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Risk-based Industrial Site Optimization

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A key consideration in the design of a new industrial site is the spatial arrangement of units with respect to required safety distances. Safety distance requirements are intended to reduce the risk of hazardous events escalating from their origin to other units as well as to limit the damage to particularly vulnerable targets (e.g., control rooms), and are typically based on industrial standards (e.g., EIGA, CGA), which rely on credible worst-case scenarios, acceptable escalation frequencies or fixed values – the latter often without clear justification. This paper proposes an optimization algorithm that aims to minimize total site cost by balancing land use and interconnection costs (e.g., for pipes and cables), while ensuring compliance with required safety constraints. For each planned unit, the risk of escalation is represented using an F-D curve – a function analogous to the traditional F-N curve, but with escalation distance (D) on the x-axis. This is provided for each pair of unit types. The escalation distance is the distance at which a secondary hazardous event occurs for a given scenario, e.g., spread of fire from one tank to another. Due to the high degrees of freedom, the problem is numerically challenging since it has many local optimization minima. To address this challenge, optimization is performed using the best1bin differential evolution algorithm which is specifically tailored to address non-monotonic problems. The resulting site layouts can be visualized in a 2D scatter plot, where each circle represents a unit and the extent of the scatter is the required lot size. The algorithm can be used both to generate early-stage input to concept development of siting projects and for theoretical investigations into optimal clustering, central placement, and proximity to lot boundaries for different unit types.

Keywords: Safety distance; Optimization; Process equipment; Domino effects; Facility siting

1. Introduction

Facility siting, defined as the process of deciding on location and spatial arrangement of hazardous industrial sites and units within such sites, is an important aspect of ensuring safety to people and the environment. Applications of facility siting processes can both address the question of retrofitting or implementing changes to existing sites as well as providing initial screening of placement of new facilities in early design phases (Jung et al. 2010). In all cases, the facility siting processes must address a range of different issues such as political, legal, economic, technological, human factors and organizational dimensions (Boholm & Löfsted, 2004; Reniers & Faes, 2013).

Typically, facility siting studies (FSS), which aim to balance safety against other societal objectives, adopt either consequence-oriented (maximum credible events) or risk-based approaches where also the likelihoods of negative events are accounted for (Mander et al. 2020). Irrespective of the adopted approach, thorough assessments are needed with respect to how toxic, flammable and explosive material may affect vulnerable targets, including people on and beyond the site as well as buildings and infrastructure.

A key concern for facility siting is to design the site to avoid domino effects. A domino effect is an event where a primary accidental scenario escalates to secondary, tertiary, etc. hazardous events (Antoniono et al. 2009); such as when an explosion triggers another explosion in a unit near-by. Domino effects may arise between units at the same site (on-site escalation) as well as other industrial facilities (off-site escalation). With the development of industrial complexes, the risk of domino effects increases (Kadri & Chatalet, 2013).

A key tool for reducing the risk of escalation is to make use of safety distances. However, using extensive safety distances comes at a cost as more of the often limited and highly valuable land must be claimed for industrial purposes. In addition, there may also be interconnection costs, such as the cost of piping and cables, that increase with increasing separation distances.

Balancing risks against costs is a key concern in facility siting. Previous studies have addressed the optimal placement of industrial process units while simultaneously considering risk levels (Jung et al., 2010). However, in their optimization approach, Jung et al (2010) did not consider the issue of escalation which means there is a lack of studies that propose optimization of safety distances taking domino effects into account.

This paper therefore proposes a risk-based optimization algorithm that aims to minimize total site cost by balancing land use and interconnection costs (e.g., for pipes and cables), while ensuring compliance with required safety constraints. The paper is structured as follows: First, a description is made of the developed algorithm. Second, the algorithm is used in a case study which includes the location of three or four hydrogen compressors. Finally, the proposed algorithm is discussed including limitations and potential development.

2. Description of the Developed Algorithm

The purpose of the method developed in this paper is to optimize the location of a number (*n*) of industrial units on a site without exceeding the acceptable risks for both escalation (internal, on-site risk) and risk exposure to the surrounding (external, off-site risk). The optimization is targeted on the physical footprint of the site and, optionally, a cost for distances between pairs of units accounting for interconnection costs such as piping and cables.

The required input, beside the number of units, is the proposed use of a "*frequency-distance-curve*" (F-D-curve) for each pair of units. This F-D-curve is similar to the more conventional F-N-curve, but instead of the number of fatalities related to a specific scenario on the x-axis, the F-D-curve have the maximum distance between units where escalation is expected for each scenario. In practice, this is developed by assessing the minimum distance for each scenario (with a given frequency) at which the defined harm criterium is exceeded. The harm criteria can be, for example, defined in terms of heat radiation, overpressure, or temperature.

Additionally, input in the form of a characteristic radius on each unit is also required since the distance between the units is measured from the edge of the unit and not the centre point.

Numerically, the optimization is performed using the *best1bin* differential evolution algorithm (Storn et al., 1997). The reason for selecting this numerical approach is to ensure a method robust against the problem's relatively high degree of freedom, which causes many local minima. In simple terms, the algorithm is based on initially generating a certain number of candidate solution vectors within a certain predefined bound. It is then assessed which of those vectors that fulfil both the constraint (i.e., maximum accepted internal and external risk) and minimizes the optimization variable (i.e., the lot area and, potentially, the cost of separation distances between units). This best solution vector is then mixed with the scaled difference between two randomly selected vectors to move slightly away from this best solution to maintain population variability. This is repeated until no further improvements are observed.

3. Case-study

To illustrate the method and give general guidance regarding localization of units of different risk levels within a site, a case-study is presented. The cases are based on a hypothetical industrial site where three or four hydrogen compressors should be located.

3.1. *Input data*

Four different unit types (“Normal”, “High”, “Low” and “Short") are defined based on a hydrogen compressor at various levels of risk. The first three unit types illustrate differences in frequency while the last refer to a unit with shorter exposure distance. The input to the calculations is found in Appendix A.

The four different categories are referred to as: “Normal”, “High”, “Low” and “Short”. Where the first three categories illustrate differences in frequency while the last refer to a unit with shorter exposure distance. The resulting F-D curve is found in Figure 1 and shouldbe interpreted as, for example referring to the point on “High” at 11 m, that the cumulative frequency of scenarios in the unit that exceed the harm criteria of another unit positioned 11 m from the unit is $2.50 \cdot 10^{-5}$ per year.

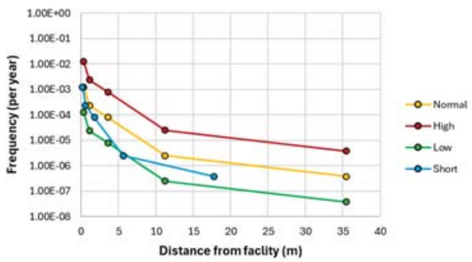

Fig. 1. F-D-curve for the four unit types used in the case study. Line colours are the same for all figures in this section.

In the base case, the acceptable risk for injury to targets outside the facility in the case study is 10^{-5}, the acceptable escalation risk (i.e. the cumulative frequency of domino effects within the facility) is 10^{-4}. Unless something else is stated in the sub-sections below, interconnections cost related to distances between units are not considered and the characteristic size (diameter) of the units is 10 m.

Input to the numerical algorithm is that the population of initial solution vectors is 15 and the control parameter for mixing between the best candidate and the random difference between vectors is 0.5. The maximum number of iterations is 1000, and the tolerance for the constraints is 10% for the lot line and escalation risk, respectively. No sensitivity analysis on those parameters has been performed due to time constraints.

3.2. *Impact of number of units*

The base case consists of four “Normal” unit types, which, as expected, align in a quadratic pattern in Figure 2.

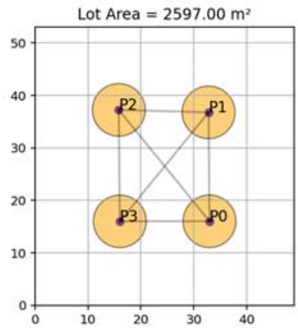

Fig. 2. Optimized location of four “normal” units (P0, P1, P2, P3).

When a fifth unit of the same type is added in the centre of the quadratic pattern, it stretches out to maintain the acceptable escalation frequency within the facility while maintaining a similar distance to the boundary to fulfil the requirement on maximum risk to targets outside the facility (see Figure 3).

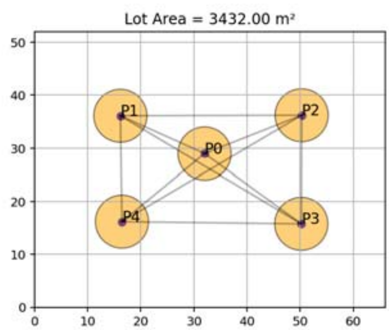

Fig. 3. Optimized location of five units.

When only three units are employed, they arrange in a linear pattern (see Figure 4).

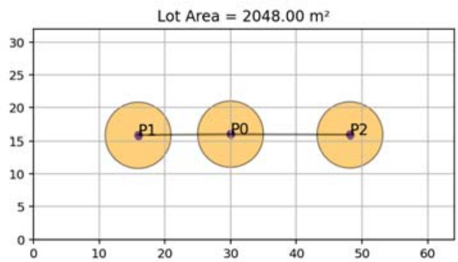

Fig. 4. Optimized location of three units.

It can be noted that the result in Figure 4 is not entirely symmetric. It is not known whether this is due to random effects or that the different gradients in the different parts of the lines in Figure 1 promote this behaviour.

The results show that a linear orientation is more efficient compared other potential orientations such as triangular.

It can be observed that from this simple analysis, 4 units appear to be the optimum in terms of lot area size per number of units when comparing to a facility of 3 or 5 units.

3.3. *Impact on differences in risks*

In Figures 5 to 7, one or two units are replaced with units of a different type. As seen in Figure 5, the units representing "high risk" level show up in a central location in order to maintain the acceptable lot line risk, while lower risk units are found in a more peripheral locations to maintain the acceptable escalation risk.

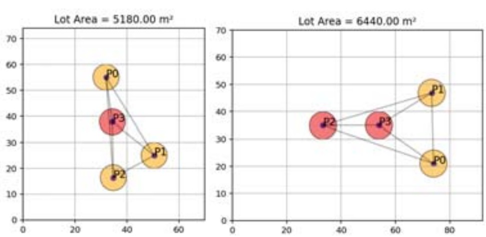

Fig. 5. Optimized location with one (left) or two (right) units of a higher risk level.

In Figure 6, one or two units are replaced with "Low" units. It can be seen that the "Low" units end up closer to the lot line, but relatively far from the "Normal" units, since this allows the "Normal" units to be located closer to each other without exceeding the acceptable escalation risk.

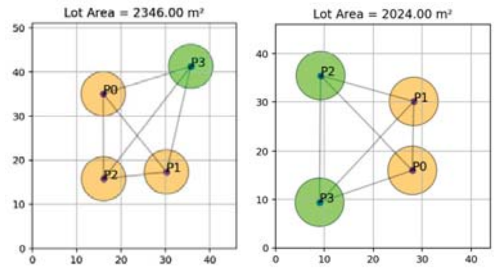

Fig. 6. Optimized location with one (left) or two (right) units of a lower risk level.

Finally, "Short" units, i.e., units with shorter exposure distances, are investigated and illustrated in Figure 7. The effect is similar to that of "Low" units.

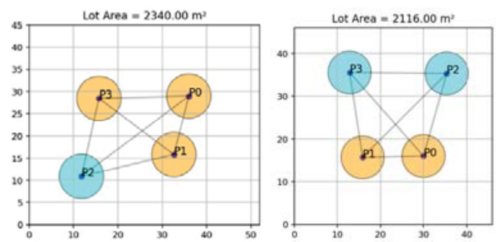

Fig. 7. Optimized location with one (left) or two (right) units of a "short" risk distance.

3.4. *Impact of cost of distance between units*

In Figure 8, a cost of distance between unit P0 and P1 is added to illustrate the impact of cost of, for example, cables or piping between units. This cost was set to 200 (i.e., equivalent to the cost of 200 m^2 of land). It can be seen that this causes P0 and P1 to move closer to each other while the other two units move further away from P0 and P1 and each other to maintain the escalation risk at an acceptable level.

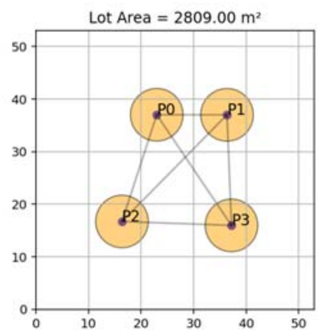

Fig. 8. Optimized location with a cost of distance between P0 and P1 added.

3.5. *Impact of acceptable risk levels*

Finally, the impact of acceptable risk levels is assessed by reducing them by a factor of 10 in Figures 9 and 10. It was found that the reduction in acceptable lot line risk more than tripled the required lot area while the reduction in escalation risk only increased the area by approximately 25%.

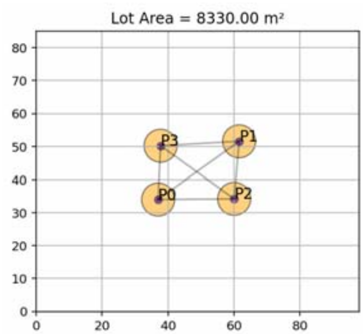

Fig. 9. Optimized location with the acceptable lot line risk reduced by a factor of 10 (i.e., from 10^{-5} to 10^{-6}).

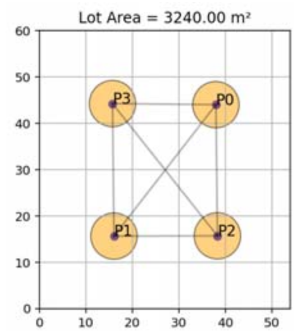

Fig. 10. Optimized location with the acceptable escalation risk reduced by a factor of 10 (i.e., from 10^{-6} to 10^{-5}).

3.6. *Summary on impact on lot area*

In Table 1, the impact on the number and type of units is summarized. Substituting one "Normal" unit for a "High" unit causes a large increase in area, but additional high-risk units have less effect. Substituting one or two units to "Low" or "Short" units have a limited effect on the footprint.

Table 1. Summary on the impact of number of units and type of units.

Number of units per type				Area Index	Fig ref.
Normal	High	Low	Short	(-)[1]	
4	0	0	0	100	Fig 2
5	0	0	0	132	Fig 3
3	0	0	0	79	Fig 4
3	1	0	0	199	Fig 5L
2	2	0	0	248	Fig 5R
3	0	1	0	90	Fig 6L
2	0	2	0	78	Fig 6R
3	0	0	1	90	Fig 7L
2	0	0	2	81	Fig 7R

Notes: (1) Area normalized relative to the base case

Table 2 shows the impact on cost of distance and acceptable risk levels. As expected, the addition of cost of distance between two units increases the lot area since the optimized solution prioritizes distance instead of only lot size. Also, as previously noted, the change in acceptable lot line risk has a greater impact on the required lot area while the decrease in acceptable escalation risk has a lower impact.

Table 2. Summary on the impact cost of distance and acceptable risk levels

Cost of distance	Lot line risk	Escal-ation risk	Area Index (-)[1]	Fig ref.
0	10^{-5}	10^{-4}	100	Fig 2
100	10^{-5}	10^{-4}	108	Fig 8
0	10^{-6}	10^{-4}	321	Fig 9
0	10^{-5}	10^{-5}	125	Fig 10

Notes: (1) Area normalized relative to the base case

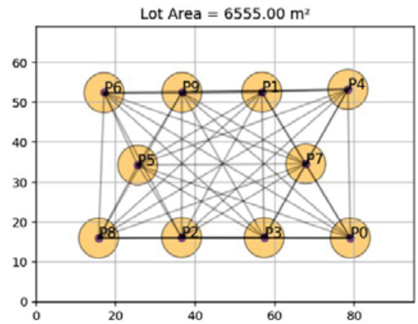

Fig. 11. Optimized location with ten units

4. Discussion

4.1. *Discussion on results*

It was found that the acceptable risk at the boundary of the facility (the lot line) had a larger effect on the size of the facility compared to the escalation risk. This is likely due to that the rate of risk reduction decreases with distance (see fig 1). Therefore, since the acceptable escalation risk was higher to begin with, the factor 10 improvement in risk level can be achieved with a smaller increase in distance.

It is beneficial to place equipment with a higher risk level in a central location of the facility (given the presence of sensitive targets on all sides of the facility) and place lower risk equipment around this (see fig 5). Similarly, single low risk equipment should be placed close to the boundary (see fig 7). The reason is similar to the effect of changes in risk level in the previous paragraph, the risk decreases slowly with distance which makes the low criteria at the boundary a determining factor.

For four or more units (see fig 11 for an example with 10 units), a quadratic pattern was found to be most efficient, while a linear pattern was efficient for up to three units. Interestingly, the area per unit remained very similar even for a facility with 10 units, with 656 m2/unit compared to 683, 649 and 683 for 3, 4 and 5 units respectively.

4.2. *Limitations*

It is acknowledged that in practice, many parameters govern how an industrial site is planned, including logistics, surroundings and pre-existing buildings. In this paper, we present a simplified idea, where it is assumed that the design is based exclusively on lot line and escalation risk, together with the cost of land and the distance between units. It will therefore, of course, not give the final result for how a site should be planned, but it is deemed to give valuable input to the early design process. Later in the process, a full QRA is usually required, but it is acknowledged that this is often performed in a late stage in the process when it is difficult to make major changes in the facility siting.

Although the numerical method employed is relatively insensitive to local optimum solutions, slight variations in the solutions and lot area requirements were found between runs. This was compensated by running each case a minimum of three times to find the actual global minimum. While this was found to be enough, it could be considered to investigate if an alternative numerical algorithm could be employed that directly finds the global minimum without extending the computational time to unacceptable values. Also, the sensitivity of the solution to the parameters that governs the numerical algorithm (i.e. number of initial solution vectors, mixing parameter, maximum iterations and tolerance) should be investigated.

5. Conclusion

The method developed in this paper can be used to increase the knowledge of how facility siting can be optimized to minimize the footprint or cost of an industrial site. This can be done through both general case studies, such as the one in the current paper, or for actual sites to inform the initial phases of design.

Through the case study presented in this paper, it was found that reducing the risk for single high-risk units was very important in order to reduce the footprint of the site. Single low-risk units led to only a marginal decrease in the footprint. It was also found that the acceptable lot line risk had a very high impact on the site footprint while the impact of reduced acceptable escalation risk was less pronounced.

The area per unit was found to be almost independent of the number of units on the facility.

Acknowledgement

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ChatGPT-5.2 has assisted in part of the Python coding used in this paper, but no GAI has been used in writing this paper.

Data availability

The python script used in this paper is available on Zenodo with DOI: 10.5281/zenodo.18482435.

Appendix A. Summary of input data used to construct the F-D-curves in the case study

In this appendix, the input data used to generate the F-D-curves used in the case study are presented. The data that is shared among all types of units can be found in Table A.1

Table A.1 General input data used to generate the F-D-curve. Leak percentages refer to fraction of the pipe area, and isolation refers to the reliability of detection and shut-off system.

Dimension	Quantity	Value	Source
Frequency (*F*)	Leak – 1%	1.25E-2	A
	Leak – 3%	2.38E-3	A
	Leak – 10%	8.00E-4	A
	Leak – 32%	3.79E-5	A
	Leak – 100%	3.75E-6	A
	Geometry factor	0.125	B
Distance (D)	Harm criteria	Flame length	C

The sources are;

A. HyRam+ – Brian et al. (2025)
B. (LaChance et al., 2009).
C. Values selected for illustrative purposes

The unit type specific data can be found in Table A.2

Table A.2 Unit-type specific input data.

Case	Pipe diameter	Isolation probability
Normal	12 mm	90%
High	12 mm	0%
Low	12 mm	99%
Short	6 mm	90%

The isolation probability of 90% is based on LaChance et al. (2009) while the other isolation probabilities and the pipe sizes are selected for illustrative purposes.

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