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Plant Layout Optimization with Pipe Rack and Frames

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Layout problem is a complex task that involves plenty of aspects of engineering design. A properly designed layout is able to allocate resources reasonably, increase the efficiency of production and operation, and respond to emergencies quickly. There are various levels of layouts, and the plant layout currently attracts the most attention. Previous researches on the plant layout have studied a lot on the facility arrangement manner but not detailed the complete plant layout with special inner structures such as frames or the in-plant pipe rack. Frames were defined in the previous work to allocate facilities into blocks, and they are found to be suitable for the pipe rack design. This paper does the follow-up work to design the in-plant pipe rack on the basis of frames. To reach a more practical result, a detailed plant layout is figured out. The positions of departments including frames and high facilities are optimized in the objective of minimizing the pipeline investment cost and material handling cost of cross-frame connections. Material handling points of these connections are specially concerned and pre-determined on the frames according to the frame internal layout. These points ensure the shortest length of internal connections. With the information above, the in-plant pipe rack can be properly designed. To ensure the practicality, plenty of regulations and considerations are applied. The width, floor number, and pipeline arrangement manner of the pipe rack are obtained. The cost of the pipelines and the pipe rack are both calculated. In the case study, the chemical plant used in the previous work is studied, including four frames, seven high facilities and 90 cross-frame connections. Preceding frame results are used subsequently for the plant optimization and the pipe rack design. Comparisons are made between the optimized and original layouts. As a result, after the optimization, there are 44,442.83 $/y reduction in the pipeline related costs and 621.75 $/y reduction in the pipe rack investment, which proves the effectiveness of the proposed method.

1. Introduction

Layout design plays an essential role in manufacturing systems. As the world is facing a serious shortage of resources, the well-designed layout is demanded to save materials and land resources. The facility layout problem (FLP) is closely related to industrial layout design and known to be NP-hard due to its complexity, aiming to figure out the optimal allocation of facilities in the given region (Drira et al., 2007). It was firstly proposed by Koopmans and Beckmann (1957), in which equal area facilities were studied and regarded as rectangles. Then unequal area studies (Anjos and Vieira, 2016) and multi-floor layouts (Ahmadi et al., 2017) were taken into account to improve layout results. Safety issues were also one of the hotspots. Fire and explosion risks were considered to ensure the production safety of plants (Wang et al., 2017).

Most published layout studies generally tended to aim at minimizing material handling cost (Azadivar and Wang, 2000). However, these material connections were often simplified as one-to-one connections to calculate piping costs (Caputo et al., 2015). When considering further pipeline arrangement, the pipe rack that supports multiple pipelines is the main aspect that should be specially considered. Previous studies focused more on the pipe rack among plants, however, the pipe rack within the plant was rarely mentioned in those research models, although it does exist in the actual industrial plants. The in-plant pipe rack in the actual situation is often simpler, manually designed into special shapes, such as T or L, which is hard to realize by the widely-used path-finding method and brings difficulties in setting mathematical models. Previous pipe rack design often took the shortest length or the lowest cost of the pipe rack as the objective. However, the decrease of the pipe rack length did not mean the decrease of the pipeline investment cost, additionally, this traditional method ignored the pumping

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cost which may account for a larger proportion, leading to the obtained result that was not necessarily optimal in terms of the total cost. Besides, the conventional facility arrangement manner was to stack facilities together in the plant area (Wang et al., 2018), which left no space for the placement of the in-plant pipe rack. Material handling points are also an aspect that should be considered in the pipe rack design. In previous studies, these points were determined either by selecting a midpoint on a random plant edge through the optimization (Wu et al., 2018), or by manual decisions according to relative position of related departments (Kulturel-Konak, 2019). However, due to there are few works considering two levels of layouts simultaneously, it is hard to ensure that these points are matched with the internal layouts, which may lead to longer material transfer distance between internal facilities and material handling points, resulting in suboptimal results.

To deal with the above issues, several aspects are focused on to reach a more practical result that can provide referential value for the industrial construction. Firstly, the in-plant pipe rack is designed on the basis of frames (introduced later) which can form the paths in the plant for the pipe rack arrangement. For a more detailed result, plenty of regulations and considerations for the pipe rack are involved. Secondly, material handling points are specially considered and pre-determined on the frames according to the respective internal layouts. These points match well with the frames and are ensured to be optimal. Lastly, a new idea for the pipe rack design is applied in this work. To avoid incomprehensive results, minimizing the sum of the annual pipeline investment and material handling cost is served as the objective to optimize the positions of departments, and then the in-plant pipe rack can be designed. Through this approach, the lengths of pipelines and pipe rack are shortened and the material pumping cost can be reduced, and a comprehensive layout result can be acquired.

2. Methodology

A proper arrangement of frames should be figured out to provide convenience for the design of the pipe rack. The simplification is made that the studied departments are regarded as rectangles. To solve layout problems, some basic information is required, such as frame sizes and flow data of cross-frame connections.

2.1 Considerations

Some considerations are necessary to design a detailed and practical plant layout. Frames defined in the previous work (Xu et al., 2019) in the use of allocating facilities into several blocks in the plant are found to be suitable to leave space for the in-plant pipe rack. They have been optimized twice to ensure that their facilities with cross-frame connections are all close to a certain point, and due to this particularity, material handling points of frames can be pre-determined, and should all be covered by the pipe rack. The relative positions of these points in the plant will change with the frame orientation. More specific pipe rack calculations and considerations are involved to obtain detailed results. The in-plant pipe rack is supported by multiple pairs of concrete piles. The pipe rack width is determined by the total width of all the pipelines disposed on it. When the total pipeline width exceeds a certain limit, the multi-floor pipe rack is required. When arranging pipelines, various national regulations are applied, such as GB 50160, GB 50187 and SCDI 333C06, which stipulate the placement order, the flange and floor requirements and safety distance of pipelines. Due to the different number of pipelines in different position of the pipe rack, when the total width varies greatly, it is allowed to divide the pipe rack into several sections, and each section possesses its width and number of floors.

2.2 Mathematical model

Before the objective function, several constraints should be considered to complete the model and ensure the practicality. Boundary constraints are set to limit that the frame area should not go beyond the plant boundary. Non-overlapping constraints ensure that there is no cross area between frames, which guarantee the practicality of the plant layout. Directional constraints stipulate the frame orientation. Because the material handling points are fixed on the frames, the orientation has a significant effect on the position of these points. Besides, parallel arrangement constraints are also applied for special departments that are always adjacently arranged in the actual plant to fit the actual situation.

Based on these constraints, the mathematical model can be established. In this work, the search of the in-plant pipe rack is shifted to minimize the investment and operating cost of cross-frame connections. As mentioned above, this method is eligible to not only effectively shorten the length of pipelines and the pipe rack through the pipeline investment cost, but also take the material handling cost into considerations at the same time, to minimize the total cost. The objective function can be described in Eq(1).

$$TAC = MHC + PIC \tag{1}$$

TAC includes two aspects, which are material handling cost (*MHC*) and pipeline investment cost (*PIC*). *MHC* is related to the pump power in the use of material handling. It can be calculated by electricity price and energy consumption due to the friction resistance. *PIC* is related to the pipeline materials and is shown in Eq(2).

$$PIC = Af \cdot \sum_{i=1}^{n} UPC_i \cdot MD_i \tag{2}$$

where, *Af* is the annualized factor, which can be calculated by Eq(3). *UPC* is the unit price of the pipeline investment ($/m) which is obtained according to the approach by Stijepovic and Linke (2011). It is presented in Eq(4)-(5). *MD* is the Manhattan distance between material handling points of departments.

$$Af = \frac{IR \cdot (1+IR)^T}{(1+IR)^T - 1} \tag{3}$$

$$UPC = 0.82wt_{pipe} + 185D_{out} + 6.8 + 295D_{out} \tag{4}$$

$$wt_{pipe} = 644.3D_{inner}^2 + 72.5D_{inner} + 0.4611 \tag{5}$$

where, *IR* is the interest rate and *T* is the plant life. wt_{pipe} represents unit quality of the pipeline (kg/m). D_{out} and D_{inner} are the outer and inner diameter of the pipeline (m).
Beside the objective function, some other formulas are also required for the calculation of the pipe rack cost, so as to design a detailed plant layout. It is necessary to verify the rationality of the pipe rack through its cost, and this cost (*PRC*) is calculated with empirical formulas, represented in Eq(6)-(7).

$$PRC = Af \cdot 11.50 \cdot wt_{rack} + \frac{s}{s_{space}} \cdot 3300 \cdot V \tag{6}$$

$$wt_{rack} = 80 \cdot n_f \cdot wd_{rack} \cdot s \tag{7}$$

where, wt_{rack} is the weight (kg) and *s* is the length of the pipe rack section (m). s_{space} is the distance between every two pairs of concrete piles (m), and *V* is the volume of a single concrete pile (m^3). n_f is the number of floors, and wd_{rack} is the width of the pipe rack section (m).

2.3 Algorithms

To solve this mathematical model, a hybrid algorithm is applied combining genetic algorithm (GA) and surplus rectangle fill algorithm (SRFA). The construction of the algorithm is not the research focus of this work, so only a brief introduction is made. SRFA is eligible to arrange rectangular frames closely in the rectangular plant. GA forms the framework of the whole algorithm, and is used to minimize *TAC* through the iteration. GA decides the frame orientation and placement order, and sends the information to SRFA. SRFA allocates frames and returns the coordinates to GA for the optimization, to minimize the total cost. These two algorithms work together to ensure their functions. The optimization process is carried out in MATLAB, and the operators of GA are default.

3. Case study

To verify the effectiveness of the methodology, as mentioned above, the catalytic cracking plant used in the previous work is subsequently studied, and the previously obtained frame data is used in this work. On the basis of frames, further explorations are carried out to reach detailed and practical plant layout results.

3.1 Data acquisition

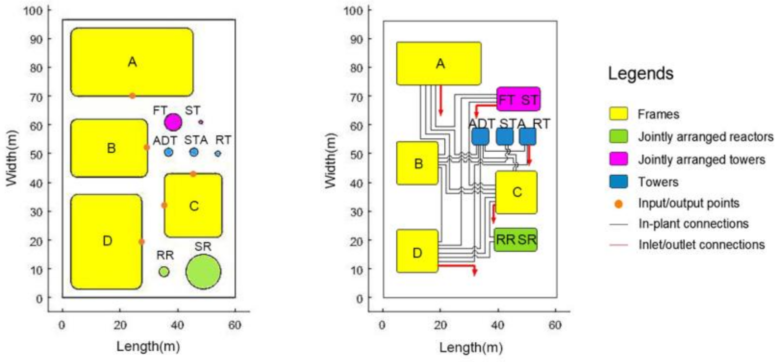
There are 11 target departments including four frames named A, B, C and D and seven high facilities involving 5 towers and 2 reactors, which ought to be placed outside the frames. These high facilities are named to be absorption-desorption tower (ADT), fractionating tower (FT), stripping tower (ST), reabsorption tower (RT), stabilization tower (STA), settler-regenerator (SR) and riser reactor (RR). The sizes of frames and high facilities are listed in Table 1. It should be noted that FT and ST are always arranged adjacently because of their close relationships, and in the calculating process, they satisfy parallel arrangement constraints and can be named as parallel facilities. The same condition is also suitable for RR and SR.

Table 1: Sizes of the studied departments

Name	A	B	C	D	ADT	FT	ST	RT	STA	SR	RR
Length (m)	23.66	20.03	20	32.88	2.8	6	1.2	1.8	2.8	12	3.4
Width (m)	42.4	26.5	22.1	24.6	2.8	6	1.2	1.8	2.8	12	3.4

3.2 Frame arrangement

Among all the material connections existed in the plant, 90 of them transport materials between frames or high facilities. They are regarded as cross-frame connections, and are studied in this case. Material handling points of frames are pre-determined, and match well with the frame internal layout. To adapt to different situations, different from other frames, two material handling points are set for frame C due to its more connections. The layout is optimized with the objective function, considering material handling points and safety distance. As a result, the final *TAC* is calculated to be 57,600.63 $/y, and the plant layout diagram is shown in Figure 1a. According to the positions of the departments, the cross-frame connections in the plant can be figured out for the subsequent steps, and are drawn in Figure 1b to link the related departments. For a clearer presentation of these material connections, the diagram is simplified. Only the relative positions of departments are preserved, and the parallel facilities such as FT, ST and RR, SR are drawn as a whole.



(a) (b)

Figure 1: (a) Optimized plant layout diagram and (b) schematic diagram of cross-frame connections

As Figure 1a shows, departments are properly arranged in the plant area. Material handling points of frames are noted. Specially, frame C is properly arranged, which proves that if a case with a two-point frame can be solved, other cases with multi-point frames can be dealt with as well. Through the diagram it can also be seen that the parallel arrangement constraints are well achieved. The close positions of material handling points and the existence of frames bring convenience for the design of the in-plant pipe rack.

3.3 Pipe rack design

To calculate the precise data of the pipe rack, cross-frame connections should be studied. The cross-frame connections that are presented in Figure 1b should be properly arranged on the pipe rack, and for a more precise result, plenty of regulations are referenced. Space between various pipelines, the sizes of flanges and the safety distance are stipulated. For the pipelines of high temperature, the insulation layers are required, and their thickness is acquired according to GB/T 8175. The placement order is also specified, such as pipelines with flammable media should be far enough from the high temperature ones, and heavy and large pipelines are required to be placed close to the support column.

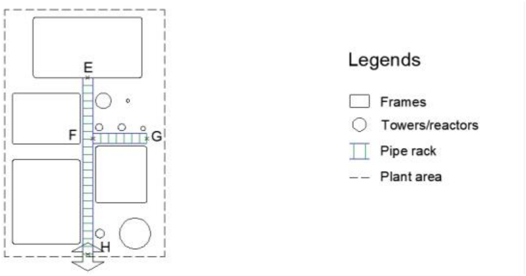


Figure 2: In-plant pipe rack of the optimized layout

The in-plant pipe rack width is set to be less than 6 m, and when the total pipeline width is larger than 6 m, the multi-floor structure is allowed. Pipelines higher than 250 °C ought to be arranged on the upper floor. The spacing between two floors is set to be 1.2 m. The pipe rack is supported by multiple pairs of concrete piles that are spaced 6 m apart. When calculating the pipe rack, 20 % of the width is reserved for the convenience of future expansion. Different sections of the pipe rack can be set to be of different length, width or floor number depending on the pipelines. In the design process, the usual shape T or L for in-plant pipe rack is also strived to achieve, and the connecting point to the external pipe rack of the plant is also considered. With these parameters and considerations, the in-plant pipe rack is designed and shown in Figure 2.

Table 2: Numerical results of the in-plant pipe rack

	Length (m)	Width (m)	Floor number	Section cost ($/y)	Total cost ($/y)
Section E-F	23.8	5.12	3	2,058.3	
Section F-H	46.1	5.04	2	3,208.97	6,425.96
Section F-G	21	4.89	1	1,158.69	

The pipe rack in this case is designed to be of T shape according to the arrangement manner of departments and is eligible to cover all the material handling points. A point H for the material exchanges outside the plant is also concerned to connect the in-plant pipe rack with that outside the plant. To reduce the construction difficulty and save the materials of the pipe rack, three sections of different sizes are determined. For each section, the size, floor number and construction cost are calculated. The total annual cost of the whole pipe rack is 6,425.96 $/y. The detailed numerical results are listed in Table 2.

3.4 Result comparison and discussion

In this work, the positions of departments are optimized considering the optimal material handling points, and then a proper in-plant pipe rack is designed. In order to prove the effectiveness of this approach, a comparison is required to verify if the optimized arrangement manner of frames and the pipe rack is reasonable. In the previous work, departments are manually arranged on the basis of preliminary estimation of the closeness of the material exchange, which considers only the rough pipeline length and may lead to suboptimal solutions. In this work, the previous layout is named as the original layout, and a pipe rack that covers all the departments is also designed under the same condition for a reasonable comparison. The same considerations are applied. As a result, four sections are determined. All kinds of costs are calculated, and are compared in Table 3.

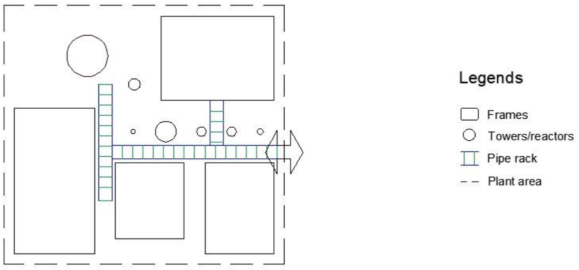


Figure 3: In-plant pipe rack of the original layout

Table 3: Cost comparison of the optimized layout and the original layout

Cost ($/y)	In-plant pipe rack	*MHC*	*PIC*	*TAC*
Optimized layout	6,425.96	36,306.51	21,294.12	57,600.63
Original layout	7,047.71	84,792.01	17,251.45	102,043.46

It can be figured out from Figure 3 that due to the arrangement manner of departments, the pipe rack of the original layout is a little longer compared with the optimized layout. More branches are required to cover all the departments and the shape T is hard to achieve. In the case that the same calculation method is used for the two scenarios, the pipe rack cost of the original layout is 7,047.71 $/y, which is 621.75 $/y more than the optimized one. The optimized pipe rack is proved to be better and reduces around 9% of the pipe rack cost.

The effectiveness of the placement manner of departments can also be well reflected. Original plant layout is manually determined according to the relationships between frames and high facilities. Departments with more connections are positioned as close as possible to reduce the total pipeline length, so as to reduce the length and cost of the pipe rack. Due to *PIC* is the cost that are directly related to the pipeline length, *PIC* of the original layout is less than that of the optimized layout because the original one focus only on manually decreasing the pipeline length. However, with the extension of the operation time of the factory, *MHC* will take more and more proportion and possess a greater impact on the total cost, which cannot be ignored in the design process. The optimized layout considers *PIC* and *MHC* at the same time to reach a final layout. According to Table 3, although *PIC* of the optimized layout is 4,042.67 $/y higher, *MHC* is 48,485.5 $/y less than the original layout, more than ten times the increase of *PIC*, which turns out to be a greater reduce, so it is not comprehensive enough to consider only the reduction in the length. When considering *MHC* and *PIC* together, there is 44,442.83 $/y reduction totally, which is an around 40 % drop and proves the advantages of the proposed method compared with the widely-used path-finding method that only shortens the pipe rack length, especially when the material handling cost is higher. As a conclusion, the plant layout considering both *PIC* and *MHC* is proved to be better. As a follow-up work, this work designs the pipe rack by means of optimizing material connections, considers the arrangement manner of departments and the detailed in-plant pipe rack design, and forms a complete methodology for the plant layout together with the previous work, which is demonstrated to be an effective and detailed plant layout study.

4. Conclusions

This work expends the content of plant layout studies and achieves a detailed industrial layout by optimizing the positions of departments in the plant and designing the in-plant pipe rack, and the material handling points are also considered. The department positions are optimized in the objective of minimizing the material handling cost and pipeline investment cost of cross-frame connections, and the pipe rack is determined according to the positions of departments and material handling points. Plenty of regulations and considerations are involved. In the case study, the layout of a chemical plant based on frames is optimized and its in-plant pipe rack is designed. To verify the effectiveness of the proposed method, costs of the original layout are calculated for comparison. Numerically, through the optimization, there are 44,442.83 $/y reduction in the costs related to cross-frame connections and 621.75 $/y reduction in the pipe rack construction cost compared with the original plant layout. Data shows that there are advantages in the plant and pipe rack design by considering the pumping and pipeline investment simultaneously. On the basis that all the material handling points are covered, the chosen objective, on the one hand, shortens pipeline and pipe rack length through pipeline investment cost, and on the other, considers the material handling cost as well to ensure the minimum of the total cost. As a result, the optimized layout saves 9 % of the pipe rack cost and 40 % of the pipeline related costs, and is proved to be better.

Efforts have been made in the plant layout studies to reach a more practical and detailed result of referential value to the actual industries. However, due to the particularity of the shape of the in-plant pipe rack, it is hard to directly added into the model, so the cost of which has not yet been involved in the objective function. This issue is planned to be solved in the future work.

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