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Layout Optimisation of Multi-Frame Process Unit

Siyu Xu[a], Yufei Wang[a,*], Xiao Feng[b]

[a]State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Beijing 102249, China
[b]School of Chemical Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, 710049, China
wangyufei@cup.edu.cn

Facility layout is a very important part in the design of a plant, a good layout can greatly reduce the cost of the plant construction and operation, which brings considerable benefits to the investors. Previous researches on facility layout problems mainly focus on arranging facilities in a single frame, however, facilities are placed in several frames rather than stacked together in an actual process unit. In this work, facilities are arranged in terms of frames and the coupling of frame scale and facility scale is studied, which makes changes in traditional layout researches. Both the frame location and the facility location in the frame are optimised by minimising the total cost. The safety distance and the fire protection distance of facilities are considered. The algorithm combining genetic algorithm and surplus rectangle fill algorithm is adopted. The objective function is the sum of the pipeline construction cost, material handling cost, land cost and floor construction cost. The impact of the key connections of high temperature is also considered to make the result layout closer to reality. The mathematical model is calculated in MATLAB. In case study, a catalytic cracking unit with 217 facilities and 245 material flows is modelled. In the process of optimisation, the ideas of multiple frames and key connections are fully addressed. As the result shows, 16 % reduction of the total cost and the locations of frames and facilities are reached, which indicates that the proposed method can acquire a reasonable facility layout, and the frames make the final layout closer to the actual situation.

1. Introduction

Facility layout is closely related to the design of plants, which is very practical in applications (Drira et al., 2007). The main objective is to arrange facilities on the premise of given sizes and connections, so as to minimise the total investment cost and ensure the smooth completion of production tasks (Azadivar and Wang, 2000).

After decades of development, facility layout problem has gradually shifted from simply arranging equal-area facilities in a single layer to multi-floor (Bernardi and Anjos, 2013) or unequal-area (Liu and Liu, 2019) studies. Material connection is also a significant aspect, which can be calculated in terms of pipeline network (Wu et al., 2017). In addition, designers tend to consider more optimisation ideas to get a more practical layout. Anjos et al. (2018) put forward a multi-row layout model to solve large-scale layout problems. Meller et al. (2010) used a new bottom-up approach instead of the traditional top-down way to get a more usable output at the cost of increasing solving difficulty. Material handling points were also taken into account to design the connection path (Friedrich et al., 2018) or aisles (Klausnitzer and Lasch, 2019). Safety factors have become the focus of layout researches (Caputo et al., 2015), and many assessment methods were adopted to evaluate plant safety (Wang et al., 2017). However, through the improvements above, current layout results are still quite different from the actual situation. This is because in the previous studies, the scale of layout problem is generally small and all facilities are often stacked together within a single frame, while in the actual process unit, there are much more facilities arranged in several frames, so as to facilitate the maintenance and management of facilities.

In this work, facilities are arranged in frames. Due to the frame position and the facility position affect each other, multiple sub-optimisation models of frames are established to study the coupling of the frame scale and the facility scale. As an improvement on previous researches, a larger number of facilities is arranged, and the frames are taken into account to fit the actual situation.

The joint optimisation process of frame scale and facility scale is carried out in several steps. All the facilities in the unit are divided into several frames according to the production process and the function of facilities. Each

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frame is optimised aiming to minimise the total cost without considering the connections between the frames. The frames are manually arranged according to the closeness of material exchange. Afterwards, the objective function of each frame is updated with the addition of material handling cost and pipeline construction cost of cross-frame connections, so as to optimise the relative position of relevant facilities within the frame. The joint optimisation of the two scales is realised. The influence of key connections between high-temperature facilities is also taken into account. Through these steps, the approximate optimal unit layout can be obtained. The multiple frames make the layout more orderly, and are also conductive to the transportation and installation of facilities. The optimised layout can not only save land resources, but also reduce the length of the pipeline, so as to reduce the cost of pipe steel and energy consumption in material transportation, which is conductive to energy conservation and sustainable development.

2. Research method

Facility layout problem can be regarded as the problem of arranging facilities in the area of a process unit. The idea of frame is fully addressed in this work to reach a practical layout, and the optimisation goes from facilities within frames to all the frames and finally to the whole layout of the process unit, which realises the joint optimisation of the two scales mentioned. To simplify the calculation, when solving this kind of problems, it is necessary to assume that the facilities, the frames and the process unit are all rectangular and placed orthogonally. When determining the sizes of facilities, safety distance and fire protection distance are considered according to the chemical facility layout design regulations.

2.1 Constraint conditions

Facility layout within a frame usually considers several aspects. Facility direction constraints and floor constraints are set to ensure the orderly discharge and effective operation of facilities. In a frame, facilities are discharged horizontally or vertically. A binary variable r_i is set to stipulate when the value of r_i is equal to zero, the facility is arranged horizontally. On the contrary, when the value is equal to one, the facility is arranged vertically. According to standards, the arrangement of some specified facilities must follow some practical constraints. For example, the air coolers should be placed on the top floor to ensure the cooling effect, pumps need to be placed on the ground floor, which prevents the cavitation. Besides, facility non-overlapping constraints and boundary constraints are also of great importance. Since only one facility can be placed in a certain position, it is necessary to avoid overlapping area between facilities to ensure the rationality of the results. The facilities need to be properly arranged within the frames, so the facility boundary should not go beyond the area of the rectangular frame.

2.2 Objective function

Besides the frames, the cost is also used to evaluate the result layout. The total cost should be kept as low as possible to bring benefits to investors. In this work, the minimum total cost is selected as the optimisation goal to acquire a reasonable facility layout within the frame. The total cost (*TC*) includes four aspects, which are land cost (*LC*), floor construction cost (*FC*), pipeline construction cost (*PIC*) and material handling cost (*POC*), as shown in Eq(1). It should be noted that all costs are expressed in terms of annual costs.

$$TC = LC + FC + PIC + POC \tag{1}$$

PIC includes the cost of pipeline material and insulation layer, as shown in Eq(2):

$$PIC = \frac{1}{T}\left(\sum_{m=1}^{n} UIC_m L_m + \sum_{m=1}^{n} W_m L_m\right) \tag{2}$$

where, *T* is the production life of the unit, UIC_m is the material cost per unit length of pipeline, referring to the calculation method proposed by Stijepovic and Linke (2011). L_m is the Manhattan distance between two connected facilities, and W_m is the cost of insulation layer per unit pipeline length, calculated by Eq(3):

$$W_m = F\pi D_{out}\delta \tag{3}$$

F is the cost of insulation layer per unit volume. δ is the optimal thickness of the corresponding insulation layer, and its approximate calculation method (Wei, 2012) is given by Eq(4):

$$\delta = 2.75\,\frac{D_{out}^{1.2}\varepsilon^{1.35}t^{1.73}}{q^{1.5}} \tag{4}$$

where, ε refers to the thermal conductivity of the insulation layer. t is the pipeline wall temperature, which can be replaced by the temperature of the medium inside. q is the maximum allowable heat loss per unit pipe length, referring to the provisions in GB/T8175.

POC is defined by the pump power cost of conveying material flows to overcome the energy consumption caused by gravity and friction resistance. A binary variable α_m is defined when material connections involve cross-layer transportations. The value of α_m is equal to one when there is a vertical bottom-up transportation. If not, the value turns to be zero.

In the final layout, the floor area is equal to the land area in the same frame, and their costs *LC* and *FC* are defined by the floor space of the frame. The optimisation process is carried out in MATLAB.

2.3 Optimisation process

Due to the position of frames and the position of facilities within the frames influence each other, sub-optimisation models are set to study the coupling of the frame scale and the facility scale. In this work, a process unit with its facilities and connections is optimised step by step to realise the joint optimisation of the two scales. Firstly, put high facilities like towers and reactors aside. All the rest facilities are divided into several frames according to the production process and the function of facilities. The optimisation is carried out in each frame without considering cross-frame connections, combined with the objective function and the constraint conditions. The relative positions of facilities, the initial sizes of frames together with all kinds of costs are acquired. Secondly, the frames of initial sizes and the high facilities previously excluded are manually arranged in the rectangular unit space according to the frequency of material exchange between two frames, so as to make the frames with more material connections adjacent to each other as far as possible. After the position of each frame is fixed, the material handling points of cross-frame connections are also determined. Finally, update the objective function by adding the cost of cross-frame connections in each related frame, and frames with updated objective functions are re-optimised. The updated results are taken as the final results. Through these steps, the optimised layout of the whole unit in the form of frames is acquired.

As for the calculation algorithm, genetic algorithm and surplus rectangle fill algorithm are combined together to solve the facility layout problem. Genetic algorithm is used to generate the arrangement order and acquire the total cost. Surplus rectangle fill algorithm is used to obtain the layout of the maximum land use rate according to the order and the sizes of facilities. The two algorithms work together to get the final layout.

3. Case study

In order to verify the effectiveness of the proposed method, a catalytic cracking unit of a chemical plant with a large number of facilities and connections is studied. There are 245 material connections and 217 facilities, including 84 heat exchangers, 43 vessels, 5 reactors, 6 towers and 79 pumps. Facility sizes, operation process and flow information are already known.

In order to simplify the final frame layout, towers and reactors are arranged separately out of the frames. According to the catalytic cracking process, the facilities are divided into five frames for arrangement, which are reaction-regeneration frame, fractionation frame, absorption-stabilization frame, compressor department frame, and flue gas recovery frame. For the convenience of arrangement and management, the pumps in each frame are arranged in the form of pump area. Among the main frames, there are 39 facilities in the reaction-regeneration frame, 47 facilities in the fractionation frame, and 43 facilities in absorption-stabilization frame. The frames and facilities are represented by rectangles, and the cylindrical devices such as towers and reactors are represented by circles. The input of facility sizes considers the safety distance and fire protection distance, which refers to the layout design regulations of chemical plants.

3.1 Parameter choice

In this case, the floor height is set as 6 m. The unit land price is 100 $¥\cdot y^{-1}\cdot m^{-2}$ (1 ¥ = 0.1321 €), and the unit floor price is 60 $¥\cdot y^{-1}\cdot m^{-2}$. The pump efficiency is set as 0.9, and the unit electricity charge is set as 0.8 $¥\cdot kW^{-1}\cdot h^{-1}$. The annual operation time is 6,000 h. The distance between frames is set as 6 m, which is determined according to the road width requirements in chemical plants.

In terms of the insulation layer, rock wool is selected as the insulation material according to the temperature range of all the material flows. The unit volume price F is 800 $¥\cdot m^{-3}$. The insulation coefficient is related to the temperature of the pipe wall, which can be approximately replaced by the medium temperature inside. The coefficient is calculated by Eq(5), where ε is the insulation coefficient of rock wool, whose unit is $W\cdot m^{-1}\cdot K^{-1}$. t is the medium temperature in unit of °C.

$$\varepsilon = 0.037 + 0.00021t \quad (5)$$

3.2 Initial frame optimisation results

In accordance with the proposed process, the optimisation is carried out in each frame firstly without considering the cross-frame connections, and the results of initial frame sizes are acquired and shown in Table 1. It should be noted that the reaction-regeneration frame, the fractionation frame and the absorption-stabilization frame are three-layer frames, and the rest frames with less facilities are two-layer frames.

Table 1: Initial frame sizes

Frame	Reaction-regeneration	Fractionation	Absorption-stabilization	Compressor department	Flue gas recovery
Length (m)	15.32	22	20	10	11.7
Width (m)	15	40	23.8	12	7.5

According to the initial sizes and the frequency of the material exchange, all the frames, towers and reactors are arranged neatly in the unit area. In the arrangement, the two frames with more connections are placed closely as far as possible. For instance, the fractionation frame has many connections with the reaction-regeneration frame and the absorption-stabilization frame at the same time, so it is arranged in the middle to ensure that the total length of cross-frame pipelines is as short as possible, so as to lower the total cost. The initial frame layout is represented as Figure 1.

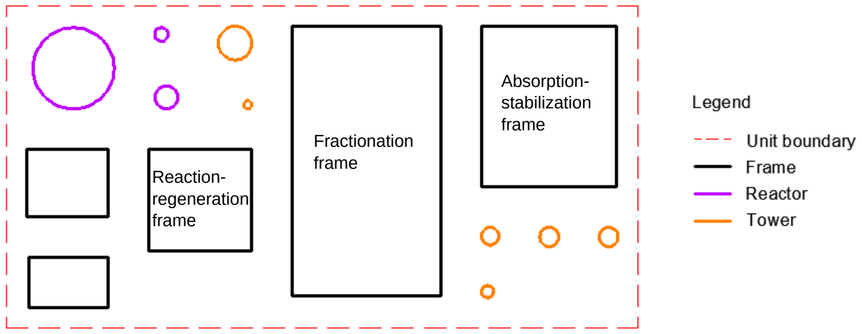

Figure 1: Initial layout of the catalytic cracking unit

In Figure 1, main frames are noted, and the rest two frames are compressor department frame and flue gas recovery frame respectively from top to bottom. Reactors include settler-regenerator, external heat removing apparatus and riser reactor. Towers cover distillation column, stripper, absorption column, reabsorption column, stabilization column and desorption column.

3.3 Updated frame optimisation results

The cross-frame connections of each frame are found according to the original flow information after determining the positions of frames, towers and reactors. It is obtained that the reaction-regeneration, the fractionation and the absorption-stabilization frames have 18, 49 and 60 cross-frame connections respectively. Then the objective function of each related frame is altered by adding *PIC* and *POC* of cross-frame connections into the total cost. The updated frame is re-optimised, and the new frame sizes and relative positions of facilities are acquired. The updated frame sizes are shown in Table 2, and the new frame layout according to the new sizes is demonstrated in Figure 2. In order to intuitively show the impact of the updated layout on various costs, all costs of the initial layout are calculated under the same conditions as the updated layout. In other words, the facility position in the original layout is kept unchanged, add the *PIC* and *POC* of cross-frame connections, so as to compare the original costs with the updated costs, as shown in Table 3.

Table 2: Updated frame sizes

Frame	Reaction-regeneration	Fractionation	Absorption-stabilization	Compressor department	Flue gas recovery
Length (m)	16.78	22	23	10	11.7
Width (m)	15.1	40	19.6	12	7.5

Table 3: Cost comparison of original layout and updated layout

Cost	TC	PIC	POC	LC	FC
Original layout (¥·y^{-1})	1,907,470.76	266,565.94	1,258,748.26	179,373.43	202,783.13
Updated layout (¥·y^{-1})	1,648,045.61	206,917.65	1,059,386.78	179,184.63	202,556.55

4. Analysis of results

Since the material handling points of cross-frame connections are determined by the sizes and positions of the frames, it is necessary to make sure that the shape of each frame does not change too much after the update. It can be seen from the two layout diagrams that the updated frame sizes are quite similar with the initial ones, thus the whole layout remains basically unchanged, which proves the rationality of the cross-frame material handling points selection.

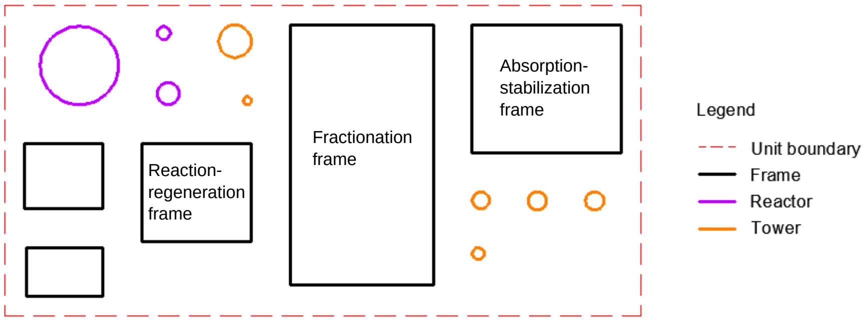

Figure 2: Updated layout of the catalytic cracking unit

The update of the objective function would certainly affect the calculation results. Besides the sizes of the frames, the locations of facilities with cross-frame connections within the frame also change to some degree due to the addition of *PIC* and *POC* in the objective function. An example of the stabilizer feed series heat exchangers in the absorption-stabilization frame is given for illustration. The facility positions within the frame before and after the update are shown in Figure 3a and Figure 3b, where the facilities studied are circled in red. Figure 3a shows the initial top floor layout, and Figure 3b represents the updated ground floor layout.

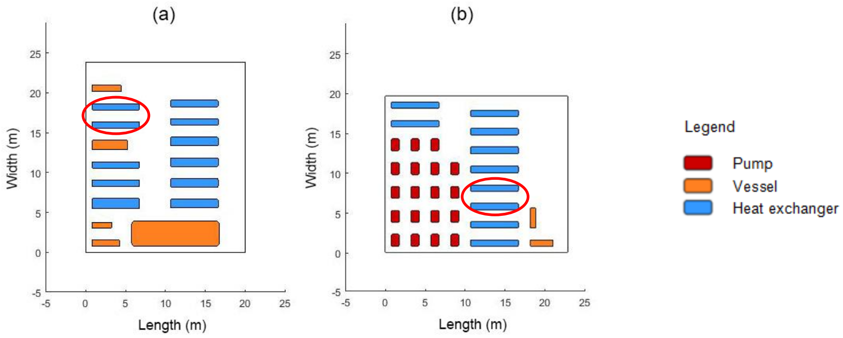

Figure 3: Specific facility location in (a) initial layout and (b) updated layout in the absorption-stabilization frame

The facility studied has four connections out of the frame with the stabilization tower. As can be seen from Figure 2, the stabilization tower is located in the middle position below the absorption-stabilization frame. The feed of the stabilization tower is set to enter on the ground floor, and the Manhattan length is calculated according to the centre coordinates of the studied facilities. The number of flows are taken into account. It can be reached that the heat exchangers are far away from the stabilization tower in the initial layout, and all the connections are cross-layer transportations. The total pipeline length is 147.2 m. The heat exchangers in the updated layout are significantly closer to the stabilization tower and do not need to go through cross-layer transportation. The pipeline length goes to 18.4 m. The total length has been reduced by 128.8 m through the update, which is a marked improvement.

Besides the example above, cross-frame pipeline length reduction also exits in other frames. In the updated layout, most of the rest similar pipelines are shortened to different degrees. Totally, the length of cross-frame connections in the process unit has been shortened by 1,573.56 m, indicating the effectiveness of the update.

The reduction in pipeline length is also reflected on the change in costs. As can be seen from Table 3, under the same calculation conditions, the total updated cost is 1,648,045.61 $¥\cdot y^{-1}$, which is 259,425.12 $¥\cdot y^{-1}$ less than the initial layout, or a 16 % drop. In terms of the other costs in the objective function, *LC* and *FC* are basically unchanged, indicating that the overall floor space of the process unit does not change too much. *PIC* and *POC* are significantly reduced by about 29 % and 19 %. This demonstrates that the updated layout has achieved the expected effect.

As the above, the optimisation process has a very significant impact on the whole layout. The manual arrangement of frames achieves the approximate optimisation of the frame scale, and the update of the objective function realises the optimisation of the facility scale by minimising the total cost. After the update, the relevant facilities move towards the direction of shortening the length of cross-frame connections, which greatly reduces the total investment cost.

5. Conclusions

In this work, the overall optimisation is carried out from facilities to frames and finally to the process unit, which achieves two-scale joint optimisation of the whole unit. The algorithm combining genetic algorithm and surplus rectangle fill algorithm is applied to solve the problem, aiming at minimising the total cost. The idea of frame is conductive to facility installation, which conforms to the actual production.

In case study, a catalytic cracking unit is studied according to the proposed process. As the result shows, frames facilitate the management and maintenance of facilities and make the layout results more practical. The joint optimisation of the two scales is reached. On the basis of frame scale optimisation, the update of the objective function realises the facility scale optimisation, which reduces the pipeline length extraordinarily by 1,573.56 m and the total cost by 16 %.

Layout optimisation is a very complex problem with abundant impact factors, and the current researches are still inadequate. In the future work, more practical constraints should be added to make the layout closer to reality. It is also one of the directions to set a single-stage optimisation model instead of the proposed two-stage model to reduce the workload and achieve the global optimisation.

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