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A Two-Level Facility Layout Design Method with the Consideration of High-Risk Facilities in Chemical Industries

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Abstract: Understanding facility layout design in chemical industries requires multi-disciplinary knowledge and experience. The recent work mainly focuses on improving safety and calculating the efficiency of the design. However, in chemical industries, facilities are always located in frames, so both facility layout and frame layout should be considered in the design, as well as safety. Such a situation has not been well studied. In this work, facilities are divided into several frames and then placed in a fixed area. The risk resources located in the frames and out of the frames are both contained, and the safety distances are compliant with relative regulations. Optimization and some heuristic rules are applied to obtain the layout of each frame and the whole plant. Moreover, fire embankments are considered to achieve a more realistic and reasonable final layout. As a result, compared with the initial one, the actual and potential safety factors and the reasonable degree of the factory layout are both improved. The total costs are reduced by 7.38×10^4 $\$\cdot a^{-1}$. Through these steps, the effectiveness of the proposed approach is proven.

Keywords: facility layout problem; safety factor; genetic algorithm; surplus rectangle fill algorithm

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1. Introduction

Understanding facility layout problems (FLPs) requires multi-disciplinary knowledge and experience. Experienced designers can offer a feasible industry layout but cannot optimize the layout. With the help of a computer-aided systematic method, an optimized layout design with lower costs can be obtained. The recent research on computer-aided layout optimization mainly focuses on improving the safety of the layout and calculating its efficiency.

For the safety aspect, several improved approaches for quantitative risk assessments (QRAs) combined with uncertain assumptions [1] or dynamic and accident simulations [2] were proposed. The previous works about layout optimization integrated with safety factors can be roughly classified into two categories. One is using the loss incurred by the accidents to measure the risk level [3]. Alves et al. [4] mitigated the hazard by minimizing consequences to nearby residential areas in the event of accidents. They used the Monte Carlo method to estimate the superposition of accident effect areas onto population polygons. According to the case evaluation, their method could obtain feasible layouts and effectively reduce risk levels. In addition, Caputo et al. [5] presented an optimization method based on the Genetic Algorithm (GA), and evaluated safety issues by calculating the expected annual loss due to the secondary unit damage, which is caused by the primary accidents happening in nearby process units. A case study was described to show the effectiveness of their approach. Although the safety level can be improved through these methods, it is often incomplete since all aspects of the loss, such as compensation for casualties and costs of environmental pollution treatment, cannot be completely covered. In the other type of work, facilities were studied through risk assessment to obtain minimum safety distances, which were accounted for in layout optimization [6]. For instance, Ahumada et al. [7] obtained the shortest isolation distances between units on the basis of loss of human life and structural damage. However, in addition to the results calculated by the mathematical models, the requirements of security-related administrative regulations for the minimum safety distance must be complied with in real design works. In addition, the former works failed to add common protection facilities into the layout, such as a fire embankment.

For the research on the algorithm used in layout design, various algorithms like Coral Reefs Optimization (CRO) [8], Variable Neighborhood Search (VNS) and Simulated Annealing (SA) [9] are examined in recent studies. Among all of them, GA is an algorithm based on the mechanisms of natural selection, which is regarded as one of the most adopted and effective algorithms in FLPs [10]. Mohamadi et al. [11] proposed a new approach including a bi-level GA to solve FLPs in an open field. They compared the proposed approach with four approaches from the literature to evaluate efficiency and performance. The quality of the method is verified by improving the best solution obtained in previous studies and obtaining the optimal solution. Besbes et al. [12] used an approach by combining GA with A * Search Algorithm to establish a 3D layout model. They studied the effectiveness of the combined algorithm, comparing it with other optimizing methods. The results show that although their method had a lower convergence speed, it could obtain a better layout. In addition, different metaheuristics can also be combined for hybrid algorithms, in order to obtain better calculating performance [13].

In the previous works, several factors were taken into account, such as material transportation cost [14], cable cost [15], production time [16], total distance of logistics and space occupation [17]. Moreover, multi-floor structures were proposed [18]. A model considering inner frame structures could reduce the interconnection cost including land, floor, pipeline construction and material handling [19]. However, in the actual layout design work, the facility layout is generally carried out in a certain position with a fixed length and width. In other words, the land cost is determined before designing the layout. So, what needs to be carried out is the increase in the utilization rate of fixed space, rather than a reduction of land costs.

In real chemical industries, facilities are arranged in several frames, and frames, high facilities and high-risk facilities are arranged in the plant area. However, by studying previous works, it is found that such two-level facilities layout design has not been well studied. In addition, safety aspects have not been well incorporated in two-level facility layout designs. In this work, GA and the Surplus Rectangle Fill Algorithm (SRFA) are combined into a two-level facility layout design method. The layouts of the facilities and frames are optimized with the minimum annual total cost as the objective function. The safety distances of risk resources are compliant with relative regulations and the corresponding costs are added to optimization objectives. In addition, fire embankments are considered in the industrial plant. To improve the practicality of the model, the area of the whole plant is fixed, and the total land utilization rate should be as high as possible.

2. Mathematical Model and Algorithm

2.1. Problem Statement

In this work, the size of the whole plant is fixed. Some basic data, such as sizes, numbers and safety distances of the facilities and flow information, are known. Frame layout and plant layout are the two specific levels of layouts. Through modeling and optimization, a complete plant layout can be acquired by considering multiple aspects. The information obtained should include the following:

- Coordinates of each facility in the frame region.
- Relative locations of frames and special facilities, including towers, reactors and compressor rooms.
- Various costs and internal layout of each frame and the whole layout.

FLPs usually contain plenty of variables and constraints. Thus, several assumptions are required to simplify the model and reduce the calculation time.

- The facilities on the same floor are arranged on a two-dimensional plane.
- Plants, frames and all the facilities are placed orthogonally.
- High facilities, including towers and reactors, are regular circles; the other facilities, plants and frames are regular rectangles.
- Compressors are placed in a rectangular area to form a compressor room, regarded as an original facility.
- Special facilities, including high facilities and the compressor room, are placed apart from the frames in the plant layout.
- The materials across two frames are defined as cross-frame connections (CFCs). The exit points of CFCs are set as the midpoints of sides of rectangle frames.
- If several risk facilities are clustered together in the plant, fire embankment(s) can be constructed between the risk source clustering area and other facilities. The corresponding safety distances can be reduced.
- If a single-floor layout is incapable of containing all the facilities, multi-floor structures can be considered in the frame.
- If multiple floors are applied, vertical materials and floor requirements for special facilities should be concentrated on.

2.2. Constraints

Frame layout deals with multiple facilities possessing various shapes and functions. Therefore, more constraints are necessary to be considered generally. To achieve a reasonable and effective frame layout, a couple of constraints are set.

Facility orientation constraints are set up to determine the length and width of each facility within the frame area. Facilities can be placed in different directions, while the direction and the original size can determine the size of the layout, which is defined as "visual size". In addition, the term "length" is defined as the size parallel to the x-axis and "width" is that in the y direction. A particular relationship between the visual size and original size of a facility can be developed. A binary variable d is defined to illustrate this relationship. It is stipulated that when $d_i = 0$, the facility i is placed vertically, that is, the original length equals its visual width. On the contrary, when $d_i = 0$, it is arranged horizontally. Then, the relationship between the visual and actual size of the facility can be described as follows:

$$l_i = (1 - d_i)l_{o,i} + d_i w_{o,i} \tag{1}$$

$$w_i = (1 - d_i)w_{o,i} + d_i l_{o,i} \tag{2}$$

where l_i and w_i are the visual length and width of facility i (m); $l_{o,i}$ and $w_{o,i}$ are the original length and width of facility i (m).

Non-overlapping constraints are applied to avoid overlapping regions of distinct facilities. These constraints are related to the length, width and the coordinates of the midpoint of each facility. Facility i and j are forced to accommodate one of the following inequality constraints to prevent a cross area:

$$|x_i - x_j| \geq \frac{1}{2}l_j + \frac{1}{2}l_i \tag{3}$$

$$|y_i - y_j| \geq \frac{1}{2}w_j + \frac{1}{2}w_i \tag{4}$$

where x_i and y_i are the center coordinates of facility i; x_j and y_j are that of facility j. Inequalities (3) and (4) represent the situations that facility i is on the right and left, top and bottom sides of facility j, respectively.

Boundary constraints demand that all the facilities cannot exceed the frame bounds. The following four constraints must be satisfied simultaneously to limit the location of a facility:

$$x_i - \frac{1}{2}l_i \geq 0 \tag{5}$$

$$x_i + \frac{1}{2}l_i \geq L \tag{6}$$

$$y_i - \frac{1}{2}w_i \geq 0 \tag{7}$$

$$y_i + \frac{1}{2}w_i \geq W \tag{8}$$

where L and W are the length and width of the frame (m).

According to the certain area of the plant, the sizes of the frames and special facilities are indispensable to meet boundary constraints:

$$X_i - \frac{1}{2}L_i \geq 0 \tag{9}$$

$$X_i + \frac{1}{2}L_i \leq L_p \tag{10}$$

$$Y_i - \frac{1}{2}W_i \geq 0 \tag{11}$$

$$Y_i + \frac{1}{2}W_i \leq W_p \tag{12}$$

where X_i and Y_i are the center coordinates of frame i; L_i and W_i are the length and width mentioned before (m). L_p and W_p are the fixed length and width of the plant (m).

Pump constraints are established to restrict all the pumps of a frame within a rectangular area for centralized management. In each frame, pumps are arranged in an orderly manner as a whole. In addition, the pump area is defined as the smallest rectangle enclosing all the pumps, even if it is not completely filled by them, in order to prevent irregular shapes in the model. The pump area is regarded as a facility to be optimized together with others. Since the relative positions of the pumps within the pump area are determined, the actual coordinates in the frame can be described as follows:

$$x_{pi} = x_{pri} + x_{pa} \tag{13}$$

$$y_{pi} = y_{pri} + y_{pa} \tag{14}$$

where x_{pi} and y_{pi} are the center coordinates of pump i in the frame; x_{pri} and y_{pri} are that in the pump area. x_{pa} and y_{pa} are the lower left coordinates of the whole pump area.

Floor constraints for specific kinds of facilities are requisite when multi-floors are applied in the frame. For instance, pumps must be placed on the first floor to prevent cavitation. Air coolers are required to be assigned on the top floor to guarantee a cooling effect. A couple of parallel heat exchangers or air coolers with similar features should be set as a whole.

2.3. Objective Function

The total cost generally serves as the measure of layout performance [20], generally containing land cost (*LC*), floor cost (*FC*), pipeline construction cost (*PCC*) and material handling cost (*MHC*). In this work, the fixed area of the whole plant means fixed *LC*. So the total annual cost (*TAC*, \$), containing the corresponding *FC*, *PCC* and *MHC*, is regarded as the objective function in each frame:

$$TAC = FC + PCC + MHC \tag{15}$$

FC (\$) is associated with the frame area:

$$FC = Af \cdot UFC \cdot S \tag{16}$$

$$Af = \frac{I(1+I)^T}{(1+I)^T - 1} \tag{17}$$

$$S = \max(x_i + l_i) \cdot \max(y_i + w_i) \tag{18}$$

where *UFC* is the unit floor cost (\$·m^{-2}); S is the frame area (m^2); Af is the annualized factor; I is the interest rate; and T is life cycle of the industrial park (y).

PCC (\$) is related to the pipeline investment:

$$PCC = Af \cdot \sum_{i=1}^{n} (UPC_i \cdot MD_i) \tag{19}$$

$$MD = |x_i - x_j| + |y_i - y_j| \tag{20}$$

where *UPC* is the unit pipeline cost (\$·m^{-1}), which is obtained by the method proposed by Stijepovic and Linke [21]; *MD* is the Manhattan distance (m) between connected facilities.

$$UPC = 0.82wt_{pipe} + 185D_{out}^{0.48} + 6.8 + 295D_{out} \tag{21}$$

where wt_{pipe} is the unit quality of pipelines (kg/m); D_{out} is the outer diameter of pipelines (m). They are determined by Equations (22)–(24) [21]:

$$wt_{pipe} = 644.3D_{inner}^2 + 72.5D_{inner} + 0.4611 \tag{22}$$

$$D_{out} = 1.052D_{inner} + 0.005251 \tag{23}$$

$$D_{inner} = \sqrt{\frac{4Q}{\pi \rho u}} \tag{24}$$

where D_{inner} is the inner diameter of pipelines (m), Q is the mass flow rate of the medium in the pipelines (kg·s^{-1}), ρ is the density of the materials (kg·m^{-3}) and u is the flow rate (m·s^{-1}).

MHC (\$) is related to the power consumed by the pumps for materials transporting, which can be calculated as follows:

$$MHC = C_E \cdot H \cdot \sum P \tag{25}$$

where C_E is the cost required for the pumps to consume per unit of operating power ($\$\cdot kW^{-1}\cdot h^{-1}$), H is the annual operating hours (h) and P is the operating power of the pumps consumed by transporting materials (kW), which can be calculated as follows:

$$P = \frac{Q \cdot h_f}{\eta} \tag{26}$$

$$h_f = \lambda \frac{MD \cdot u^2}{2D_{inner}} + \alpha \cdot gz \tag{27}$$

where h_f is the energy used during the material handling process for overcoming resistance and gravity ($J\cdot kg^{-1}$), η is the pump operation efficiency, λ is the friction coefficient, g is the gravity constant ($m\cdot s^{-2}$), z is the length of vertical material transportation (m) and α is a binary variable, which is introduced to stipulate whether there is a connection transporting materials vertically from bottom to top.

2.4. Optimization Algorithm

Since complex FLPs involve multiple variables and constraints, it is difficult to solve them manually. Therefore, algorithms are often utilized in optimization progress. In this work, a composite algorithm combining GA and SRFA is used. A simple introduction is proposed for the two algorithms and their combined approach.

Compared with other metaheuristics, GA has evident advantages in dealing with FLPs. Due to the strong randomness of solutions generating, GA possesses significant strength in global searching [22]. There are numerous individuals having one-to-one correspondence with facilities, respectively. Just like genes on chromosomes determine the performance of individuals, GA sets a number of variables to determine the number, orientation and placement order of each facility, the length of each frame and the facility number in each floor (if there is a multi-floor structure). Variables are arbitrarily valued within the predetermined range to reflect the randomness of the optimization. The desired results with minimized TAC can be obtained through GA.

Although GA is suitable to solve FLPs according to its features, it has disadvantages in acquiring a final precise layout. It is difficult to consider the sizes and safety distances of facilities while using GA, causing hardly generating efficient and tight layouts. Therefore, an additional algorithm is required to solve the problems. SRFA [23] is capable of dividing a rectangular plate into several parts. This feature is in line with the concept of arranging rectangular facilities within a rectangular area. SRFA creates a residual rectangle data set to collect available space for the arrangement of facilities, which is utilized to obtain the final layout along with the coordinates of the facilities.

Although SRFA proves to be appropriate for arranging rectangular facilities in a given region, it cannot independently solve FLPs since it is unable to minimize TAC through iteration. In addition, it requires initial and essential conditions like facility placement order and orientation. These can be available through GA. Thus, a hybrid algorithm combined with GA and SRFA can achieve optimization of the frame layout. For the optimization of frame layouts, GA randomly generates feasible solutions, including facility placement order, orientation and frame bottom length, based on the given information such as facility numbers and sizes. With all the data above, SRFA designs the precise layout from the residual rectangle data set to achieve corresponding facility coordinates, and returns them to GA as input parameters, in order to minimize TAC with flow information. The iteration continues until the termination condition is satisfied. Then, the layout with the smallest fitness value is selected as the output result. In addition, for the optimization of plant layouts, the initial information entered into GA is about the frames and CFCs. Figure 1 shows the workflow of the hybrid algorithm of frame layout optimization. The algorithm is carried out in MATLAB 2019b, and the relative operators in GA are the default in the toolbox.

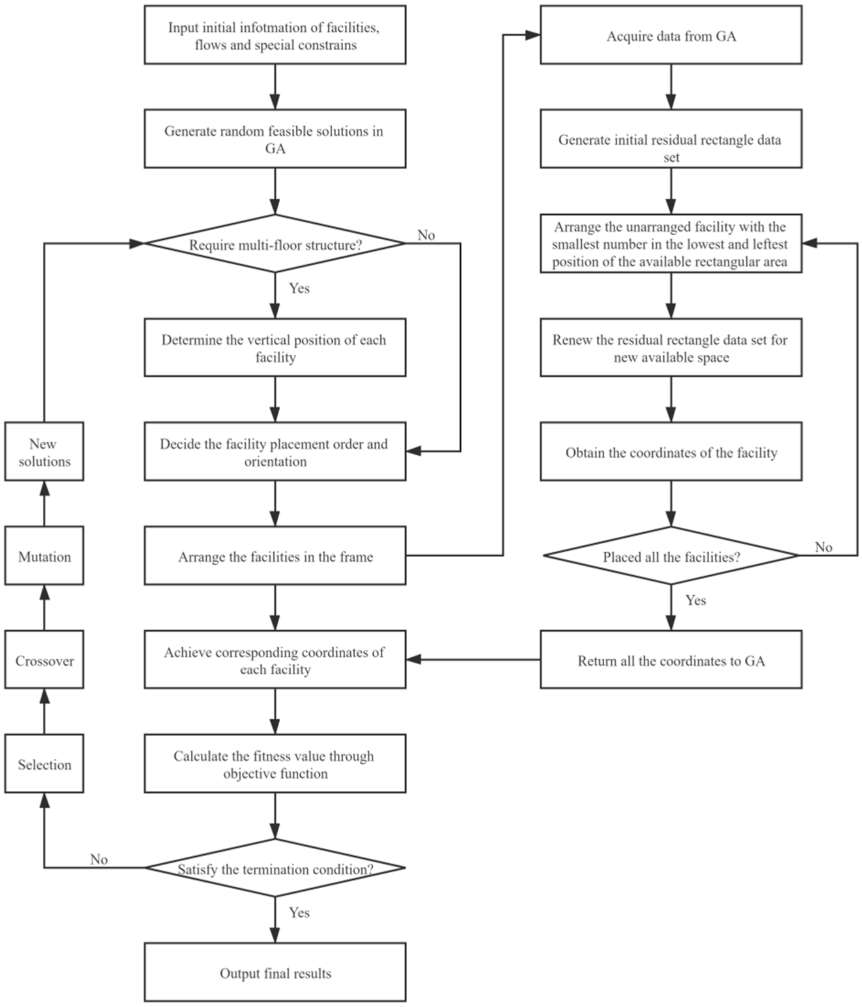


Figure 1. Workflow of the hybrid algorithm.

3. Optimization Approach

In this work, the implementation of frame layouts for facilities and plant layouts for frames are the two levels of layout design. Before dividing the facilities into a couple of frames, the safety distances of the high-risk facilities are considered. A quantitative approach is used with the objective of minimizing the number of cross-frame material connections during the segmentation of facilities. The initial size and internal layout of each frame are obtained through the first-step optimization. Then, the frames are arranged together with the special facilities (towers, reactors and compressor room in this work) in the specified area according to the combination of optimization and designer decisions. According to the layout optimization of frames in the previous step, the exit positions of the CFCs are determined on the boundaries of the frames. The second-step optimization in each frame is carried out to obtain an improved layout of the plant with consideration of CFCs. Moreover, fire embankment(s) can be added between risk resources and other facilities in the plant to reduce safety distances. Therefore, the third-step optimization of the plant layout is required. The above steps can be described in detail as follows.

- Facilities are classified depending on their features. Longer fire distances specified in the regulations are necessary to be added to the sizes of the hazard resources. Parallel heat exchangers should be arranged as a whole. Pumps and compressors are required to be placed in an orderly manner within the pump area and compressor room, respectively. The special facilities, like reactors, towers and compressor rooms, should be separated from the frames. Attention should be paid to the relevant floor constraints associated with particular facilities such as pumps and air coolers if there is a multi-floor structure in the frame.

- According to the flow information, material connections are categorized into internal ones within the frame and cross-frame ones.
- The facilities, except the special ones, are divided into several frames. The number of frames is determined according to the actual situation. The classification principle is to find out the cutting positions with the least total number of CFCs. This approach will be elaborated in detail in the following statements.
- Each frame is optimized utilizing the hybrid algorithm, while only internal connections (ICs) are considered. Then, the initial sizes and layouts of frames are obtained. Multi-floor frame(s) may be required to prevent exceeding the specified area of the plant.
- Hybrid algorithms are applied to arrange the frames together with the special facilities within the specified space, as the same way of arranging facilities within the frame. The positions can be altered according to designer decisions.
- After arranging the frames and special facilities, an initial plant layout is obtained. In addition, the exits of CFCs are determined at some midpoints of the sides of the frames.
- Each frame is re-optimized by additionally considering CFCs, and the sizes and structures of frames are updated.
- The whole plant layout is updated with the updated frames and changeless exit positions of CFCs.
- Fire embankment(s) are constructed between risk resources and other facilities to reduce safety distances. Sizes and structures of a part of frames probably convert during manual adjustment.
- The whole plant layout is optimized again with the adjusted frames.

The designer’s decisions, added to the model during the process of arranging frames and special facilities, can save unnecessary space by ensuring enough safety distances. Frames and special facilities are arranged by computational optimization theoretically. However, the calculation results may lead to reduced space utilization. For instance, when a facility with high risk is located near the edge of the plant, the safety distance on the side close to the edge is unnecessary. The manual adjustment of the example is shown in Figure 2. Therefore, designer decisions are required to prevent such problems.

A quantitative method is proposed to sort facilities into several frames. CFCs usually mean longer material transportation distances. Therefore, the minimization of the number of them while sorting can theoretically reduce the costs of the final plant layout.

To minimize the number of CFCs, some work needs to be carried out. All the facilities, except special ones, are arranged in a single-floor area. The number of frames depends on the result obtained. The width of each frame is described as follows:

$$\frac{H}{n}i - h \leq cp_i \leq \frac{H}{n}i + h \tag{28}$$

$$W_i = \begin{cases} cp_i, i = 1 \\ cp_i - cp_{i-1}, 1 < i < n \\ H - cp_{i-1}, i = n \end{cases} \tag{29}$$

where H is the width of the whole single-floor area (m), m is the number of frames, cp_i is the coordinates in the direction of y-axis of cutting point i and h is the range that cp_i can fluctuate. W_i is the width if frame i.

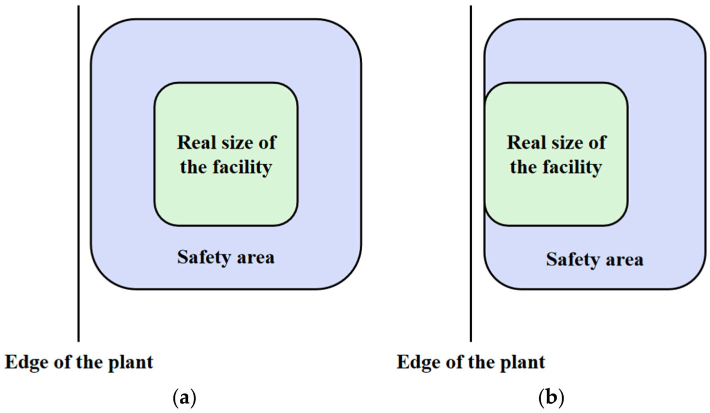


Figure 2. Manual adjustment of the position of facility: (**a**) original position and safety area; (**b**) modified position and safety area.

After determining all the cp_i, the frame number i each facility belongs to can be obtained. If the two facilities connected by one flow are placed in different frames, the flow connection is regarded as a cross-frame one. The hybrid algorithm is adopted in the objective function to minimize the total number of CFCs (TN):

$$TN = \sum_{i=1,j=1,i\neq j}^{n} N_{ij} \tag{30}$$

In the single-floor layout in Figure 3, facilities are simplified as center points (in red). The cutting lines (in green) are set to be perpendicular to the y-axis and move within a certain range to divide all the facilities into several frames. The width of each frame can be slightly different in order to minimize the number of CFCs. All the flows are drawn in the form of right-angle lines. The connections judged as a cross-frame one by the approach are drawn in black and the internal ones are drawn in blue. Obviously, when more than two frames are required, if the length of a connection exceeds the width of a single frame, it will be cut by multiple cutting lines. Therefore, if the total number of cutting points is treated as the objective, a suboptimal result may be obtained due to the repeated calculation of the number of CFCs. The calculation method proposed above can avoid this issue.

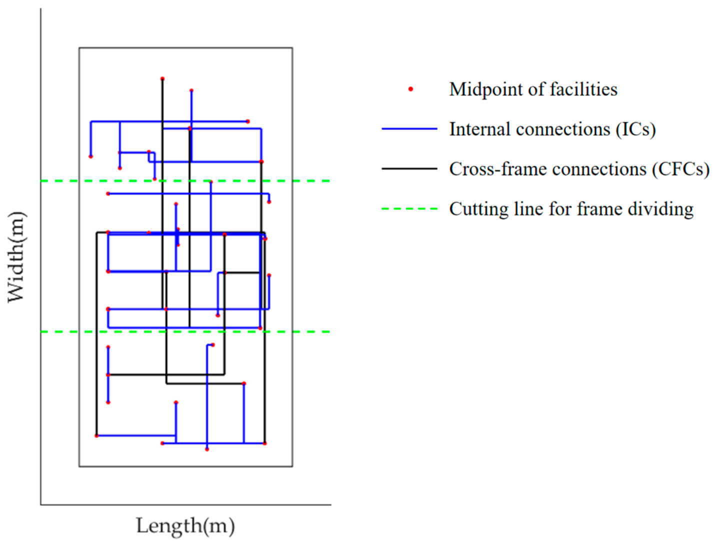


Figure 3. Schematic diagram for choosing cutting points.

4. Case Study and Result Analysis

To verify the effectiveness of the proposed method, a 70 m $\times$ 70 m-area plant with 141 facilities and 247 material connections is designed and optimized. In this case, numerous rectangular facilities, with different visual and original lengths, and widths are placed in a fixed rectangular space. Facilities possess various functions and specific placement constraints. Risk resources arranged in frames and separated from them are contained. Parallel placements and centralized arrangements are involved. Multi-floor structure frame(s) and fire embankment(s) are utilized. Therefore, if the case is verified as successfully coped with, other types of block layouts can be solved through the proposed method with slight modifications according to the situation.

In this case, there are ten special facilities, which are riser reactor (RR), settler–regenerator (SR), fractionating tower (FT), stripping tower (ST), absorption–desorption tower (ADT), stabilization tower (STA), reabsorption tower (RT) and three compressors. The high-risk compressors are arranged together in a compressor room for ease of management and fire prevention. The basic data on the flow information, the sizes and categories of the facilities have been acquired. The remaining 131 facilities, containing 5 risk resource facilities, 82 heat exchangers and air coolers, 6 vessels and 38 pumps, should be divided into several frames and then optimized with the objective of minimizing the number of CFCs.

Before the optimization, the number of frames required should be defined. There is no doubt that the fewer frames there are, the fewer CFCs. The respective optimized results when 3, 4, 5 and 6 frames are required are shown in Table 1.

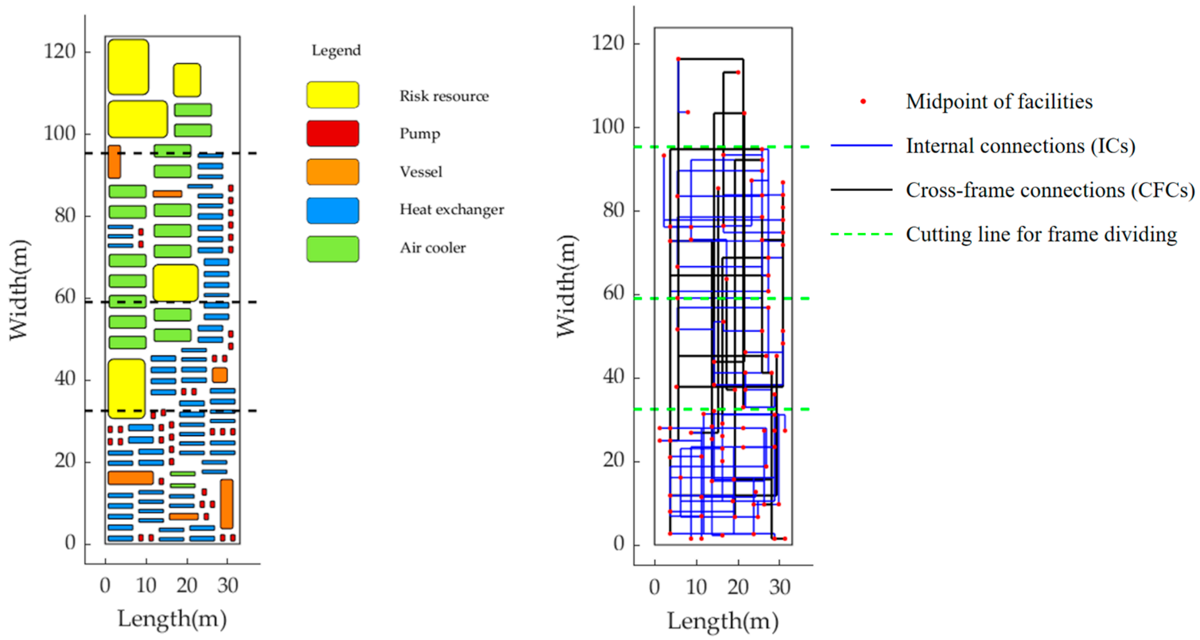
Table 1. Information on the total number of CFCs of different arrangement plans.

Number of Frames	Total Number of CFCs
3	31
4	35
5	49
6	70

The results of 3 and 4 frames are similar, and far fewer than that of 5 and 6 frames. To receive the minimal number of CFCs, the layout should be divided into three frames. However, numerous facilities being divided into one frame leads to the excessive width of each frame if the number of frames is only three. With the consideration of safety factors, fire and emergency accesses should be constructed both inside and outside the frames. The increase in the length of the passages, caused by the longer frame widths, will extend escape time. More outer safe passages can be arranged with smaller frames. Thus, the allocation plan of four frames and three cutting points is selected.

Heat exchangers, including air coolers, are placed in the same direction for neatness. A couple of parallel ones can be regarded as a whole to simplify the diagram. The bottom length is set to be approximately 30 m. The optimization results of the facility arrangement and the frame segmentation are shown in Figure 4a,b, as well as the ICs and CFCs. The calculation process takes around 600 s.

The calculation results show that the length and width of the single-floor layout are 32.97 m and 124 m. The width of each frame is approximately 32 m. Thus, the locations of the three cutting points are about 32 m, 64 m and 96 m in the y-direction, respectively. Four frames are named A to D from the bottom to the top. The optimization result is shown in Tables 2 and 3.



(**a**) (**b**)

Figure 4. Facility separation of the single-floor layout: (**a**) the result of the facility arrangement and frame segmentation; (**b**) ICs and CFCs in the layout.

Table 2. Information about CFCs between each frame.

	A	B	C	D	Total Number of CFCs
A	-	6	8	1	35
B	-	-	8	9	
C	-	-	-	3	

Table 3. Information about cutting point positions and widths of each frame.

Frame	Precise Extents in Widths (m)		Width of Each Facility (m)
	Lower Point (m)	Upper Point (m)	
A	0	32.55	41
B	32.55	59.10	14
C	59.10	95.45	18
D	95.45	124.00	5

Obviously, facilities are arranged more closely in frames A and C. According to the result shown in Figure 4, more than half of the pumps are arranged in frame A; risk resources are mostly placed in frame D; and parallel air coolers are mainly contained in frame C. Thus, it can be figured out that facilities with similar functions tend to be centrally arranged in the same frame. This situation is in line with the actual layouts.

According to the layout of an actual plant, special facilities (reactors, towers and compressors) should be located outside the frames. Therefore, the connections for material transport between the special facilities and frames are also regarded as cross-frame ones. Table 4 presents the number of facilities, ICs and relative CFCs of each frame.

Table 4. Information on facilities and corresponding connections of each frame.

Frame	Number of Facilities Inside	Number of ICs	Number of Connections Between this Frame and Special Facilities
A	44	69	41
B	18	23	14
C	28	40	18
D	4	1	5

Through the above steps, four frames are determined. However, this step is only used to assign facilities to minimize the number of CFCs, without consideration of costs. The sizes and layouts should be then optimized to minimize *TAC*. In this step, only ICs are considered because the material existing points of CFCs are not determined since the relative locations of frames are not fixed.

All the frames are firstly optimized to be single-floor, in order to maximize the utilization rate of the certain plant area. The optimized layouts are listed in Table 5.

Table 5. Initial size of single-floor layout of each frame.

Frame	Length (m)	Width (m)	Area (m^2)	Total Area (m^2)
A	23.07	46.70	1077.40	3724.00
B	26.11	31.60	825.11	
C	29.80	41.00	1222.00	
D	33.12	18.10	599.48	

When the special facilities are added to the whole plant, the safe distances of all the frames and special facilities should be considered. As a result, the total area required exceeds the fixed space. So, multi-floor frame(s) are required. Frame D cannot be transformed because of the very few number of facilities contained in the frame. The information on optimized multi-layer frames A, B and C are shown in Table 6.

Table 6. Initial size of multi-floor layout of each frame.

Frame	Length (m)	Width (m)	Area (m^2)	Reduced Area (m^2)
A	30.83	19.10	588.86	488.54
B	31.11	15.60	485.27	339.85
C	26.09	25.00	652.19	569.82

After comparing three optimized multi-layer frames, it is found that if frame A or B is transformed into a multi-floor one alone, the total area required still cannot meet the land restrictions. Thus, frame C is selected to be a double-floor layout to ensure the feasibility of the whole plant due to the most reduced area. The selected results of each frame are shown in Table 7.

Table 7. Selected initial size of each frame.

Frame	Length (m)	Width (m)	Area (m^2)	Total Area (m^2)
A	23.07	46.70	1077.40	3154.18
B	26.11	31.60	825.11	
C	26.09	25.00	652.19	
D	33.12	18.10	599.48	

Through the layout optimization based on economy, the sizes and internal structures have been adjusted for the convenience of the further arrangement of the plant layout. It is necessary to confirm the exit positions of CFCs at the edge of the frame. All the positions are set at the midpoint of any side of the frames for simplification. The whole plant layout of the first optimization is presented in Figure 5.

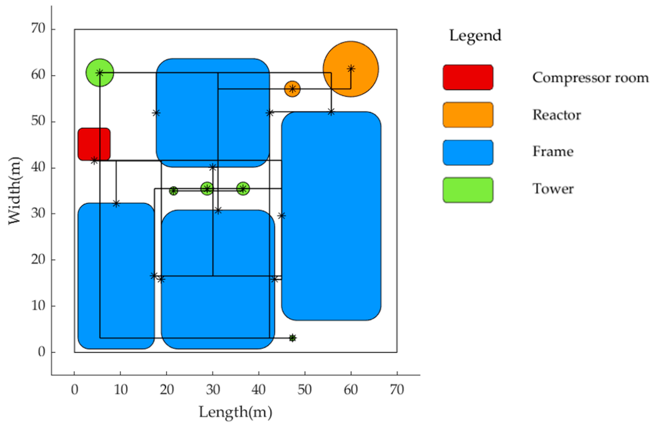


Figure 5. Plant layout with CFCs and exit positions of the first optimization.

In Figure 5, an initial plant layout is proposed. However, there are still several problems in the layout obtained by theoretical calculation. CFCs (connected with "*") are not taken into account. In addition, the location of ST is far away from other towers, which also goes against the experience of an actual design process. Thus, modifications of the initial frames are required to achieve an optimal layout. CFCs are added to the objective function in this step to minimize the total cost in each frame, and the modified results are shown in Table 8.

Table 8. Modified size of each frame.

Frame	Length (m)	Width (m)	Area (m^2)	Total Area (m^2)
A	23.58	46.60	1098.88	3211.89
B	26.61	32.00	851.64	
C	25.27	25.80	652.08	
D	19.10	31.90	609.29	

It is determined that the shapes and sizes of the four frames basically remain the same, which means the positions of material exit points can be applied to the modified plant layout. The result is shown in Figure 6.

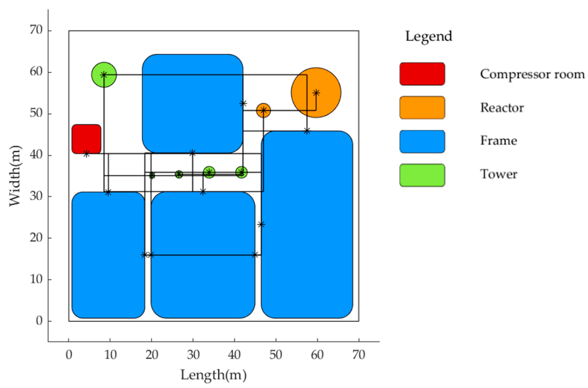


Figure 6. Plant layout with CFCs and exit positions of the second optimization.

In the modified plant layout with the consideration of CFCs, the positions of towers are also more reasonable. As mentioned earlier, risk resource facilities are mostly placed in frame D. According to the regulations, fire embankments can be constructed to decrease the pipeline length. In frame D, manual modification is added to obtain a structure including fire embankments. Figure 7 shows the modification approach of the structure.

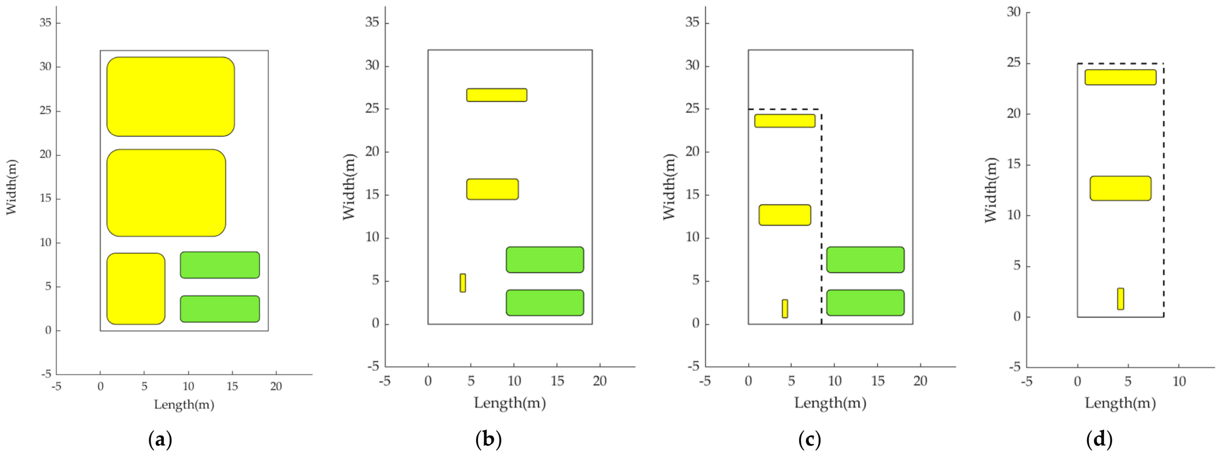


Figure 7. Adjustment process of frame D: (**a**–**d**) step 1 to step 4.

Figure 7a shows the original layout of the facilities in frame D with safety distances, and (b) shows the net sizes of them. Adjusted positions and added fire embankments are shown in (c). The structure of frame D is changed and the area is saved. To obtain a more reasonable and neater plant layout, the air cooler in frame D is moved to frame B, in order to minimize the increased number of CFCs. New frame D is obtained with the method above, and new frame B is achieved through optimization with consideration of new facilities and CFCs to minimize TAC. Figure 8 shows the plant layout with the original structures of frames A and C and adjusted B and D, and the sizes of adjusted frames B and D are shown in Table 9.

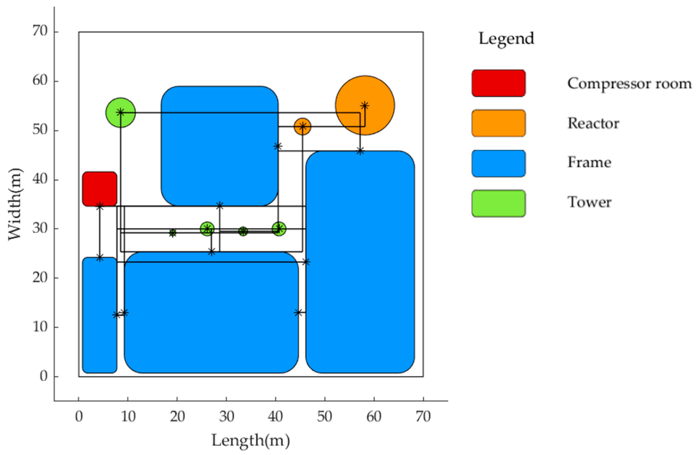


Figure 8. Plant layout with CFCs and exit positions of the third optimization.

Table 9. Sizes of the adjusted frames.

Frame	Length (m)	Width (m)	Area (m^2)
B	26.12	36.90	963.93
D	8.50	25.00	212.50

With the addition of fire embankments, the plant layout is more in line with the actual situation. The number of CFCs passing through the frames is further reduced to 9. This means lower hidden costs of the actual layout.

The respective *TAC* of initial, modified and adjusted plant layouts should be compared to prove the effectiveness of the optimization and the improvement of fire production. However, the contents of *PCC* and *MHC* in the objective function are different between the initial plant layout and the modified and adjusted one. Therefore, the *PCC* and MHC of cross-frame connections are calculated according to flow information, exit position and facility position, and are added to the costs of the initial results. Then, the comparison is made between the three layouts. Information on the three layouts is listed in Tables 10–12 and Figure 9. It should be noted that the area utilization in Tables 10–12 is calculated by the total area of all the frames. The area of all special facilities is constant in the three layouts. So, the comparison of the total area of all frames can reflect the real utilization rate.

Table 10. Results of the first optimization.

	IC		CFC
PCC (10^4 \$·a^{-1})	2.24		1.37
MHC (10^5 \$·a^{-1})	2.11		1.73
LC (10^4 \$·a^{-1})	0		6.69
FC (10^3 \$·a^{-1})	5.35		0
TAC (10^5 \$·a^{-1})	2.39		2.53
Total cost (10^5 \$·a^{-1})		4.92	
Area (m^2)	3154.18		4900.00
Area utilization (%)		64.37	

Table 11. Results of the second optimization.

	IC		CFC
PCC (10^4 \$·a^{-1})	2.71		1.43
MHC (10^5 \$·a^{-1})	1.94		1.42
LC (10^4 \$·a^{-1})	0		6.69
FC (10^3 \$·a^{-1})	5.34		0
TAC (10^5 \$·a^{-1})	2.26		2.23
Total cost (10^5 \$·a^{-1})		4.50	
Area (m^2)	3211.89		4900.00
Area utilization (%)		65.55	

Table 12. Results of the third optimization.

	IC		CFC
PCC (10^4 \$·a^{-1})	2.62		1.36
MHC (10^5 \$·a^{-1})	1.58		1.49
LC (10^4 \$·a^{-1})	0		6.69
FC (10^3 \$·a^{-1})	5.34		0
TAC (10^5 \$·a^{-1})	1.89		2.29
Total cost (10^5 \$·a^{-1})		4.18	
Area (m^2)	2927.39		4900.00
Area utilization (%)		59.74	

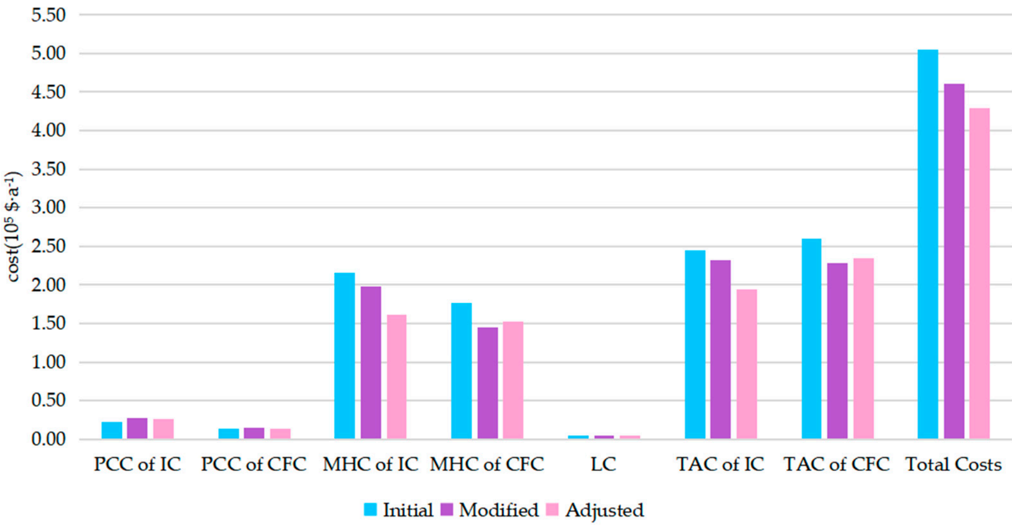


Figure 9. Cost comparison of three layouts.

According to the tables and figures, the land utilization rate of the second layout is the highest of the three, while that of the third one drops to the lowest due to the addition of fire embankments and the reduction in safety distances. The vacated land can be used to build fire protection facilities to improve the safety of the whole layout further. It seems to be contrary to the original idea of reducing costs by maintaining the highest possible land utilization. However, in fact, the total cost of the third layout is 4.18×10^5 $\$\cdot a^{-1}$, which is 14.99% lower than that of the first one (4.92×10^5 $\$\cdot a^{-1}$) and 6.93% lower than the second one (4.50×10^5 $\$\cdot a^{-1}$), mainly due to the reduction in MHC of IC. This is because the flow rates of adjusted ICs are faster, or their medium temperatures are higher. Thus, when the lengths of them are reduced, the resulting reduction in *MHC* is more obvious. In addition, in the three layouts, a tendency of CFCs to be concentrated in a certain area is demonstrated. This is consistent with the actual layout design. The centralized arrangement of pipelines also facilitates subsequent design works, such as erecting pipe racks and constructing safe passages outside frames.

As a conclusion, the actual and potential safety factors and reasonable degree of the factory layout are both improved, by increasing the fire distance and adding fire embankments. The total costs of the plant are also effectively reduced through the combination of optimization algorithm and manual adjustment. As a result, compared with the initial layout, the total costs are reduced by 540,086.70 ¥/a after modification and adjustment.

5. Conclusions

In this work, efforts are made to arrange facilities in a two-level layout and increase the safety level of a plant layout through several steps. By using the proposed method, facilities can be well arranged in a frame and frames can then be well arranged in a plant. The risk of the whole plant is reduced, mainly by increasing safety distances of the risk facilities and adding safety protection facilities according to the structures and layout. This method added more options for the safety design of FLPs, facilitating multifaceted coordinated optimization. Compared with the previous work, the rationality of the layout has been improved. In the case study, the total costs of the layout after modification and adjustment are reduced as the objective function. After modification and adjustment, the *TAC* of the third layout is 4.18×10^5 $\$\cdot a^{-1}$, which is 7.38×10^4 $\$\cdot a^{-1}$ lower than that of the first one and 3.12×10^4 $\$\cdot a^{-1}$ lower than that of the second one. According to the lowest area utilization rate (59.74%) of the three layouts, more fire protection equipment can be built in the third one for the further improvement of safety. In addition, the third layout is more reasonable and realistic, due to the addition of fire embankments and the tendency towards centralized arrangement of pipelines. Thus, the effectiveness and rationality of the proposed method can be proven.

As mentioned in the introduction, FLPs are complex and multi-branched. This work emphasizes the safety factor of two-level layout designs but ignores some other realistic problems, such as the 3D structures of the frames and facilities and the space occupied by the pipelines. Therefore, one of the future directions is to combine as many practical factors as possible. In addition, manual operation is still required in this work. For the convenience of the application in the industry in the future, complete automation of the solution is requisite.

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