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A Multiobjective-driven Approach to Reduce Risk in Process Layouts

Laura N. García-Sánchez[a], Richart Vázquez-Román*[a], Christian Díaz-Ovalle[b], M. Sam Mannan [c]

[a]Instituto Tecnológico de Celaya, Departamento de Ingeniería Química, Av. Tecnológico y A.G. Cubas s/n, Celaya, Gto., CP 38010, Mexico
[b]Instituto Tecnológico de Roque, Departamento de Ingenierías, Carretera Celaya-Juventino Rosas Km 8, Celaya, Guanajuato, 38110, Mexico
[c]Mary Kay O'Connor Process Safety Center, Artie McFerrin Department of Chemical Engineering, Texas A&M University, College Station, Texas 77843-3122, U.S.A
richart@iqcelaya.itc.mx

A multi-objective programming (MOP) approach is applied in this work to produce optimal facility layouts when some of the facilities may release toxic gas. A conflict appears when solving the optimization problem because reducing the occupied area increases the individual risk. In this approach, a utopia point is introduced as a reference, which is defined as the layout where no toxic releases are considered, *i.e.* the objective function consists on minimizing the total cost of interconnections and the occupied area. Then the Pareto set is built-up by incorporating individual risk to visualize the effect of the two contradictory objective functions. The closest point in the Pareto curve to the utopic reference is adopted here as the neutral risk point. A case-study is used to visualize risk-neutral, risk-averse and risk-seeking layouts where the overall stochastic individual risk is set up to a certain value. The optimization facility layout problem is formulated as a mixed-integer non-linear program (MINLP), which is highly non-convex.

1. Introduction

Defining a process layout is a highly complex process with many unknowns and concerns that are difficult to resolve. From the safety point of view, choosing a bad distribution results in additional measures to prevent or mitigate dangerous situations. These measures, such as protective systems to counter potential exposure risks, represent a cost effective effort. Any attempt for risk reduction increases separation distances among units but the interconnections cost and occupied area are also increased. The process layout has been typically addressed using heuristic rules and involving many different areas of expertise. A wide range of minimum distances between process units have been suggested to produce several existing layouts (Mecklenburgh, 1985). It is considered here that safety engineering should be involved through all the layout process to ensure that hazards and risks are properly managed. In particular, the control room siting represents the main challenge for safety and several standards and publications have been produced to advice it (CCPS, 1999; CCPS, 2003). A risk analysis is usually performed to verify the tolerance level when a layout is synthetized (CCPS, 2007). Risk evaluation depends on the type of potential hazard associated in the analysis (API752, 2003). A comprehensive procedure to estimate risk for a given location of control rooms has been developed based on improving the estimation of the vapour cloud explosion frequency (Badri, 2011).
The facility layout problem has been recently formulated in such a way that it involves numerical optimization strategies to get the best layout (Díaz-Ovalle et al., 2010; Vázquez-Román et al., 2010; Jung et al., 2011). A single objective function has been used in these optimization models so that risk is included in economic terms.

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In this work, a bi-objective function for the layout optimization is formulated to separate risk terms from costs such as the occupied area and interconnection. Thus an ordering concept is introduced to produce the Pareto front, named after the economist W. F. Pareto. A methodology to estimate the Pareto set is proposed and applied to a case study to highlight the advantages of performing the proposed analysis. This work focusses on laying out facilities where toxic materials may be released.

2. Layout problem description

The first challenge for the layout problem consists on determining a distribution for the process units in a given piece of land. This portion of land is referred to as a facility and it typically has a rectangular shape with predefined dimensions. The facility concept includes control rooms and administrative buildings. Some of the difficulties emerging include avoiding potential damages to process units due to fires, explosions, etc. However, the main hardship in this work is related to finding the best position for the control room when some facilities may release toxic materials. A second challenge for the layout problem, referred in this work, consists on allocating all facilities in a given portion of land.

For the sake of simplicity, each *i*-facility is assumed to have rectangular shape footprint so that their position can be represented by its (x_i,y_i)- coordinates of the center point, length (Lx_i) and depth (Ly_i) values. The mathematical model includes land constraints, Lx and Ly, so that all facilities will be allocated inside this rectangular land. Non-overlapping constraints are included to avoid that two or more facilities could be allocated in the same physical space. Two methods have been successfully applied to impose the non-overlapping: using the convex hull approach (Vázquez-Román, et al., 2010) and the big-M model (Patsiatzis et al., 2004). This second choice is adopted in this work. The separation between facilities used in the dispersion analysis corresponds to the Euclidian distance. The total occupied area is calculated as the rectangle that includes all facilities. Probit functions provide means to estimate the death risk as a function of concentration and exposure time where Pasquill's dispersion model is used to calculate concentrations for the risk evaluation. Finally, the total cost includes piping and occupied land costs. The constraints of the proposed model are shown in Table 1 and the objective functions are discussed in the following section. The model clearly represents a MINLP containing a highly non-convex feasible region.

3. Multiobjective optimization methodology

The multiobjective optimization problem (MOP) is gaining wide interest in engineering since many of its optimization models should be formulated in this way. A MOP appears when the purpose for optimization becomes a vector-valued function, *i.e.* there are several objective functions. The fields of application is diverse and it includes finance, biomedicine, management, design, environmental engineering, etc. (Liu et al., 2010; Elazouni and Abido, 2011; Pozo et al., 2012). The general MOP is:

$$\begin{aligned} &\min \mathbf{f}(\mathbf{x}) \\ &\text{s.t. } \mathbf{g}(\mathbf{x}) \leq \mathbf{0} \end{aligned} \tag{1}$$

where **x** is a n-vector of variables and **f** is a k-vector-valued function.

Given the conflict between objectives, a solution **x*** would rarely produce a solution where all objectives in the MOP were minimized. A single point **x*** belongs to the Pareto set when none of the objectives can be improved without deterioration of at least one of the other k-components. Optimality conditions for the unconstrained non-convex MOP have been established somewhere else (Qu et al., 2011). The optimality conditions for several others constrained MOP have been also analysed (Chinchuluun and Pardalos, 2007). Finding each Pareto optimal point is not an easy task and it becomes too expensive and time consuming. Typical approaches to deal with these problems, the weighted-sum method for instance, consist on formulating a single objective via Lagrange multipliers to provide units consistency.

However, there are some cases where no Lagrange multiplier can be appropriately established (Lu and Juang, 2011). The methodology developed here to solve a bi-objective optimization problem is as follows: It starts by calculating the two extreme optima where only one objective function is minimized. The two objective functions used to solve the layout problem are: total risk and total cost, which includes interconnection and occupied area costs. Each point contains the minimum overall value for one objective, which corresponds to the maximum value for the other objective function. The utopia point is normally calculated by minimizing each independent objective function and the results correspond to the coordinate's values. To give more relevance to safety, it is proposed here that the coordinates for the utopia point should be $(0,f_2^*)$, which means that no risk is allowed and f_2^* is the corresponding minimum cost. The two objective functions are then properly bounded with the two extreme optimal values. The utopia layout is used as initial point to calculate each remaining Pareto points. The rest of the unknowns are averaged with the results of these two extreme-optimal points to use these values as initial values for the rest of the calculations. To calculate a predefined number of Pareto points, one objective is fixed to a value, i.e. corresponding coordinate value, while the other objective is bounded to find the Pareto point. To ensure Pareto solutions when the feasible region is non-convex, a global optimizer such as Baron is used in each step. An advantage of having just two objectives is that all optima can clearly be indicated in a plane. Table 2 shows the procedure used and the numerical solution is obtained through the GAMS system Brooke et al., 1998).

Table 1: The layout model

Number	Equation	Description
1-2	$\frac{Lx_s}{2} + st \le x_s \le Lx - \left(\frac{Lx_s}{2} + st\right)$ $\frac{Ly_s}{2} + st \le y_s \le Ly - \left(\frac{Ly_s}{2} + st\right)$	Land constraints to keep facilities inside the available land.
3-6	$x_s - x_i + Lx(E1_{s,i} + E2_{s,i}) \ge \frac{(Lx_i + Lx_s)}{2} + st$ $x_i - x_s + Lx(1 - E1_{s,i} + E2_{s,i}) \ge \frac{(Lx_i + Lx_s)}{2} + st$ $y_s - y_i + Ly(1 + E1_{s,i} - E2_{s,i}) \ge \frac{(Ly_i + Ly_s)}{2} + st$ $y_i - y_s + Ly(2 - E1_{s,i} - E2_{s,i}) \ge \frac{(Ly_i + Ly_s)}{2} + st$	Non-overlapping between siting-installed facilities, big-M formulation. $\forall\, i = 1, \dots, N-1, j = j+1, \dots, N$
7-10	$x_s - x_k + Lx(E3_{s,k} + E4_{s,k}) \ge \frac{(Lx_k + Lx_s)}{2} + st$ $x_k - x_s + Lx(1 - E3_{s,k} + E4_{s,k}) \ge \frac{(Lx_k + Lx_s)}{2} + st$ $y_s - y_k + Ly(1 + E3_{s,k} - E4_{s,k}) \ge \frac{(Ly_k + Ly_s)}{2} + st$ $y_k - y_s + Ly(2 - E3_{s,k} - E4_{s,k}) \ge \frac{(Ly_k + Ly_s)}{2} + st$	Non-overlapping between siting-siting facilities, big-M formulation. $\forall\, i = 1, \dots, N-1, j = j+1, \dots, N$
11	$D^2_{k,r,l} = (x_l - (x_k + Px_{k,r}))^2 + (y_l - (y_k + Py_{k,r}))^2$	Euclidian distance from facility *k* having a release *r* to facility *l*.
12-14	$A_x = max\left(\frac{x_s + Lx_s}{2}\right)$ $A_y = max\left(\frac{x_y + Ly_s}{2}\right)$ $Area = A_y A_x$	Total occupied area.
15	$Y_{i,r,s} = \beta_0 + \beta_1 ln(C^n t)$	Probit function.
16-18	$Conc_{i,r,s} = \frac{Qf_{i,r}}{3.1416 v \sigma z_{i,r,s} \sigma y_{i,r,s}}$ $\sigma z_{i,r,s} = \frac{0.016 D_{i,s}}{1 + 0.0003 D_{i,s}}$ $\sigma y_{i,r,s} = \frac{0.04 D_{i,s}}{\sqrt{1 + 0.0001 D_{i,s}}}$	Pasgill's dispersion model
19	$Risk = \sum_{s} \sum_{r i(i,r)} f_{i,r}\, p_s Y_{i,r,s}$	Risk evaluation
20-21	$C_{piping} = 0.5 \sum_{(i,j) \in M_{ij}} C_p\, d_{i,j}$ $C_{land} = c_1 A_x A_y$	Total costs: piping and occupied land.

Table 2: The Pareto Estimation Procedure for bi-objective Optimization

For a given *n*-number of points to calculate the Pareto set containing $P_1, P_2, ..., P_{n+1}$:
Step 1. Get the two dimensional vectors P_1 and P_{n+1}. The objective-components for P_1 is obtained from: min $f_1(\mathbf{x})$, s.t. $\mathbf{g}(\mathbf{x})\leq\mathbf{0}$. The objective-components for P_{n+1} is obtained from: min $f_2(\mathbf{x})$, s.t. $\mathbf{g}(\mathbf{x})\leq\mathbf{0}$.
Step 2. Calculate the utopia point. In the layout problem, this point corresponds to minimizing all costs and assuming nil for the risk function.

Step 3. To calculate each intermediate Pareto point, solve min $f_1(\mathbf{x})$, s.t. $\mathbf{g}(\mathbf{x})\leq\mathbf{0}$ and $f_2(\mathbf{x}) \geq z\, P_{n+1,2}$, where z is a fraction impose on the risk function to produce equally distributed Pareto points.

Table 3: General data for the case study

Facility	Personal	*x* (meter)	*y* (meter)	*Lx* (meter)	*Ly* (meter)
FA	5	97	20.5	45	30
FB	1	21.5	30	30	50
FC		57.9	31.7	25	20
FD		88.7	49.5	30	20
NA	2			25	45
NB				60	60
NC				35	20
ND				35	20
CR	10			15	15

4. Case Study and Results

The case study used in this work consists on allocating four new facilities and the control room in a giving land where four facilities have been already installed. Expected individuals and dimensions for each facility are given in Table 3. This table also includes the positions of all installed facilities. Names for installed facilities start with “F”, for new facilities start with “N” and “CR” is the control room. The interconnected facilities are NA-FC, NA-NB and NB-NC and the interconnection cost is considered as 60.8 $/m. The land cost is considered as 16.00 $/m^2 and the available land is a square with 700 m/side. Two types of release materials are probable to occur: H_2S and Cl_2. The corresponding Probit parameters are $\beta_0 = (-31.42, -8.29)$, $\beta_1 = (3.008, 0.92)$, and $n = (1.43, 2)$. The worst-case scenario is considered where the wind speed in calm is fixed to 1.5 m/s. Table 4 indicates what facility is releasing as well as the type of release, flow scenarios, frequency and pipe diameter.
Applying the above described approach, the results of the Pareto estimation are shown in Figure 1. The main reference points are the extreme optimal points, the neutral point and the utopia point. The layout produced in the risk-neutral point is indicated in Figure 2. In additional results, it is clear that the facilities tend to occupy the whole land when risk is minimized while the occupied land is reduced when the cost is minimized, Figure 3. Yet layouts with neutral risk look disperse indicating that mitigating devices should be installed to maintain low risk and appropriate separations. It can also be observed that, in this particular case study, there exists a zone close to the neutral point in direction to low risk which has almost the same distance to the utopia point. It means that the neutral risk could be accepted as a region rather than defining a single neutral point.

Table 4: Releasing data for the case study

Facility	Toxic type	*Flow* (g/s)	*Released time* (min)	*Frequency*	*Diameter* (m)
FC	H_2S	50	12	0.001	0.0254
FC	Cl_2	114	12	0.0005	0.0254
NC	Cl_2	114	12	0.0025	0.0254
ND	Cl_2	114	12	0.001	0.0254

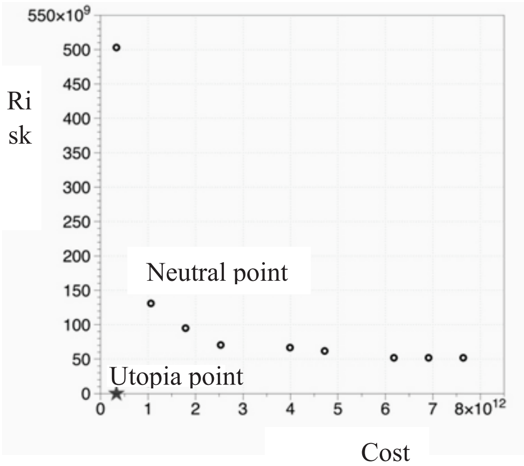


Figure 1: Pareto set for the case study.

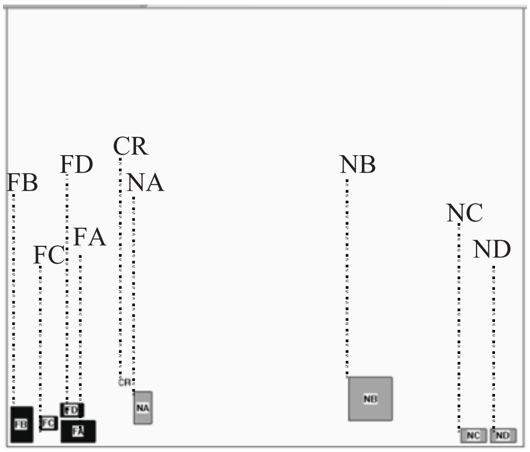
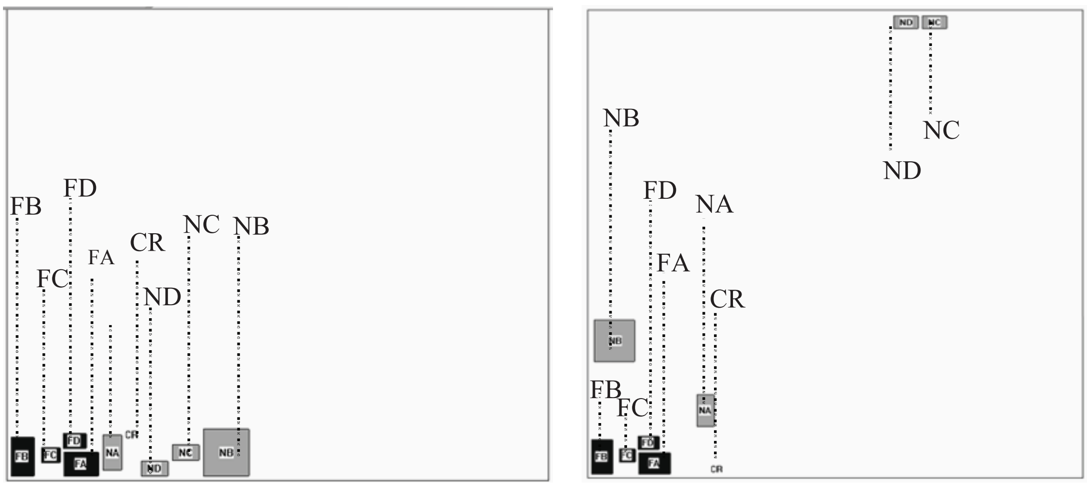


Figure 2: Optimal facility layout at neutral point.



(a)

(b)

Figure 3: Facility layout with a) minimum cost and b) minimum risk.

5. Conclusions

The layout problem has been formulated as a bi-objective MINLP problem. It is clear that economic performance of the occupied area conflicts the individual risk in the layout of facilities where toxic releases are possible. The proposed approach separates risk and costs to easy decisions according to the risk inclinations in each decision maker. The advantage of using a utopia-tracking approach is clear since it helps to find the numerical solution corresponding to the Pareto front. Thus, risk-averse decisions could focus on finding solutions from broad separations to those produce in the neutral point and vice versa.

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