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Process plant layout optimization with uncertainty and considering risk

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ABSTRACT

Facility layout is an important factor in designing of process plants such as petrochemical units and refineries. An appropriate design of layout ensures proper performance of corresponding departments as well as providing an equilibrium between large number and sometimes inconsistent structural design constraints. In this research, a mixed integer non-linear programming (MINLP) formulation is proposed for process plant layout problem, considering the toxic release risk and possible scenarios of fire, explosion and the domino effects of them. Then the Bat metaheuristic algorithm was employed to solve it. Finally, the model was implemented on 6th refinery, unit 101 of Iran's South Pars gas field, and the results showed the effectiveness of the model, in costs reduction and safety improvement.

1. Introduction

Process industries are chemical production units in which the final products are continuously generated through chemical and biological processes or separating out from raw materials. Engineering studies in order to set the placement ordering and the layout of the units and equipment, is one of the main factors for a process plant, playing a fundamental role in raising safety levels of these sites, providing economic conditions in the context of costs, and optimizing the utilization of these facilities.

From an economic perspective, some believe that piping costs may include up to 80% of total installation costs, in case of inappropriate layout of a unit (Peters et al., 1968). Also, it can be concluded that 15% to 70% of total operation costs in a process unit depends on the way of facilities layout together (Tompkins et al., 1996). In terms of safety, the role of incident prevention seems to be much more significant comparing with reaction to accidents, as almost all of the processing units deal with extremely dangerous materials such as toxic and high potential for fire or explosion substances (Finch and Lees, 1997). A proper layout can prevent occurrence of these incidents to a large extent.

Ideally, plant locating and layout placement should establish a balance between risks and costs (Grossel, 2004). Most previous researches in the field of plant layout design were generally based on personal experiences (Anderson, 1982; Arinze and Banerjee, 1992; House, 1969; Kern, 1977, 1978; Mecklenburgh, 1982a, 1982b, 1985). However, in the last three decades, articles also were published which attempted to do this through mathematical programming and applying optimization techniques. In the way that firstly a few researchers developed some procedures based on fundamental location model and methods (and common heuristic algorithms) (Mannan and Lees, 2005; Mecklenburgh, 1973) and other researches provided models that mainly focused on economic aspects of layout (Georgiadis and Macchietto, 1997; Jayakumar and Reklaitis, 1994, 1996).

In the following years, financial risk (Penteado and Ciric, 1996) and total exceeding amount of safety distance described by Mond (Castell et al., 1998) has been added to these models alongside the other objective functions such as total length of pipes connecting units, total costs of land required for layout, in order to achieve a more prominent role of security in layout problems. Later, some indexes were joined including risk measure index like human risks (Han et al., 2013), and Dow fire and explosion index (AIChE, 1994; Patsiatzis et al., 2004).

Some scholars suggested dividing manufacturing process of chemical products into sub processes (modules) and performing facility siting in each module at first. Then locating these arranged modules in the factory land. Both the equipment layout inside the

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Nomenclature

Parameters

A_i, B_i, C_i Dimensions for the facility i
$Area_i$ Cross-sectional area of the facility i
$C_{AL,i}$ Direct asset loss cost for the failure of the facility i
$C_{ECC,i}$ Environmental cleanup cost for the failure of the facility i
$C_{HHL,i}$ Human health loss cost for the failure of the facility i
C_f Compensation cost to pay per fatality
C_i^{Sa}, C_i^{Sb} Cost unit factors for the height support of the facility i
C_k^P Cost per length unit for the pipe k
C_l Cost per square meter of land
D_{ij}^{HO} Minimum horizontal distance between facilities i and j
D_{ij}^{VE} Minimum vertical distance between facilities i and j
E_i^e Minimum elevation of facility i
En_i Explosion energy for the facility i
F_p^x, F_p^y, F_p^z Relative positions of the nozzle p
$K^d(k)$ Nozzle destination for the pipe k
$K^o(k)$ Nozzle origin for the pipe k
N^{Fa} Number of facilities
N^{NZ} Number of nozzles
N^{Pipe} Number of pipes
FS_i Facility state
N^{int} Number of total element
P_a Barometric pressure
Po_i Expected population in the facility i
Q_r^x, Q_r^y, Q_r^z Relative positions of the releaser point r
$S_\alpha^{\Delta x}, S_\alpha^{\Delta y}$ N^{int}- vectors to define quadrant position
U^{FS} Safety distance due to the facility state
$a^\circ, b^\circ, c^\circ$ Parameters for exponential decay
a^1, b^1 Constant and variable costs for placement of each square meter of facility per height
a_{FS}^2, b_{FS}^2 Constant of the probit function based on facility state
df_i^h Flame envelope produced by the primary unit i in the scenario h
f_r Release frequency for the releaser point r
m_α Maximum slope in element α
t_l Expected life time of the plant
$\tau_{t_l,IR}$ Capital recovery factor for period t_l and interest rate IR
IR Interest rate
M a large number
$\propto$ Something factor
ν Annual probability of domino event occurrence
$i(p)$ the facility on which the nozzle p is located

Binary Variables

$B_{ij}^{h,G}$ the binary variable related to position of the facilities i and j in situation G under scenario h
$S_{i,r,\alpha}$ the binary variables related to positioning of the facility i in element α with respect to the release point r
$w_{ij}^x, w_{ij}^y, w_{ij}^z$ the binary variables for the relative position between facilities i and j
w_{it} the binary variable for rotation of the facility i in the manner t

Positive Variables

X, Y, Z Size of the box that encloses the plant layout
x_i, y_i, z_i Position of the center of the facility i
x_i', y_i', z_i' Auxiliary variables
x_p^N, y_p^N, z_p^N Position of the nozzle p
$x_r^{RP}, y_r^{RP}, z_r^{RP}$ Position of releaser point r
C_i^S Height support cost for the facility i
$d_{ij}^x, d_{ij}^y, d_{ij}^z$ Manhattan distance between the centers of facilities i and j
$xf_{ij}, yf_{ij}, zf_{ij}$ Variable for relative situation facilities i and j in each direction
$l_k^{x+}, l_k^{x-}, l_k^{y+}, l_k^{y-}, l_k^{z+}, l_k^{z-}$ Length of pipe k using manhattan distance
$dr_{ir}^x, dr_{ir}^y, dr_{ir}^z$ Manhattan distance between the center of facility i and releaser point r
D_{ij}^{Min} Minimum distance between surface of facilities i and j
$DHS_{ij}^{h,G}$ Domino hazard score between facilities i and j in scenario h and situation G
DHI_{ij} Domino hazard index between facilities i and j
Ro_{ij} Characteristic distances between facilities i and j
ΔP_{ij} Overpressure affected the facility j generated by the facility i
Pr Probit variable
P_{ij}^{BW} Damage probability of the facility j caused by blast wave of the facility i
ω_{ij} Credit factor for domino escalation

Subscripts

i, j Indexes for facilities ($i = 1,..., N^{Fa}$)
p, q Indexes for nozzles ($p = 1,..., N^{NZ}$)
k Index for pipes ($k = 1,..., N^{Pipe}$)
r Index for facilities that with possible release point ($r \in R$)
α Index for direction slice ($\alpha = 1,..., N^{int}$)
h Index for fire and explosion scenarios ($h = \{FF, FB, JF, PF, BW\}$)
t Index for rotations ($t = 1,..., 8$)

modules and the modules layout in the factory site are executed by a similar model (Guirardello and Swaney, 2005).

Since most of the large scale process plant layout problems can't be solved using the exact methods, there have been efforts to develop heuristic algorithms to solve them (Xu and Papageorgiou, 2007a, 2007b, 2009). These methods convert the layout problems to smaller sub-problems with a solvable complex integer programming format by using iterative algorithms, based on the described model of Papageorgiou and Rotstein (1998).

In last few years, the annual amount of damage and loss expected for each layout is calculated as the sum of expected values of probability for the amount of damage caused by incident in each unit (Caputo et al., 2015); and assumption of having the potential toxic release (Vázquez-Román et al., 2010) and various methods for calculating different scenarios of domino events in layout problem (de Lira-Flores et al., 2014; López-Molina et al., 2013) have been introduced, too. All of these studies used the restrictive assumptions (involving considering the layout in a two-dimensional form or considering pre-positioned facilities) to reduce the scale of the problems, and included just one of the incident modes. Thus, it seems necessary to provide a study in order to achieve a comprehensive model which contains methods for calculating the