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An Area-wide Layout Design Method Considering Piecewise Steam Piping

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The optimization of interconnection cost among plants is a significant work in the process of area-wide layout design of industrial area, since pipeline network influences the costs of investment and operation, and even energy loss. Unfortunately, few papers focus on the further study about this aspect. Most current methods are used to calculate the cost of one-to-one connected piping of material flows. However, this method is not applicable to the pipeline network with branches and different diameters, for example, the steam piping. This paper presented a method, which put Kruskal algorithm and arrangement and combination for the calculation of length and linear programming (LP) model for the calculation of cost together, to calculate the total investment of steam piping. In addition, the unit prices of pipelines with different diameters according to the steam production and usage condition in different plants are considered when calculating steam piping cost. As another factor of area-wide layout, some simple geographical constraint is added in the model to make the optimized layout be more practical. The objective function is to minimize the costs of pipeline network. The mathematical model is solved by genetic algorithm (GA) toolbox in MATLAB. Finally, the case study shows the accuracy and rationality of the proposed method.

1. Introduction

Area-wide layout has a profound influence on the development of manufacturing enterprises. A lot of models and methods are proposed to solve this kind of problem. A quadratic assignment problem (QAP) is proposed to formulate this problem in the early years (Koopmans and Beckmann, 1957). Jayakumar and Reklaitis (1994) proposed an mixed integer programming (MIP) model to solve the layout problem considering the constraint of non-overlap and connection cost. Medina-Herrera et al.(2014) using mixed integer nonlinear programming (MINLP) model optimized the layout on the basis of quantitative risk analysis (QRA), it is applied to new plant installation and old plant retrofit.

There are many aspects influence the design of area-wide layout, such as connection cost between plants and safety analysis. At present, the layout considering safety issues are researched a lot because of its importance. For example, Jung et al. (2011) optimized the layout considering fire and explosion. However, most of the researches ignore the further optimization of the connection cost. Caputo et al.(2015) optimized process plant layout considering safety issue and connection cost simultaneously. But the optimization of connection cost was just for the material flows piping which is one-to-one connection. The pipeline network with branch is not taken into consideration leading to the incomplete optimization. Wu and Wang (2016a, 2016b) enriched the method of piping cost optimization which is used to calculate the shortest length of pipeline network. But the diameter of the branch pipe in network is a fixed value. This point should be improved because the flow rates influence the piping investment and the area-wide layout.

In this paper, the optimization of connection cost including the costs of material flows piping and steam pipeline network are improved compared with previous methods. The cost of branch pipe changes according to the flows rate. This help to obtain a more reasonable piping cost which is used to evaluate the scheme of area-wide layout. To solve the problem of piecewise calculation in steam piping among the plants with different flow rates,

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an LP model is proposed. Furthermore, to increase the feasibility of the optimal scheme, some actual conditions are considered by fixing the locations of special plants. GA is used to solve the proposed method.

2. Methodology

2.1 Problem statement

The proposed method is used to optimize the connection cost of area-wide layout in the industrial area in detail. It is mainly for the piecewise calculation of steam pipeline, because the steam flow would change if the pipeline passes the plants which use or produce steam. The calculation method presented before (Caputo et al. 2015) for the cost of material flows piping, is applied in this paper. In this section, it is assumed that each plant is a node which has no size and shape. Between each two adjacent plants, the distance is same. Additionally, the distance between the plant and pipe rack is neglected. There is a constraint about the actual situation in the industrial area. It is that the pipeline should be laid horizontally or vertically.

Before using the proposed method, there are some givens should be listed as below. (1) The number of plants; (2) the transport direction of material flows between plants; (3) the usage or production of steam of each plant; (4) some simple geographical condition of industrial area. On the basis of the givens, the optimized area-wide layout and total piping cost include material flows and steam piping investments are obtained by the proposed method.

2.2 Mathematical model

The objective function of the model is single, which is computed as Eq(1).

$$\min C = \sum_{\alpha}^{n} a_{\alpha}^{S} L_{\alpha}^{S} + \sum_{\beta}^{m} a_{\beta}^{M} L_{\beta}^{M} \tag{1}$$

Where C (\$) is the total piping cost, n is the number of steam levels, m is the number of material flow, while a_α^S (\$/m) and a_β^M (\$/m) are the unit prices of steam and material flows piping, L_α^S (m) and L_β^M (m) are the length of each level of steam and material flows piping. L_α^S is calculated by Kruskal algorithm and arrangement and combination (Wu and Wang, 2016) which is shown in Eq(2). It represents the total length of the steam pipe network with branches.

$$\begin{bmatrix} N_{min\text{-}tree} \\ L \geq N_p - 1 \\ L_\alpha^S = d \times L \end{bmatrix} \vee \begin{bmatrix} -N_{min\text{-}tree} \\ L < N_p - 1 \\ L_\alpha^S = 0 \end{bmatrix} \tag{2}$$

Where N_p is the number of the plants (nodes in minimum spanning tree-MST) which produce or use the same level of steam, L is the total number of connections (edges in MST, the line connecting two nodes) between plants, d is the distance between two adjacent plants which is a fixed value. MST is obtained by Kruskal algorithm.

The weight of each edge is defined as Eq(3) to meet the constraint about pipe laying above in 2.1.

$$\begin{bmatrix} \omega_{i,j} = 1 \\ (x_i - x_j)^2 + (y_i - y_j)^2 = 1 \end{bmatrix} \vee \begin{bmatrix} \omega_{i,j} = \infty \\ (x_i - x_j)^2 + (y_i - y_j)^2 > 1 \end{bmatrix} \vee \begin{bmatrix} \omega_{i,j} = 0 \\ (x_i - x_j)^2 + (y_i - y_j)^2 = 0 \end{bmatrix} \forall i, j \in \mathrm{N} \tag{3}$$

Where $\omega_{i,j}$ are the weights of the edges, which mean the relative length of the connection between each two nodes, where 1 means there are a pipeline with a certain length which connects the two plants, 0 means there isn't any pipe and ∞ means the pipeline between the two plants is infinite. N is a set of natural numbers, its maximum value is the number of plants. (x_i, y_i) and (x_j, y_j) are the coordinates of plants.

Additionally, L_β^M is computed as Eq(4) which computes the Manhattan distance between each two plants.

$$L_\beta^M = \left| x_\beta^I - x_\beta^O \right| + \left| y_\beta^I - y_\beta^O \right| \tag{4}$$

Where (x_β^O, y_β^O) are the coordinates of the plants which produce material flows and (x_β^I, y_β^I) are the coordinates of the process material flows users.

a_α^S and a_β^M are calculated as Eq(5)-(8) (Stijepovic and Linke, 2011).

$$D_{in} = \sqrt{\frac{4W}{\rho v \pi}} \tag{5}$$

Where D_{in} is the inner diameter of pipe (m), W is the mass flow rate (kg/s) in each pipe, ρ is density (kg/m^3) and v is velocity of the flow (m/s).

$$D_{out} = 1.101 D_{in} + 0.006349 \tag{6}$$

$$W_t = 1330 D_{in}^2 + 75.18 D_{in} + 0.9268 \tag{7}$$

$$a = A_1 W_t + A_2 D_{out}^{0.48} + A_3 + A_4 D_{out} \tag{8}$$

Where D_{out} is the outer diameter of pipe (m), W_t is the weight per unit length of pipe (kg/m), a is the unit price of pipe (\$/m). A_1 is the pipe cost per unit weight (0.82 \$/kg), A_2 is the installation cost (185 \$/m$^{0.48}$), A_3 is the right-of-way cost (6.8 \$/m) and A_4 is the insulation cost (295 \$/m).

It should be noted that the W in Eq(5) changes piecewise in steam piping after passing the plants. Therefore in order to calculate W of steam piping, an LP model is established as follow. It is on the basis of the results of L of MST. The results will give the nodes on each edge in MST, the node is corresponding to the plant and the edge is corresponding to the pipe between two plants.

The objective function for this is shown in Eq(9). It should be noted that Eq(9) is included in the objective function which is described as Eq(1), it is used to calculate W.

$$\min W_{total} = \sum_{\substack{m=1\\k}}^{n} \left(w_{1,m,k} + w_{1,k,m} + w_{2,m,k} + w_{2,k,m} \right) \tag{9}$$

Where n is the number of nodes in MST, m are the serial numbers of each nodes in MST, k is the serial number of another node on the edge which includes node m. w is the mass flow rate between node m and node k. In addition, 1 represents that if the pipeline is laid horizontally (east-west direction), the transport direction of flow in pipe is from east to west, if the pipeline is laid vertically (south-north direction), the transport direction of the flow is from south to north. Two represents the opposite directions which are from west to east and from north to south separately.

The constraints are shown as follow.

$$\begin{cases} \sum_a (-1)^r w_{1,m,k} + \sum_a (-1)^r w_{1,k,m} + \sum_a (-1)^r w_{2,m,k} + \sum_a (-1)^r w_{2,k,m} - W_m = 0 \\ \begin{bmatrix} r = 1 \\ k < m \end{bmatrix} \vee \begin{bmatrix} r = 2 \\ k \geq m \end{bmatrix} \quad m = 1, 2, 3 \cdots n \\ w_{1,m,k} \geq 0 \\ w_{1,k,m} \geq 0 \\ w_{2,m,k} \geq 0 \\ w_{2,k,m} \geq 0 \end{cases} \tag{10}$$

Where W_m is the steam mass flow of each plant. If the plant produce steam, W_m is a negative value, on the contrary, it is a positive value. In fact, first constraint represents the material balance for each node, which means that the sum of the steam which flows into the node, flows out of the node and the node produces or uses is 0. The proposed model is optimized by GA which is implemented by MATLAB. The selection of GA is due to the applicability of it for the discrete optimization problems. In this paper, the problem is to find the optimal relative positions of plants in the industrial area considering the connection cost. This just belongs to the above kind of problem.

3. Case study

The case study, which is established from a petrochemical industrial area, includes two scenarios whose objection functions are material flows piping cost and total piping cost separately. Both of the two scenarios consider the simple actual issue to make the scheme be more reasonable. In this section, the industrial area has 16 plants. And the steam is divided into three levels: 3.5 MPa, 1.4 MPa and 0.4 MPa. The plants are located in 4 rows and 4 columns. The serial numbers of locations are [1 2 3 4; 5 6 7 8; 9 10 11 12; 13 14 15 16]. Considering the city and highway are near the northwest of the petrochemical industrial area, the central control room is fixed in the location 1. And the railway transport department is fixed in location 13 because the railway is near the southwest of the industrial area.

3.1 Data acquisition

The usage and production of steam in each plant is shown in Table 1 and Table 2

Table 1: The usage and production of steam in plants

Number	Name of plant	Abbreviation	3.5 MPa (t/h)	1.1 MPa (t/h)	0.4 MPa (t/h)
1	power station	PS	-52	-63	0
2	crude oil fractionation	COF	42	3	-11
3	gas separation	GS	0	0	0
4	Hydrogenation	HU	170	-9	-122
5	residue and wax hydrodesuifurization	RWH	98	3	-47
6	air compression and separation	ACS	0	0	0
7	fluid catalytic cracking	FCC	-75	-25	0
8	liquefied petroleum gas desulfuration and demercaptan	LPGDD	0	0	0
9	sulfur recovery plant	SR	-87	40	187
10	hydrogen production	HP	-99	0	18
11	continuous reforming	CR	-2	59	-35
12	naphtha hydrotreating	NH	0	0	0
13	delayed coking	DC	5	-13	0
14	tank farm	TF	0	5	10
15	railway transport department	RTD	0	0	0
16	central control room	CCR	0	0	0

Table 2: The design data of steam piping

Pressure (MPa)	Temperature (℃)	Velocity (m/s)	Density (kg/m^3)
3.5	450	55	10.88
1.1	350	40	3.90
0.4	210	30	1.68

The design data of material flows piping is shown in Table 3. The velocity of material flow is set to 1.5 m/s for liquid and 20 m/s for gas. The annual on-stream time is set to 8,400 h.

Table 3: The design data of material flows piping

Number	Name of material flow	Transport direction	Mass flow (10^4 t/y)	Density (kg/m^3)
1	crude oil	TF-COF	1,200	900
2	distilled aviation kerosene	COF-TF	140	800
3	refined aviation kerosene	HU-TF	140	800
4	gasoline	HU-TF	100	720
5	gasoline	FCC-TF	50	720
6	distilled diesel	COF-HU	280	820
7	refined diesel	COF-TF	80	820
8	refined diesel	HU-TF	50	820
9	atmospheric and vacuum residue	COF-RWH	280	910
10	wax oil	COF-RWH	150	760
11	wax oil	RWH-TF	150	760
12	refined naphtha	NH-TF	260	720
13	heavy naphtha	RWH-CR	100	910
14	heavy naphtha	NH-CR	70	910
15	FCC naphtha	RWH-HU	60	800
16	FCC naphtha	FCC-HU	60	800
17	separating column bottom oil	RWH-FCC	100	920
18	separating column bottom oil	NH-DC	130	920
19	tail oil	HU-FCC	200	820
20	rich amine solution	COF-SR	250	1,000
21	LPG	LPGDD-TF	45	580
22	liquid ammonia	SR-TF	50	600

Table 3: The design data of material flows piping

23	hydrogen	HP-HU	0.14	0.09
24	hydrogen	HP-RWH	0.40	0.09
25	hydrogen	HP-NH	0.30	0.09
26	noncondensable gas	GS-FCC	5	1.20
27	noncondensable gas	HU-FCC	5	1.20
28	propane	GS-TF	10	2.02
29	propylene	GS-TF	17	1.73
30	propylene	GS-TF	20	1.73
31	low pressure separation gas	RWH-HP	8	1.50
32	low pressure separation gas	HU-HP	25	1.50

3.2 Results and discussions

The total piping cost evolution during GA run in scenario 2 is shown in Figure 1. And the results are shown in Table 4.

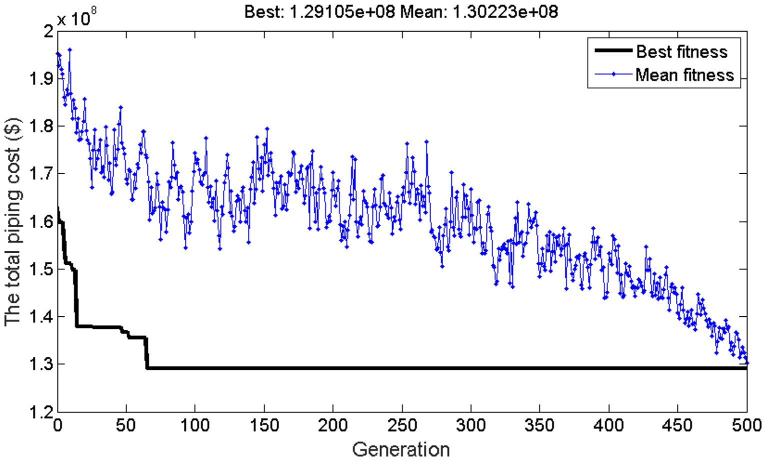

Figure 1: The total piping cost evolution during GA run in scenario 2

Table 4: The results of three scenarios

	Material flows piping cost (10^6 $)	Steam piping cost (10^6 $)	Total piping cost (10^6 $)	Relative location of each plant
Scenario 1	78.03	65.87	143.90	16 6 5 10; 1 11 2 4; 9 12 14 7; 15 13 3 8
Scenario 2	85.21	43.90	129.11	16 1 11 12; 9 5 4 10; 6 2 14 7; 15 8 3 13

From the results, it can be found that when the objective function is the cost of material flows only, the steam piping cost is 65.87×10^6 $, which is 21.97×$10^6$ $ more than the ones in scenario 2 which optimized the cost of material flows piping and steam piping simultaneously. Though the material flows piping cost in scenario 1 is 7.18×10^6 $ less than that of scenario 2, the total piping cost is 14.79×10^6 $ more than 129.11×10^6 $ in scenario 2. The results show the necessity of the optimization of steam piping cost. Additionally, the piecewise calculation of steam piping makes the results accurate and reasonable. Consequently, the work in this paper can not only effectively reduce pipeline investment in area-wide layout, but also make the optimization results and schemes be more realistic. From the results, the area-wide layout scheme in scenario 2 is better. The layout scheme and the steam piping of scenario 2 is shown in Figure 2.

From Figure 2, the steam piping is laid together which not passing the plants without connection relationship, such as LPGDD, GS, RTD and ACS. This is the main reason to the less cost of steam piping. Another reason is the addition of the piecewise calculation of steam piping cost, because this can let the plants which use a lot of steam be more close to the ones that produce steam, such as HU and HP, RWH and PS. This results not only reduces the steam piping cost, but also reduce the energy loss in the transport of the large amount of steam. Additionally, TF which has the most connection of material flows, is located in the middle of the industrial area. ACS, PS and LPGDD, which have less connection, are laid on the edge of the industrial area. All the results are in line with the expectation and illustrate the feasibility of the optimal scheme.

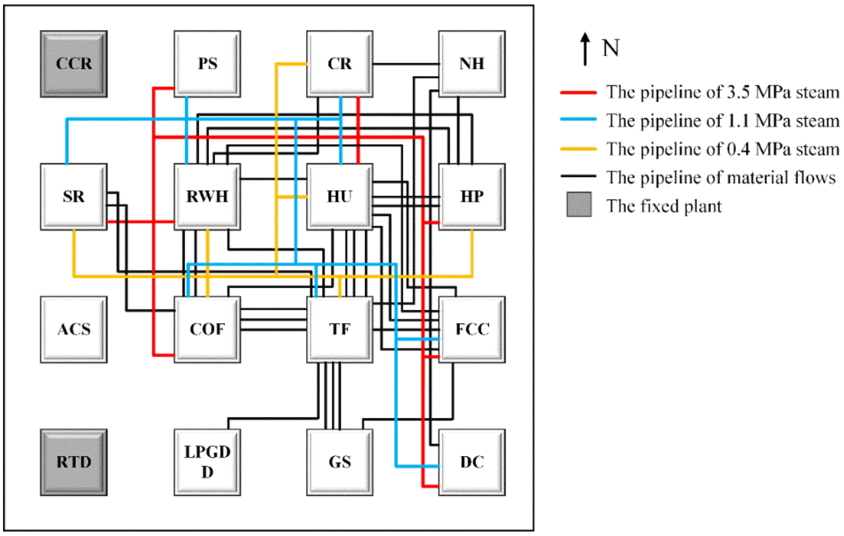

Figure 2: The optimal layout scheme and steam pipeline network in scenario 2

4. Conclusions

This paper proposed a method to design area-wide layout of industrial area considering steam piping with piecewise variable diameters, enriching the optimization of connection cost. For the calculation of piecewise cost in steam piping, an LP model is established to obtain the flow rates of each branch pipe. The paper put it together with the Kruskal algorithm and arrangement and combination. Using GA toolbox in MATLAB optimized the area-wide layout and selected an optimal scheme successfully. It should be noted that the piecewise calculation of steam piping cost considers the changes of flows rate in each branch pipe which influences the area-wide layout, increasing the accuracy of area-wide layout investment. Meanwhile, it reduces the energy loss in pipeline network effectively, because the layout scheme which is obtained by using the proposed method puts the plant that produce a large amount of steam and the plant that use a lot of steam together. Furthermore, it makes the optimal scheme be more consist with the experiences of engineering design. Results of the case study proves the advancement of the presented method.

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