CHEMICAL ENGINEERING TRANSACTIONS

VOL. 61, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S Varbanov, Rongxin Su, Hon Loong Lam, Xia Liu, Jiří J Klemeš

ISBN 978-88-95608-51-8; **ISSN** 2283-9216

DOI: 10.3303/CET1761158

A Surplus Rectangle Fill Algorithm for Petrochemical Industry Area-Wide Layout Optimization with Key Plant Constraint

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Plant layout is an important and long-term field in industrial research and practice, which can reduce capital cost, shorten production time and increase productivity. At present, most researchers studied on the layout design of facilities in a plant but not plants in an area. Industrial area-wide layout problem is more complex. The relationship between plants and the conditions around the industrial area have a significant impact on area-wide layout design, but few researchers considered these aspects. A plant is a basic production unit in the petrochemical industrial area. There are many material connections between plants. Besides, the land cost accounts for a large proportion of the total infrastructure cost. A new methodology is proposed in this work to consider both aspects. The objective function of the proposed mathematical model in this paper is to minimize the land cost and piping cost. In this paper, each plant is simplified as a rectangle with fixed area, which can be placed horizontally or vertically in the area. As some plants may have great influence on the whole occupied area, these plants are regarded as the key plants whose aspect ratios are adjusted to optimize the layout while whose areas are constant. Considering the requirement on the natural conditions, transport conditions and other factors around the industrial area, the locations of some plants are fixed. The consideration makes the layout more reasonable and practical. A new algorithm which combines surplus rectangle fill algorithm and genetic algorithm is proposed to optimize the problem. A case study is described to demonstrate the effectiveness of the proposed methodology.

1. Introduction

Plant layout problem is complex. It has a significant effect on capital cost, production efficiency and energy saving. Mecklenburgh (1986) proposed that a good layout should have low piping cost, a small area and a safe design. Among capital cost, land cost accounts for a large proportion. It is necessary to reduce land cost. Besides, piping connection is an important factor. A shorter length of the pipeline can save energy, reduce piping and pumping cost and increase productivity. Industrial area-wide layout is more complex. It needs to consider not only the relative positions of plants but also the natural conditions, external transport conditions, environmental protection and other factors around the industrial area. Few researches consider these factors when optimizing industrial area-wide layout. Xu et al. (2013) optimized the area-wide layout whose objective function was land cost and piping cost considering safety factor. The total cost was reduced only by changing the relative positions of plants. Wu et al. (2016) considered the cost of material piping and steam piping. They simplified each plant as a point with no shape and no size.

Koopmans and Beckman (1957) were the first to propose layout problems. They formulated the layout problems as quadratic assignment problems (QAP). Balakrishnan et al. (2003) used this model to minimize the total material handling cost when determining the relative locations of facilities. But QAP cannot represent the exact position of each plant in the site and it cannot appropriately model specific constraints such as the orientation of plants. Then, Jayakumar and Reklaitis (1994) proposed a mixed integer programming (MIP) model to solve the layout problem considering the connection cost. The constraint of this model is that the plants cannot overlap.

Please cite this article as: Zhao H., Wang Y., Feng X., 2017, A surplus rectangle fill algorithm for petrochemical industry area-wide layout optimization with key plant constraint, Chemical Engineering Transactions, 61, 961-966 DOI:10.3303/CET1761158

The layout problem is actually to determine the relative positions of plants. Genetic algorithm (GA) consists of chromosomes. The plants to be allocated can be easily coded by GA. Besides, GA is easy to combine with other algorithms. GA is widely used in solving layout problems in recent years. Caputo et al. (2015) used GA to optimize process plant layout considering land cost, piping cost, pumping cost and safety issue. Surplus rectangle fill algorithm is used to solve the rectangle packing problem. Quan and Shen (2016) combined the surplus rectangle fill algorithm and the simulated annealing to solve this problem. The surplus rectangle fill algorithm arranges rectangles in given space to minimize the occupied space. It is used in work for dealing with area-wide layout problem to minimize the land area. It combines GA to find a better layout.
In this paper, the plants are assumed as rectangular shapes. The natural conditions and external transport conditions are considered as constraints so that some plants have fixed positions. The objective function is to minimize the total cost of land cost and piping cost. The total cost is reduced not only by changing the relative positions of plants but also by changing the aspect ratios of key plants which have great influence on the whole occupied area. The new algorithm combining GA and the surplus rectangle fill algorithm is used to solve industrial area-wide layout problems.

2. Problem statement

The problem in this paper can be described as the problem of arranging *n* plants which are assumed as rectangular shapes. They cannot overlap and the pipe length between two plants is the rectangular distance. The area-wide layout problem can be stated as follows:
Assumption:

- The plants are assumed as rectangular shapes.
- The plants can only be laid horizontally or vertically.
- The distances between every two adjacent plants are the same and satisfy the minimum safety distance.
- The plants which have close material relationships are put together.
- Some plants have fixed positions considering the requirement on the natural conditions, transport conditions and other factors around the industrial area.
- The areas of key plants are constant while their aspect ratios can be adjusted.

Given:

- A set of *n* plants and their sizes.
- Given total space which is bounded to the length of site area.
- The connection data of process material flowsheets.
- The installation and connection cost of piping and land cost.
- The geographical location, natural conditions and transport conditions around the industrial area.

Determine:

- The allocation of each plant and the orientation of the plant.
- The land area.

So as to minimize the area-wide layout cost including piping and land cost.

3. Mathematical formulation

3.1 Plant orientation constraints

The plant *i* can be placed in the given space horizontally or vertically. The length and width are determined by its orientation decision. r_i is a binary variable. If r_i=0, the plant is placed horizontally. Otherwise, it is placed vertically. The relationship between r_i and the length and width of the plant *i* is as follows:

$$l_i = (1 - r_i) l_i + r_i w_i \quad \forall i = 1, \cdots, n, \tag{1}$$

$$w_i = (1 - r_i) w_i + r_i l_i \quad \forall i = 1, \cdots, n. \tag{2}$$

Where l_i and w_i are the length and width of the plant after placed.

3.2 Non-overlapping constraints

Two different plants cannot be allocated to the same location. Each location can be occupied at most by one plant. When the relative position between the plants *i* and *j* meets one of the following four constraints, they do not overlap:

$$x_{1j} \geq x_{2i} \quad \forall i = 1, \cdots, n, j = 1, \cdots, n, \tag{3}$$

$$x_{1i} \geq x_{2j} \quad \forall i = 1,\cdots,n, j = 1,\cdots,n, \tag{4}$$

$$y_{1i} \geq y_{2j} \quad \forall i = 1,\cdots,n, j = 1,\cdots,n, \tag{5}$$

$$y_{1j} \geq y_{2i} \quad \forall i = 1,\cdots,n, j = 1,\cdots,n. \tag{6}$$

Where x_{1i} and y_{1i} are the lower left coordinates of plant *i*, x_{1j} and y_{1j} are the lower left coordinates of plant *j*, x_{2i} and y_{2i} are the upper right coordinates of plant *i*, x_{2j} and y_{2j} are the upper right coordinates of plant *j*. Constraints (3)-(6) represent the plant *i* is on the left, right, top and bottom sides of the plant *j* respectively. Besides, the plant cannot be allocated out of the given space. The constraints that the plant allocated in the given space are as follows. The location of the plant needs to meet all of the following four constraints:

$$x_{1i} \geq 0 \quad \forall i = 1,\cdots,n, \tag{7}$$

$$x_{2i} \leq L \quad \forall i = 1,\cdots,n, \tag{8}$$

$$y_{1i} \geq 0 \quad \forall i = 1,\cdots,n, \tag{9}$$

$$y_{2i} \leq W \quad \forall i = 1,\cdots,n. \tag{10}$$

Where *L* and *W* are the length and width of the given space.

3.3 Objective function

The objective function is to minimize the total cost which considers land cost and piping cost.

$$TC = LC + PC \tag{11}$$

Where *TC* is total cost, *LC* is land cost and *PC* is piping cost.

$$LC = UL \times \max(x_i + 0.5l_i) \times \max(y_i + 0.5w_i) \quad \forall i = 1,\cdots,n. \tag{12}$$

Where *UL* is unit land cost, x_i and y_i are the *x* and *y* coordinates of the centre of the plant *i*, l_i and w_i are the length and width of the plant *i*.

$$PC = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n}\alpha_{ij} UIC_{ij} d_{ij} \quad \forall i = 1,\cdots,n, j = 1,\cdots,n. \tag{13}$$

Where α_{ij} represents if the plant *i* connects plant *j*: α_{ij} =1 when they are connected; α_{ij} =0 when they are not connected, UIC_{ij} is unit interconnection cost between plants *i* and *j*, and d_{ij} is the interconnected distance between plants *i* and *j*. It is assumed that all pipes run from the centre point of a plant. The pipe length between two plants *i* and *j* is the rectangular distance:

$$d_{ij} = \left|x_j - x_i\right| + \left|y_j - y_i\right| \quad \forall i = 1,\cdots,n, j = 1,\cdots,n. \tag{14}$$

3.4 Surplus rectangle fill algorithm

Surplus rectangle fill algorithm is used to solve rectangle packing problems. It arranges the rectangle in a given area so that the space occupied is minimum. This algorithm is proposed to arrange the unequal-area and rectangular plants. It uses a rectangular data set to represent the available space in the given area. The most suitable position is selected in the remaining rectangle when a new plant is arranged. Then the new remaining rectangle is generated and the rectangular data set is updated. The remaining rectangle whose area is zero or less than the area of remaining plant is removed. And the remaining rectangle with a small area that is completely contained in a bigger remaining rectangle is also removed. Then a new remaining rectangular data set is obtained for the next placement. The plants are placed from the bottom of left corner to the direction of right. Since the sequence of the placement influences the optimization result, the proposed model is optimized by the algorithm combining the surplus rectangle fill algorithm and GA. GA changes the sequence of the placement. The combined algorithm can get a better layout than using single algorithm only. The proposed model is implemented by MATLAB.

4. Case study

A refinery is described as a case to illustrate the effectiveness of the proposed methodology. The case study has two sections. In Section 4.1, the length and width of all plants are fixed. In Section 4.2, some plants are regarded as the key plants whose aspect ratios are adjusted to optimize the layout while whose areas are constant. There are many facilities in a key plant. The way the facilities arranged and the safety distances between them may influence the length and width of the plant. The aspect ratios can change while areas are constant. There may exist an exact aspect ratio to minimize the objective function. The parameters of GA are: maximum number of iterations 500, crossover probability 0.4, mutation probability 0.3, initial pop 20.

Table 1: Dimension and area for each plant

Number	Plant	Plant identification code	Length (m)	Width (m)	Area (m^2)
1	Power Station	PS	280	320	89,600
2	Crude Oil Fractionation	COF	130	260	33,800
3	Gas Separation	GS	50	80	4,000
4	Hydrotreating Unit	HU	240	260	62,400
5	Residue and Wax Hydrodesuifurization	RWH	225	260	58,500
6	Fluid Catalytic Cracking	FCC	100	260	26,000
7	Light Hydrocarbon Recovery	LHR	80	60	4,800
8	Liquefied Petroleum Gas Desulfuration and Demercaptan	LPGDD	80	200	16,000
9	Sulfur Recovery	SR	110	260	28,600
10	Aromatic Combine	AC	268	120	32,160
11	Hydrogen Production	HP	125	260	32,500
12	Continuous Reforming	CR	120	200	24,000
13	Naphtha Hydrotreating	NH	120	80	9,600
14	Polypropylene and Polyester	PP	100	200	20,000
15	Delayed Coking	DC	170	280	47,600
16	Air Compression and Separation	ACS	135	110	14,850
17	Central Control Room	CCR	126	95	11,970
18	Railway Transport Department	RTD	160	600	96,000
19	Tank Farm	TF	800	600	480,000
20	Sewage Treatment Area	STA	240	440	105,600

Table 2: Plant interconnection and unit cost

Number	From	To	Unit cost (¥/m)	Number	From	To	Unit cost (¥/m)
1	TF	COF	88	15	HU	FCC	161
2	TF	COF	58	16	NH	CR	60
3	TF	HU	58	17	NH	AC	60
4	HU	TF	58	18	CR	AC	161
5	FCC	TF	58	19	COF	SR	349
6	COF	TF	110	20	HU	SR	349
7	RWH	TF	110	21	RWH	SR	349
8	RWH	TF	110	22	FCC	SR	349
9	FCC	TF	110	23	LHR	SR	349
10	HU	TF	110	24	LPGDD	SR	349
11	RWH	HU	161	25	FCC	LPGDD	110
12	FCC	HU	161	26	LHR	LPGDD	110
13	RWH	DC	163	27	LPGDD	TF	110
14	NH	FCC	163	28	COF	SR	110

The refinery has twenty plants. Their sizes are shown in Table 1. The interconnections between the plants and the unit piping cost are shown in Table 2. In this case, some plants have fixed positions considering the requirement on the natural conditions, transport conditions and other factors around the industrial area. The tank farm (TF) should be arranged at the edge of the area. The railway transport department (RTD) should be located at the edge of the area where is near the railway. The sewage treatment area (STA) should be located at low-lying areas.

Table 2: Plant interconnection and unit cost

Number	From	To	Unit cost (¥/m)	Number	From	To	Unit cost (¥/m)
29	HU	SR	110	40	GS	PP	285
30	RWH	SR	110	41	FCC	PP	285
31	FCC	SR	110	42	LHR	LPGDD	60
32	LPGDD	SR	110	43	COF	LHR	60
33	NH	SR	110	44	CR	LHR	60
34	DC	SR	110	45	HU	LHR	60
35	SR	TF	474	46	LHR	LPGDD	60
36	SR	STA	65	47	RWH	HP	163
37	HP	HU	60	48	RWH	HP	163
38	HP	RWH	60	49	HU	HP	163
39	AC	CR	187	50	DC	HP	163

The air compression and separation (ACS) should be located at the lower side of the annual minimum frequency wind direction of the area. And the central control room (CCR) should be located at the edge of the area and as close as possible to the town and residential area. The geographical and traffic conditions around the refinery are as follows: the minimum frequency of the year is south wind, the southeast corner of the area is low-lying, the railway is in the west of the area and the road is in the east of the area.

4.1 Case study based on plants with fixed length and width

In this section, all plants have fixed length and width. There are three scenarios based on different optimization targets. They are land cost, piping cost and total cost. The results are shown in Table 3.

Table 3: Results of three scenarios

	Land cost (10^7 ¥)	Piping cost (10^6 ¥)	Total cost (10^7 ¥)
Scenario 1	4.032	5.705	4.603
Scenario 2	4.725	4.256	5.150
Scenario 3	4.158	4.444	4.602

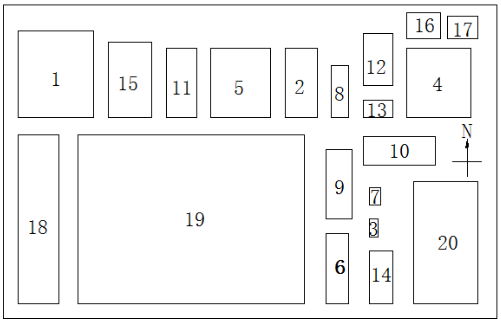
In Table 3, land cost of scenario 1 is the least while piping cost is the most. The total cost of scenario 1 is more than that of scenario 3. Piping cost of scenario 2 is 4.256×10^6 ¥, which is less than that of scenario 3. But the total cost of scenario 2 is 5.480×10^6 ¥ more than that of scenario 3. The optimization of land cost and piping cost simultaneous is better than that of land cost or piping cost only. In scenario 3, land cost is 90.34 % of total cost. It reveals that land cost has an important impact on total cost. Besides, the piping cost is a rough estimation in this work. Piping cost consists of capital cost and operating cost. It only considers capital cost when calculating piping cost. Piping cost is not so important of total cost in this specific case study.

4.2 Case study based on plants with flexible length and width

From the results of Table 3, land cost accounts for a large proportion of total cost. As some plants may have great influences on the whole occupied area, these plants are regarded as the key plants whose aspect ratios are adjusted to reduce the land cost while whose areas are constant. In this case, TF occupies a larger area compared with other plants. The change of its aspect ratio may affect the overall arrangement of plants. There exists an exact aspect ratio so that the total occupied area is the minimum. TF is as the key plant. The aspect ratio of TF is adjusted. Its area is constant. The range of aspect ratio represents the constraints defined by the way the tanks are arranged in TF. According to the way tanks arranged, the lengths of tanks and safety distances between tanks, the upper bound of aspect ratio is 2.08 and the lower bound is 0.33.

Table 4: Results comparison of Type-1(fixed size) and Type-2(aspect ratio)

	Land cost (10^7 ¥)	Piping cost (10^6 ¥)	Total cost (10^7 ¥)	Sequence of placement
Type-1	4.158	4.444	4.602	6 14 3 9 1 7 15 10 11 5 2 8 13 4 12
Type-2	3.982	4.569	4.438	14 15 7 10 9 8 13 6 1 3 4 11 5 12 2



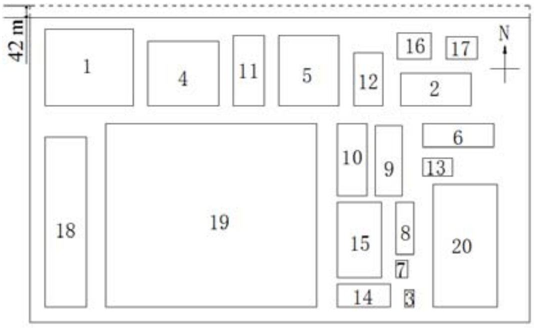


Figure 1: Layout comparison of Type-1(fixed size) and Type-2(aspect ratio)

The lengths and widths of other plants are fixed. The objective function is to minimize the total cost. The results compared with that of plants with fixed sizes are shown in Table 4. And the layout is shown in Figure 1. Compared with Type-1, the width of the occupied area is reduced by 42 m. The aspect ratio of TF is 1.14 after optimization. The length and width of TF is 740 m and 648 m respectively. Land cost is 3.982×10^7 ¥. The total cost is 4.438×10^7 ¥. It is less than the total cost of Type-1. The adjustment of the aspect ratio of TF changes the arrangement of other plants. As the length of TF is shorter than before, the space between TF and STA becomes larger, which leads to more plants to be placed in this space. The layout is more compact so that the space utilization is improved and the occupied area is reduced.

5. Conclusions

A new algorithm combining the surplus rectangle fill algorithm and GA is proposed to solve area-wide layout problems. The objective function is to minimize the total cost including land cost and piping cost. The natural conditions and transport conditions around the industrial area are considered as constraints, which leads to some plants with fixed positions. This makes the layout more reasonable and practical. The aspect ratio of key plant is changed to reduce land cost. In this paper, a refinery is proposed as a case. In the case study based on fixed sizes, the scenario which considers land cost and piping cost simultaneously is the most economic. Then, the aspect ratio of the key plant is changed. A suitable aspect ratio makes the use of space more efficient. The results obtained give a better layout plan with lower land cost and total cost. It demonstrates the effectiveness of the proposed method.

Acknowledgments

Financial support from the National Natural Science Foundation of China under Grant No. 21576286 are gratefully acknowledged.

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