Process Plant Layout Optimization Considering Domino Effect and Economy

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Abstract: The layout design of process plant has a significant impact on the economy and safety of factories. In most previous work, security issues were transformed into economic numbers and incorporated into the economic objective function to obtain the lowest economic layout scheme. This conversion is inappropriate as it may result in the generated layout plan not meeting the actual safety needs, and economic figures cannot clearly represent the safety level of the factory. In this work, a multi-objective optimization method for chemical plant layout was proposed, with economy and safety as independent objectives to attempt to achieve different trade-offs between the two. The economic objective function is to minimize the capital costs related to layout, including piping costs, land costs, protective device costs, and expected property losses from accidents; The safety objective function is to minimize domino risk, and the domino risk under different layouts is measured by the domino hazard index (DHI). The proposed model is solved using the non-dominated sorting genetic algorithm II (NSGA-II).

Keywords: Process plant, Domino risk, Layout optimization, Multi-objective optimization

1 INTRODUCTION

Layout design is one of the most important aspects in the process of chemical engineering design, which can improve the performance of the factory and reduce economic losses in the event of accidents. In previous research, most layout work has focused on the most economical spatial allocation of process units and facilities, which minimizes the total cost of land and piping [1-4]. For layout safety issues, although some scholars have conducted research, the vast majority tend to incorporate safety issues into economic numbers into the objective function [5-8], which leads to two serious problems: (1) the environmental and social impact of accidents is difficult to measure using economic factors; (2) From previous methods based on single objective optimization, only one layout plan can be obtained, which may not meet the actual production needs. Therefore, in our current work, we consider safety and economy as two separate goals to seek the optimal layout of the process equipment. In this work, the safety level under a specific layout is measured using DHI, and the economy is measured using the total cost of capital related to the layout. A systematic layout design model including directional constraints, boundary constraints, and non-overlapping constraints has been established. The proposed model is solved using genetic algorithm.

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2 PROBLEM STATEMENT

This work aims to propose a method for optimizing the layout of chemical plants. The purpose of this method is to determine the location of facilities in a factory and the types and quantities of protective devices required for each equipment within a certain spatial range, while minimizing the domino effect hazards and economic investment of the chemical plant. In this method, available space and devices are assumed to be rectangles of different sizes. The device can be placed horizontally or vertically in any position within the available space. In order to meet the actual situation, this method also considers constraints such as boundaries and non-overlapping.

The parameters to be given and the variables to be determined are as follows:

Give:

- A set of process units, indexed i =1, ..., I;
- Dimensions of each unit (L_i, W_i);
- The type, operating conditions, damage index values and possible primary events of each unit;
- A set of interconnected units *Inter*;
- Cost data (equipment, connection, land, protection devices);
- The dimensions of a rectangle of available land (L, W).

Determine:

- Coordinates of the center point of each unit (x_i, y_i);
- Orientation of each unit (o_i);
- the safety devices that should be installed at each unit (B_i^{FI}, $B_{j,i}^{FW}$, $B_{j,i}^{FW}$).

3 METHODOLOGY

3.1 Objective Function

The objective is to minimize the domino effect hazard and total cost associated with the layout design. The domino effect hazard is characterized by the domino hazard index. The total cost consists of piping cost, land cost, protective device cost and expected property damage related to the accident, which can be mathematically expressed by Eqs. (1)-(2).

Objective function 1:

$$\text{Min } C_{total} = C_{pipe} + C_{land} + C_{pro\_device} + C_{damage} \tag{1}$$

Objective function 2:

$$\text{Min } DHI = \sum_{i \in I} DHI_i ,\ \forall i \in I \tag{2}$$

where C_{total} is the total cost related to layout (\$), C_{pipe} is the piping cost (\$), C_{land} is the land cost (\$), C_{pro_device} is the protective device cost (\$), C_{property} is the expected property loss (\$), *DHI* is the sum of the domino hazard index values for all units, DHI_i is the domino hazard index values for units *i*, *I* is the set of all units.

3.1.1 Piping cost

In this study, pipelines can be laid parallel to the x-axis or y-axis. Assuming that all pipelines are connected from the center point of the equipment, the calculation of piping cost is shown in Eq. (3)-(4).

$$C_{pipe} = \sum_i \sum_j D_{i,j}^M \times U_{pipe}, \ \forall (i,j) \in Inter \tag{3}$$

$$D_{i,j}^M = \left|x_i - x_j\right| + \left|y_i - y_j\right|, \ \forall (i,j) \in Inter \tag{4}$$

where $D_{i,j}^M$ is the length of the pipeline connection between units *i* and j (m), U_{pipe} is the unit price of pipe (\$), x_i, y_i, x_j, and y_j are the coordinates of the central point of units *i* and j, and *Inter* is the set of interconnected units.

3.1.2 Land cost

The cost of land is related to the area occupied by all units, which is represented by Eqs. (5)-(10).

$$C_{land} = A_{land} \times U_{land} \tag{5}$$

$$A_{land} = (x_u - x_l) \times (y_u - y_l) \tag{6}$$

$$x_u = \text{Max}\left(x_i + \frac{L_{x,i}}{2}\right), \forall i \in I \tag{7}$$

$$x_l = \text{Min}\left(x_i - \frac{L_{x,i}}{2}\right), \ \forall i \in I \tag{8}$$

$$y_u = \text{Max}(y_i + \frac{W_{y,i}}{2}), \ \forall i \in I \tag{9}$$

$$y_l = \text{Min}(y_i - \frac{W_{y,i}}{2}), \ \forall i \in I \tag{10}$$

where A_{land} is the total area occupied by the units (m^2), U_{land} is the unit price of land ($\$/m^2$), x_u, x_l, y_u and y_l are the boundaries of the available space where the process plant can be accommodated, and Lx_i and Wy_i are the edge lengths of unit *i* parallel to the x-axis and y-axis respectively (m).

3.1.3 Protective device cost

In this study, protective device such as fire insulation, fire resistant walls, and blast walls were considered to reduce the risk of domino effects between units. The total cost of protective device is shown in the Eq. (11).

$$\begin{aligned} C_{pro-device} = & \sum_i C_i^{FI} B_i^{FI} + \sum_i \sum_j C_i^{FW} B_{j,i}^{FW} \\ & + \sum_i \sum_j C_i^{BW} B_{j,i}^{BW} \end{aligned} \quad \forall i,j \in I \tag{11}$$

where C_i^{FI}, C_i^{FW} and C_i^{BW} are the costs of installing fire insulation, fire resistant wall and blast wall protective device for unit *i*, respectively ($), and B_i^{FI}, $B_{j,i}^{FW}$ and $B_{j,i}^{BW}$ are binary variables. When B_i^{FI}=1, it means that unit *i* is equipped with fire insulation protection devices. When B_i^{FI}=0, it means that the fire insulation devices are not installed. When $B_{j,i}^{FW}$=1 and $B_{j,i}^{BW}$=1, it means that a firewall and explosion-proof wall are installed around unit *i* to prevent the impact of fire and explosion accidents on the primary unit *j*, respectively. When $B_{j,i}^{FW}$=0 and $B_{j,i}^{BW}$=0, it means that the fire resistant wall protective device and blast wall protective device are not installed.

3.1.4 Expected property loss from accidents

Expected property losses consist of two parts: primary event losses and domino escalation event losses, and its calculation formula is shown in the Eqs. (12)-(15)

$$C_{damage} = \sum_i C_i^{primary} + \sum_i C_i^{domino}, \ \forall i \in I \tag{12}$$

$$C_i^{primary} = \mathrm{Pr}_i \times CAL_i, \ \forall i \in I \tag{13}$$

$$C_i^{domino} = \sum_j s_{i,j} \times CAL_j, \ \forall i,j \in I \ and \ i \neq j \tag{14}$$

$$s_{i,j} = \omega_0 (DHS_{i,j})^3 + \omega_1 (DHS_{i,j})^2 + \omega_3 \quad \forall i,j \in I, i \neq j \tag{15}$$

where $C_i^{primary}$ is the loss caused by the initial accident of unit *i* ($), C_i^{domino} is the loss caused by the domino upgrade accident caused by unit *i* ($), Pr_i is the probability of unit *i* occurring the initial accident, CAL_i is the direct asset loss caused by the initial accident of unit *i*, detailed calculations can be found in the work of Khan et al. [9], $s_{i,j}$ is the reliability factors that affect the target unit *j* of accident unit *i*, ω_0, ω_1, and ω_2 are constants, $\omega_0 = 6.7374 \times 10^{-4}$, $\omega_1 = 4.9158 \times 10^{-4}$, $\omega_2 = 2.7498 \times 10^{-4}$, and $DHS_{i,j}$ is the highest domino hazard score for target unit *j* under the impact of accidents in primary unit *i* , and its calculation process will be described in detail in the next section.

3.1.5 DHI

The DHI value of the primary unit *i* is the sum of the DHS of all target units, as shown in Eq. (16).

$$DHI_i = \sum_j DHS_{i,j}, \ \forall i \neq j, (i,j) \in H^E \tag{16}$$

where H^E is the set of all possible dangerous unit pairs, where *i* is the primary unit and *j* is the target unit. $DHS_{i,j}$ is the highest domino hazard score for target unit *j* under all possible initial scenarios in initial unit *i*, as shown in Eq. (17). The initial accident scenarios here include flash fire (FF), fireball (FB), pool fire (PF), jet fire (JF), and blast wave (BW).

$$DHS_{i,j} = \mathrm{Max}_h (DHS_{i,j}^h), \ \forall (i,j) \in H^E \tag{17}$$

where *h* is a collection of possible initial accident scenarios. The calculation formula for DHS in different scenarios is as follows. A more detailed description can be found in the work of de Lira-Flores et al [10].

Flash fire (FF)

$$DHS_{i,j}^{FF}=\begin{cases}0 & D_{i,j}^{E}>df_{i}^{FF}\\ 10 & D_{i,j}^{E}\le df_{i}^{FF}\end{cases}\forall i\ne j,(i,j)\in H^{E} \tag{18}$$

$$D_{i,j}^{E}=\sqrt{(x_i-x_j)^2+(\mathrm{y}_i-y_j)^2} \tag{19}$$

where $DHS_{i,j}^{FF}$ is the domino hazard score of target unit j located in the flash fire scenario of primary unit *i*, $D_{i,j}^{E}$ is the linear distance between unit *i* and *j*, and df_i^{FF} is the length of the flame generated by unit *i* (m).

Fire ball (FB)

$$DHS_{i,j}^{FB}=\begin{cases}0 & D_{i,j}^{E}>df_{i}^{FB}\quad \forall i\ne j,(i,j)\in H^{E}\\ 5 & D_{i,j}^{E}\le df_{i}^{FB}\quad \text{Fire insulation}\qquad j\in A\\ 10 & D_{i,j}^{E}\le df_{i}^{FB}\quad \text{No Fire insulation}\end{cases} \tag{20}$$

where $DHS_{i,j}^{FB}$ is the domino hazard score of target unit *j* located in the fire ball scenario of primary unit *i*, df_i^{FF} is the fireball radius generated by unit *i* (m), and A is a collection of atmospheric equipment.

Pool fire (PF) and Jet fire (JF)

$$dr_{i,j}^{s}=D_{i,j}^{E}-df_{i}^{s},\ \forall(i,j)\in H^{E} \tag{21}$$

$$DHS_{i,j}^{s}=\begin{cases}0 & dr_{i.j}^{s}>0\\ 10-\sum_{k=1}^{4}a_k^s\delta_{ijk}^{s} & 0<dr_{i.j}^{s}\le U^{s},\ dr_{i.j}^{s}=\sum_{k=1}^{4}b_k^s\delta_{ijk}^{s},j\in A\\ 10-\sum_{k=1}^{4}a_k^s\delta_{ijk}^{s} & 0<dr_{i.j}^{s}\le U^{s},\ dr_{i.j}^{s}=\sum_{k=1}^{4}b_k^s\delta_{ijk}^{s},j\in P\\ 1 & 0<dr_{i.j}^{s}\le U^{s},j\in E^{FW}\\ 10 & dr_{i,j}^{s}\le 0\end{cases} \tag{22}$$

$$\begin{cases}\delta_{ij1}^{s}\le 1,\delta_{ij4}^{s}\ge 0,\ \forall i,j\in I,i\ne j\\ \delta_{ijk+1}^{s}\le B_{ijk}^{s}\le\delta_{ijk}^{s},B_{ijk}^{s}\in[0,1],\ \forall k=[1,2,3,4]\end{cases} \tag{23}$$

where $DHS_{i,j}^{s}$ is the domino hazard score of target unit *j* located in the pool fire or jet fire scenario of primary unit *i*, df_i^s is the flame length of pool fire or jet fire (m), s= PF, JF, the values of a_k^s and b_k^s are shown in Table 1, E^{FW} is the collection of units with fire resistant wall installed, and U^s is the safety distance proposed by Cozzani et al. [11], where U^s=19 for pressurized equipment and U^s =50 for atmospheric equipment.

Blast wave

For atmospheric equipment:

$$DHS_{i,j}^{BW}=\begin{cases}0 & D_{i,j}^{E}>Au_{i}^{BW}\\ 1 & l_{i}^{BW}\le D_{i,j}^{E}\le Au_{i}^{BW}\\ \alpha_i^{BW}D_{i,j}^{E}+\beta_i^{BW} & D_{i,j}^{E}\le Au_{i}^{BW},j\in E^{BW}\\ 10 & D_{i,j}^{E}\le l_{i}^{BW}\end{cases}\ j\in A \tag{24}$$

$$\alpha_i^{BW} = 10/(l_i^{BW} - Au_i^{BW}),\ \forall i \in I \tag{25}$$

$$\beta_i^{BW} = -\alpha_i^{BW} Au_i^{BW},\ \forall i \in I \tag{26}$$

Where $DHS_{i,j}^{BW}$ is the domino hazard score of target unit j located in the blast wave scenario of primary unit i, and l_i^{BW} and Au_i^{BW} are the distances corresponding to the static peak overpressure values of 22 kPa and 5 kPa when an explosion accident occurs in unit i (m).

For pressurized equipment:

$$DHS_{i,j}^{BW} = \begin{cases} 0 \ \ D_{i,j}^{E} > Pu_i^{BW} \\ 1 \ \ D_{i,j}^{E} < Pu_i^{BW}, j \in E^{BW} \ \forall j \in P \\ 10 \ D_{i,j}^{E} < Pu_i^{BW} \end{cases} \tag{27}$$

where Pu_i^{BW} is the distances corresponding to the static peak overpressure values of 16 kPa when an explosion accident occurs in unit i (m), and P is a collection of pressure equipment.

3.2 constraint condition

3.2.1 Orientation constraint

Using a binary variable (o_i) to control the direction of the device, when o_i=1, the long side of the device is parallel to x, and when o_i =0, the short side of the device is parallel to the y-axis, as is expressed by Eqs. (28)-(29).

$$L_{x,i} = o_i L_i + (1 - o_i) W_i \quad \forall i \in I \tag{28}$$

$$W_{y,i} = (1 - o_i) L_i + o_i W_i \quad \forall i \in I \tag{29}$$

L_i and W_i are the lengths of the long and short edge of unit i respectively.

3.2.2 Boundary constraint

All units must be located within the available land area. The corresponding constraint is represented by Eq. (30).

$$\begin{gathered} (x_i + \frac{L_{x,i}}{2} < L) \cap (x_i - \frac{L_{x,i}}{2} > 0) \cap \\ (y_i + \frac{W_{y,i}}{2} < W) \cap (y_i - \frac{W_{y,i}}{2} > 0) \end{gathered} \tag{30}$$

3.2.3 Non-overlapping constraints

Non overlapping constraints are used to avoid unit overlap. In two-dimensional space, any two units must avoid each other in at least one dimension to satisfy non overlapping constraints, as shown in Eq. (31).

$$\begin{gathered} \left[|x_i - x_j| - \frac{L_{x,i} + L_{x,j}}{2} + d \geq 0 \right] \cup \\ \left[|y_i - y_j| - \frac{W_{y,i} + W_{y,j}}{2} + d \geq 0 \right] \end{gathered} \quad \forall i, j \in I, i \neq j \tag{31}$$

3.3 Solution algorithm

In the work of Wang et al. [12], the NSGA-II has been proven to be more suitable for solving layout optimization models. Thus, in this work, NSGA-II algorithm are used to solve the above mathematical models.

Table 1 Piecewise parameters to evaluate the radiation effect by pool fire and jet fire scenarios [10].

Scenario	k	Atmospheric equipment				Pressurized equipment			
		Unprotected		Fire insulated		Unprotected		Fire insulated	
		a_k^s	b_k^s	a_k^s	a_k^s	a_k^s	b_k^s	a_k^s	b_k^s
Pool fire	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2	0.5	4.5	7.6	4.5	1.4	4.5	7.8	4.5
	3	2.5	35.5	0.6	35.5	3.0	11.7	0.8	11.7
	4	7.0	10.0	1.8	10.0	5.6	2.8	1.4	2.8
Jet fire	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2	1.0	5.0	7.6	5.0	3.0	5.0	8.2	5.0
	3	2.2	40.0	0.0	40.0	2.2	10.0	0.6	10.0
	4	6.8	5.0	1.8	5.0	4.8	4.0	1.2	4.0

4 CONCLUSIONS

In this work, we propose a multi-objective optimization model for process plant layout with the goal of minimizing economic cost and domino risk. The DHI is used to evaluate the safety of chemical processing plant layout. The most significant advantage of the proposed layout optimization method is that it can provide designers with a considerable degree of freedom to achieve different trade-offs between economy and security, resulting in layout solutions that are more in line with practical requirements. However, classical methods with a single objective model can only provide one solution, and designers lose the right to make trade-offs.

REFERENCES

[1] Ejeh, J.O., Liu, S., Chalchooghi, M.M., Papageorgiou, L.G. (2018a). Optimization-Based approach for process plant payout. Ind. Eng. Chem. Res. 57(31), 10482-10490.

[2] Ejeh, J.O., Liu, S., Papageorgiou, L.G. (2018b). Optimal multi-floor process plant layout with production sections. Chem. Eng. Res. Des. 137,488-501.

[3] Ejeh, J.O., Liu, S., Papageorgiou, L.G. (2019). Optimal layout of multi-floor process plants using MILP. Comput. Chem. Eng. 131(0), 106573.

[4] Wang, R., Zhao, H., Wu, Y., Wang, Y., Feng, X., Liu, M. (2018). An industrial facility layout design method considering energy saving based on surplus rectangle fill algorithm. Energy 158, 1038-1051.

[5] Jung, S., Ng, D., Diaz-Ovalle, C., Vazquez-Roman, R., Mannan, M.S. (2011). New approach to optimizing the facility siting and layout for fire and explosion scenarios. Ind. Eng. Chem. Res. 50(7), 3928-3937.

[6] Latifi, S.E., Mohammadi, E., Khakzad, N. (2017). Process plant layout optimization with uncertainty and considering risk. Comput. Chem. Eng. 106224-242.

[7] Medina-Herrera, N., Jiménez-Gutiérrez, A., Grossmann, I.E. (2014). A mathematical programming model for optimal layout considering quantitative risk analysis. Comput. Chem. Eng. 68, 165-181.

[8] Wang, R., Wang, Y., Gundersen, T., Wu, Y., Feng, X., Liu, M. (2020). A layout design method for an industrial park based on a novel arrangement algorithm – Consideration of pipe network and multiple hazard sources. Chem. Eng. Sci. 227, 115929.

[9] Khan, F.I., Amyotte, P.R. (2005). I2SI: A comprehensive quantitative tool for inherent safety and cost evaluation. J. Loss Prev. Process Ind. 18(4-6), 310-326.

[10] de Lira-Flores, J., Vázquez-Román, R., López-Molina, A., Mannan, M.S. (2014). A MINLP approach for layout designs based on the domino hazard index. J. Loss Prev. Process Ind. 30(1), 219-227.

[11] Cozzani, V., Gubinelli, G., Salzano, E. (2006). Escalation thresholds in the assessment of domino accidental events. J. Hazard. Mater. 129(1-3), 1-21.

[12] Wang, R., Wang, Y., Gundersen, T., Wu, Y., Feng, X., Liu, M. (2021). A multi-objective optimization method for industrial park layout design: The trade-off between economy and safety. Chem. Eng. Sci. 235(0), 116471.