Performance Based Gas Detection: Geographic Vs Scenario Based Approaches using CFD

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Performance-based approaches have started being used in the design practice of fire and gas systems. In particular, two different approaches have been developed:

Geographic Approach. Once the target sizes of gas cloud to be detected have been fixed, the Geographic Approach consists in a geometric exercise to determine a regular array of detectors spatially arranged to achieve the required availability and coverage performance.

Scenario Approach. This approach is based on a complete assessment of the potential release scenarios in terms of frequency of release and modelling of dispersion.

This paper presents and compares the performance of two different gas detectors layout engineered for the same process area. The first layout is based on a regularly spaced layout of detectors; the second layout is defined based on an algorithm that exploits a Scenario Approach based and a large number of CFD dispersion scenarios. The results show that the Scenario Based approach can result in significant improvements in the performance of gas detection systems without any need to increase the number of detectors or increase costs.

Keywords: Fire and Gas Detection Systems, Performance Based, Scenario Based Approach, CFD.

Introduction

The Fire & Gas (F&G) Detection System is an important Safety Critical Element (SCE) of installations handling flammable/toxic fluids.

Prescriptive practices have traditionally been employed in the evaluation of the spatial layout of detectors [NFPA 72, EN 54-2]. The prescriptive approaches have advantages since they provide simple methods of detector layout generally giving good coverage and the design can be implemented relatively quickly. However, this could mean a larger number of detectors are required and may not give optimal coverage, particularly for open process areas, and there is no room for optimization of layout during design. Additionally, prescriptive practices do not allow a sound link to be established between the Risk Assessment of the installation and the F&G System design. This link is naturally present in that the risk assessment will assume values for the availability and coverage of detectors, which both contribute to a successful detection. Correctly modelling the probability of successful detection, allows the mitigating effects introduced by the detection to be represented properly in the risk assessment.

As a consequence, performance-based approaches have started being developed in the design practice of fire and gas systems [ISA-TR84.00.07-2010]. In particular, two different approaches have been developed:

Geographic Approach. Once the target sizes of gas cloud have been fixed, the Geographic Approach consists in a geometric exercise to determine a regular array of detectors spatially arranged to achieve the required availability and coverage performance.

Scenario Approach. This approach is based on a complete assessment of the potential release scenarios in terms of frequency of release and modelling of dispersion.

There are pros and cons between these two approaches. The Geographic Approach involves relatively simple algorithm with little physics of gas release and dispersion involved. This procedure can be done manually. The Scenario Approach, while computationally more intensive - especially when Computationally Fluid Dynamics CFD codes are employed - allows detector layout to be optimized to achieve high level of availability and coverage for key scenarios and above a threshold level for all others.

It should also be noted that current target performances for F&G systems – as developed by most operators – rely on the definition of a separation distance between adjacent detectors in a regularly spaced array. This distance depends on the characteristics of the area under consideration (in terms of confinement and congestion) and is clearly the main driver of the layout in terms of number of detectors. Whilst the Geographic Approach can readily allow for a regular array of detectors to be implemented, it is generic and lacks any real ability to take account of variations within the area. On the other hand, the Scenario Approach, especially when performed with CFD tools, is the natural tool to determine detector location because it can take into account the specific details of the area under consideration by properly modelling dispersion and explosion scenarios from actual pipework locations.

To date, the Geographic Approach has been the preferred approach used by Companies and Consultants due to its simplicity. The Scenario Coverage approach, on the other hand, is more computationally intensive but has the potential to provide an optimized layout of detectors which may result in important saving in terms of number of detectors [Benavides-Serrano, 2015] and better coverage.

The main purposes of this paper are:

- To introduce a specific methodology for the definition of a gas detector layout that is based on a Scenario Approach
- To test its performance against a Geographic Approach.

The comparison will be carried out for two well characterised and defined installations: the first one is a process area of an onshore gas-oil separation plant and the second one includes the topsides of a FPSO (Floating Production Storage Offloading).

Geographic and Scenario Based Approaches: Description of Methodologies

Both the Geographic and Scenario Based approaches considered in this study are "volumetric" approaches after the nomenclature provided in [CCPS, 2010]. The "volumetric" approach recognizes that the hazard associated with flammable gas clouds is the resultant overpressure that can occur upon ignition. The "volumetric" approach regards it as impractical to design a network that can detect all the leaks down to the smallest release rates. The network should rather be designed considering the size of releases that can result in a gas cloud of sufficient size to generate damaging overpressure (upon ignition). In particular, a 0.15barg overpressure is often considered to be the minimum overpressure that can result in damage. Based on this, a critical size of the gas cloud is determined as the size of the gas cloud capable of resulting in 0.15barg upon ignition ("critical gas cloud"). The volumetric approach is based on the principle that in the given volume the "critical gas cloud" cannot exist without being detected.

Geographic Approach

As already mentioned, traditionally, the "volumetric" approach has been based on a purely geometric method indicated as "Geographic Approach" [ISA-TR84.00.07-2010]. In the Geographic Approach, the gas detectors are regularly spaced based on the size of the "critical gas cloud" (see Figure 1). The principle is simple: no gas cloud larger than the critical size will exist without being detected.

One of the potential weaknesses of this approach is that the detectors are distributed on a regular grid that is not based on the actual flow patterns or the preferential regions of gas accumulation. In other words, the detectors are distributed uniformly in the space but, in reality, the actual map of probability of gas presence is far from being uniform. Reasons for a non-uniform distribution of gas probability in the space can be: prevailing wind directions, recirculation/stagnant areas and high pressure versus low pressure process segments. Due to the natural non-uniformity of the gas distribution, a uniform distribution of detectors is likely to result in a layout of detectors that is not optimised.

An equally important potential weakness consists in the foundation itself of the approach. The principle behind the layout engineered with a Geographic Approach is that an accidental release occurring within two adjacent detectors is successfully detected. Whilst this assumption has a physical foundation for optical devices (that are characterised with a well-defined field of view like IR flame detectors) its validity is questionable for point gas detectors that can only record the presence of gas when the gas reaches the precise location of the device. In fact, a realistic elongated cloud (due to a pressurised release) may well originate within the detector network without being detected (see Figure 1).

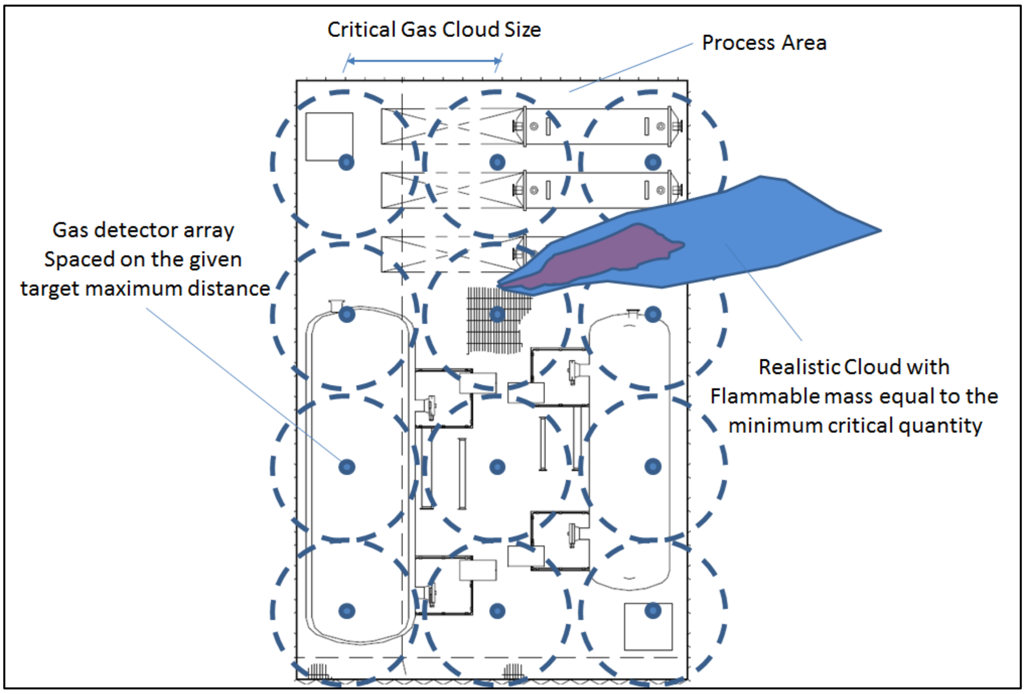

Figure 1: Schematic of a point gas detection layout based on a Geographic Approach. In the "geographic approach", the gas detectors are regularly spaced based on the size of the "critical gas cloud".

Scenario Based Approach

The Scenario Based Approach developed in this work still exploits a "volumetric approach" but explicitly models the dispersion scenarios. Depending on the accuracy of the model used to calculate dispersion, the approach can embrace, in principle, all the physics underlying the problem:

- rate of release and dispersion,
- density of the release,
- equipment arrangement,
- patterns of wind flow
- transient nature of the gas cloud build-up.

The Scenario Based Approach considered in this study exploits 3D CFD modelling. The use of CFD allows realistic modelling of the effect of site specific wind conditions, geometry and the composition of the release (heavy or buoyant gas). The approach is clearly more "fundamental" than the Geographic Approach because it provides the realistic gas concentrations at any point in the space following the release. Differently from the Geographic Approach, this allows it to determine, without any further assumptions, whether the detectors are able to detect a given release. Several steps of the approach described in the following are in common with the QRA (Quantitative Risk Assessment) that would normally be carried out for the facility. Hence, much of the data required in the analysis may be relatively easy to retrieve from existing analysis.

The workflow for the Scenario Based Approach applied in this study is described in the following.

Geometry Representation.

The detailed 3D geometry of the process areas is created by importing the 3D model of the facilities into the FLACS CFD software. This procedure is quite well-established when using CFD for the QRA of offshore facilities and since it exploits existing data (in terms of the 3D model) guarantees a detailed description of the geometry with relatively little effort.

Selection of the Leak Rate

As already mentioned, the Scenario Based Approach considered in this study is a "volumetric approach". The approach is based on explicitly modelling the dispersion scenarios that can result in the "critical gas cloud". Preliminary dispersion and explosion CFD simulations are needed to find the leak rate (kg/s) that can result in the "critical gas cloud". For simplicity, this leak rate is then used for all the CFD simulations and is indicated as "design leak rate". The selection of this release rate is based on a balance between the need for detecting all the leaks and the need to avoid expensive overdesign. In other words, the "design leak rate" must be small enough so that it correctly represents the smallest category of leaks that need to be detected, whilst being large enough to avoid over conservative design that would require an unrealistic number of detectors (for detecting non-hazardous releases). In this study, the flammable clouds which, upon ignition can generate overpressures equal or above 0.15 barg (considered as a damage threshold) have been considered hazardous. Hence, the approach to find the "design leak rate" was to calculate the size of the flammable cloud (m^3) corresponding to 0.15 barg and from this to calculate the (minimum) release rate (kg/s) that can lead to this size of cloud. In order to accomplish this, specific dispersion simulations were preliminary run and the relative explosion overpressures recorded.

Determination of the Release Conditions

This step identifies the conditions of the release in terms of temperature and composition. It is important to have a good representation of these quantities since they will affect the dispersion behaviour in terms of the relative density of the plume with respect to air (heavy gas or buoyant gas). This step can also exploit data available from the QRA or, in the absence of these, specific "discharge calculations" can be performed starting from project specific data such as the Heat and Material Balances.

Selection of Wind Conditions

The wind conditions, in terms of wind direction and wind speed, have an important effect on the ventilation flow patterns in the process areas which, in turn, may greatly affect the effectiveness of the position of gas detectors. The ventilation flow patterns will determine the preferential dispersion routes of accidentally released gas. The spatial gas concentration profiles will be determined to a great extent by the local ventilation characteristics: effective ventilation will quickly dilute the gas while poor ventilation will determine potential areas of gas accumulation. Wind direction and wind speed are far from being constant with time and follow a statistic distribution of occurrence. Whilst it is impractical to model the ventilation conditions for all the possible wind combinations, it is important to capture the prevailing combinations of the site-specific wind conditions distribution.

Selection of Leak Locations

The gas concentration profiles following an accidental release will depend on the position of the release point. Whilst it is obviously impossible to simulate releases originating from any point in the area, it is important to select the most likely positions in the process area that can originate leaks: flanges, valves, rotating machineries, areas with high density of small bore tubing etc.

Determination of the Release Frequency

As it will be further discussed, the 3D dispersion results, in terms of the spatial extent of the gas clouds, are coupled with the frequency of release in order to obtain a 3D map of probability of presence of gas (following an accidental release). Each release scenario is then assigned a frequency of occurrence (events/year). This frequency of occurrence will be the combination of the frequency of the accidental release and the probability of the specific wind condition considered. The frequency of release can be, again, obtained from the QRA which in turns may refer to well-established database of historical data. It should be noted that only one release rate has been modelled in the study ("design leak rate") and a detailed split of the frequency of release based on the actual leak category (small, medium, large) has not been attempted. In particular, the total frequency of release has been assigned to the representative release rate. It should be noted that the aim of the study is not to provide a detailed coupling of consequence and frequency that are split after release categories (as it would be done in a QRA). The aim of the analysis is rather to exploit the frequency of release data in order to identify the areas with the higher potential for accidental release.

Determination of the gas concentration profiles

This step aims at simulating the 3D dispersion for a significant number of release scenarios. The word "significant" in this context means that the selected scenarios include the most likely release points together with the most likely wind conditions and several leak directions (as a minimum 6 leak directions are considered). This can well result in over 1000 CFD simulations for each process module (depending on the complexity of the process).

Determination of the Probability of Gas Presence

One of the most important outputs of the methodology is a 3D map that combines all the single CFD simulations and weighs them based on their frequency of occurrence. This map provides - for each point in the space - the total frequency (events/year) of gas exceeding a given threshold (typically the lower detection threshold). This map takes into account at the same time the correct physics of dispersion, realistic points of release and the actual frequency (as calculated for example from QRA). Overall this map conveys all the available realistic information that determines and characterizes the spatial distribution of probability of gas upon accidental release. Intuitively, selecting the location of the gas detectors based on this map can result in a more soundly based selection of the detector layout (compared to the Geographic Approach).

Determination of the optimum Location for Gas Detectors

The map obtained in the previous step is used to define an optimal position for the gas detectors. Details of the algorithm can be found in [Huser, 2004] and here is just worth to mention that the algorithm prioritizes the position of the detectors based on the areas with the higher probability of gas presence.

The latter point is thought to be relevant in understanding the differences in the layout that can be proposed respectively by the Geometric Approach and the Scenario Based Approach and will be further discussed in the following.

Results and Discussion

This Section will present the gas detection layouts (in terms of number and position of devices) as obtained from applying to the same facilities respectively the Geometric Approach and the Scenario Based Approach.

Coverage

In the context of the Geographic Approach the performance of the detection layout is measured in terms of a volumetric coverage. Based on the selected size for the critical gas cloud, the volume where potential leaks can be detected is estimated and its ratio to the overall volume calculated. Though more refined approaches based on a risk rating of the process areas are also used, this quantity is usually indicated as the coverage when a Geometric Approach is used. As already discussed, is not entirely legitimate assuming that a point gas detector is characterised with a radius of detection. On the other hand, the Scenario Based Approach offers the possibility to quantify in a more clear way the performance of the network. Knowing the concentration profiles and the position of the detectors will directly result in the number of detected leaks. In this context the coverage can be expressed as the ratio of the number of detected leaks to the total number of scenarios.

Terms of Comparison

The terms of the comparison are summarised as follows:

- Two different facilities will be assessed: one is an onshore process module (indicated as Facility 1) and the other one consists in the topsides of an FPSO (indicated as Facility 2)
- Two different detector layouts will be assessed for each facility: one is based on the application of the Geographic Approach and the other one is obtained by the Scenario Based procedure described above.
- The two layouts (Geographic vs Scenario Based) will be assessed against the same set of dispersion simulations (one set of dispersion scenarios for each Facility)
- The performance of the two methods will be measured in terms of the fraction of the detected leaks

Facility 1

Facility 1 is an onshore process module where inlet gas is chilled before being dehydrated. The module consists of three main levels with two gas chillers and one high pressure separator. An isometric view of this module is shown in Figure 2.

The probability map was obtained by combining about 700 simulations that were run with a release rate of 2 kg/s.

The two detector layouts are sketched in Figure 2. The layout based on the Geographic Approach (Figure 2a), consists of a regular array of point detectors (10m spacing for a total of 21 point detectors) distributed on three levels and a set of LoS (Line of Sight) distributed on one level of the module (5 LoS detectors in total; not displayed in the picture). The choice of the spacing is based on the CCPS publication [CCPS, 2010] and current industry practice for open, moderately congested areas. The layout based on the Scenario Based Approach is shown in Figure 2b and consists of exactly the same number of gas detectors (21 point detectors + 5 LoS) but is obtained with the Scenario Based Approach described in Section 2. Starting from these configurations, the number of the detectors has been increased in the two layouts in order to obtain the trends plotted in Figure 3. In particular, for the Geographic Approach, another layout has been obtained by halving the spacing (5m) between detectors and obtaining a total of 64 detectors. One additional layout has been obtained using the Scenario Approach with the same number of detectors (64) but at optimised locations.

Figure 3 summarizes the performance of the layouts that have been described above. It provides the coverage as a function of the number of detectors for the layouts calculated respectively with a Scenario Based Approach (solid lines) and a Geographic Approach (dotted lines). The plot displays results for two voting logics: 1ooN and 2ooN, often used for Alarm and Shutdown respectively. From Figure 3 it is evident that the layouts based on the Scenario Approach provide a much better performance since they guarantee a higher coverage with the same number of detectors. It is also interesting to note that the trends suggest that while the layout based on the Scenario Approach can achieve a satisfactory coverage (90%) with 64 detectors, many more detectors will be necessary to reach the same coverage for the layout based on the Geographic Approach.

Reference to the probability maps helps in understanding the reasons behind the different performances of the two approaches. Figure 4 displays the map of probability of gas presence at several vertical cuts (planes xz) for Facility 1. As already mentioned, this map represents the regions that are most likely to be occupied by the gas due to the prevailing flow patterns. It can be noted that the left side of the module tends to have higher probabilities of gas presence. This is explained in terms of both the prevailing wind direction of the site and the higher density of potential release points close to the gas chillers. The non-uniformity of the gas distribution explains why a regular array of detectors will not be optimal. The fraction of detected leaks is maximised by using a higher density of detectors where the probability of gas presence is higher. Equally, the high density of detectors where the probability of gas presence is low does not contribute to the coverage and may result in a costly over-design if a Scenario Approach is not used. This over-design would also result in increased maintenance and testing costs in operations.

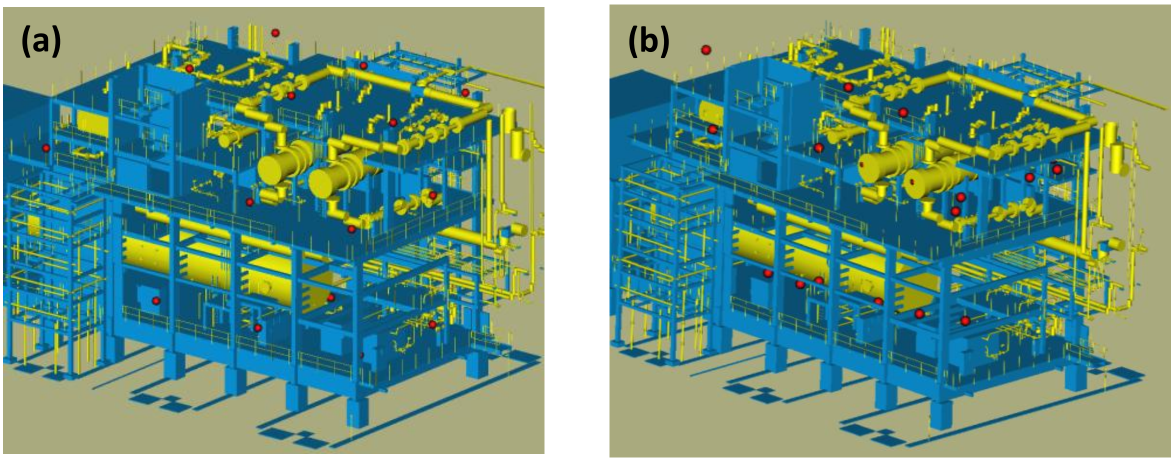

Figure 2 – Isometric views of Facility 1 (a): point detector layout in a regular array after the Geographic Approach for 10m spacing; (b) Scenario Based Approach layout.

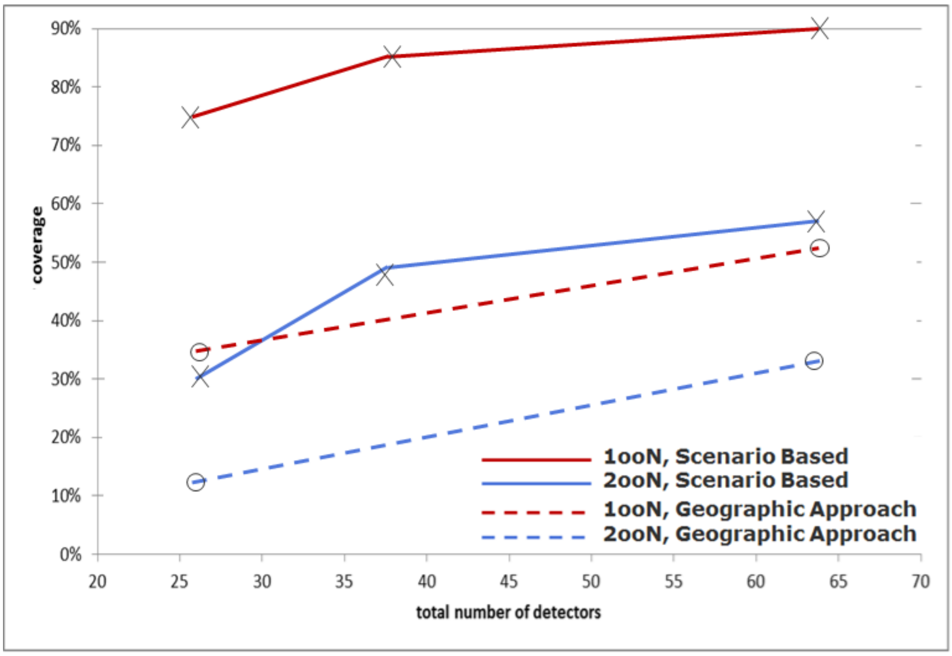

Figure 3 – Facility 1; Coverage as a function of the number of detectors for the layouts calculated respectively with a Scenario Based Approach (solid lines) and a Geographic Approach (dotted lines). The plot displays results for two voting logics: 1ooN and 2ooN.

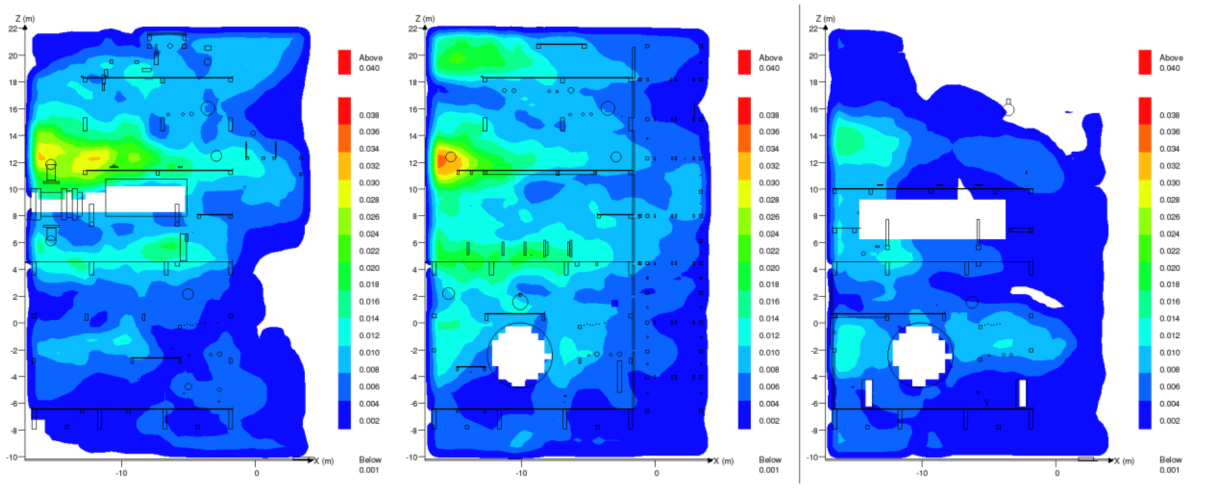

Figure 4 – Map of probability of gas presence at several vertical cuts (planes xz) for Facility 1. The map displays some "hot spots" where the probability of gas presence is larger.

Facility 2

The second facility consists in the topside of a turret moored FPSO. The topsides include process modules to stabilise the crude and to export the gas and utility modules for power generation and chemicals injection. An isometric view of the FPSO is shown in Figure 5.

The probability map was obtained by running about 2000 dispersion simulations that were run with a release rate of 1 kg/s.

The two detector layouts are sketched in Figure 5. The layout based on the Geographic Approach (Figure 5a), consists of a regular array of point detectors with 5m spacing for a total of 104 point detectors distributed on one level of the topsides (the layout also includes a set of 14 LoS not displayed in picture). The choice of the spacing is based on the CCPS publication [CCPS, 2010] and current industry practice for congested areas. The layout based on the Scenario Based Approach is shown in Figure 5b and consists of the same number of gas detectors (104 point detectors + 14 LoS). Starting from these configurations, an additional two layouts have been created by increasing the number of detectors and the trends plotted in Figure 6 have been obtained. In particular, for the Geographic Approach another layout has been obtained by adding another layer of equally spaced detectors at another elevation (for a total of 204 point detectors plus 28 LoS detectors). The same number of detectors has been used for creating the second layout based on the Scenario Approach.

From Figure 6, as already observed for Facility 1, it can be seen that the layouts based on the Scenario Approach provide a much better performance: for the same number of detectors the Scenario Approach provides a higher coverage.

The same considerations used to discuss the results for Facility 1 also apply here. Reference to Figure 7 suggests that the probability of presence of gas is far from being uniform for Facility 2 as well. In this case, preferential gas accumulation occurs on the Starboard side of the FPSO (gas treatment) due to an elevated concentration of potential gas release points. It can be seen that also in this case a regular array of detectors equally spaced is not the optimal choice in terms of maximising the coverage.

Conclusions

Performance based approaches for determining the F&G layout of Oil & Gas facilities have become industry practice. The quantification of the coverage of the F&G system can be used for a realistic estimation of the effectiveness of mitigation systems activated by the F&G system. Different approaches have been developed to evaluate the coverage of process areas. The methodologies differ for the principles they are based on and the cost/complexity of defining the layout.

This paper has shown that an approach that explicitly models the dispersion scenarios (Scenario Based Approach) and the likelihood of the releases can in principle provide an optimized layout as opposed to an approach that does not consider the physics of dispersion. In this context the word "optimized" means the capability of maximising the coverage with a given number of detectors. An optimised F&G layout ensures that the maximum benefit is obtained from any investment in a gas detection system and avoids costly over-design or misuse of resources. The significant improvement in the performance in gas detection systems this offers will ultimately improve safety and reduce the threat to an asset at no additional cost.

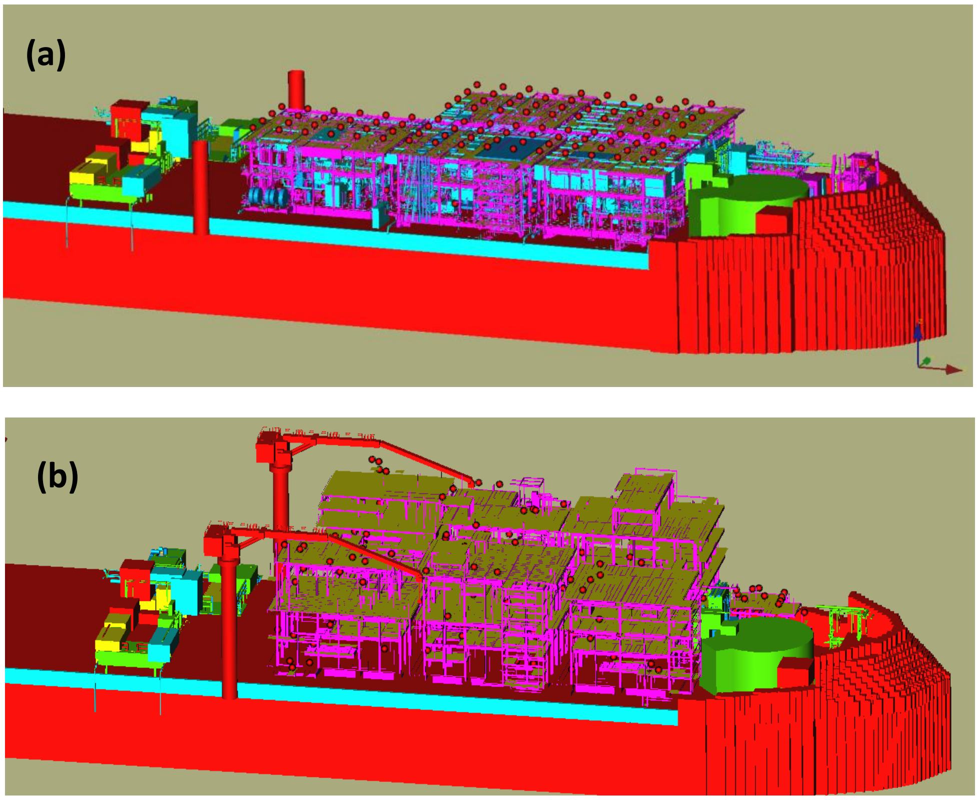

Figure 5 – Isometric views of Facility 2 (a): point detector layout in a regular array after the Geographic Approach for 5m spacing; (b): Scenario Based Approach layout.

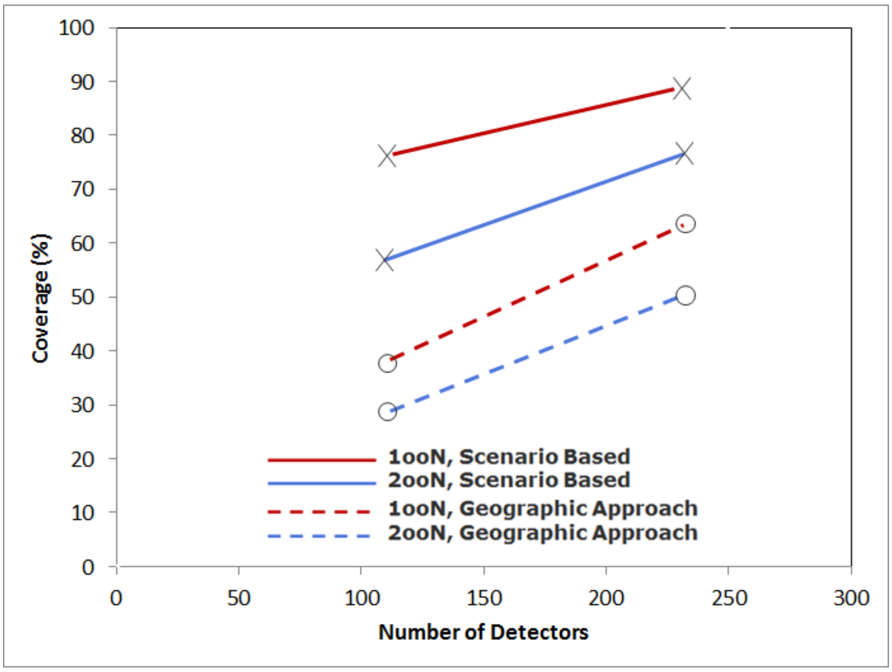

Figure 6 – Facility 2; Coverage as a function of the number of detectors for the layouts calculated respectively with a Scenario Based Approach (solid lines) and a Geographic Approach (dotted lines). The plot displays results for two voting logics: 1ooN and 2ooN.

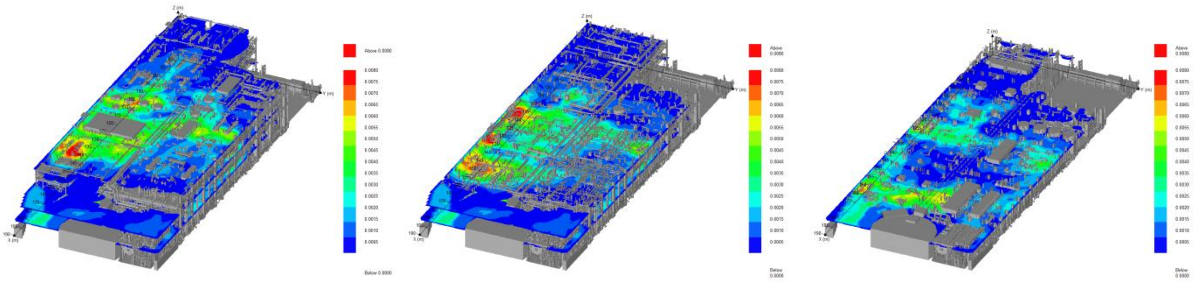

Figure 7 – Map of probability of gas presence at several horizontal planes for Facility 2. The map displays some "hot spots" where the probability of gas presence is larger.

References

A.J. Benavides-Serrano, M.S. Mannan, C.D. Laird, 2015, A Quantitative Assessment on the Placement Practices of Gas Detectors in the Process Industries, Journal of Loss Prevention in the Process Industries Volume 35, 339–351.

CCPS, 2010, Continuous Monitoring for Hazardous Material Releases.

EN 54-2: *Fire Detection and Fire Alarm Systems Part 2: Control and Indicating Equipment*.

A. Huser, L. F. Oliveira; J. Dalheim, 2004, Cost Optimization of Gas Detector Systems, Proceedings of OMAE04 23rd International Conference on Offshore Mechanics and Arctic Engineering, Vancouver.

ISA-TR84.00.07-2010 Technical Report, 2010: *Guidance on the Evaluation of Fire, Combustible Gas and Toxic Gas System Effectiveness*.

NFPA 72, *National Fire Alarm Code*, National Fire Protection Association.