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A model to optimize facility layouts with toxic releases and mitigation systems

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ABSTRACT

The possibility of including mitigation systems in layout models is explored in this work. The model is based on a previous work by the authors to estimate toxic concentrations around each releasing facility surrounded by a mitigation system. The mitigation systems considered here includes water, steam, and air curtains and exponential decays are assumed for the concentrations shapes before and after the installed curtain. The selection of the mitigation system type to install is included as a variable to determine when solving the proposed *MINLP* model. Additional constraints include the conventional non-overlapping and risk estimations based on *probit* functions. The objective function includes occupied land costs, interconnection costs, risk damage costs, and mitigation costs. A software package called *TROL* has been developed to automatically interact with *GAMS* and ease the initial and final layout descriptions. Numerical results indicate that the proposed model produces more practical and optimal layouts.

1. Introduction

×Several accidents that include explosions, fires or toxic releases have occurred in the chemical industry. Explosion and fire accidents affect workers and property whereas accidents involving toxic releases may not produce any damage to equipment but augment the vulnerability of personnel at the plant, and even civilians in the surrounding areas. Some of the damage caused by the accidents could have been reduced if minimal changes in the installation layout were made (CCPS, 2003). Facility layout represents an effective option to reduce the risk of accidents in production systems. The plant layout is considered a fundamental problem in chemical plant design. Several strategies have been developed to solve this problem based on practical experience and using different computational tools or heuristic rules (Mecklenburgh, 1985). An extended list of methods to solve layout problems include partition algorithms, genetic algorithms, and evolutionary methods (Drira, Pierreval, & Hajri-Gabouj, 2007).

Solving the plant layout based on risk analysis has initially considered the possibility of explosion accidents where risk is modeled as a function of the distance between the probable explosion point and the affectation points (Penteado & Ciric, 1996; Patsiatzis, Knight, & Papageorgiou, 2004). An old work has presented a graph-based algorithm to produce optimal partitioning to allocate units in different sections where edges' values reflect safety costs (Jayakumar & Reklaitis, 1994). In the case of toxic releases, it has been convenient to group some process units in facilities and the concept has been extended to include other buildings, such as control rooms, so that a facility refers to the portion of land surrounded by streets where units and people are located (Vázquez-Román, Lee, Jung, & Mannan, 2010). The probability of death is computed via *probit* functions, where the concentration is typically used as an independent variable though the probability of death inside a building tends to be inferior (Geeta, Tripathi, & Narasimhan, 1993). The actual concentration values depend on the dispersion phenomena so that dispersion models are required to estimate the exposure concentration, which is subsequently converted to the probability of death.

Dispersion modeling was initially approached by the statistical distribution of the concentration in the space. Requirements for accurate predictions and advances in computational tools have encouraged formulations to include thermal effects and momentum considerations; see, for instance, the models SLAB (Zeman, 1982), FEM3 (Ermak, Chan, Morgan, & Morris, 1982), DEGADIS

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Nomenclature

a	parameter for exponential function of concentration
a^M	parameter for exponential function of concentration post-mitigation
A^P	*probit* parameter for each gas
A_x	length of occupied land in x-direction
A_y	length of occupied land in y-direction
b	parameter for exponential function of concentration
b^M	parameter for exponential function of concentration post-mitigation
B	binary variable to indicate the angular position of the facility
B^C	binary variable for no-mitigation case
B^M	binary variable related to applying mitigation
$Bmit$	binary variable to select a mitigation system from a set
B^P	*probit* parameter for each gas
C	selected concentration
C_D	cost willing to avoid a fatality
C^L	total cost land
C_L	land cost per square length
C^M	concentration of gas post-mitigation
CM	total mitigation cost
$CMit$	cost of a mitigation system in a facility
C^P	total cost for piping
C_P	pipe cost per length
C^R	concentration for a release from a facility
C_T	total cost
D	separation distance between the point of a release and the center of a facility
$D_{a,b}$	separation distance between facilities
D^M	distance from release point to the facility border
$D^{min,x}$	minimum separation in x-direction between facilities
$D^{min,y}$	minimum separation in y-direction between facilities
f	frequency of occurrence in a toxic release accident in a facility
LX	length of land
Lx	length of a facility
LY	width of land
Ly	width of a facility
$M_{a,b}$	set of interconnectivity
m	tangent of angle α
Pe	persons inside in a facility
P	probability of death in a release
P_L	expected life time of the plant
Px	distance from the facility center to the source in x-coordinate
Py	distance from the facility center to the source in y-coordinate
R	risk in terms of affected people/year for a release
$S^{\Delta x}, S^{\Delta y}$	slice-vectors to define quadrant positions
st	street length
t	personal exposure time
x	x-coordinate of a facility
y	y-coordinate of a facility
Y	*probit* value in a release from a facility

Subscripts

i	already existing facilities
s	new facilities for sitting
r	release types
m	mitigation systems
k	release facility
l	affected facility

Greek letters

α	direction slice

(Spicer, Havens, Tebean, & Key, 1986), and HEGADAS (Witlox, 1994). Then, dispersion models added physical features from the surroundings, like boundary conditions, to produce more accurate predictions; this is represented in computational fluid dynamics – CFD-tools (Blocken, Carmeliet, & Stathopoulos, 2007; Hanna, Hansen, Ichard, & Strimaitis, 2009). However, the weather is a rather difficult variable in dispersion modeling because of its stochastic nature in parameters such as atmospheric condition, wind direction, wind speed, temperature, and humidity (Sullivan, Holdsworth, & Hlinka, 2004; Marx & Cornwell, 2008).

The facility layout problem may use a stochastic formulation for weather conditions, where calculation of random data is included to get probability distribution of the damage in toxic releases (Vázquez-Román et al., 2010). Moreover, dispersion parameters in specific conditions have shown risk reduction. This set of conditions is defined as the worst credible scenario (Teles, Castro, & Matos, 2012). The definition of the worst credible scenario is formed by a low wind speed, stable atmospheric conditions, and non-terrain obstructions (Crowl & Louvar, 2002; Díaz-Ovalle, Vázquez-Román, & Mannan, 2009). The stochastic approach considers micrometeorological effects on the toxic dispersion phenomenon, whereas the deterministic approach is based on the worst-case scenario. Optimal solutions to the facility layout problem may reduce risk to acceptable levels (Díaz, Vázquez-Román, Jung, & Mannan, 2009). However, both deterministic and stochastic approaches may suggest large unpractical separation distances between releasing and occupied facilities (Díaz-Ovalle, Vázquez-Román, & Mannan, 2010). Distances between facilities might be reduced if the concentration is decreased, in which case a mitigation system should be used.

Mitigation systems are currently used in real process plants to decrease the concentration during toxic dispersions. The selection of a mitigation system strongly depends on the mitigating fluid and the fluid to mitigate. The selection is formulated by considering design parameters and a dispersion factor to achieve more efficient mitigation (Molag et al., 2001). Mitigation systems are also selected based on the type of accident: Foams are used for liquid leaks, air curtains or water curtains for gases presenting physic effects, dilution effects or absorption effects (Dimbour, Dandrieux, Gilbert, & Dusserre, 2003). Three mitigation systems are incorporated here in the layout model to decrease separation distances between facilities based on a previous work by us (Diaz-Ovalle, Vazquez-Roman, Lesso-Arroyo, & Mannan, 2012).

2. Problem statement

The problem here considers a set of new facilities to be accommodated in a given land where other facilities may have been already installed. Facilities may interact among them so that the interconnectivity is given. Interconnectivity is an important factor and its impact on cost is evident in this problem. The typical approach, based on minimum distances between facilities, is incorporated in the model and also assuming that there must be a street around each facility (Vázquez-Román et al., 2010). The problem is focused on risk constraints, where the estimations come from modeling the toxic release of a dense gas using a mitigation system. The risk is considered a result of the frequency times