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Optimal layout of a chemical process plant to minimize the risk to humans

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Abstract

The process layout of chemical plants is usually designed in a compact configuration for economic efficiency. However, most of the chemical process units are vulnerable to accidents such as fires and explosions, and these accidents can cause severe damage to humans. In this study, direct risks to humans from such hazards were quantitatively assessed as individual risk and converted into safety distances for each piece of process equipment. Then, a process layout optimization problem was formulated with risk zones constructed using those safety distances. Boundary factors accounting for land uses around the process site and protection factors from additional protective devices were also considered. A case study for an ethylene oxide plant was conducted. With the proposed methodology, a cost-efficient and inherently safe layout can be provided in the early stage of the design of a process plant.

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Keywords: Process layout; MILP; Quantitative risk assessment; Individual risk; EO plant.

1. Introduction

Chemical process layout optimization is a task to efficiently determine the relative position of the equipment or facility of the process. Here, efficiency means economic efficiency, operability and flexibility, availability for future expansion, safety and reliability, and/or environmental friendliness [1]. In many cases, economic efficiency is the main objective, but considering the other elements, especially safety, is important for the sustainability of the process.

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Many studies on layout optimization using various approaches have been done. Initially, the allocation of a facility was based on heuristic rules or a method using graph theory [2,3], but in recent years, mathematical programming has become the mainstream method. Layout problems formulated as mixed integer linear programming (MILP) [4,5] have been studied in the last two decades. Discrete grid and continuous plane approaches have been used for the domain of a process site as well as for its expansion to a multi-level process [7]. Stochastic formulation [1,8] and efficient solution algorithm of layout problems [9,10] have also been studied recently.

For the arrangement of hazardous process units, safety is the most important element of the layout. This can be seen through the history of related accidents. For example, an explosion occurred at LPG filling stations in Bucheon, Korea in 1998 causing one death and 96 injuries [11]. The number of fatalities and injuries could have possibly been reduced if there had been a clear set of rules regarding the placement of equipment and safety distance between the facilities. In 2005, a fire and explosion occurred in a refinery in Texas, USA with 15 fatalities and 170 injuries [12]. The direct cause of the accident was the ignition of flammable gas; however, the large number of casualties was the result of a tank trailer not being properly positioned.

In this study, the risk to humans from process equipment was assessed as individual risk and then converted into safety distance. Based on the safety distance and minimum clearance required for operation, risk zones and maintenance zones around the process equipment were constructed. A layout optimization problem was then formulated in MILP with the non-overlapping constraints of these zones. Boundary factor and protection factor were also considered for the surrounding land use and additional protective devices. The proposed methodology was applied to an ethylene oxide plant as a case study.

Nomenclature	
i, j	process equipment
p	protective device
r	distance from process equipment
s	site candidate
v	accident event outcome
a_i, b_i	dimension of equipment
A_{ij}, B_{ij}	vertical distance between equipment
C_{ij}^{pipe}	unit cost of pipeline
C^{land}	unit cost of land
C_p^{prot}	cost of protective device installation
D_{ij}	rectilinear distance between equipment
$f_{eo,v}$	frequency of v
l_i, d_i	horizontal and vertical length of equipment
O_i	binary variable for equipment orientation
$p_{fat,r,v}$	probability of fatality at r by v
R_{ij}, L_{ij}	horizontal distance between equipment

x_i, y_i	coordinate of center of equipment
Q_s	binary variable for site selection
$E1_{ij}, E2_{ij}$	binary variables for non-overlapping constraints
ES_i	spacing for equipment
IR_r	individual risk at r
LA	land area
$PI_{i,p}$	binary variable for protective device installation
AR_s	land area condidate
BF	boundary factor
PF_p	protection factor
PS_i	spacing for the public
WS_i	spacing for workers

2. Assessment of risk to humans

The risk from process equipment can be quantified by quantitative risk assessment (QRA) [13]. Possible hazards from a target chemical process are identified and their frequency and consequences are analyzed. For frequency analysis, historical data or the frequency modeling technique can be used. For consequence analysis, there are several empirical models for each accident type such as vapor cloud explosion (VCE), fireball, flash fire or boiling liquid expanding vapor explosion (BLEVE). These models provide the quantity of thermal radiation or overpressure from an accident. Then, probit analysis [14] is applied to get the probability of fatality. Generally, the product of frequency and consequence gives the measure of risk.

2.1. Modified individual risk

Among several risk measures based on the QRA result, we adopted the individual risk (IR) for the risk measure to humans in this study. IR is the risk to an individual near the hazard which considers the nature, the likelihood, and the time period of a possible injury to an individual [13]. One of the ways to obtain IR from the frequency and consequence analysis was suggested by the Health and Safety Executive (HSE) [15]. Here, a simplified version of IR calculation assuming the worst-case accident scenario and weather- and direction-independent effects of an accident was used. In that case, IR is the product of the frequency of the event outcome v and the probability of fatality by the event outcome v at distance r:

$$IR_r = \sum_v f_{eo,v}\, p_{fat,r,v} \tag{1}$$

HSE also proposed tolerable criteria for individual risk for people near a hazard. It is recommended to keep IR lower than 10^{-3} and 10^{-4} per annum for workers who are related to the source of the hazard, and for the public, respectively [16].

2.2. Risk-based equipment spacing for humans

Since the effects of an accident vary by the distance from the source to the receptor, IR from hazardous equipment also varies by the distance from that equipment. Therefore, the minimum distance from process equipment to make the IR value lower than the recommended tolerances can be calculated. We defined such distances as WS_i for workers and PS_i for the public, and constructed risk-based zones for process equipment shown in Fig. 1. In addition to these risk-based separation distances, some equipment requires space for operability, maintenance or safety. This equipment spacing ES_i constitutes the maintenance zone.

These hypothetical zones should not overlap the appropriate target, e.g. Risk zone I and worker space, Risk zone II and public area and the maintenance zone of the equipment and that of the other equipment. Conventional non-overlapping constraints in the layout problem were modified to prevent overlapping of these zones rather than the equipment itself.

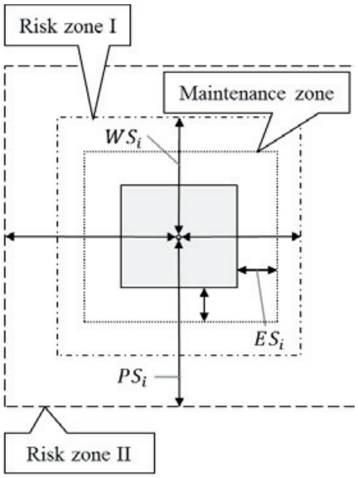

Fig. 1. Risk-based zones around process equipment

3. Formulation of layout optimization

Based on the MILP model proposed by Papageorgiou and Rotstein [5], many features are replaced, modified or added to account for the risk-based zones in the following mathematical formulation.

3.1. Objective function

The objective of process layout in this study was to minimize the capital cost of the layout. Three types of costs were considered here: pipeline connection cost, land cost and installation cost of the additional protective devices. To maintain the linearity of the problem, the land area was selected from candidates by adopting a binary variable. Eqs. (3)-(7) represent the case of a square site; however, a rectangular site was also considered using similar constraints with two binary variables.

$$minimize \sum_i \sum_{j \neq i} C_{ij}^{pipe} D_{ij} + C^{land} LA + \sum_i \sum_p PI_{i,p} C_p^{prot} \tag{2}$$

$$LA = \sum_s AR_s Q_s \tag{3}$$

$$AR_s = wid_s dep_s \tag{4}$$

$$\sum_s Q_s = 1 \tag{5}$$

$$x^{max} = \sum_s wid_s Q_s \tag{6}$$

$$y^{max} = \sum_s dep_s Q_s \tag{7}$$

3.2. Equipment dimension, orientation and relative distance

The dimensions, orientation and rectilinear distance between the centers of equipment are defined with the same equations in [5].

$$l_i = a_i O_i + b_i(1 - O_i) \tag{8}$$

$$d_i = a_i + b_i - l_i \tag{9}$$

$$R_{ij} - L_{ij} = x_i - x_j \tag{10}$$

$$A_{ij} - B_{ij} = y_i - y_j \tag{11}$$

$$D_{ij} = R_{ij} + L_{ij} + A_{ij} + B_{ij} \tag{12}$$

3.3. Maintenance zone constraints

Eqs. (13)-(16) represent the non-overlapping constraints for the maintenance zone. By using two binary variables and the appropriate upper bound *M*, the relative positions of the maintenance zones for the equipment are set among left, right, above or below.

$$x_i - x_j + M\left(E1_{ij} + E2_{ij}\right) \geq \frac{l_i + l_j}{2} + ES_i + ES_j \tag{13}$$

$$x_j - x_i + M\left(1 - E1_{ij} + E2_{ij}\right) \geq \frac{l_i + l_j}{2} + ES_i + ES_j \tag{14}$$

$$y_i - y_j + M\left(1 + E1_{ij} - E2_{ij}\right) \geq \frac{d_i + d_j}{2} + ES_i + ES_j \tag{15}$$

$$y_j - y_i + M\left(2 - E1_{ij} - E2_{ij}\right) \geq \frac{d_i + d_j}{2} + ES_i + ES_j \tag{16}$$

3.4. Risk zone constraints

As a special case of non-overlapping constraint, Eqs. (17)-(20) were used for Risk zone I. These constraints secure the safety distance between the process equipment and workspace.

$$x_i - x_j + M(E1_{ij} + E2_{ij}) \geq WS_i + \frac{l_j}{2} \tag{17}$$

$$x_j - x_i + M(1 - E1_{ij} + E2_{ij}) \geq WS_i + \frac{l_j}{2} \tag{18}$$

$$y_i - y_j + M(1 + E1_{ij} - E2_{ij}) \geq WS_i + \frac{d_j}{2} \tag{19}$$

$$y_j - y_i + M(2 - E1_{ij} - E2_{ij}) \geq WS_i + \frac{d_j}{2} \tag{20}$$

For the upper and lower bound of the *x*- and *y*-coordinate of the equipment, the boundary factor *BF* is used together with spacing for public, PS_i. According to the land use and type of corresponding boundary of the process site, four boundary factors are implemented. Here, the values of *BF* are 1 for a residential area, 0.8 for an industrial area and 0.5 for a vacant area such as a sea or wide road. These constraints force the Risk zone II to be placed within the process boundary.

$$x_i \geq PS_i BF_{west} \tag{21}$$

$$y_i \geq PS_i BF_{south} \tag{22}$$

$$x_i + PS_i BF_{east} \leq x^{max} \tag{23}$$

$$y_i + PS_i BF_{north} \leq y^{max} \tag{24}$$

When additional protective devices are installed on hazardous process equipment, the risk to people can be reduced. This reduces the required safety distance, also. Therefore, actual risk-based spacing is calculated as follows:

$$WS_i = WS_i^{init}\left(1 - \sum_p PI_{i,p} PF_p\right) \tag{25}$$

$$PS_i = PS_i^{init}\left(1 - \sum_p PI_{i,p} PF_p\right) \tag{26}$$

4. Case study

The proposed layout optimization methodology was applied to an ethylene oxide (EO) plant [6]. Ethylene oxide is a valuable raw material for various chemicals; however, there have been many related accidents because of its high reactivity and toxicity [17]. Therefore, a layout that minimizes the risks and costs rather than just costs alone is crucial for a sustainable process.

4.1. Process description

There are seven main process units in the EO plant shown in Fig. 2 (left). Their dimensions, cost, and connectivity are given in Table 1. In addition to the process equipment, we considered three workspaces – a control room, laboratory and office – to minimize the risks to employees. All equipment was considered to have possible hazards. The selected accident scenarios were VCE, BLEVE, pool fire and flash fire.

The effect of the boundary factors was examined by selection problem between two candidates for the construction site of the EO plant. The candidates for the site are depicted in Fig. 2 (right): both sites are surrounded by two industrial areas, one residential area and one vacant area (sea); however, their directions are different.

Moreover, information on additional installation of protective devices is presented in Table 2 and 3 [18]. The protective devices reduce the risk from the process equipment and therefore, the required land area; however, additional costs are also required to achieve this.

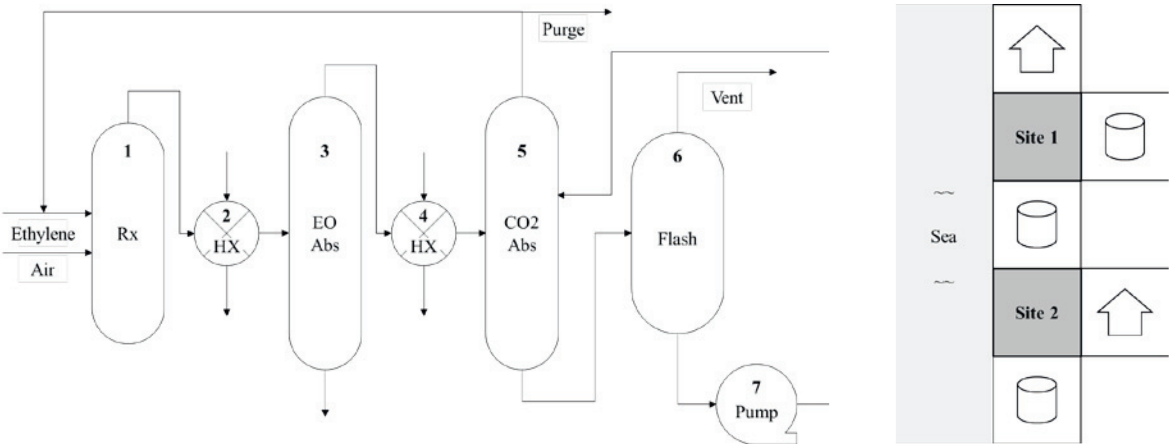

Fig. 2. (left) Schematic diagram of the Ethylene oxide plant (right) Land uses around the candidate EO plant sites

Table 1. Equipment and their connectivity in the EO plant

Equipment	Width [m]	Depth [m]	Purchasing cost [$]	Connectivity	Connection cost [$/m]
1 Rx	5.22	5.22	335000	(1,2)	346
2 HX1	11.42	11.42	11000	(2,3)	118
3 EO Abs	7.68	7.68	107000	(3,4)	111
4 HX2	8.48	8.48	4000	(4,5)	85.3
5 CO2 Abs	7.68	7.68	81300	(5,1)	416.3
6 Flash	2.6	2.6	5000	(5,6)	86.3
7 Pump	2.4	2.4	1500	(6,7)	6.5
				(7,5)	82.8

Table 2. List of additional protective devices

Protective Device		Installation cost [$]	Risk reduction factor
P1	Additional cooling water	5000	0.1
P2	Additional overpressure relief devices	20000	0.24
P3	Additional fire relief devices	15000	0.25
P4	Second skin on reactor	65000	0.6
P5	Explosion protection system on reactor	20000	0.2
P6	Duplicate control system with interlocking flow on reactor	20000	0.32
P7	Duplicate control shutdown system on absorption tower	30000	0.46

Table 3. Applicable configurations of the protective devices

Configuration	Reactor	Absorbers
K1	-	-
K2	P1	P1
K3	P3	P2
K4	P1,P3,P6	P1,P2
K5	P1,P3,P5,P6	P1,P7
K6	P1,P3,P4,P5,P6	P1,P2,P7

4.2. Layout results and discussion

Fig. 3 shows the layout results of the four cases considered. The thick solid lines represent the equipment and workspaces, while the dashed lines are maintenance zones. For Site 1 (a and b), the workspaces are allocated near northern boundary of the process site because the residential area is located on the northern process boundary, which provides the maximum spacing for the public for that direction. On the contrary, the workspaces are placed on the eastern boundary for Site 2 (c and d). The position of the residential area (east for this case) is the main reason for this layout.

The square and rectangular site formulation resulted in different shapes of the site and land areas for Site 1, but not for Site 2. This is because the surrounding land use of Site 2 consists of a symmetrical industrial area, while that of Site 1 does not.

The results for the comparison of the costs, site dimensions, and selected protective device configurations between sites 1 and 2 are presented in Table 4. The total layout cost was minimized for the rectangular site for option 1. The square site required more space because maximum spacing for the public in all four directions should be applied regardless of the boundary land use.

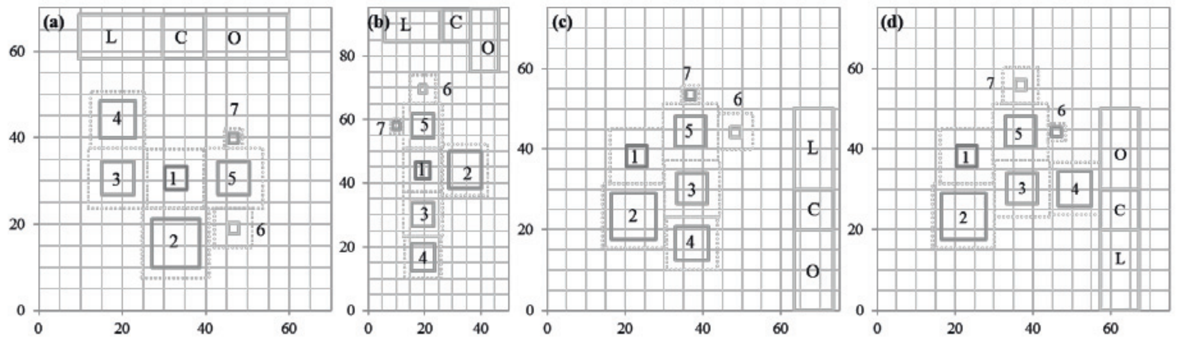

Fig. 3. Optimal layout results: (a) Site 1, square; (b) Site 1, rectangle; (c) Site 2, square; (d) Site 2, rectangle

Table 4. Comparison of layout results

Site option	Site shape	Cost [\$]				Site dimension [m, m^2]			Protection configuration		
		Connection	Land	Protection	Total	Width	Depth	Area	Rx	EO Abs	CO2 Abs
Site 1	Square	21308	130340	40000	191648	70	70	4900	K3	K2	K3
	Rectangle	21308	126350	25000	172658	50	95	4750	K3	K2	K2
Site 2	Square	22058	149625	10000	181683	75	75	5625	K2	K2	K1
	Rectangle	22058	149625	10000	181683	75	75	5625	K2	K2	K1

A simple sensitivity analysis was conducted for some of the cost and safety parameters. As shown in Fig. 4, the boundary factor, spacing for the public, protection factor and land cost affected the total cost to a large extent. These parameters are related to the required land size needed for the construction of the process site and the cost of the land accounts for most of the total layout cost. The spacing for the public PS is actually a calculated value from the quantitative risk assessment; however, it was included in this sensitivity analysis because it was treated as parameters in the layout optimization problem.

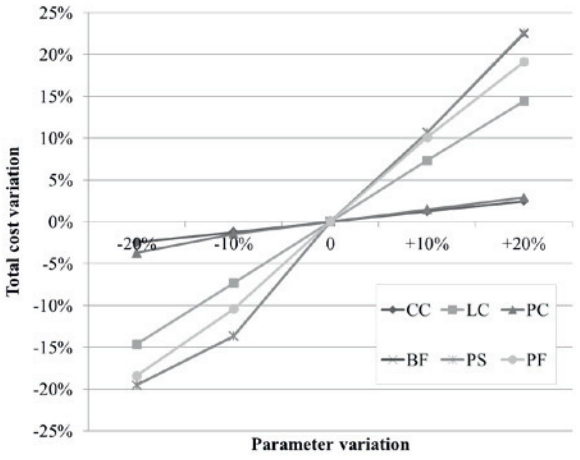

Fig. 4. Parametric sensitivity on total layout cost

5. Conclusion

In this study, a process layout optimization method based on quantitative risk assessment of a chemical process was presented. The risk zones were constructed from the safety distances for humans, which were converted from the modified Individual risk (IR) of the process equipment. Then, MILP formulation for layout optimization was carried out. This includes the constraints for the minimization of risks to people such as non-overlapping constraints of these risk zones, boundary land use factor, and additional protective device installation. This framework was applied to an ethylene oxide plant, and the optimal layout considering the risks to people was found. The proposed methodology provides an economically efficient layout while the inherent safety of the process is enhanced by considering individual risks in the early stage of the design of a process plant.

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