A practical approach to risk-based gas monitoring system design for oil and gas offshore platforms

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Abstract: The paper discusses the framework of a practical but rigorous approach for designing a risk-based gas monitoring system for offshore oil and gas platforms, able to provide early warnings of gas leakage to anticipate the occurrence or the escalation of hazardous events. The appropriate placement of sensors within a specified platform geometry is a key factor to ensure a proper detection of leakages. The approach, based on modelling and mathematical formulations, aims at optimizing the placement of the sensors in terms of safety assurance and costs, going beyond the common practice of placing the sensors near the potential release points or spatially distributed according to predefined grids. The described work focuses on the process early steps and suggests a method for identifying a sufficient set of representative release scenarios for fluid-dynamic simulations. Their results are then aggregated to highlight the critical points on the platform decks, i.e. those where the gas concentration surpasses the lower flammable limits, either near but also far from the release points. Whenever the number of critical concentration points is too large with respect to constraints such as the maximum allowed number of sensors, optimization methods are used for selecting their best combination and placement.

Keywords: Smart Sensing, Gas Detectors, O&G Release Scenarios, Risk Assessment, CFD Simulations

1. INTRODUCTION

Since year 2014, the Italian Ministry of Economic Development has been supporting research projects to address the issue of oil and gas offshore safety in coherence with the adoption of the 2013/30/EU Directive. The SEADOG (Safety and Environmental Analysis Division for Oil&Gas) Laboratory at Politecnico di Torino has been founded within this supporting framework with the aim of multidisciplinary approaching a set of safety issues. A safety related research topic that is carried out within the Laboratory concerns the development of practical but rigorous approaches for the design of a risk-based gas monitoring system for offshore oil and gas platforms, able to provide early warnings of gas leakage to anticipate the occurrence or the escalation of hazardous events. The appropriate placement of sensors within a specified platform geometry is a key factor to ensure a proper detection of leakages. The methods most commonly employed for designing network of sensors are based on heuristic techniques that often do not address the optimization of the overall monitoring system and its ability to detect the full spectrum of potential release events. However, according to Legg et al. [1], "*there is significant uncertainty to consider when trying to determine the appropriate number and placement of gas detectors, including: leak location, gas composition, process conditions, the impact of surrounding geometries on dispersion, and weather conditions*" and with reference to the potential leak scenarios they support the opinion that the "*uncertainty associated with different leak scenarios is captured through hundreds of process-specific computational fluid dynamics (CFD) simulations*".

Based on these considerations, the research aims at defining a pragmatic approach based on modelling and mathematical formulations and at permitting an optimized and efficient placement of the sensors in terms of health and safety and costs by reducing the above-mentioned uncertainties.

Input to the method are the results of a sufficient set of the most credible release scenarios obtained by numerical simulations of gas spreading throughout the platform decks. To validate the method for its

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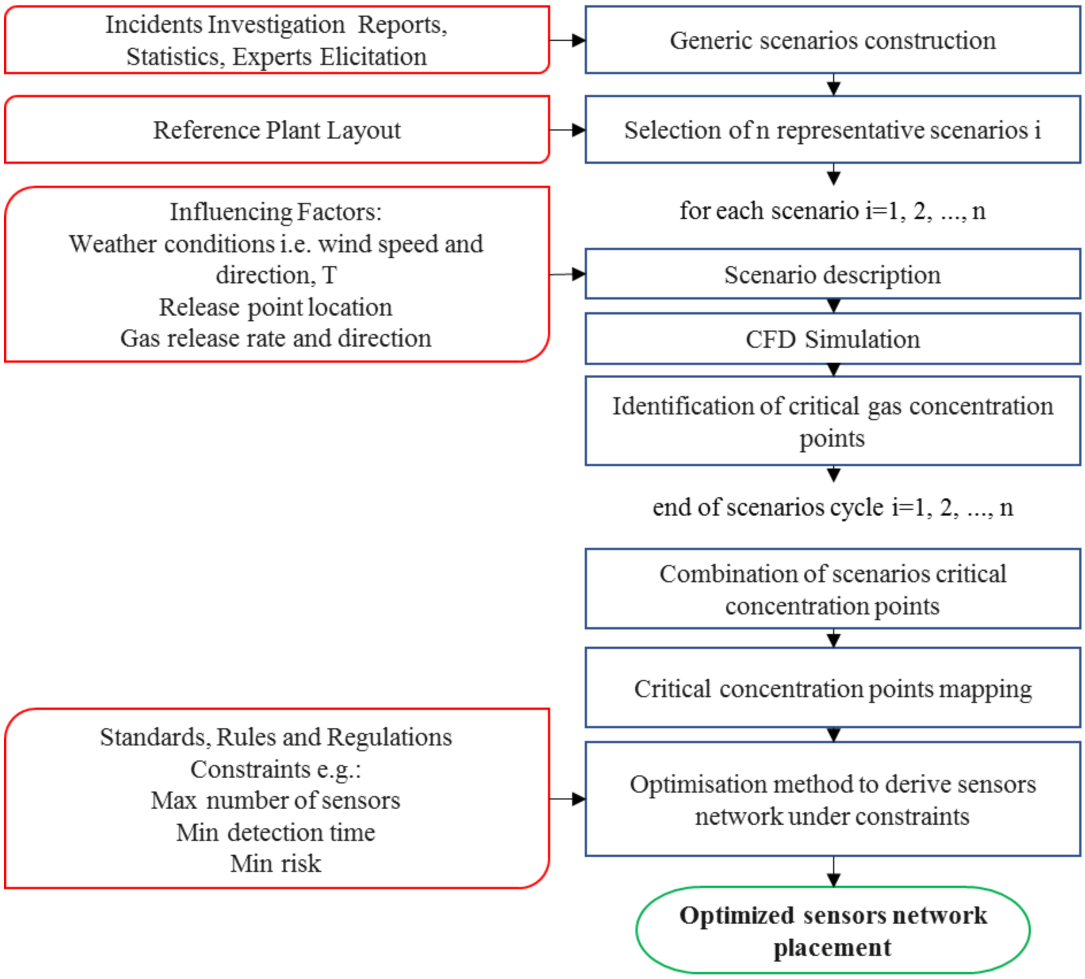
use on real projects of gas leakage monitoring design, tests of optimized sensor networks designed according to the suggested approach will be carried out on a reference platform design.

Following the description of the general risk-based framework (Figure 1) and the implementation process of the method for the design of the fire and gas detection system, the paper expands on the first steps of the procedure. Namely, it discusses and suggests a method for identifying a sufficient set of representative release scenarios for fluid-dynamic simulations. Their results are then aggregated to highlight the critical points on the platform decks, i.e. those where the gas concentration surpasses the lower flammable limits, either near but also far from the release points. Whenever the number of critical concentration points is too large with respect to constraints such as the maximum allowed number of sensors, the detection time, the risks among others, optimization methods are used for the selection of the best combination and placement of fire and gas detectors.

The method for the selection of the representative scenarios able to capture the most comprehensive set of the critical areas where the leaked gas could accumulate and reach the concentration leading to fire ignition, is subject to a few constraints. More precisely, when it is used during the design phase, the computational cost should be compatible with the project schedule so as to ensure the design reviews and milestones are met. To achieve that, we suggest that the method starts identifying the full spectrum of credible scenarios, considering process and material parameters, as well as external influencing factors, such as wind, air humidity and temperature, platform design and equipment layout but then uses a logic to select an exhaustive group for numerical simulation.

Figure 1: Risk-based framework for optimal gas detectors placement



Each scenario development is dynamically simulated using computational fluid dynamics methods and provides a three-dimensional map of the critical zones of the area of concern. The results of each scenario are aggregated to those obtained from the other scenarios to build a comprehensive 3D map of the system critical zones where potential fire and/or explosion could occur, and therefore where the presence of sensors for early warning is recommended. The specific design of a network of sensors is then conditional on constraints, such as their maximum number, the capability of installing them in the selected points, the logic used for defining the alarm and the action levels, and so on. The use of optimization methods will help the identification of the preferred network of sensors and their placement, able to satisfy the constraints given by the designers while complying with the requirements of the existing national and international regulations and standards [2,3,4,5,6,7,8,9].

2. METHODOLOGICAL APPROACH

The method developed in the current research is generic enough to be applied to different O&G platform designs and sizes and installed in different geographic locations and so subject to varied environmental conditions. It could also be applied to other industrial installations running process plants with characteristics similar to the O&G platforms.

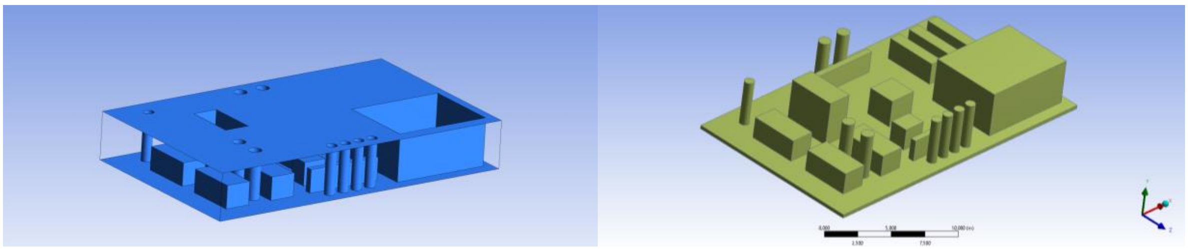
However, to deliver results with high technological readiness, the research described in the paper is carried out following an engineering method, where a reference platform design and its geographical location has been selected to test and adjust the general principles to realistic operational conditions dictated by a specific plant layout.

The simplified platform design and its location is described in the following section.

2.2. Reference platform design and location

The reference platform chosen for the simulations is drawn starting from a real oilrig design. While the platform topside is constituted by several decks and supported by a conventional jacket structure, for the sake of scenario assessment a single middle position deck, such as a production deck, is addressed and this only is the reference domain for the simulations (Figure 2). The considered deck is single as floor and ceiling are assumed to be plated: this is a conservative assumption since when natural gas is accidentally released, it is not allowed to disperse towards the upper decks through metal grated floors, but it is assumed to accumulate below the deck ceiling. The representative deck hosts process equipment, typically pressurised items such as pipelines, separators, compressors. For the purpose of the simulations, horizontal, vertical, cylindrical and flat equipment are considered as the most probable shapes that a gas jet would impinge during its release phase and be diverted by during dispersion.

Figure 2 Representative platform deck for CFD simulations (with and without ceiling)



As the SEADOG programme refers to the framework of the Italian Ministry of Economic Development task to overview and regulate Italian shelf platforms operations, the typical location chosen for the simulations is set in the central area of the Adriatic Sea. There, according to publicly available statistical data, the wind speed is in the range 3-7 m/s, recorded at 25 m above the sea level [10].

2.3. Scenarios numerical simulation

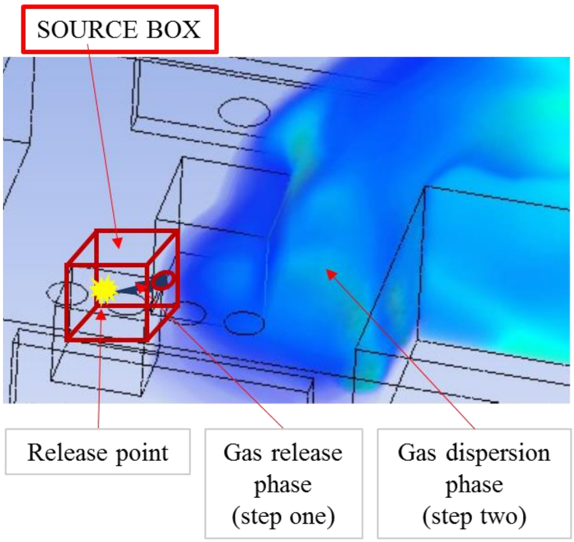
Computational Fluid Dynamic (CFD) simulations of release and dispersion of a gas can be carried out usually at a high computational cost, leading to possible failures of convergence, and quite often to a high time-consuming exercise. In these cases, the current practice is to limit the number of simulations to a very small set of scenarios, with the drawback that they may not represent the real variety of accidental conditions.

A hybrid CFD model [11] is proposed instead, to deal with the fluid dynamic problem of supersonic releases combined with subsequent dispersion. This two steps approach involves firstly the adoption of a strategy to parametrize the release phase, addressing it as a single phenomenon evolving within a geometric domain that is defined starting from the release dynamic characteristics (e.g. the jet velocity out of the rupture). This domain, which can be treated as a "source box", allows performing CFD evaluations in a more sustainable way, as only one macro-phenomenon is simulated. The source box can also host obstacles representing the real congestion of the deck induced by the presence of plates and cylinders grounded on the floor.

The CFD simulation of the release will take due account of the interactions of the jet with the surfaces of these obstacles. Once these simulations are performed, the gas molar profile and the flow field results calculated on the surface of the source box can be supplied to a second step simulation, that of the dispersion phase carried out in a domain that is large enough to include the whole remaining deck/platform.

Figure 3 shows an illustration of the two steps simulation of the hybrid CFD model.

Figure 3 Illustration of hybrid CFD model two steps simulation



The main advantage brought by this approach lays in the possibility of creating an offline library of source boxes representative of the most, possibly all, credible release scenarios (step one) while the real CFD simulations would benefit from the import of input data from this library to address only the dispersion phase (step two). This approach saves computational time allowing the analyst to address a larger number of release/dispersion simulations on the given layout. This last feature is largely valuable for the proposed method for optimizing the sensors positioning because it is expected that it will facilitate the simulation of an exhaustive number of scenarios, thus covering a sufficient spectrum of events.

2.4. Scenarios construction

The generic gas release scenarios discussed in this section are derived for the normal operation and maintenance of a single offshore O&G platform and they do not address simultaneous operations such as construction or drilling.

The scenarios construction started with the identification of the initiating events by complementing studies published in literature concerning loss of containment of offshore O&G platform process plants with review of statistics and incident investigation reports. According to Sklet [12], the initiating events can be divided into seven main categories, including plant and maintenance related events, human factors and external events. Among them and in a first instance, only the plant and maintenance related events are considered of relevance for our study because generic enough to represent a large variety of installations and geographical location and independent from operational staff performance. It was thus assumed that the following initiating events could produce a comprehensive set of release scenarios:

- latent failure introduced during maintenance,
- maintenance of hydrocarbon system requiring disassembling,
- technical/physical failures and
- process upsets.

Starting from the selected initiating events, an initial generic list of potential release events was derived, including mal-operation of valve(s) during manual operation, mal-operation of temporary hoses, incorrect fitting of flanges or bolts during maintenance, valve(s) in incorrect position after maintenance, erroneous installation of sealing device, failure of the isolation system during maintenance, degradation of valve sealing, degradation of flange gasket, loss of bolt tensioning, degradation of welded pipe, internal corrosion, external corrosion, erosion and overpressure.

A review of statistics [13], literature [14,15,16,17] combined with expert elicitation is currently underway to derive the range of frequency of each release event and their most probable physical occurrence on typical platform decks.

2.5. Representative scenarios selection

The most significative positioning of the sensors for early warning is highly influenced by the representativeness of the set of scenarios selected for the numerical simulation. It follows that the construction of the scenarios has the objective of creating a space of plausible events as much exhaustive as possible. They should be representative of the residual risk that the platform could experience such events during its life with negligible probability and for which the barrier system has been designed to mitigate the effects.

The general criteria for the construction of the space of scenarios are the following:

- at least one scenario per relevant potential release event should be selected,
- those release events which have higher frequency of occurrence should be covered by a greater number of scenarios,
- those release events located in areas where the influence of the external factors such as wind direction and speed and/or temperature is high, should be covered by a greater number of scenarios.

The number of scenarios to be analyzed, that can vary between e.g. 300 and more than 1000 [18] is influenced by the type and geometry of the platform under study and should be decided on a case by case basis. The significative and exhaustive number will be specified according to predefined criteria specifically determined by the type of plant. Example of criteria are the low, medium or high variability of wind direction and speed, the compactness of the layout, the barriers design, and so on.

The plant-related scenarios are then built by considering the following:

1. selection of realistic events from the set of generic release events as discussed in the previous section;
2. identification of the most probable locations for release occurrence;
3. map of the selected points of release and extraction of the most representative by applying criteria such as: frequency, existence of barriers, position with respect to the center or border of the deck, and so on.

An example of the application of the criteria set in point three above is given by a selected release point from a pressurised equipment installed in the central area of the deck or of the plant. In such a case, the release can be assumed being typical of a large quantity of accidental scenarios that may affect internals. Indeed, with reference to the representative platform of Figure 2, the release in a deck with plated floor and ceiling would run over the nearest equipment and be partially influenced by the wind stream which, in turn, has already lost some of its momentum flowing through the congested spaces of the platform. Another example of a complementing set of scenarios can feature a selected release point from an equipment set near to the platform edge that is primarily impacted by the wind stream: in this case, the gas release would invest the widest internal part of the platform, pushed by the wind in its flow within the deck.

It is worth mentioning that, even if the representative platform discussed in the previous paragraph has its own features, e.g. plated floors, the criteria defined above are sufficiently generic to be applicable to a variety of O&G platform designs. For example, in the case of grated floors, the considered release areas could be similarly chosen as for the representative platform, for accumulation spot investigation typically on upper decks.

The outcome of the current step will be a narrative description of each of the identified release scenarios typical of the platform under study.

2.6. Influencing factors

2.6.1 Weather conditions

The weather conditions, and primarily the atmospheric temperature and the wind direction and intensity influence the scenarios development. It is known that these factors may vary during the day time and the seasons within quite large ranges, e.g. wind speed [1 m/s, 30 m/s], temperature [-40°C, +50°C] and the construction of a representative set of scenarios should take into account these changes. The method here presented implements in first instance the following approach.

For each scenario the temperature is randomly selected from the mean annual distribution characteristic of the zone under study. Once the temperature is selected, the corresponding month is known, and the wind speed and direction are randomly selected from the mean wind distribution of the month. In this way each scenario is characterized by its own quantitative values of these factors, that are different from the other scenarios. The randomness of the approach has the advantage of covering a very large spectrum of wind and temperature variations during a typical year and this is captured individually by each scenario.

2.6.2 Gas flow rate and direction

The typical operations performed on a production deck involve low to high pressure fluids being supplied from wellheads to the rest of the processing units. To cover the widest possible set of scenarios, the following assumptions have been made to evaluate flow rates and dispersion patterns:
- A range of release pressures, varying from 5 to 100 bars,
- A set of rupture diameters, as standardized for risk analysis in [19]: 5mm, 30mm and 100mm.

Also, the direction of the release is an influencing factor; the horizontal and vertical upward or downward directions are chosen as the extreme most representative cases.

For general use of the hybrid CFD approach during the design of an O&G platform, the preparation of a catalogue of source boxes is preliminary carried out. In this first step, the numerical simulations are performed combining each rupture diameter with the set of pressure values in the range, preferably chosen adopting a 5 bar step increase from case to case and with the three representative release directions. The overall flow rates are then evaluated, so that a complete matrix is obtained. By using these results, the flow rate that characterizes each scenario is randomly selected from the matrix cells while the release direction is randomly selected among the three representative ones. The obtained figures are then used to extract from the offline library of source boxes the one representative of the specific release scenario under analysis, thus limiting the computational cost to the CFD simulation of the dispersion phase.

To be conservative, the release phase and the following dispersion are assumed to be continuously fed by the gas leakage through the rupture in a steady state flow condition after the initial acceleration up sonic and later supersonic condition. The release is then decelerated in space down to a speed comparable to the wind speed, when the dispersion phase starts.

It is important to note that only physically credible combination of influencing factors will be finally chosen for building the final set of scenarios to be numerically simulated and for each scenario the overall set of input data will be prepared.

An example of complete scenario characterization is given in Table 1.

Table 1: Example of scenario characterization for numerical simulation

Scenario # i	
Initiating event	"Degradation of valve sealing (release event)"
Release Point Location	Equipment in the central area of the deck
Gas Composition	100% CH_4
Pressure Release[1]	50 bars
Rupture Diameter[1]	30 mm
Release Direction[1]	Horizontal
Wind speed (at 25 m above sea level)[1]	6 m/s
Wind Direction[1]	North
Temperature (on the deck)[1]	28°C
Note[1]: each of these factors have been randomly selected according to the criteria set above	

A typical CFD dispersion result is shown in Figures 4 and 5.

Figure 4 CH4 concentration field from a dispersion simulation after a release in the central area

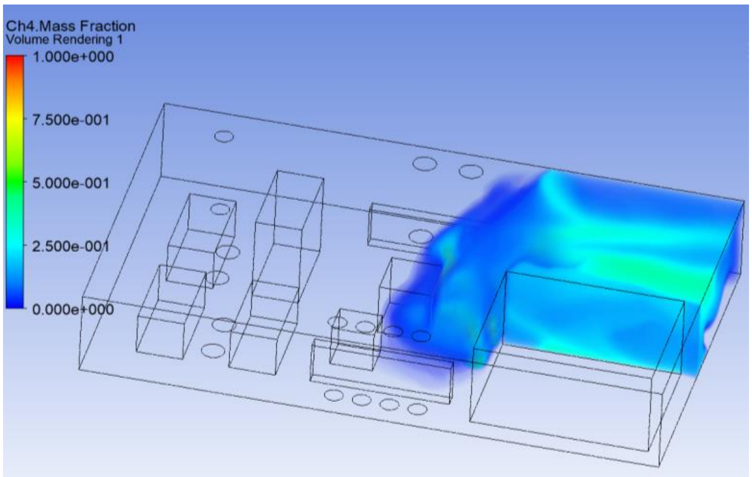
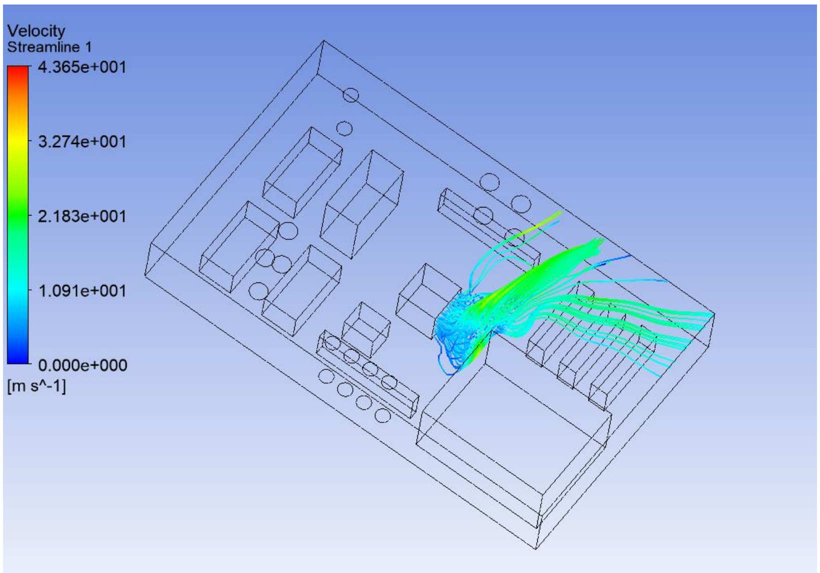


Figure 5 CH_4 velocity field from a dispersion simulation after a release in the central area



2.7. Optimization methods for sensors placement

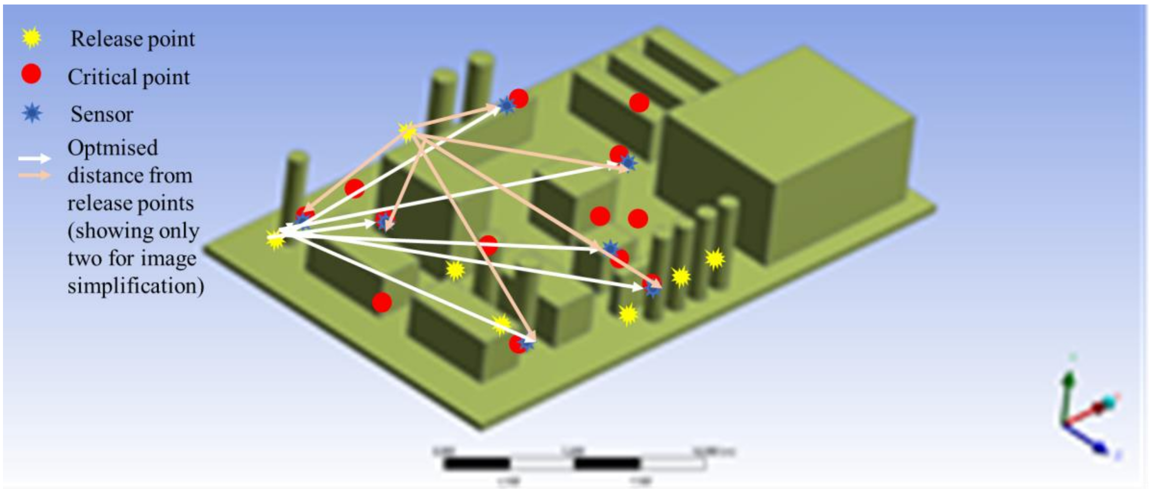
As stated in the previous section, a hybrid computational fluid dynamic method is applied to dynamically simulate each scenario development providing as result a 3D map of the critical zones of the area of concern. To capture the uncertainty associated with potential different leakages, the simulation is repeated for each selected scenario and the overall results are aggregated to build a comprehensive 3D map of the system critical zones where potential fire and/or explosion could occur. These are the areas where the gas concentration falls between lower and upper flammable limits. Indeed, within these limits the gas concentrations in air allow a flame front to spread when exposed to an ignition source, therefore where the presence of gas detectors for early warning is recommended, knowing that the combustible gas detectors are calibrated to alarm at a specified fraction of lower flammable limits.

The network of sensors is subject to constraints, such as their maximum number, the capability of installing them in the selected points, the logic used for defining the alarm and the action levels, and so on, independently of the number and location of plant-specific critical zones which are not known a priori. In the literature, few articles have provided a review and suggested optimization methods [20,21,22,23,24] aiming at the identification of preferred networks of sensors and their plant-specific placement and able to satisfy the constraints given by the designers while complying with the requirements of the existing national and international regulations and standards. Therefore, using simulation results, an optimization formulation is being developed to perform optimal placement of gas detectors by minimizing, e.g. the expected detection time over all scenarios, the maximum number of sensors, the risk [25] or relevant others. An exemplified representation of an optimized network of sensors is provided in Figure 6.

The time required to solve the resulting optimization problem is usually small compared to the computational burden of the typical CFD simulations of leakage scenarios as implemented in the current practice and often only the dispersion phase is modelled [1]. This could lead to the selection of a number of scenarios to be considered in the optimization not sufficient to cover the overall space of events, in some cases smaller than the number of detectors to be placed thus compromising the robustness of the results.

The high computational cost necessary to run a number of scenarios sufficient to adequately represent the uncertainty space is expected to be significantly reduced by employing the hybrid CFD method described in the previous section. Such a method should permit to simulate the representative set of scenarios within an acceptable timeframe thus providing the necessary input data for the design of the optimized network of sensors within the schedule of the plant design development phase.

Figure 6 Exemplified representation of optimized sensors network



3. CONCLUSIONS

The paper has presented a risk-based process for the design of an optimized network of gas sensors for an oil and gas offshore platforms. The process combines a set of methods and practices currently or in future use by the industry that if applied following the procedure presented in Figure 1, should enable the achievement of an optimized design of a network of sensors helping anticipate potential incident escalation by providing early warnings of incipient gas release.

The process main composing blocks are represented by:

- A method to build a comprehensive set of gas release scenarios on a given platform geometry,
- A hybrid approach employing CFD methods for numerically simulating the gas release and dispersion in the part of the platform interested by the incident at a contained computational cost,
- An optimization method that starting from the results of the scenarios simulations facilitates the design of an optimized network of gas sensors.

The implementation of the process is underway with an engineering mindset. Indeed, notwithstanding it is intended to be generic and applicable to a wide variety of O&G offshore platform designs, to make it technologically ready for use it is applied step by step to a reference platform design and adjusted according to the information and lessons given by the results. One of the key questions that the practical implementation should be able to answer will concern the numerical burden of this heavy computationally based approach and whether it could be accommodated during the design phase of a commercial O&G platform. If this hurdle is overcome, this approach should contribute to the enhancement of the design practices of gas sensors networks, by providing a pragmatic method to build a plant specific gas monitoring system, while complying with the existing regulatory requirements.

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