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An approach to solve the facility layout problem based on the worst-case scenario

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A B S T R A C T

A new approach to determine the optimal distribution of process facilities is presented in this paper. The formulation considers a set of facilities already installed in a given land and a new set of facilities to be accommodated within the same land. In addition, it is considered that a set of facilities either installed or to be laid out presents the possibility of toxic release. Based on previous analysis, the worst-case scenario implies calm wind and stable atmospheric condition. Since these conditions tend to exist during several days of the year, the proposed model is formulated assuming these deterministic values for wind and atmospheric conditions. The final model is formulated as a disjunctive model that is converted into a mixed-integer non-linear program (MINLP) via the convex-hull method. The model is then solved with local and global optimizers in the GAMS package. Using the current approach based on minimum distances for a particular case study results in a distribution with a very high risk whereas the optimal results using this proposed approach indicate large separations between releasing facilities and the inhabited facilities due to the high toxicity of the released material. More elaboration will be aggregated into the developed model to include prevention and mitigation systems to produce more compact but optimal and safe layouts.

1. Introduction

Several historical accidents such as BP Texas City incident (2005) and Bhopal disaster (1984) involved gas dispersion through an unsuitable plant layout (Mannan, 2005). A process plant layout problem deals with finding a spatial arrangement of all process units on a given land. The plant layout is a chemical engineering problem which has been typically solved using heuristic rules though it does not necessarily produce the optimal distribution (CCPS, 2003). For this reason, several mathematical models have appeared to improve equipment allocations where the cost is typically minimized. These plant layout models have resolved one-floor (Barbosa-Póvoa, Mateus, & Novais, 2001; Georgiadis, Schilling, Rotstein, & Macchietto, 1999), 2D multi-floor (Jayakumar & Reklaitis, 1994, 1996; Papageorgiou & Rotstein, 1998; Patsiatzis & Papageorgiou, 2002), and even 3-D (Barbosa-Póvoa, Mateus, & Novais, 2002; Georgiadis, Rotstein, & Macchietto, 1997; Westerlund, Papageorgiou, & Westerlund, 2007) problems.

There is little work reported in literature for layouts based on process safety analysis though development of good layouts is considered as a pre-release mitigation for accidents (CCPS, 1997). The Dow index (AIChE, 1994) was specially developed for fire and explosion hazard analysis by the Dow Chemical Company as well as the Mond index by ICI Mond Division (Imperial Chemical Industries PLC, 1985) as a direct consequence of the Flixborough disaster. A comparison of both Dow and Mond indices has been presented in (Andreasen & Rasmussen, 1990). The first reported approach, where unsafe risk is included, has optimized the layout based on the inclusion of optional protection devices to be installed, which were taken from a list of safety features and preventive measures from Mond index (Penteado & Ciric, 1996). The problem was formulated as a mixed-integer non-linear optimization program (MINLP). Arrangement of process modules based on evolutionary searching rules to improve safety has been effective in some cases (Fuchino, Itoh, & Muraki, 1997). The use of stochastic optimization techniques such as genetic algorithms has also proved to be effective in obtaining practical solutions (Castell, Lakshmanan, Skilling, & Bañares-Alcántara, 1998). A multi-floor process plant layout model has been proposed where safety issues were reduced to simple minimum separation distances between process units (Patsiatzis & Papageorgiou, 2002). The Dow Fire and Explosion Index have been used in a mixed-integer linear programming (MILP) formulation to reduce the financial risk in an ethylene oxide plant layout (Patsiatzis, Knight, & Papageorgiou, 2004). Yet the use of safety issues provides an immense unexplored research area in process design.

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Most of chemical processes accidents occur when a released gas, dispersed into the environment, achieves ignition conditions or dangerous levels of concentration. The dispersion phenomena depend on meteorological conditions prevailing during the accident so that any predicted scenario may demand a stochastic analysis. The main random factors affecting the gas dispersion are wind direction, wind speed and the atmospheric stability. Atmospheric stability depends also on other random variables such as solar altitude, ceiling height and cloud cover. A stochastic approach to optimize the plant layout based on facilities with toxic releases has been developed in (Vázquez-Román, Lee, Jung, & Mannan, 2008, in press). The problem is formulated as a disjunctive program which is transformed into a MINLP via the convex-hull theory and solved with several solvers from GAMS (Brooke, Kendrick, Meeraus, & Raman, 1998).

The inclusion of the natural variation of the dispersion variables produces more realistic scenarios to estimate the best layout. However, calm conditions have prevailed in some severe historic cases such as the explosions in San Juan Ixhuatepec, Mexico in 1985. In addition, the wind in calm has been indicated for worst-case scenario analysis (Crowl & Louvar, 2002). Thus, this paper concerns with optimizing the layout based on the worst-case possible scenario. The following sections describe what has been considered as the worst-case scenario description of the dispersion model used in this study. The deterministic model is also presented and applied to a case study to finally establish the conclusions.

2. Defining the worst-case scenario

The harm due to toxic releases strongly depends on the possibility of dispersing the toxic gas in the environment. In any scenario, the wind effect analysis is a very important variable to include. Both wind speed and direction are stochastic variables from meteorological changes and their effect has been considered in previous mathematical models (Vázquez-Román et al., 2008, in press). A stochastic model can provide the best solution from multiple available solutions but with a certain risk associated with them. Achieving the solution takes time since the model requires historic data of wind velocity, wind direction and other relevant atmospheric parameters to produce models based on Monte Carlo simulations. On the other hand, it has been considered that a better assessment for chemical plants safety should be based on the worst-case scenario (Leggett, 2004). This type of decision making is supported in the Wald's paradigm which results in a conservative attitude of caution though it is based on a pessimistic criterion since it assumes that the worst will happen (Wald, 1950). For toxic release, the worst-case scenario can be described as the one that produces the biggest concentration in the gas dispersion calculations far away from the source of dispersion.

The worst-case scenario for dispersion modelling has been defined as the Pasquill–Gifford stability class F but very few tests have been available to ratify this statement (Woodward, 1998). Stability influences the dispersion and describes the turbulence as well as capacity of mixing during the dispersion (Crowl & Louvar, 2002). In addition, the wind speed produces turbulence and its profile marks the downwind extend of dispersion (Patra, 2006). The meteorological data from industrial accidents have shown that the two more probable wind speeds are 6.0 m/s (Wiekema, 1984) and 1.5 m/s (Crowl & Louvar, 2002). Moreover, non-flat terrain increases the risk of dispersion for toxic gas dispersion in continuous or instantaneous releases (Hankin, 2004a, 2004b).

By using Gaussian dispersion models, it has been demonstrated that the worst-case scenario is produced when the wind speed remains in calm for stable atmospheric condition on rural terrain (Díaz-Ovalle, Vázquez-Román, & Mannan, 2009). The influence of the atmospheric condition was analysed using the extreme stability class, stable and unstable. These conditions were combined with wind speeds of 1.5 and 6.0 m/s. Lower speeds were not included because of limitations in predictability of the Gaussian method. Thus, the worst-case scenario can be defined as a combination of rural and stable atmospheric condition with wind speed of 1.5 m/s. Since the low wind speed can appear in all directions, the wind direction is not included in the deterministic model and the wind effect is considered symmetrical circular with respect to the emission point.

The level of dangerous toxic concentration has been typically inferred from experimental proofs on different animals. The results are statistically distributed and the parameters are published in terms of the probit model (Crowl & Louvar, 2002). However, the use of probit models in risk analysis demands the inclusion of a damage cost for human harm which is a sensitive issue. Another method to analyse safety in toxic releases consists of avoiding concentrations above certain level. Values for several species have been defined in different organisms such as ACGIH, AIHA, OSHA, etc. (Alexeeff, Lewis, & Lipsett, 1992). In this work the ERPG-3 values from AIHA are considered for the description of the lethal effect on the people during one hour of exposure. The next section describes the dispersion models used in this study.

3. Dispersion models

The concentration of the toxic gas in a dispersion scenario comes from solving the convective–diffusive equation (Crowl & Louvar, 2002). The type of resulting dispersion has been classified as passive and dense. In the passive dispersion, the behaviour of the gas cloud could be either a float or immersion plume, and the mathematical model demands the knowledge of the diffusivity coefficients values. The several solutions which have been proposed include numerical and statistical approximations such as the K theory and the Gaussian approximation (Mannan, 2005). Other analytical models have used Eulerian and Lagrangian coordinates to include the Boussinesq turbulence (Markiewicz, 2006). The Gaussian approximations adjust the spatial distributions of the concentration like the Gifford model (1961) which considers all the Pasquill class (Mannan, 2005). The Pasquill–Gifford method is nonlinear and presents several limitations since it is applicable only to neutrally buoyant dispersion. However, it provides explicit equations to allow MINLP formulation, and it seems to be valid for distances of 0.1–10 km (Crowl & Louvar, 2002), which are typical in the facilities layout problem. Thus, the Pasquill–Gifford model is used in this work as described in (Crowl & Louvar, 2002).

The case for dense gas dispersion is more complex than the passive dispersion. It starts by displaying a cloud over the ground because of the gravity influence but, in a further distance, the dense gas cloud becomes a passive dispersion as shown in the van Ulden's experiment in 1974, see for instance (Mannan, 2005). The mathematical problem in the dense gas dispersion comes from the simultaneous solution of the heat, momentum and mass transfer equations which is a challenge for the modern mathematics. Several models such as SLAB, FEM3 and DEGADIS have proposed realistic solutions to obtain the spatial distribution of the concentration. Solutions from a CFD (Computer Fluid Dynamics) program is becoming popular in dispersion problems to yield more realistic models where several physical features such as obstructions are now considered (Sklavounos & Rigas, 2004). However, conventional dispersion models like the Germeles model simplify the mathematic calculations and yield acceptable concentration values (Ermak, Chan, Morgan, & Morris, 1982). In this study, conventional models are used in both the dense gas and the passive dispersions