quantitative Risk Assessment) study most of the required data were available. A set of 394 release scenarios was defined at three weather categories and 4 wind directions. Leak sizes were selected from a range of 20 to 50 mm. Required data including frequency of leak events, ignition sources , probability of delayed ignitions, wind rose, occupied locations were provided from the QRA study. Dispersion study and Consequence assessment for each scenario were performed using DNV PHAST software. Monitored area was gridded with around 408 potential locations at three elevation levels (1-3 m).

4.2 Results

The optimization problem was solved by MILP solver of MATLAB changing the maximum number of possible detectors (p) up to 80 detectors. Coverage (fraction of detected scenarios) of the optimal layouts has been computed as shown in Figure 2. Increasing the number of gas detectors will lead to a raise in detection coverage. Full coverage is provided by 51 detectors while 19 detectors are required for 90 % coverage. To analyse risk reduction performance, Figure 3 shows the Risk Reduction fraction (RRF) which is given by :

$$Risk\ Reduction = 1 - \frac{f}{\sum_{\forall s \epsilon S} R(s)} \tag{12}$$

Where f is computed from Eq(4) at the optimum layout and the denominator is total risk of the all scenarios. This parameter shows how much the proposed layout could reduce the overall risk of defined scenarios. From this figure, the number of required detectors for 90 % reduction in risk would be 29 while there would be only 19 detectors required for 90 % coverage (as a normal goal for a detection systems). With 19 detectors RRF would be 80 %. This result demonstrates that relying on coverage goal may not reduce risk to the same desired level set as acceptable risk. Figure 2 and Figure 3 provide a valuable tool for deciding on the required number of detectors according to the desired risk reduction target. As observed in Figure 3, RRF does not converge to 1 by increasing the number of detectors further and approximately 10 % of total risk remains irreducible. This could be explained by the fact that the set of potential locations has a minimum distance to sources of scenarios and according to Eq(11) weight factor may not essentially converge to zero. The optimum layout for 29 detectors (90 % Risk Reduction) is shown in Figure 4.

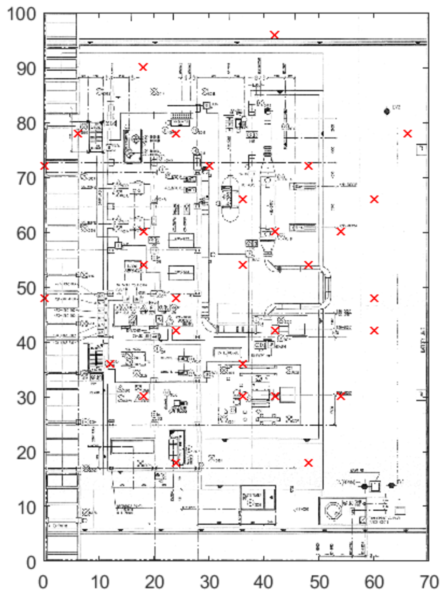

Figure 4: Detector Layout in the process unit for 29 detectors- (×) shows detector location

5. Conclusion

A risk-based methodology consisting of four main steps for gas detector placement was proposed. Using the proposed optimization formulation, minimum number of detectors could be easily found to achieve a certain risk-reduction goal. The output of this methodology including coverage and risk reduction diagrams could be combined with the current standards to improve the design of gas detection systems in open process plants. The applicability of this methodology was demonstrated in a case-study and it was shown that the risk-based approach can improve the detection layout design by reducing the risk to the desired level.

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