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Bacterial-foraging optimization algorithm for non-hazardous plant layouts

Diego Alejandro Sierra Arcila[1], Juan Felipe Rueda Mantilla[1], Felipe Muñoz[1], Ivan Mura[2], Camilo Mejía[3]

[1]*Universidad de los Andes, Department of Chemical Engineering, Bogotá, Colombia*

[2]*Universidad EAN, Department of Industrial Engineering, Bogotá, Colombia*

[3]*Universidad de los Andes, Department of Industrial Engineering, Bogotá, Colombia*

Presenter E-mail: da.sierra2021@uniandes.edu.co

Abstract

The following article approaches a safe plant layout design problem based on a bacterial-foraging optimization algorithm. Our approach finds the position in the two dimensional plane for each main process unit and evaluates the possibility of secondary contention for pertinent units, in order to minimize capital costs associated to equipment loss, piping, secondary contention, and usage of area. Fire and Explosion hazard is considered as the relevant safety aspect for distribution, and it is assessed through Dow's Fire and Explosion Index. The proposed solution approach provides an alternative to hard-optimization methods, by allowing greater flexibility in accounting for both safety and economic aspects, while providing high quality solutions in a limited computation time. The aim of our proposed solution approach is to provide support to expert decision-making during the early plant layout design steps. A case study based on an acrylic-acid production plant, which has been used by several other papers that appeared in the literature, serves the purposes of showing the appropriateness and effectiveness of the method.

1. Introduction

Plant layout is a relevant factor in the performance of a chemical process plant. Distribution designs are usually driven by expert judgment, and involve several steps of increasing detail and complexity. The plant layout design problem is widely discussed in Mecklenburgh (1985) and several techniques of distribution are described in Mannan (2012). The literature focuses on four important factors: critical examination, classification of areas, economic optimization and hazard assessment (Center for Chemical Process Safety, 2003). Out of those, the last one plays the most important role in layout designs. Unfortunately, there is not an agreed way of assessing hazard, and several models have been proposed to estimate the likelihood of critical scenario occurrence and the magnitude of their impacts. Most of these models tend to be heuristic and dependent on aspects that can either mitigate or worsen critical events, like pressure relief valves or confinement.

By taking into consideration a large number of process variables, layout design problems seek to coordinate different and contrasting objectives. Specifically, the definition of the spatial arrangement of process units determines the efficiency and yield of the production process (Tugnoli et al., 2008b), and the same time affects the safety features of the plant area, influencing the probability of occurrence of critical scenarios such as fires, explosions, toxic releases, their propagation and impacts.

Current methods for layout distribution are based on design heuristics, such as guidelines for spacing of units, which aim to prevent loss in critical cases, such as explosion over-pressure and fire exposure damage (Global Asset Protection Services LLC, 2001). Given that these methods take a considerable amount of time and do not ensure optimality, computational methods are nowadays becoming more common for layout planning.

Given that contrasting nature of the plant layout design objectives, it makes sense to formulate it as an optimization problem, which aims at finding layout designs that provide optimal trade-offs between economical and safety aspects. Early formulations of the plant layout optimization problem only aimed at optimizing the economic aspect, leaving behind safety considerations and assessing only the cost of safety devices and their loss. However, safety considerations shall not be left for posterior distribution steps, but should rather be taken into account during early stages on.

An interesting approach on safety considerations in plant layout, called inherent safety, is introduced by Kletz and Amyotte (2010). Its goal is to diminish the hazard in a chemical process plant, and to reduce the cost associated to plant life cycle. Several proposals have been made for the applicability of the inherent safety theory (Kletz and Amyotte, 2010) (Nicholas A. Ashford et al., 1993) (Bollinger et al., 1998) (Khan and Amyotte, 2003).

There is not yet an established approach that includes safety in the early stages of the layout design, but several proposals in this directions have appeared in the literature. An approach that includes safety considerations and optimization models is the one made by Penteado and Ciric (1996), who propose an integrated formulation of safety and economic aspects, in which the layout cost takes into account both the cost of the total area of the process units and the financial risk. The method presented by Penteado and Ciric (1996) has been modified and simplified by Patsiatzis et al. (2004), who replaced risk calculation by hazard approximation with exposure radius. The proposal by Tugnoli et al. (2008a) defines a domino hazard methodology for quantifying the damage due to a potential undesirable event, by assessing the risk in each unit and the possible increase of damage associated to the closeness of the other process units. Lira-Flores et al. (2014) develops a mathematical formulation of the layout design problem that considers the domino hazard index proposed by Tugnoli et al. (2008b). Thiago et al. (2016) reconsider risk calculations by using Monte Carlo simulations and simulated annealing techniques to reduce the affected area to surrounding public populations. On a similar note, Neghabi and Ghassemi Tari (2016) propose a new concept of adjacency, applying closeness ratings to pairs of neighbor equipment, and determining their proximity in order to estimate economic and safety considerations for an optimal facility layout.

However, hazard assessment still poses relevant issues in terms of layout design given that randomness in risk calculation is hard to combine with hard optimization methods (Caputo et al., 2015). Meta-heuristic approaches have the clear advantage of facilitating the integration of probabilistic aspects and design constraints into solution schemes for various types of optimization problems. They have been for instance used to address the definition of manufacturing layouts, specifically cell distribution problems. Mejia et al. (2014) propose a discrete optimization algorithm based on bacterial foraging to solve this problem, an idea also approached by Nouri et al. (2010), Nouri and Hong (2012), Nouri and Hong (2013), Nouri (2016) and Atasagun and Kara (2013) with different variations on the discrete search of solutions. On the contrary, the application of meta-heuristic approaches to the safe design of plants layout is incipient. An example of application can be found in Caputo et al. (2015), where the authors proposed a risk assessment approach based on a genetic algorithm solution scheme, a meta-heuristic method previously used by Castell et al. (1998) and Xu et al. (2013), with less complex risk calculation.

Bearing this in mind, this article aims at introducing a meta-heuristic approach of the plant layout design problem. Specifically, we define a bacteria optimization algorithm inspired to the bacterial foraging optimization algorithm proposed by Passino (2002), which quantifies hazard with the Dow's Fire and Explosion Index (F&EI) (American Institute of Chemical Engineers, 1994). Our proposal aims at finding adequate distributions of equipment in the process area, simultaneously optimizing the cost incurred for the total used area, piping, and the losses due to adverse events such as fires and explosions. Moreover, we take into account the possibility of installing sets of additional safety devices and contention barriers, which at the expense of additional costs can reduce the impact of hazardous events. The proposed layouts provided by our solution approach can serve as an aid for guiding expert criteria during the initial stages of layout design.

As for the rest of the article, Section 2 provides a description of the methodology used, and Section 3 introduces a case study that serves the purpose of showing the applicability and effectiveness of our proposed approach. The analysis of obtained results is discussed in Section 4. Finally, Section 5 provides conclusions and recommendations for future work.

2. Our proposed approach to the plant layout design problem

Our objective in this section is to propose a formulation of the plant layout design problem as an optimization problem, taking into account the hazard determined by the plant distribution in terms of the possible consequences of undesirable scenarios. Our proposed approach, graphically described in Figure 1, starts from a description of the chemical process of the plant, in terms of the required equipment units, the logical order, the materials and the operating conditions. These, elements, shown on the left side of Figure 1, are complemented with two distinct types of safety-related information for the chemical process units: A collection of sets of additional safety devices and diking options that can be applied to the units; and the likelihood of occurrence of hazardous events, such as fires and explosion, which might affect the process units.

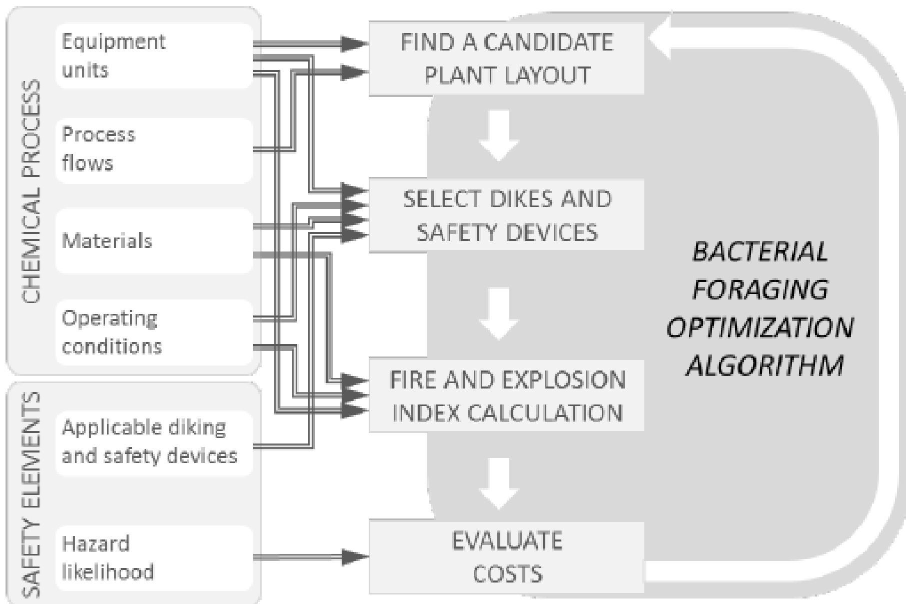

Figure 1 - Main elements and flow description of the proposed plant layout design approach

These input elements are used within a meta-heuristic based approach to determine generations of possible plant design layouts. Candidate plant layouts are defined based on the process units to be allocated and the flows of materials between them, as specified by the logical order of the production process. Then, a selection is made of the additional safety elements to be included in the design layout. This decision that has to consider the operating conditions and the materials being handled inside each process unit, as well as the set safety elements that can be applied to each unit. Once the above decision have been taken, our proposed approach performs a hazard assessment of the candidate layout. In the literature, risk assessment for plant layout mainly uses probabilistic models to determine loss scenarios. The goal of these models is to measure hazard for a specific design (Center for Chemical Process Safety, 2003). These methods consider various approximations to compute the occurrence probability of undesired events. We consider that the F&EI provides the most useful tools for hazard assessing, as suggested by Mannan (2012). Based on the materials, the operating conditions and the selected safety elements, the F&EI is calculated for each unit, and used to estimate a minimal safety radius. It is worthwhile noticing that the addition of safety devices has the effect of reducing costs due to losses, while secondary contention barriers (dikes) reduce the F&EI and thus the minimal safe distance between pieces of equipment. As a result, a set of exposure radii and other parameters are calculated, which permit to evaluate the total cost of the proposed plant layout design.

These four steps are embedded into a bacterial-foraging meta-heuristic, which generates candidate layouts that include the two-dimensional coordinates specifying the positions of process unit, their associated safety elements and the piping connections. This specific type of meta-heuristic was chosen for its flexibility in constraint management, which allows an easy representation of multiple optimization facets, and for its computational efficiency (Nouri et al., 2010).

In the following sections, we provide a description of the two main ingredients that get combined in our meta-heuristic solution scheme, i.e. Dow's Fire and Explosion Index and the Bacterial Foraging Optimization Algorithm.

2.1. Fire and Explosion Index methodology

The F&EI is a convenient mechanism to assess possible hazardous events that may trigger fire or explosion scenarios, and to identify its reactivity potential. By taking into account historical loss data, the possible energy release of the processed materials and specifications of the process itself, the F&EI computes the maximum capital loss associated to the most unfortunate situation in a single process unit (or equipment). Units without hazardous material containment are not eligible for this method, so they should be left out from the analysis since the very beginning (American Institute of Chemical Engineers, 1994).

A diagrammatic representation of the algorithm for calculating the F&EI is presented in Figure 2. First of all, the material factor MF (a measure of the intrinsic rate of potential energy released from fire and explosion (American Institute of Chemical Engineers, 1994)) is computed for all substances involved, and the most representative one is chosen as the MF of the given unit. The MF is calculated using the NFPA 704 (National Fire Protection Association, 2009). After that, the General F1 and Special F2 process factors are computed. The first factor relates to hazard applicable to most process situations, like spacing conditions or reaction thermodynamics, while the second one refers to specific process situations or conditions that may cause an increase in the probability of a loss event, like toxic releases and sub-atmospheric pressures. The F&EI, found as the product of these three factors, describes the degree of process unit hazard. Once computed, it is possible to obtain a distance r which represents the radius of a circular area of exposure. Moreover, the F&EI allows the calculation of a damage factor (DF), which represents the real damage to the exposure area; the damage factor is obtained using cubic equations based on the material factor and the process hazard unit factor.

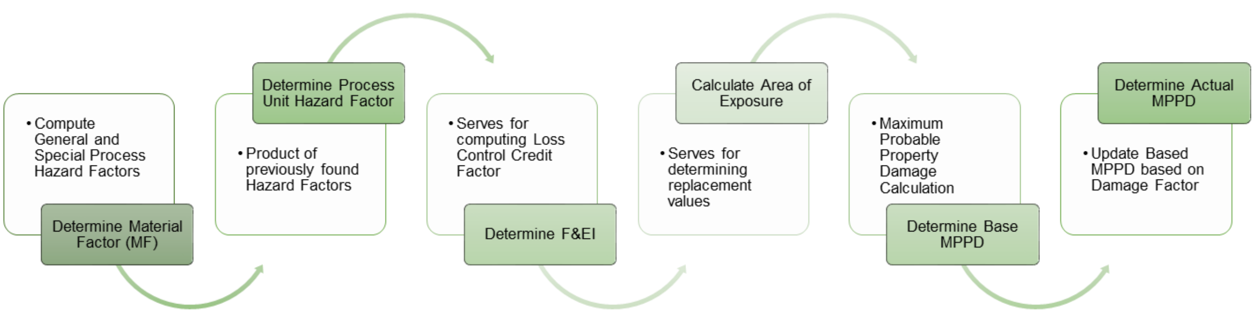

Figure 2 - Fire & Explosion Index computed algorithm

In terms of capital cost, a base maximum probable property damage (MPPD) can be determined from individual replacement costs of pertinent equipment. The algorithm also calculates a loss control credit factor that measures the benefits of installing safety devices, which are divided in three main categories: process control, material isolation and fire protection. This factor is later included to calculate an actual MPPD, which is the best estimate for the capital cost in a fire or explosion incident.

2.2. The Bacterial Foraging Optimization Algorithm

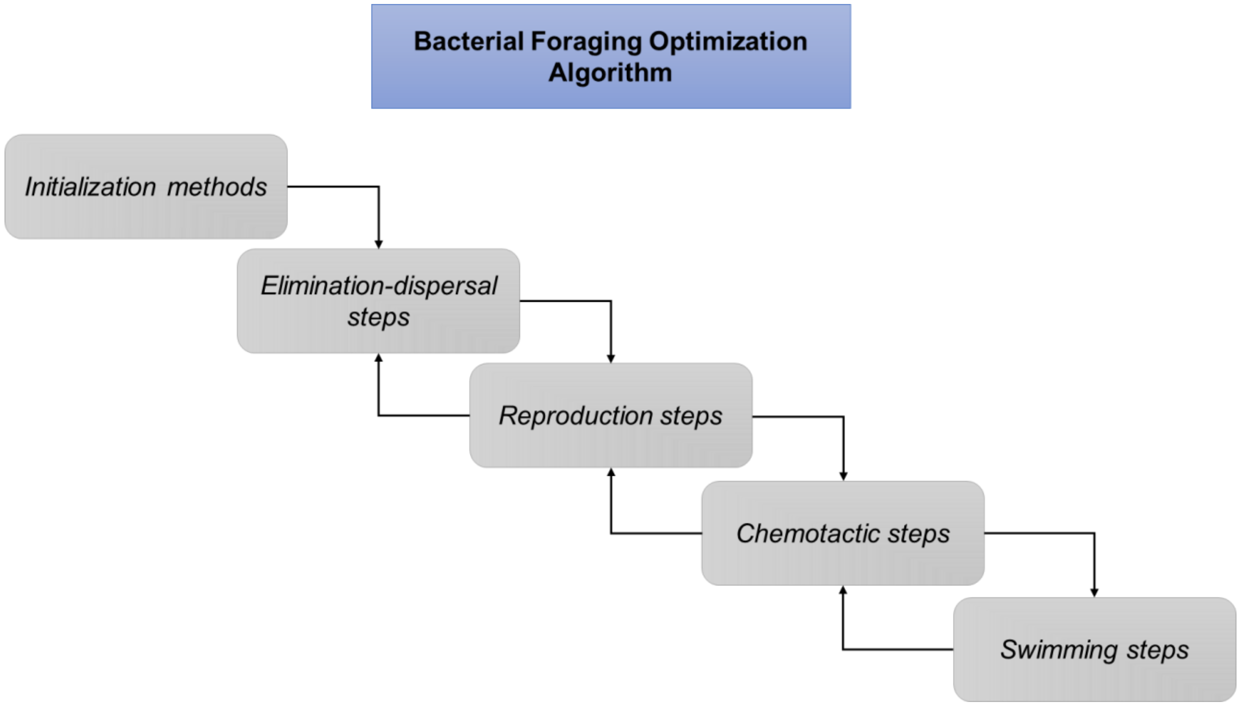

Figure 3 - BFOA description.

Inspired on the foraging strategy of E.coli bacteria, the BFOA is a meta-heuristic method that searches good solutions in randomly generated directions (Passino, 2002). The method starts with the generation of an initial population of bacteria, each representing a possible solution for a specific problem. These solutions start to vary in randomly generated directions, moving in what Nouri (2016) calls a biased random walk. Once this direction has been found, bacteria will explore either a fixed number of times (called swimming steps, or Ns), or until no improvement of the objective function has been found, as seen in steps ii) and iii) of Figure 4. This exploration process is repeated N_c times, and is known as chemotaxis (Passino, 2002). Once the first generation of bacteria has finished exploration, they are expected to provide a set of good solutions for the problem. Bacterial movement is the basis of bacteria reproduction, which can be seen as multiplication of the best bacteria and elimination of the worst, as seen in step ii) of Figure 5.

Let C be the set of natural numbers where $|C| = N_c$,
Let B be the set of natural numbers where $|B| = N_b$, *with* N_b *being the number of bacteria in the population.*
Let S be the set of natural numbers where $|S| = N_s$, *with* N_s *being the number of swimming steps*

for $i \in C$
    for $j \in B$
i.)   *Movement direction = Randomly generated direction*
        for $k \in S$
ii.)   *Temporal bacteria = Bacteria j + Step × Movement direction*
            if Objective function[Temporal bacteria]<Objective function[Bacteria j] (for minimization case)
iii.)   *Bacteria j = Temporal bacteria*
            else
iv.)   *break (Exit current for)*
            $end\ if$
        $end\ for$
    $end\ for$
$end\ for$

Figure 4 - Pseudocode for the chemotaxis cycle

Reproduction process takes into account chemotaxis cycles and gives continuity to the search by discarding unfavorable solutions in favor of promising ones.

Let R be the set of natural numbers where $|R| = N_{re}$, *with* N_{re} *being the number of reproduction steps*
Let B be the set of bacteria ordered by increasing objective function, with $|B| = N_b$,
Let W be a subset of the last $\frac{N_b(S_r-1)}{S_r}$ *bacteria in B, with* S_r *being the ratio of bacteria that reproduces.*
Let G be a subset of the first $\frac{N_b}{S_r}$ *bacteria in B.*

for $i \in R$
    for $j \in W$
i.)   *Bacteria j = Bacteria* $k \in G$, *restarting each* $\frac{N_b}{S_r}$ *bacteria*
    $end\ for$
ii.)   *Perform Chemotaxis*
$end\ for$

Figure 5 - Pseudocode for the reproduction cycle.

Finally, elimination-dispersal events (ED) take place. These events mimic the death of bacteria by external causes and other unexpected events that may affect solution search. In terms of the algorithm, it means rebooting unpromising solutions with initialization processes (as seen in step ii) of Figure 5. Hierarchically, elimination-dispersal is located in the top of the algorithm, meaning that both chemotaxis and reproduction take place, as seen in step i) of Figure 6. ED does not always happen, so Passino (2002) simplifies this aspect by setting a discrete probability of occurrence (an aspect we considered). By eliminating and dispersing, bacteria are forced to avoid local optima, and the search space is widened because of solution movement to unexplored regions.

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Let E be the set of natural numbers where |E| = N_ed, where N_ed is the number of elimination-dispersal steps
Let B be the set of bacteria ordered by increasing objective function, with |B| = N_b,
Let W be a subset of the last N_b(S_r−1)/S_r bacteria in B, with S_r being the ratio of bacteria that reproduces.

for i ∈ E
i.)      Perform reproduction
    for j ∈W
ii.)         Bacteria j = Generate new bacteria with initialization procedure
     end for
end for
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Figure 6 - Pseudocode for the elimination-dispersal cycle

2.2.1. BFOA for layout design problem

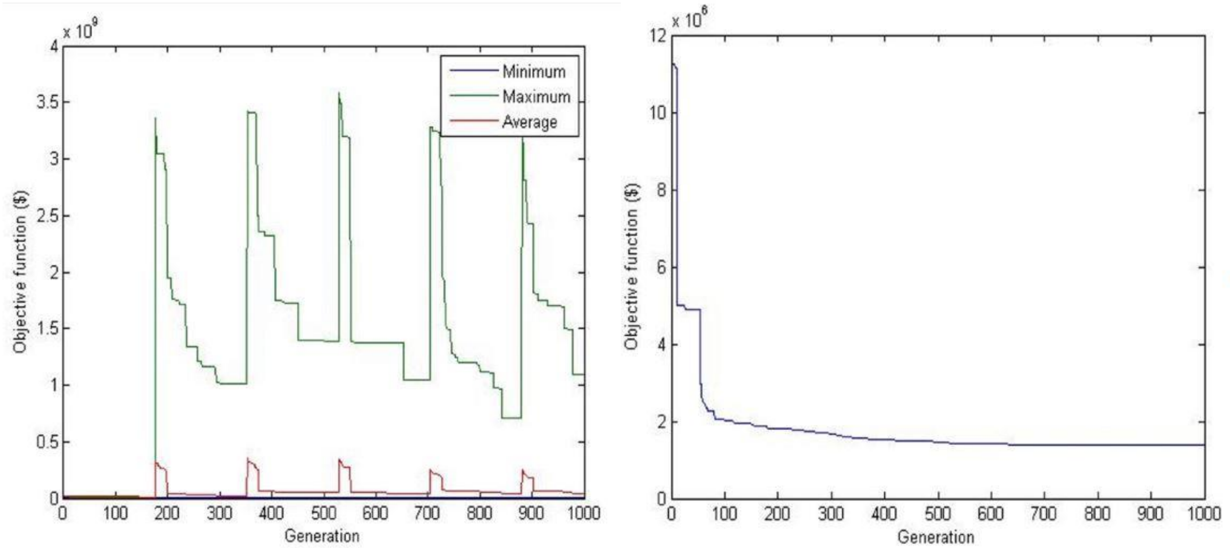
In this section we present the main adaptations we propose to the general BFOA meta-heuristic scheme to take into account the specific aspects of the safe plant layout design optimization problem.

An initialization method is required to generate the first population of bacteria. As for equipment positioning, we proposed and evaluated five possible initializations:

1. U-shaped initialization, which uses initial radius calculation for adjusting the first half of the equipment on an inferior line and allocating the rest of units in a U-shape;
2. two-lined positioning, which arranges units in two different lines with a determined space between them;
3. linear proximity, which positions equipment in a single line, ordered by their logical order defined by the process flow;
4. random allocation;
5. same-place arrangement, which puts all process equipment on the same spatial coordinates.

Notice that the two last one initialization procedures are likely to generate designs that are not physically meaningful, as equipment units may overlap. Indeed, feasibility is an aspect that original BFOA enforces when searching the possible set of solution. This mean that the solution space is not restricted, so constraint handling is needed in order to make the algorithm avoid unfeasibility. In this proposal, and given the constraints stated in Section 2.3, a penalty factor is calculated and included in the objective function, which severely impairs the value of unfeasible solutions. Our approach is that of turning feasibility into the most important aspect when it comes to direction generation.

The definition of suitable search stopping criterion is another important aspect for a meta-heuristic scheme. The evaluation of the best objective function for all bacteria generations is of course used to measure the performance of the algorithm with different parameter values, like the number of chemotactic or reproduction steps. Once bacteria have found solutions with comparable quality, it is clear that exploration will be rather limited in comparison with previous steps. However, the evaluation of the worst (maximum, for our optimization problem) objective function value, together with the average value, for the current generation of bacteria, is also relevant, as they can shed light on the contribution that elimination-dispersal steps are providing, as shown in Figure 7.



(a) Minimum, maximum, and average. (b) Evolution of the best objective function.

Figure 7 - Objective function evaluation for all bacteria generation for a minimization case.

2.3. Mathematical formulation

Low piping costs, small areas and safety aspects are relevant considerations for a quality layout (Mecklenburgh, 1985). However, there are constraints associated to the process operation, which bring difficulties to the design (Center for Chemical Process Safety, 2003). This section translates these considerations into a mathematical language, in order to be used in later sections of the article.

2.3.1. Used process area

Consider a chemical plant with a set U of process equipment. Let x_i and y_i be the coordinates on the horizontal and vertical axis for the center of a certain equipment $i \in U$, and let r_i be the exposure radius of unit i. The process area, defined as the rectangle determined by the farthest exposure radius of the whole equipment in both axis, is calculated as

$$A = (x_{max} - x_{min}) \cdot (y_{max} - y_{min}), \qquad (1)$$

Where

$$x_{max} = \max_{i \in U}(x_i + r_i), \qquad (2)$$

$$y_{max} = \max_{i \in U}(y_i + r_i), \qquad (3)$$

$$x_{min} = \max_{i \in U}(x_i - r_i), \qquad (4)$$

$$y_{min} = \max_{i \in U}(y_i - r_i), \qquad (5)$$

2.3.2. Flow principle constraints

According to the flow principle given in a process flow diagram (PFD), connection between units implies adjacency (i.e. if two equipment are connected, they must be close to each other) (Mecklenburgh, 1985). Mathematically, we can formulate this as follows:

$$|x_i - x_j| \cdot t_{ij} \leq mat_x, \qquad \forall (i,j) \in U, i \neq j, \qquad (6)$$
$$|y_i - y_j| \cdot t_{ij} \leq mat_y, \qquad \forall (i,j) \in U, i \neq j, \qquad (7)$$

where t_{ij} is a binary parameter which equals to 1 if equipment i and j are connected, or 0 otherwise; and mat_x and mat_y are the maximum distances allowed between equipment unit pairs, as required by the flow principle. These distances depend on the process, and are subject to change according to expert criteria, meaning that they are parameters for our optimization problem.

2.3.3. Piping constraints

Direct pipe connections among units has been commonly used along the literature, as for instance in Han et al. (2013) and Lira-Flores et al. (2014). While it is true that this approach reduces pipework cost, it is not practical because it leads to disordered designs and can increase friction losses. Instead, a pipe rack, allows flow tracing and proves easier for piping installation and maintenance (Drake and Walter, 2010). The width (w_{rk}) of the pipe rack is calculated as follows:

$$w_{rk} = (1.5 \cdot n \cdot s) + B, \qquad (8)$$

where n is the number of lines, s is the average spacing between lines and B is an allowance for future provision of 20%. This equation is proposed by El-Reedy (2011). Considering the final layout, the pipe rack should be located in the middle of the distribution and must be horizontal (Drake and Walter, 2010). In case there is not space, equipment should be moved until the rack fits in the design, as described in Equations 9 and 10.

$$|y_i - y_{rk}| \geq w_{rk}/2, \qquad \forall i \in U, \qquad (9)$$

where y_{rk} is the vertical coordinate of the pipe rack. If Equation 9 is not satisfied, the vertical coordinate of the equipment i should be modified as follows:

$$y_i = y_i + w_{rk}/2, \qquad (10)$$

Once the pipe rack has been modeled, the piping distance $d_{i,rk}$ of unit i from the rack is calculated as the vertical distance from the center of the equipment i to the rack, as described in the following equation:

$$d_{i,rk} = |y_i - y_{rk}|, \qquad \forall i \in U, \qquad (11)$$

The total pipe distance, should take into account the length of the pipe rack, this can be seen as

$$d_p = \sum_{i \in U} d_{i,rk} + dh_{rk}, \qquad (12)$$

2.3.4. Secondary contention barriers

We also consider the possibility of building secondary contention barriers in order to avoid spillage (El-Reedy, 2011). These kind of barriers only apply for vessels in which leakage of liquid substances can occur (Center of Chemical Process Safety, 1996). To model the choice of whether or not to build a secondary containment barrier, we introduce the binary variable δ_i for each equipment unit i, which takes 1 if a secondary contention barrier is selected for that unit. The effect of setting $\delta_i = 1$ is the one of modifying the exposure radius, so to allow a more compact and hence less costly design, without impairing safety.

2.3.5. Hazard assessment constraints

Hazard assessment is based on fire and explosion events, and is mathematically represented as an exposure radius computed by the F&EI (American Institute of Chemical Engineers, 1994). In order to avoid damage to equipment caused by critical scenarios occurring at other unit, safety distance constraints can be formulated as follows:

$$\sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \geq \max\left(r_i, r_j\right), \qquad \forall (i,j) \in U, i \neq j, \qquad (14)$$

Note that the left hand-side of Equation 14 is the euclidean distance between equipment, meaning that this constraint also considers non-overlapping of units.

2.3.6. Objective function

As mentioned before, piping cost, small areas and safety issues are performance measurements in a good layout. Gathering all these aspects, the goal in this work is to minimize the cost associated to these three factors. The objective function can be modeled as follows:

$$pen \cdot \left(\sum_{i \in U} \sum_{k \in S} (s_{ik} \cdot CS_k) + \sum_{i \in U} (\delta_i \cdot CD_i) + (CA \cdot A) + \left(d_p \cdot CT\right) + \sum_{i \in U} \left(p_i \cdot (CC_i \cdot DF_i)\right) \right) \quad (15)$$

In this equation, CS_k is the cost of the safety devices, CD_i is the cost of secondary contentions barriers, CA is the cost of process area, CT is the piping cost (including installation and maintenance) and CC_i is the the equipment cost. In order to prevent a miscalculation of the cost in a loss scenario, a p_i factor for each unit i is proposed as a weighting parameter based on the frequency of occurrence of a certain critical event (SINTEF Industrial Management, 2002). Finally, in the objective function the multiplicative factor pen works as a penalization for the objective function in case of unfeasibility. In case the current solution is a possible solution for the problem, pen takes the value of 1, so that the value of the objective function is only calculated in terms of problem variables.

3. Case Study

In this work we use as a case study the process described by Lira-Flores et al. (2014), initially presented by Tugnoli et al. (2008b) and Palaniappan et al. (2002). Specific information about the operation conditions, material flows and equipment sizing can be found in those works. The process consists in a catalytic oxidation of propylene for acrylic acid production in a packed bed reactor followed by a separation train made by absorbing, distillation and extraction towers, whose main function is to remove byproducts generated by non-desired reactions. The process flow diagram is shown in Figure 8.

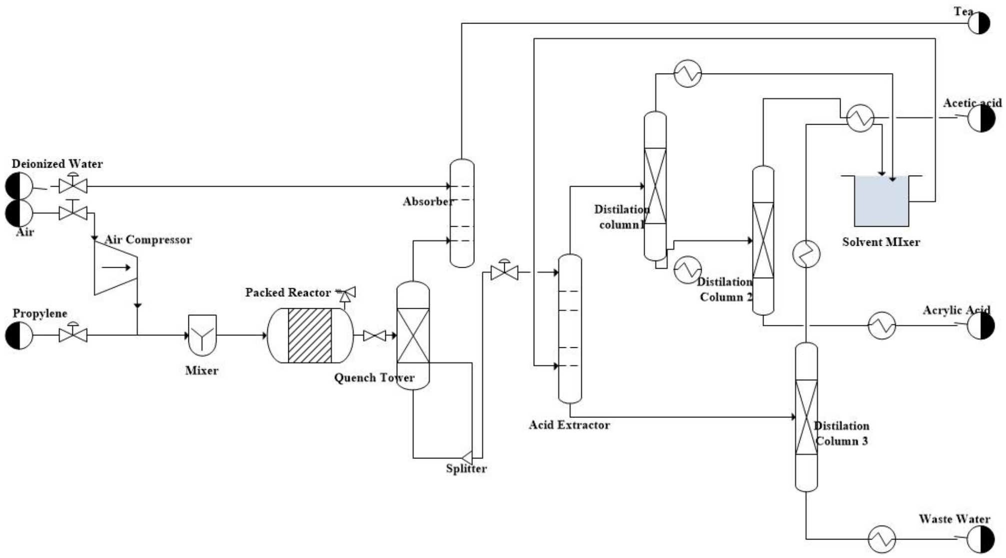


Figure 8 - : Process flow diagram for the acrylic acid production (Lira-Flores et al. (2014))

The most hazardous substances involved in the process are acrylic acid and propylene due to their flammability and reactivity; they represent the center of hazard evaluation for MF calculation. As for the economic values for the process equipment, Lira-Flores et al. (2014) obtained an initial approximation for the year 2002; rescaling of those costs to obtain current values was done according to the Chemical Engineering Plant Cost Index (U.S. Department of Labor's Bureau of Labor Statistics, 2015). Note that the same procedure had to be applied to safety device costs, which were obtained from Penteado and Ciric (1996). Table 1 and Table 2 show the present values for the equipment costs CC_i and the safety device costs CS_j, respectively.

Equipment	Number	CC_i[$]	p_i
Compressor	1	8,253	0.01
Mixer	2	45,592	0.12
Reactor	3	135,081	0.25
Quench Tower	4	69,642	0.17
Gas-absorber	5	94,710	0.07
Solvent-Splitter	6	25,524	0.56
Acid-Extractor	7	103,129	0.07
Distillation-column 1	8	142,528	0.35
Solvent-mixer	9	36,505	0.12
Distillation-column 2	10	73,431	0.35
Distillation-column 3	11	88,956	0.35

Table 1 - Nomenclature, cost and ratio of failure frequency for process equipment units.

Percentage reduction of the cost i for each safety device is also presented in Table 2, together with a description of the safety measure of each device. In general terms, the possible safety devices are chosen specifically to reduce hazard in the reactor and the separation train, although fire reliefs for vessels and additional cooling water are included as well to prevent overheating of any unit. Secondary contention barriers costs are fixed in \$4000, while process area costs are taken as \$320/m^2 (Center of Chemical Process Safety (1996)).

Safety device	**Description**	CS_j[\$]	γ_i
S_1	additional cooling water, at least 150 % of flow requirements available for 10 minutes	7,168	0.9
S_2	additional overpressure relief devices for process equipment	28,672	0.76
S_3	additional fire relief for vessels	21,504	0.75
S_4	additional skin for the reactor in order to protect against overpressure	93,183	0.4
S_5	a system for explosion protection system for the reactor	28,672	0.8
S_6	duplicated control shutdown system on absorption towers	28,672	0.54
S_7	duplicated control system with interlocking for flow control in the reactor	43,008	0.68

Table 2 - Safety devices description, their cost and percentage reduction of the loss cost.

The p_i parameter presented in Equation 15 is assumed for this specific case as a ratio of failure frequencies between the critical events associated to fire and explosions, and the total of failure scenarios (SINTEF Industrial Management, 2002). The values for this parameter are presented in Table 1.

As mentioned in Section 2, not all safety devices are applicable for all equipment; likewise, secondary contention is only applicable for certain units. Compatibility of safety devices and process equipment units are presented in Table 3. For instance, it is assumed that each distillation tower includes its respective reflux drum, hence the applicability of secondary contention barriers in these cases. It is also assumed that minimum requirements of safety devices are installed.

As for the pipe rack, the width is calculated using Equation 9. It is remarkable that a two level pipe rack is selected in order to reduce the occupied space (Drake and Walter, 2010). An average space between lines of 300mm and 7 lines per level is assumed, given a w_{rk} of 3:78m.

Equipment	S_1	S_2	S_3	S_4	S_5	S_6	S_7	Secondary contention barrier
Compressor								
Mixer								
Reactor	√	√	√	√	√		√	√
Quench-tower	√	√				√		
Gas-absorber		√	√			√		
Solvent-splitter								
Acid-extractor		√				√		
Distillation-column 1	√	√	√			√		√
Solvent-mixer								
Distillation-column 2	√	√	√			√		√
Distillation-column 3	√	√	√			√		√

Table 3 - Applicability of the safety devices and secondary contention barriers for the process equipment.

4. Results and discussion

The optimization problem is solved in the continuous space domain, simplifying the geometry shape of the equipment to squared units. The BFOA parameters are set as follows:

- number of elimination-dispersal steps N_{ed} = 8,
- number of reproduction steps N_{re} = 16,
- number of chemotactic steps N_c = 24,
- number of swimming steps N_s = 28,
- number of bacteria per generation N_b = 45.

An important factor in the convergence of a good solution is a correct initialization, reason for which a U-shape is selected. The software employed for solving the case is MATLAB.

The best design option obtained by running the algorithm that implements the BFOA meta-heuristic results is shown in Figure 9. Circular dotted lines represent exposure radii for process equipment, whose values are shown in Table 4. Horizontal red lines illustrate pipe-rack connections, while the green ones show connections between equipment and pipe supports. Black lines limit the process area, based on Equation 1. Finally, as mentioned above, equipment are represented by square shapes, with additional space to its physical limits, considering access to the units and avoiding confinement.

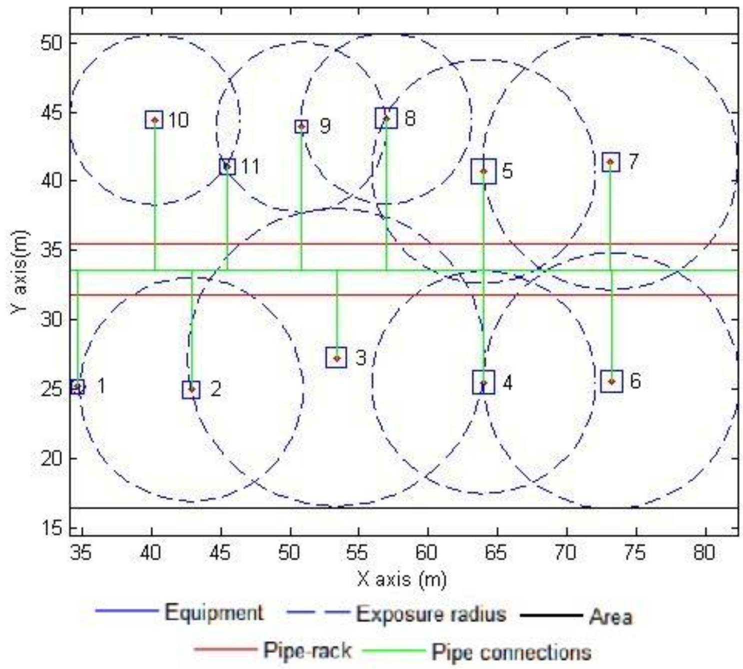


Figure 9 - Best layout distribution for an acrylic acid production plant obtained by the BFOA

The value of the total cost obtained for the layout design is \$809.000, with a process area of 1650m^2 and a total piping distance of 253m. As for the safety considerations, safety devices and secondary barriers are selected as presented in Table 4. The selection of the devices for pertinent units is low as a result of their cost, which tends to be high. Therefore, in the evaluation of the objective function, the installation of those devices does not bring benefit to the MPPD. However, as seen in table 4, additional cooling water is chosen for the first distillation column and the solvent mixer, in order to reduce the temperature in case any of these equipment overheat. Also, the acid extractor and the gas absorber choose to duplicate the shutdown system, in case any of these operate under anomalous temperature and pressure conditions.

As for the secondary contention, the algorithm selects these barriers for all the four possible units, given that it reduces the exposure radius. In the current scenario, avoiding leakage turns into a priority due to the inflammability of most of the compounds considered. Secondary barrier selection also increases the closeness between units, so that area costs also get reduced. Note that the most hazardous unit (number 3), given its exposure radius, forces the other equipment to satisfy constraints. Thus, the reactor determines the distribution based on its position and allows the minimization of the risk due to the movement of the other units, reducing the probability of a domino effect.

Equipment	Exposure radius (m)	Safety devices	Secondary contention barrier
Compressor	0.5		
Mixer	8.1		
Reactor	10.8		√
Quench-tower	8.1		
Gas-absorber	8.1	S_6	
Solvent-splitter	9.2		
Acid-extractor	9.2	S_6	
Distilation-column 1	6.1	S_1	√
Solvent-mixer	6.1	S_1	
Distilation-column 2	6.1		√
Distilation-column 3	0.4		√

Table 4 - BFOA selections for safety devices and secondary contention barriers, also showing the resulting exposure radii of process equipment units.

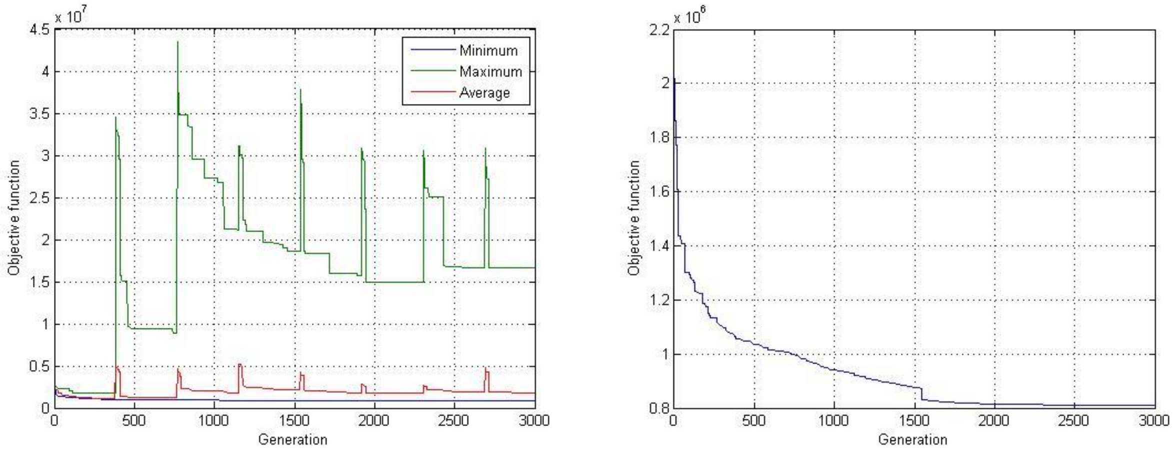
In the literature, similar works have been done for the acrylic acid production problem, as the ones reported by Lira-Flores et al. (2014) and Tugnoli et al. (2008a). A comparison between the results obtained with our meta-heuristic approach and the ones achieved by those works is presented in Table 5. It should be noted that both the approach of Lira-Flores et al. (2014) and Tugnoli et al. (2008a) do not consider area cost in the objective function, so we estimated it for their layouts from the graphical information reported in the papers to ensure comparability with our results.

Parameter/Method	BFOA	MINLP(Lira-Flores etl.)	3 Option of (Tugnoli etl.)
Pipe length (m)	253	165	165
Area (m2)	1650	1125	1125
Total Cost (k$)	809	1023.83	1594.33

Table 5 - Result comparison between layouts.

Both literature approaches consider direct piping connections between equipment, which reduces piping costs; however, a pipe rack (like the one assumed in this work) increases pipe length but ensures order and is more reasonable for the layout. It is also remarkable that the area presented by Lira-Flores et al. (2014) is not variable and is indeed constraining the problem. Even so, the total process area we obtain with our BFOA meta-heuristic approach is similar to the one presented in their work. In addition, propagation of a critical scenario is not allowed, hence, a safety design is guaranteed following the principles introduced by Kletz and Amyotte (2010). Also, loss costs are reduced in comparison to the other two options, given that the expected loss is an average depending on the equipment, and loss events (fire and explosion) can only affect one unit at a time.

Note that the optimization in Lira-Flores et al. (2014) is based on a different risk calculation, for which consequences to external areas are not considered. Given those differences between models, our proposal presents advantages by avoiding equipment positioning that may threaten anything beyond the process area. For instance, it can be seen in Figure 9 that the reactor (unit number 3) gets positioned in a way that avoids cornering positions so that adjacent external areas are not affected in critical cases, which is clearly a better choice than those made with previous approaches.



(a) Minimum, maximum, and average. (b) Evolution of the best objective function.

Figure 10 - Objective function evolution for the acrylic acid production obtained by the BFOA.

We show in Figure 10 the evolution of the objective function with the progress of the BFOA search. Figure 10a shows the average, minimum and maximum values of the functions in the generations. Peaks in the maximum graph-line corresponds to the steps when elimination and dispersal were taking place. The sudden subsequent reductions indicates that previous solutions proved to be better. Figure 10b shows the objective function for the first (and best) bacteria of each generation, initiating at a high value and dropping steadily along the generations. From generation 2500 onwards, the value of the function stabilizes and there is no further improvement, indicating that the population of bacteria has reached a solution quite close to what the real optimum should be, and the stopping criteria is met. The total computational time is reported in 321 seconds, a good result if one takes into account the high number of swimming steps performed by the BFOA meta-heuristic.

5. Conclusions and future research

The approach presented in this work solves the layout design problem with the BFOA, assessing hazard with the F&EI. Safety considerations are represented by secondary contention barriers on specific units, and additional safety devices that aim to reduce damage or prevent critical scenarios. Piping is modeled with a pipe-rack crossing the process area and avoiding piping between equipment, an aspect rarely approached by other authors. A weighting factor is also taken into account to model occurrence of undesired events, instead of assuming the simultaneous occurrence of critical cases on every unit.

A case study is solved to demonstrate the usefulness and improvement of the current method over previous approaches, obtaining solutions of similar quality while taking into account operational and safety aspects not considered before. Our approach proved to be highly efficient in terms of computational time.

Safety considerations enhance the attractive of the current approach, as they are based on positioning of equipment whose hazard might affect nearby units. Domino effect considerations are not directly factored into the problem, yet the results presented in Section 4 confirm that propagation of critical events is reduced by constraining the problem with a hazard approximation. In this sense, the approach provides a starting point for inherent safety designs based on simple techniques that seek to produce robust layouts without requiring significant amounts of computational effort (Kletz and Amyotte (2010)).

The results presented in the current work do not favor any aspect over the rest, although it is possible to do so in order to produce several alternatives. The objective is to strengthen expert criteria in the decision-making process of the first stages of plant layout. Bear in mind that BFOA characteristics, such as flexibility in constraint handling and exploration based on initial solutions, allow applications for other types of cases. For instance, including other units in a given layout or modifying a specific design to improve it in terms of safety considerations are problems that this approach can solve effectively. Secondary areas can also be included in future cases, with the aim of distributing an entire process plant. Further research in terms of adjacency calculation between units and weighting factor computation, as well as refining of hazard assessment, can enhance the proposed approach.

6. Conclusions and future research

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