OPTIMIZATION OF GAS DETECTORS WITH THE AID OF COMPUTATIONAL FLUID DYNAMICS - IMPOSITION OF REALISTIC RESTRICTIONS

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ABSTRACT

Flammable or toxic substances are present during oil extraction, production, and refining stages and their derivatives. Therefore, control measures, protective barriers, and devices responsible for mitigating consequences are necessary. In this stage, flammable or toxic gas detectors play a fundamental role since they usually have an interface with the emergency shutdown, blowdown, ignition source control, ventilation, alarm system, and firefighting systems. However, technical standards and recommendations do not indicate the exact location or the required number of detectors. Although gas detectors are the most effective devices for gas-phase releases, they respond to approximately 39% of leaks. Several methodologies have been presented to optimize the position and quantity of the detectors. However, it is not guaranteed that mathematical solutions to the optimization problem are really possible to be implemented in practice. Since these can indicate that the sensors are either in a very high position, requiring cable-stayed support and making maintenance and calibration difficult or that they are very close to the leak source, which can make it difficult to detect if the leak does not occur exactly in that direction. For these reasons, the present study incorporates distance restrictions from the leak point, distance restrictions from the ground, and the equipment side. In this way, it is intended that the solutions obtained with the optimization are feasible in the real world for the stage of construction and assembly in the field. In addition, the present study compared the position of the detectors considering Heuristic algorithm and Binary integer linear programming, position of the initial detectors with and without restrictions, 4 spacings between the initial detectors, restrictions of proximity to the leak point and alarm conditions by 20% and 60% of the lower flammability limit (LFL), which resulted in 60 different optimization scenarios. The main results showed that even with the restrictions imposed, it was possible to reach the minimum number of detectors compared to the cases without restrictions. All cases were detected when the initial matrix was less than or equal to 1 meter, regardless of the other conditions. The 5 m spacing, adopted in most studies involving optimization of gas detectors, presented its best result with twice as many devices.

1. INTRODUCTION

The petroleum industry consists of several areas: the exploration, production, transportation of oil and gas, as well as refining, transportation, and commercialization of derivative products. The primary source of Brazilian oil comes from offshore production fields. Offshore oil and gas production facilities are usually installed to enable the safe and efficient transportation of the main products – stabilized oil is either transported through oil pipelines or tankers, and dry gas through gas pipelines. In addition, offshore production facilities may also perform gas treatment to meet end user and environmental requirements .. In the refineries, several units perform oil processing, also known as the refining stage. Depending on the nature of the oil and the desired products, the processing units are set up to carry out transformations that meet the products most in demand or with the greatest commercial value.

Due to the severe operational conditions and the presence of flammable and toxic substances present in chemical and petrochemical plants, the equipment and pipelines that transport, store and process these products need to be kept intact [7]. The loss of containment of these products can be caused by the formation of a hole, crack or rupture in the side of the equipment or in the walls of the pipes. In addition to these, it is also possible to leak through the pipe sealing flanges through the valve structure, pumps, compressors, instrument connection, PIG receiver and launcher, risers, and vessel drain [12, 22].

In a simplified way, these containment losses can generate gaseous releases that would result in a fire jet if ignited quickly or a cloud explosion in case of late ignition . On the other hand, Liquid releases can

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generate fire in puddles [6, 17]. From the design phase to the operation, loss of containment of substances in the liquid, gaseous or two-phase state is always considered. For this reason, control measures, protective barriers, and devices responsible for mitigating consequences are necessary to ensure employees' safety, the neighboring community, the integrity of equipment, and the environment.

The gas detection system must provide a pre-alarm indicating the presence and location of toxic or flammable gas quickly and reducing the chances of the cloud increasing in concentration and size [5, 8]. This system is the primary tool that triggers automatic actions or under manual mitigation control to limit the consequences and severity of a given event, which can include: emergency shutdown, blowdown, ignition source control, ventilation, public alarm, alarms, and firefighting systems [1, 2, 4, 7, 8, 14, 21].

Unlike other safety devices such as flame, radiation, or temperature detectors, the standards do not define the quantity and location of flammable and toxic gas detectors. Therefore, as [10] mentioned, the project depends on the designer's experience, which can lead to oversized or undersized systems. In addition, studies by different companies and even by different teams can lead to different results regarding the location and number of detectors.

2. BACKGROUND

The main function of the design of the fixed gas detection system is to specify the quantity and location of the detectors [26]. It can be done considering several factors that include industrial standards and the legal, safety and environmental requirements of the installation site [2].

Among the main recommendations present in standards we can highlight that the sensors need to be located close to any potential source of release of a greater amount of gas. However, they must not be immediately adjacent to the equipment that can produce a minor leak and without consequences to avoid spurious alarms; the location of the detectors must consider easy access for calibration, maintenance, and inspection of electrical safety [2, 14]; the detection of flammable gas must be provided in all areas where flammable gas leaks may occur [21]. Currently, standards cite that numerical simulations can be adopted to position and optimize the sensors [2, 21]. However, they do not inform about methodologies or steps to achieve these objectives.

The hydrocarbon leakage data in marine installations presented in [13] collected some statistics about the severity of the leaks, types of leaks, and the forms of detection on platforms. It was found that leaks with significant severity are the most frequent, corresponding to 56.3%. The significant severity corresponds to leaks with a mass between 1 and 300 kg, flow between 0.1 and 1 kg/s or leak time of 2 to 5 minutes. Moreover, it is noted that the gas detector device is the most effective in detecting leaks, although only accounts for 38.9% of leaks detected. More than half of the leaks are detected by sources other than the detectors. Thus, there is the great importance of gas dispersion study to predict the gas leaks and the correct positioning of the detectors.

Detection through process variables occurs where pressure, level, temperature, and flow are used to control and process monitoring. These variables are used to indicate uncontrolled occurrences during the process, indicating whether the values are normal, low, or high, and may also be absent as for flow (no flow). Using these variables as leak alerts is much more effective when it occurs in large proportions, as occurred in rupture pipe and large leaks in flanges joints. Small leaks are more difficult to be detected by the process variables, as the system can interpret this decrease as an oscillation in the process and use the control variables to compensate for the loss.

For the reasons above, positioning gas detectors based on CFD simulation with an optimization algorithm becomes extremely important, with great potential to improve the low detection efficiency achieved through other methodologies.

2.1 GAS DISPERSION STUDY (GDS)

According to [8], the dispersion study is developed by raising some simulation scenarios. These should consider a combination of wind conditions and leak characteristics. These combinations represent one of the great challenges of a real dispersion study, which is the large amount of data necessary for a correct assessment. A typical study in a given area (a sector can be a platform or a process unit in a refinery, for example) reaches about 100 to 600 provided simulations.

The scenarios are usually set up considering the following parameters [3, 8, 9, 23]: leakage point; leak direction; wind speed and frequency (profile and stability); wind direction of the wind; release rate; gas composition; hole size and geometry; operating conditions of the equipment or line (e.g., pressure, temperature, flow, and volume). Computational fluid dynamics (CFD) is a technique that considers all these parameters in the analysis. This is achieved through the numerical solution of the conservation equations on a given domain representing the real geometry, allowing to obtain the spatial and temporal evolution of the field variables of interest (e.g. velocities, species concentration, etc), under appropriate boundary and initial conditions.

2.2 DETECTOR LOCATION

Gas Detection System (GDS) design is challenged by the numerous sources of uncertainty that include environmental conditions, area ventilation, leak location, process and leak characteristics and conditions, unit complexity (example. platform, refinery, ...), and others [18, 25]. This system aims to provide reliable and fast detection of flammable and toxic leaks before a gas cloud reaches a certain concentration and size, which could cause risk to people and the facility [8].

One of the first studies published in the literature to position gas detectors was that of [25]. Since no optimization algorithms, objective function, or iterative methods were used, the positioning of the detectors was done considering a ranking of the possible detectors. Later, several studies positioned the detectors using CFD together with some rules based on recommendations of standards or with a network of sensors distributed in space [8, 15, 27-29]. The first work that used mathematical programming and CFD to position detectors was conducted by [26], who adopted a 2D configuration of detection points. [30] developed stochastic programming to determine the optimal positioning of gas detectors in a petrochemical unit, being the first work to consider an objective function to minimize the number of detectors. [4] made a quantitative assessment of the practice of positioning gas detectors in the process industry.

Recently, [26] developed an approach based on the color pattern to optimize the number and location of gas detectors in a set covering problem (SCP) using the Balas algorithm. [5] adopted a risk-based methodology for locating toxic gas detectors, considering the probability of the scenarios and the cost as a constraint to solve the problem. In addition, [18, 31] also adopted the probability in the detector optimization problem.

3. METHODOLOGY

Previous studies involving gas dispersion with optimization or positioning of detectors typically focused on the actual algorithms. However, some important steps also need to be considered in order to assist the optimization process. These are:

1. **Selection of leakage scenarios:** this step consists of using some criteria to select the equipment, valves, or areas that will be evaluated in the study of gas dispersion and will be sources of leaks. For this reason, scenarios classified as non-tolerable or moderate in APR can be adopted;
2. **Exclusion of equipment or lines**: some equipment or lines in the study can be removed because they do not have a flammable gas concentration or sufficient flow to generate a critical scenario;
3. **Evaluation of the ventilation condition:** to know the winds that will be used in a study of gas dispersion, it is necessary to know the value of the wind speed and frequency of occurrence of these in relation to the eight main directions of the wind rose. In addition to these directions, it is important to assess the condition of calm atmosphere, which is when the wind speed is below 0.5 m/s. This condition is important due to the fact that with the absence of wind, or in conditions of very low speeds, the plume generated tends to reach large dimensions. This is due to the greater diffusive effect compared to the convective effect generated under ventilation conditions, an effect responsible for diluting and reducing the volume of the plume under flammable conditions;
4. **Exclusion of wind directions:** depending on the limitations of the study, a given wind direction with lower wind frequency values than a given percentage can be eliminated, thus reducing the number of simulations. In addition, wind directions that point out of the Unit can be disregarded when they are not at risk. Since such a cloud would have as a final consequence only the dispersion of the plume;
5. **Delimitation of detection regions**: during one of the stages of the study, the regions where the detectors can be allocated are delimited. Initially, this region has to do with where the selected

equipment to be evaluated by the study are located. However, an even greater refinement can be considered and this must contemplate the maximum height from the ground level where the detectors can be positioned in open regions and minimum height in relation to the ground. In addition to these cases, when the detectors are on elevated equipment at different levels of the ground, it is also important to define the distances in relation to the vertical and in relation to the side of the equipment and structures where the initial detectors, which will be tested, can be positioned;

The purpose of detection is to predict the concentration of a leaked gas that can generate a consequence (e.g., explosion, fireball, jet of fire). For such consequences to occur, there must be a flammable product, a source of ignition, and people who may suffer the consequences of these events. When the equipment is in a well-ventilated, elevated location, with leaks in directions that do not accumulate between the equipment (e.g. for open regions, leak upwards on elevated equipment), these cases may be neglected due to the low probability of occurrence of a consequence.

As mentioned earlier, these last three considerations help in the optimization process since they eliminate: some leak points in a careful way; some scenarios due to a low frequency of winds for a given direction; some regions of initial detectors, taking into account the positioning restrictions. CFD simulations were performed using the Ansys CFX program, and the optimization routines and auxiliary programs were developed in Python.

3.1 SCENARIO CONFIGURATION

The selected Unit as the basis for the gas dispersion study (GDS) is the same presented by [10], which was built similarly to an HDT unit of the Brazilian oil company PETROBRAS. However, the boundary conditions that represent the lateral borders were very close to the equipment. For this reason, these dimensions have been extended to a domain with the dimensions of 289 x 164 x 72 m. In Figure 1, it is possible to verify that the adopted process unit was still built with a level of geometric simplification involved in the initial stages of design details. The main equipment, pipe hack and compressor houses are present. However, the pipes are not detailed in the model.

In this first stage of demonstrating the methodology, only two equipment were used. These devices are highlighted in red in Figure 1. Even though it contains only two pieces of equipment, it allows us to evaluate the optimization of the detectors, since a sensor can alarm plumes of different equipment in different wind directions. Two jet directions were adopted for each of the equipment, one for low and the other towards each other. In addition, 8 wind directions were simulated, totaling 32 simulations.

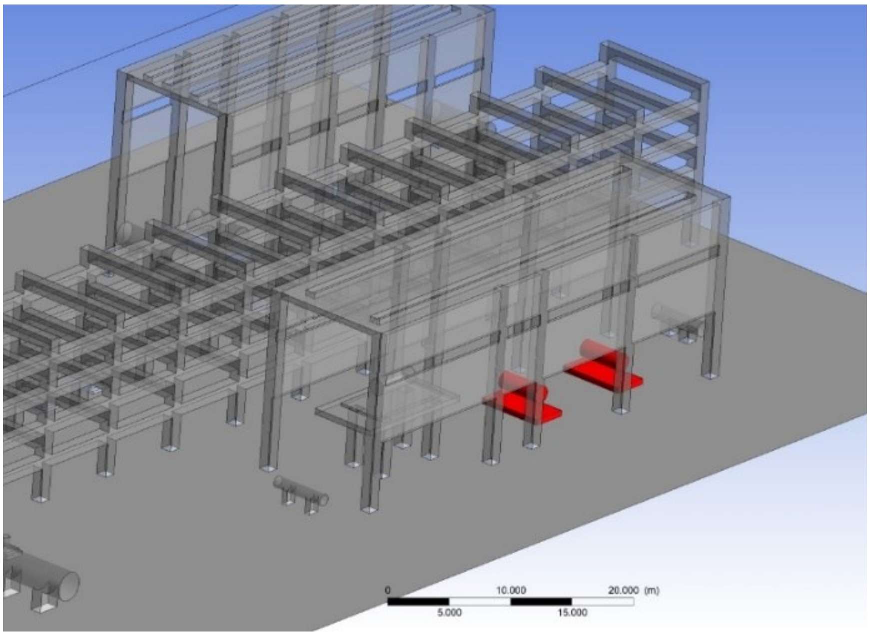


Figure 1: Equipment selected for preliminary gas dispersion study

3.2 *CREATION OF POSSIBLE DETECTION POINTS*

The step of creating the possible detection points is to determine the region where the possible detectors will be evaluated. In addition, it is necessary to define the spacing between points, as shown in Figure 2. The main spacing between detectors adopted is 5 m [4, 15, 23, 26]. However, if the plumes are smaller than this value, they may not be detected.

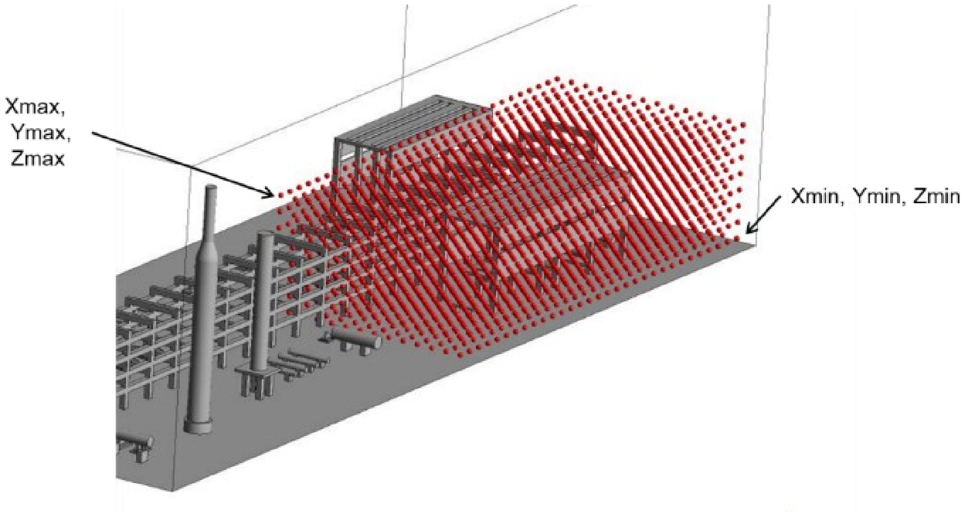
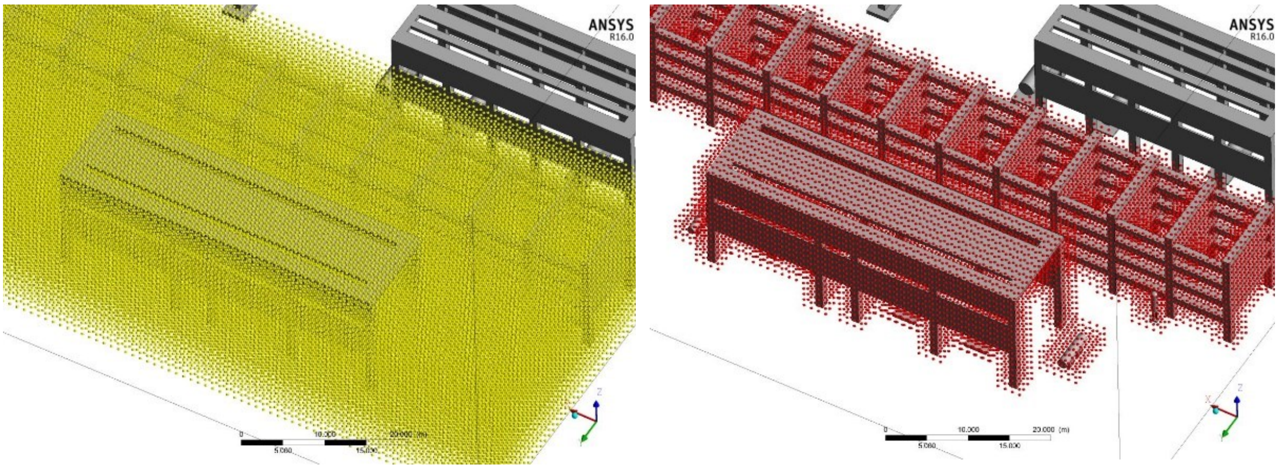


Figure 2: Process unit with possible gas detectors

An evolution of this process of selecting the possible detectors aims to delimit the regions that may in fact contain detectors. It can be seen that if a detector is selected in the x_{min}, y_{min} and z_{max} position, in this example, where z represents the vertical direction, it will need to be installed on a pole that will make the project more expensive, make maintenance difficult and possibly detect a case where there is no risk to people and no source of ignition nearby.

For this reason, a step was included in the methodology that delimits the minimum height, maximum height concerning the ground, and maximum distance from the side of the equipment or structure (if it is possible to support the detector in this equipment). In this way we will leave only those places that can be physical solutions to the real problem, imposing this restriction in advance. With that, we will avoid writing complex equations to include mathematical constraints in the algorithms. Figure 2 and Figure 3 (a) represent the complete initial detection matrix and Figure 3 (b) the reduced version.



(a) (b)

Figure 3: Isometric view of the position of the initial detectors in the full version (a) and in the reduced version (b).

In Figure 3, it is clear that the algorithm will have a smaller number of possibilities for detectors to search, thus helping in the optimization process. In addition, the possibility of rework is significantly reduced, since for the case with initial detectors in the full version, it would be possible to choose an impracticable detector for the construction and assembly stage, which would require redoing the optimization at each allocation in positions not approved by this step. These restrictions can also take into account maintenance zones, escape routes and streets.

The definition of the concentration of interest takes into account the gas to be detected and the detection strategy. For this example, hydrogen is a flammable gas released into the atmosphere. The detection strategy for this analysis consisted of detecting plumes with concentrations above 20 and 60% lower flammability limit (LFL). In this way, the plume will be detected before it becomes flammable at that point.

Table 1 shows the low and high level values for point and open path detectors recommended by different standards, authors and companies. Values are presented as a percentage of the (LFL) for point detectors and in LFL.m for open path detectors, which represents the percentage of the LFL multiplied by the distance between the source and receiver of this device.

Table 1: Alarm levels for point and open path flammable gas detectors considered by different standards, authors and companies, as a percentage of lower flammability limit (LFL). Note 1: typical practices [20]; Note 2: recent trends [20]; LL: low level alarm point; HL: high level alarm point; -: not presented by references.

Autor	Point detector (% of LFL)		Open Path detector (LFL.m)
API 14C (2001), [1]	LL	≤25	-
	HL	≤60	-
KELSEY *et al.* (2002), [15]	LL	20	1
	HL	50	3
HSE (2004), [11]	LL	≤10	-
	HL	≤25	-
NFPA 15 (2007), [19]	LL	10-20	-
	HL	25-50	-
NORSOK (2008), [21]	LL	≤20	1
	HL	≤30	2
DAVIS *et al.* (2011), [8]	LL	10-25	1
	HL	30-60	2
NOLAN (2011), [20]	LL	25^1; 10^2	-
	HL	50^1; 25^2	-
PETROBRAS - Plataforma	LL	20	-
GOMES (2012), [10]	HL	50	-
PETROBRAS - Refinery	LL	20	1
GOMES (2012), [10]	HL	60	2

3.3 HEURISTIC ALGORITHM

The Heuristic algorithm positions the detectors following some basic rules. First, candidates for detectors are ranked according to criteria, such as reducing detection time, reducing the total probability or maximizing coverage [25]. Subsequently, the next detectors are positioned to detect only those cases not yet covered by the predecessors [4, 23].

The Heuristic algorithm proposed in the present work includes some tiebreaker layers in relation to what was previously proposed since when adopting such criteria, it was found that many possible detectors were able to detect the same cases. The first tiebreaker criterion chooses the detector capable of alarming more cases, which will guarantee greater redundancy. The second tiebreaker criterion considers the cases closest to the leak point, which will reduce the alarm time.

3.4 LINEAR PROGRAMMING

Linear programming or linear optimization is the nomenclature adopted for a set of methods used to optimize problems that present both objective functions and restrictions represented by linear functions [16] in relation to the parameters that are being solved. Mathematically, the linear optimization problem is defined using the relations present in Equations (1), (2), (3), and (4):

Minimize

$$f(D) = c_1 D_1 + c_2 D_2 + \cdots + c_n D_n \tag{1}$$

where c_i are the polynomial constants of the linear objective function, which may be related to time, probability or concentration. D_i represents whether the detectors are being optimized.

The problem is subject to restrictions of equality and inequality

$$h_k(D_i) = 0 \qquad k = 1, 2, \dots, m_1 \tag{2}$$

$$g_j(D_i) \geq 0 \qquad j = 1, 2, \dots, m_2 \tag{3}$$

$$\boldsymbol{D} = \begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_n \end{bmatrix} \tag{4}$$

When solving the linear programming problem considering the same probability for all selected cases, the target of the objective function becomes to minimize the number of detectors,resulting in a binary integer programming (BIP) problem.

4. RESULTS AND DISCUSSION

In order to analyze the performance of the methodology, 32 simulations were generated representing leakage in two hydrogen compressors, indicated in red in Figure 3. For this step two optimization methodologies were tested, the Heuristic algorithm and the binary integer linear Programming (BIP). For this, the influence of the following variables was studied:

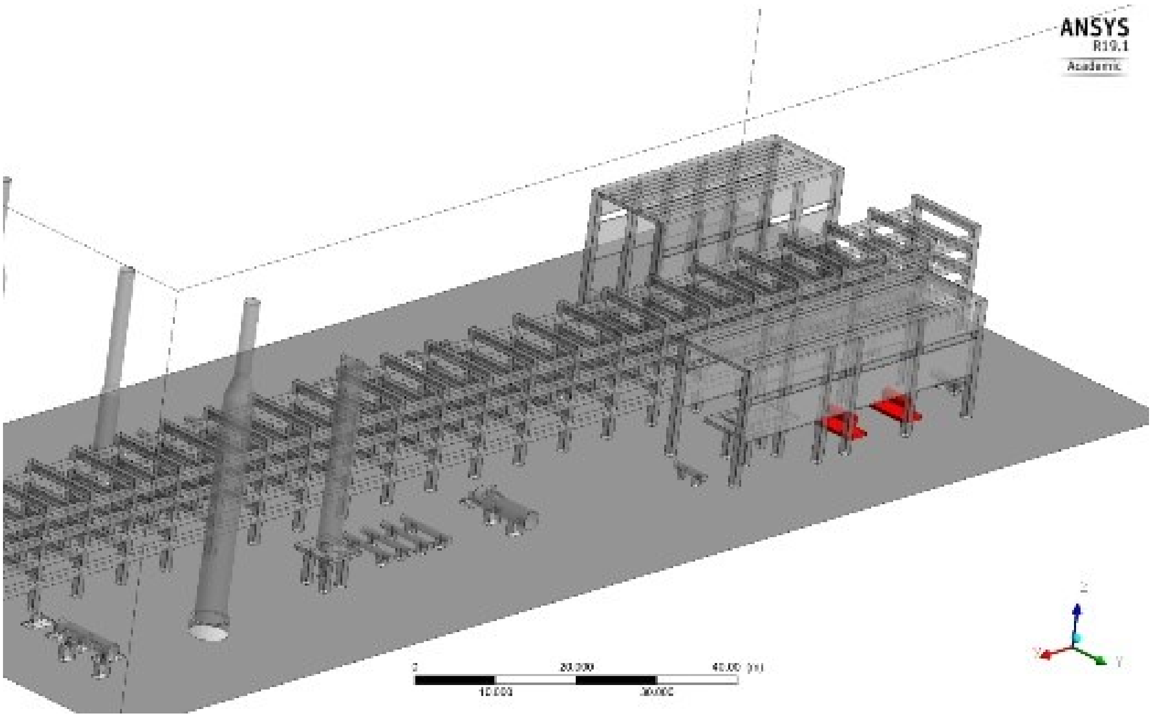
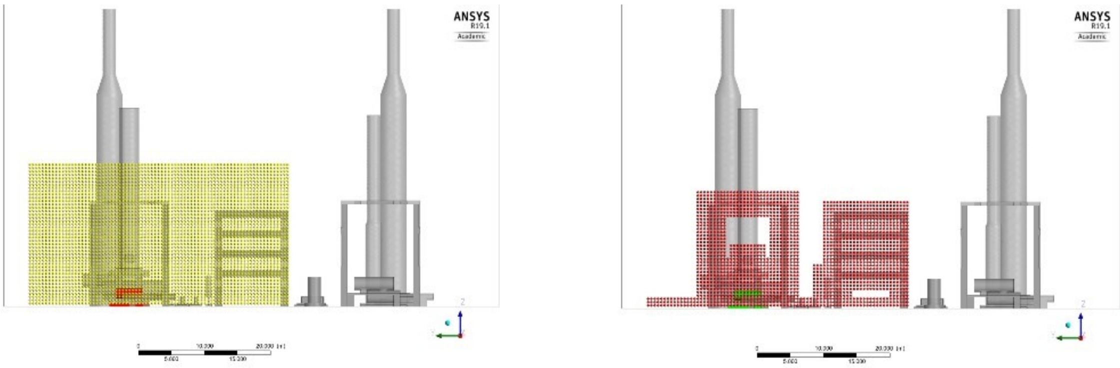


Figure 4: Highlight for the region of the Unit's compressors.

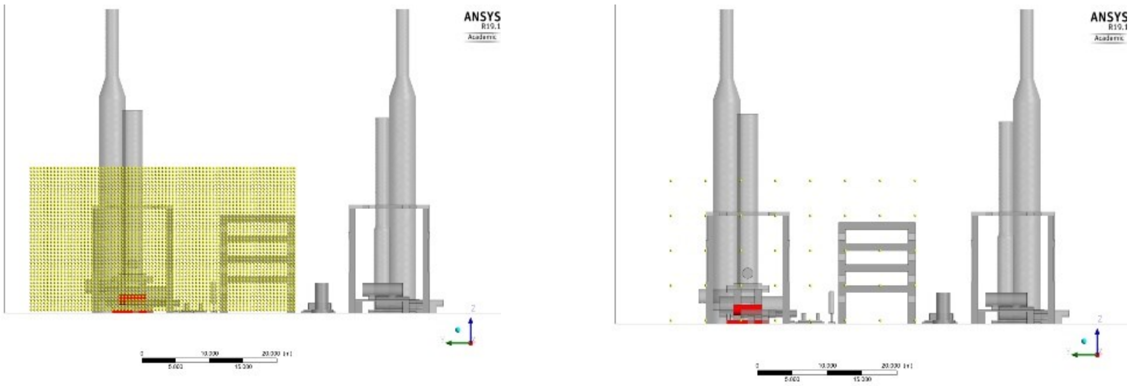
a) Possible detection points: Full detection matrix and reduced detection matrix;



(a) (b)

Figure 5: Full detection matrix (a) and reduced detection matrix (b) for 0.5x0.5 spacing;

Spacing between detectors: distances of ½, 1, 3, and 5 meters were evaluated;



(a) (b)

Figure 6: Complete detection matrix for spacing of 0.5 m (a) and 5.0 m (b).

c) Definition of the concentration of interest: Concentrations of 20 and 60% LFL;

d) Restriction of detection points: Elimination of detection points near the points of leakage, a case with 3 meters is considered and with no constraint;

Performing all combinations of the conditions presented above, 64 optimization cases were generated. For each of them, the number of detectors (ND) and the number of undetected cases (NUC) were obtained, shown in Table 2.

Table 2: Evaluation of optimization using the Heuristic algorithms and Binary Integer Programming (BIP) for possible detection points, lower flammability limit (LFL), spacing between detectors and restriction of detection points. IDM: initial detection matrix; % LFL: lower flammability limit; ND: number of detectors; NUC: number of undetected cases;

Optimizer	IDM	% LFL	Spacing	Restriction	ND	NUC	Optimizer	IDM	% LFL	Spacing	Restriction	ND	NUC
Heuristic	complete	20	0,5	Yes	3	0	BIP	complete	20	0,5	Yes	3	0
Heuristic	complete	20	0,5	No	3	0	BIP	complete	20	0,5	No	3	0
Heuristic	complete	20	1	Yes	3	0	BIP	complete	20	1	Yes	3	0
Heuristic	complete	20	1	No	3	0	BIP	complete	20	1	No	3	0
Heuristic	complete	20	3	Yes	5	0	BIP	complete	20	3	Yes	5	0
Heuristic	complete	20	3	No	6	0	BIP	complete	20	3	No	5	0
Heuristic	complete	20	5	Yes	7	0	BIP	complete	20	5	Yes	7	0
Heuristic	complete	20	5	No	6	0	BIP	complete	20	5	No	6	0

Optimizer	IDM	% LFL	Spacing	Restriction	ND	NUC	Optimizer	IDM	% LFL	Spacing	Restriction	ND	NUC
Heuristic	complete	60	0,5	Yes	3	0	BIP	complete	60	0,5	Yes	3	0
Heuristic	complete	60	0,5	No	3	0	BIP	complete	60	0,5	No	3	0
Heuristic	complete	60	1	Yes	3	0	BIP	complete	60	1	Yes	3	0
Heuristic	complete	60	1	No	3	0	BIP	complete	60	1	No	3	0
Heuristic	complete	60	3	Yes	9	0	BIP	complete	60	3	Yes	9	0
Heuristic	complete	60	3	No	10	0	BIP	complete	60	3	No	9	0
Heuristic	complete	60	5	Yes	11	6	BIP	complete	60	5	Yes	11	6
Heuristic	complete	60	5	No	8	6	BIP	complete	60	5	No	8	6
Heuristic	reduced	20	0,5	Yes	3	0	BIP	reduced	20	0,5	Yes	3	0
Heuristic	reduced	20	0,5	No	3	0	BIP	reduced	20	0,5	No	3	0
Heuristic	reduced	20	1	Yes	3	0	BIP	reduced	20	1	Yes	3	0
Heuristic	reduced	20	1	No	3	0	BIP	reduced	20	1	No	3	0
Heuristic	reduced	20	3	Yes	5	0	BIP	reduced	20	3	Yes	5	0
Heuristic	reduced	20	3	No	6	0	BIP	reduced	20	3	No	5	0
Heuristic	reduced	20	5	Yes	7	0	BIP	reduced	20	5	Yes	7	0
Heuristic	reduced	20	5	No	6	0	BIP	reduced	20	5	No	6	0
Heuristic	reduced	60	0,5	Yes	3	0	BIP	reduced	60	0,5	Yes	3	0
Heuristic	reduced	60	0,5	No	3	0	BIP	reduced	60	0,5	No	3	0
Heuristic	reduced	60	1	Yes	3	0	BIP	reduced	60	1	Yes	3	0
Heuristic	reduced	60	1	No	3	0	BIP	reduced	60	1	No	3	0
Heuristic	reduced	60	3	Yes	8	1	BIP	reduced	60	3	Yes	8	1
Heuristic	reduced	60	3	No	10	0	BIP	reduced	60	3	No	9	0
Heuristic	reduced	60	5	Yes	10	7	BIP	reduced	60	5	Yes	10	7
Heuristic	reduced	60	5	No	8	6	BIP	reduced	60	5	No	8	6

All cases where the optimization was done considering the alarm condition with 20% of the lower flammability limit were detected. However, for cases considering plumes with concentrations of 60% LFL, 75% of the optimization cases detected all leaks. The higher the percentage of the LFL, the smaller the plumes will be and, necessarily, the greater the difficulty of detection. Therefore, two consequences must be considered: an increase in undetected cases or an increase in the number of detectors to cover all cases. For this reason, it is necessary to evaluate a cut volume to limit the size of the cloud, thus defining the smallest detectable size and the smallest size that presents risks to the installation, people and process.

Regarding spacing, when the distance between the detectors was 0.5 m and 1 m, all optimization scenarios detected all cases of leakage, regardless of the other optimization parameters. All cases containing 5 m spacing and 60% LFL concentration did not achieve 100% detection, since there was a decrease in the size of the cloud and an increase in spacing between the detectors.

Regarding the initial detection matrix (IDM), the two conditions presented in Figure 5 were evaluated for all spacings. The difference between the complete and reduced initial detection matrix was only noticed for the conditions containing 60% concentration of the LFL with detector spacing of 3 meters and 5 meters. This variation in the results was due to the reduction in the number of points due to the reduction in the initial detection matrix, which affects more strongly the cases with greater spacing.

As this optimization was made for a dispersion study containing few cases, it is possible to graphically verify the impact of using the complete matrix and the reduced matrix, as well as the detection concentration in% of the LFL in the reduction in the initial detection matrix (IDM).

Figure 7 shows the number of detectors capable of detecting each case before optimization, that is, with the presence of all detectors whose initial spacing was 5 m. It can be seen that before the optimization stage, some cases evaluated at 60% LFL concentration are no longer detected by any device (cases 4, 6, 18, 24, 26 and 30).

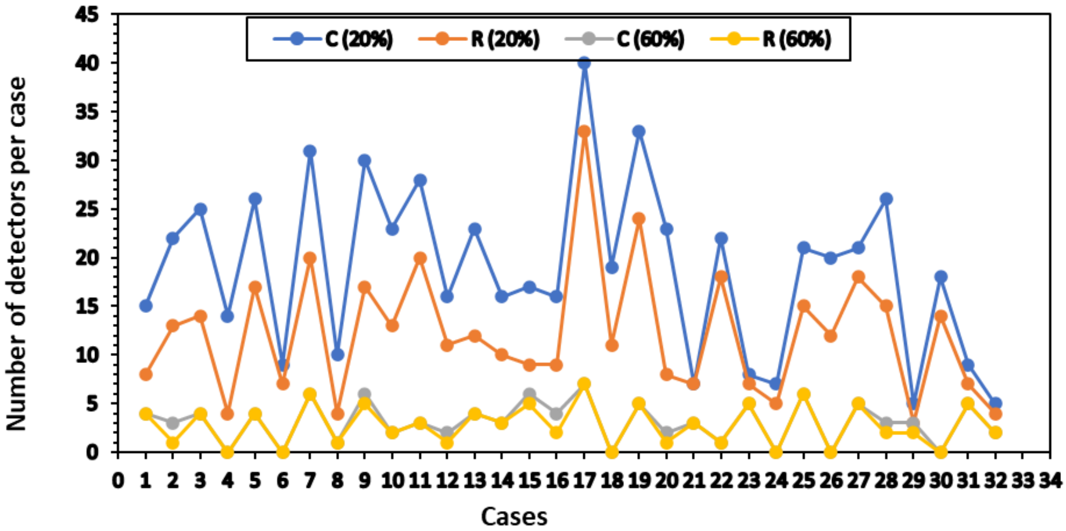


Figure 7: Number of detectors capable of detecting each case before optimization with spacing of 5 m between the detectors. Initial matrix complete (C), reduced (R), with 20 % LFL or 60% LFL.

The increase in the LFL percentage reduces the volume of the plumes making the cases with small plumes more difficult to be detected. Reducing the spacing between detectors increases the number of points in the initial detector array. With this, we have more points available in the optimization stage, which helps us improve the optimization, increasing the number of detected cases. On the other hand, with a smaller spacing, we can have detectors very close to the leak point.

This fact is not desirable, since in general only a few jet directions are evaluated and not the 360 ° as can occur in reality. With detectors further away, it is believed that the devices will perceive cases with less influence from the original direction. For this reason, a restriction has been included in the program that prevents the presence of detectors very close to the leak points. Table 2 shows this implementation in the column that says "with restriction" or "without restriction". We can observe that, even with a restriction of 3 m in relation to the leakage point, the cases with smaller spacing were not affected in terms of quality of detection.

The cases with the same number of detectors for each of the methodologies were composed of different sets of detectors, which shows that this problem has multiple optimal solutions.

5. CONCLUSION

In the present work, two methodologies for positioning gas detectors were tested: Heuristic and Binary integer programming (BIP) algorithms. The spacing between the detectors, two concentrations of interest, restrictions on possible positions of the initial detectors were evaluated, with the objective of generating only detector positions that can be physically installed. In addition, the detection restriction near the leak point was evaluated.

It was possible to include these physical restrictions in the initial detection matrix to reduce the complexity of defining it mathematically within the optimization method. With this, only detectors that can be chosen and scenarios that are relevant and cannot be overlooked will be present in the optimization. For these considerations, the criterion adopted was the detection of all cases with the least number of detectors possible.

The Heuristic and BIP methods showed almost the same results for the vast majority of tests performed. However, for cases with spacing of 3 meters between detectors and without the nearby detector's restriction of the leak point, it was found that the heuristic algorithm presented one detector more. However, it achieved 69% redundancy, against only 25% obtained with BIP. This fact could be observed even in cases where both methods obtained the same number of detectors. Redundancy is important for security, since, in the event of a device failure, the leak can still be detected, without incurring an increase in cost.

All cases were detected where the optimization was done considering the alarm condition with 20% of the lower flammability limit (LFL). However, for the cases that considered plumes with concentrations of 60% LFL, 75% of the optimization cases detected all leaks. When the distance between the detectors was 0.5 and 1 m, all optimization scenarios detected all cases of leakage, regardless of the other optimization parameters. However, the smaller the spacing between the closer detectors, the devices tend to stay at the leak point.

All cases with a spacing of 5 m and a concentration of 60% LFL did not achieve 100% coverage of the cases, since there was a decrease in the size of the cloud and an increase in the spacing between the detectors, making them incompatible in relation to detection. The plumes that leak downwards have more influence of the wind directions, when they hit the ground losing speed. The plumes from other jet directions are less influenced by the wind in directions close to the leak, being mainly influenced by the direction of the leak.

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