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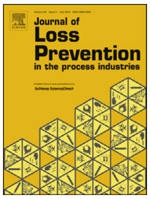

Optimal determination of chemical plant layout via minimization of risk to general public using Monte Carlo and Simulated Annealing techniques

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A B S T R A C T

A new algorithmic approach is presented to optimally locate process or storage units in the plant area (layout) of industrial facilities. The proposed formulation defines a configurational optimization incorporating spatial constraints for locating units inside the industrial area and an objective measuring the consequences to near residential areas in the event of accidents. The Monte Carlo method is used to estimate superposing areas in order to check constraints and to evaluate the objective, which measures the superposition of accident effect areas onto population polygons. The method is fed with an initial feasible layout where the coordinates of all units are given. Then, a Simulated Annealing search randomly moves units throughout the industrial area, penalizing unfeasible configurations, until a feasible layout is found minimizing the consequences of accidents to general public. The method was validated through two hypothetical case studies: (i) a new marine fuel terminal; and (ii) the addition of a new LPG storage yard to an existing refinery. In each case, it was demonstrated that the method effectively reduced risks to the surrounding communities, since it achieved, in both cases, feasible plant layouts minimizing the populated area reached by the accident effect range of each unit in the installation.

1. Introduction

Due to the continuous worldwide necessity of new industrial facilities processing and/or storing substantial inventories of flammable and/or toxic products, companies and environmental agencies are always concerned to avoid the occurrence of accidental releases (spillages) which may cause damages to the general public and the environment (Lees, 1996). This is a global concern since the 70's decade due to the drastic repercussions of catastrophic accidents near to densely populated area, most notably those that happened in Flixborough, UK (1974); Seveso, Italy (1976); and Bhopal, India (1984) (AICHE, 2000). In this context the European Union issued Seveso I & II Directives (European Union, 1982; European Union, 1996) for preventing accidents with dangerous inventories, as well as mitigating their consequences to neighbor communities and the environment. Beside this, in addition to HSE issues, there is also the interest of avoiding accidents because they can result in severe financial losses, either due to operational discontinuity or damage to company image (a critical asset in nowadays globalized world) — (Crowl and Louvar, 1990; Lees, 1996; AICHE, 2000; CCPS, 2008).

Consequently, a large amount of resources (both financial and human) has been spent by industry in order to achieve acceptable HSE standards and safety in general. Investments are made in security and firefighting systems, workforce training, risk management programs, contingency plans, HSE assessments, etc.

Undoubtedly, these and other accident prevention actions not mentioned above are essential, but in some circumstances solutions conceived and implemented during the design stage require much lower costs and time for implementation, and are more effective from a safety point of view (Medina et al., 2009).

In consonance with this context, this work proposes a new algorithm based on the Monte Carlo (MC) method (Woller, 1996; Fishman, 1996) for calculating areas and Simulated Annealing (SA) search (Kirkpatrick et al., 1983; van Laarhoven and Aarts, 1987;

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Nomenclature used

AER_k	Accident Effect Range of unit k (m)
AI	Area of Interest (m^2)
A_Γ, A_Θ	Areas of convex polygon Γ and of non-convex polygon Θ
$A_{OVL}(i,j)$	Overlapping area of units i and j (m^2)
A_R	Area of intersection of AI with all PP_i taken individually (m^2)
A_{REC}	Area of the Sampling Rectangle enveloping all AER_i for MC sampling (m^2)
$DT_i^{(\Gamma)}$	i-th Delaunay triangle as a partition of the convex polygon Γ
F_i	Weighting factor for polygon PP_i proportional to its demographic density
F_C	Weighting factor for the fraction of AI not belonging to PP_i, $i = 1..NPP$
F_{OVL}	Weighting factor for overlapping areas of units
$\underline{\underline{M}}$	Simplex Matrix with size $n \times n$ in Eq. (5)
n_{AI}, n_R	Number of MC points within AI and within A_R
$n_{DTi}^{(\Gamma)}$	$NDT^{(\Gamma)}$ Number of MC points within $DT_i^{(\Gamma)}$ and total number of $DT_i^{(\Gamma)}$ on Γ
n_{NH}	Number of MC points within AI and on sectors precluding occupation
n_{PPi}	Number of MC points within AI and PP_i.
NPP	Number of population polygons
n_{TOTAL}	Total number of MC points in the Sampling Rectangle
NU	Number of fixed and mobile units for FLP optimization
$OBF^{(I)}$	Contributions of AI and PP_i, $i = 1..NPP$ to the FLP Objective
OBF	Complete objective for FLP optimization
P	Probability of acceptance of a new, but worse, layout
$\underline{P}_0$, $\underline{P}_1$, .., $\underline{P}_n$	Vertices of nD Simplex with $n + 1$ vertices
PFL, PIA	Polygon of Facility Limits and Polygon of Industrial Area
PP_i, PP	ith Population Polygon; $PP \equiv$ Union of all PP_i
$\underline{r}$	Vector position of the center of mass of Simplex S
S	General nD Simplex
$T^{(n)}$	nth level of temperature analogue in the SA search

Greek symbols

α	Rate of cooling analogue in the SA search
$\underline{\alpha}$	Vector of Simplex coordinates given by $\underline{\alpha} = \underline{\underline{M}}^{-1}(\underline{r} - \underline{P}_0)$
ΔE_{ij}	Difference between objective values of layouts i and j
Γ	Arbitrary convex polygon on x–y plane
Θ	Arbitrary non-convex polygon on x–y plane

Meller and Bozer, 1992) to optimally locate process or storage units within the industrial area (layout) inside chemical plants.

The present approach is an example of the so-called *Facility Layout Problem* – FLP (Kusiak and Heragu, 1987; Singh and Sharma, 2005) but with two main specific characteristics: (i) it works only on two-dimensional projected layouts on the x–y plane; (ii) it strictly focuses on the minimization of risks to residential areas (also projected on the x–y plane) that already exist or would be present in the plant surroundings in the future. The reader must not make confusion with the SA and MC contexts employed in this work: classical SA is based on MC method, but in this implementation the MC method is also, *per se*, a critical tool to calculate the FLP objective by estimating certain important areas on the x–y plane that impact the objective value and, therefore, are pertinent to the problem.

The proposed methodology incorporates location constraints of units within the industrial area and an objective function whose numerical optimization corresponds to the minimization of the area corresponding to the projection of accident effect ranges extrapolating the facility limits. In other words, the proposed methodology searches the optimum positioning of process units in the industrial area that minimizes the impact on population areas in case of accidents. The numerical value of several critical areas that compose the FLP objective are evaluated on the plane x–y via MC integrations. This always guarantees numerical estimation of several irregular, tortuous, non-convex, not necessarily contiguous, not necessarily disjoints or connected areas. The SA search, on the other hand, promotes stochastic moves of units until a feasible layout emerges minimizing the mentioned objective. FLP constraints are formulated in order to avoid physically unfeasible solutions with overlapping units and/or units projecting outside the industrial area. Constraint violations are evaluated geometrically.

The implemented SA search is a variant of the classical Metropolis et al. (1953) algorithm and was successfully used for numerical optimization of the proposed FLP objective, since it leads to the minimization of risk to general public regarding hazardous installations. In this context, the proposed methodology in this work can be considered aligned with the basic principles of international directives related to the prevention and mitigation of major accidents, such as Seveso I and II above.

2. Facility layout optimization and risk assessment

The Industrial Plant Layout Problem, often mentioned in the literature by the acronym FLP (*Facility Layout Problem*), essentially consists in determining the optimal spatial arrangement of a given production system. According to the information assembled by Singh and Sharma (2005), this type of optimization can be applied in several areas, such as establishing the design of electronic circuit boards; the definition of hospital plant, schools and airports; storage products; design of hydraulic turbines, etc.

Regarding specifically the Process Industries, layout optimization has been applied aiming at different objectives, mainly in order to reduce land use and construction costs (Georgiadis et al., 1999); to diminish piping length interconnecting units, pumping and transportation costs (Povoa et al., 2002; McKendall Jr. et al., 2006), and to organize more efficiently the production (Wu and Appleton, 2002; Zhang et al., 2008; Önüt et al., 2008). However, the requirements resulting from these approaches typically focused on minimizing CAPEX (capital expenditure) and OPEX (operational expenditure) related to the design process of chemical plants. Since mere CAPEX and OPEX optimizations commonly lead to FLP solutions that antagonize safety concerns (Caputo et al., 2015), recently FLP studies incorporating this topic had become more frequent.

In this context, Patsiatzis et al. (2004), Young Lee et al. (2005), López-Molina et al. (2012) and Lira-Flores et al. (2014) additionally included in their methods costs for damages to industrial property due to domino effects, which can be defined as a cascade of events in which the consequences of a previous accident are enhanced by the subsequent ones, leading to a major accident (Casal, 2007). The main idea in these works is to develop mathematical algorithms based on minimum separation distances in