AN EVOLUTIONARY METHOD OF ARRANGING THE PLOT PLAN FOR PROCESS PLANT LAYOUT

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The equipment layout of a process plant is a multi-objective problem in which not only various costs (piping, site and so on) but also preferences about the equipment arrangement influencing its operability, maintenance and the like. It is difficult to obtain the best solution of this problem analytically. In this study, preferences are weighted as penalities so that they can be evaluated in an objective function with costs. To reduce the calculation load, equipment having spatial relations in a local area is put together into "modules" as units in layout work, and these modules are grouped into "sections" as functional groups of equipment. Furthermore, the module arrangement in each section is considered to be two variables (permutation and partition), and an algorithm based on an evolutionary method is developed to search a good plot plan efficiently. The effectiveness of this proposed method is demonstrated by an example problem.

Introduction

Equipment layout is important to the design of a process plant, because its result (plot plan) influences piping, instruments, utilities, foundations and so on. Investigating possible layouts, the following items must be considered[6]:

(1) Process requirements
(2) Safety
(3) Economy
(4) Operation
(5) Maintenance
(6) Construction
(7) Appearance

In general, (1) and (2) are dealt with as constraints, and (3) is regarded as an objective function. However, a suitable plant is designed by considering all these items. For example, grouping equipment of the same type is carried out for the effectiveness of items (5)–(7), and arranging equipment according to process flow improves items (4) and (7). Such grouping and arranging are called "preferences" in this study, and they must be considered in relation to costs and constraints. Then a great quantity and variety of information must be managed and interpreted. Accordingly, skillful engineers are necessary to make a plot plan in consideration of these items. Furthermore, a plot plan must often be modified in the course of plant design because of changes in equipment specifications and/or the plant owner's intention. Then computer-aided layout becomes necessary, and many methods have been proposed.

These methods for process plants are divided into two groups. In one group, computer-aided design (CAD) systems for plant layout are developed by using interactive programs, computer graphics and XY-plotters (for example, Leesley and Newell[4], Madden and Taylor[5]). These studies propose practical models of a man-machine interface system for layout.

In the other group of methods, computational methods are proposed for layout because layout problems involve a large calculation load. For example, Amorese *et al.*[1] proposed a method based on heuristics, Gunn and Al-Asadi[3] studied a modular approach using a hill-climbing method, and Nolan and Bradley[7] reported a simplified technique considering safety. Despite the large calculation load involved, their methods consider costs such as piping only, and do not consider the preferences.

It is difficult to consider preferences and costs simultaneously because the layout problem is multi-objective and mixed-integer nonlinear programming (MINLP).

In this study, to solve the multi-objective problem, preferences are weighted according to their intensities and are accounted for in the objective function with piping and site costs. Equipment in the plant is grouped into "modules," and modules are grouped into "sections" in order to reduce the calculation load. An individual formulation for permutation and ratio of modules and an algorithm based on an evolutionary method are developed to search the solution efficiently.

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The effectiveness of this proposed method is demonstrated by an example problem of equipment layout in a methanol plant.

1. Preferences in Layout

The following may often be regarded as preferences in layout work:

(1) grouping equipment of the same type

(2) arranging equipment according to process flow

These preferences are not directly considered in the computer program, but must be translated into a number of "practical preferences." For example, they are translated into the following practical ones regarding relations between equipment units in the plant:

(1) neighboring Equipment 1 and 2

(2) not neighboring Equipment 1 and 2

(3) placing Equipment 1 and 2, 3 in a row

Each practical preference is weighted as a penalty cost according to its intensity, and is accounted for in an objective function with the piping cost and the site cost. In this way, it becomes possible to consider the preferences mentioned above in the computer program. For simplification, the other costs, such as the elecrical and instrument cable costs and the foundation cost, are not accounted for in an objective function.

The objective function adopted in this study is defined as:

$$\min F(=f_1+f_2+f_3)$$

where f_1, f_2, f_3 are respectively terms of preferences, the piping cost and the site area cost. f_1 is set up as follows:

$$f_1=\sum_{k=1}^{m} w_k v_k$$

where w_k is the weight factor of Preference k. If Preference k is satisfied, $v_k=0$; otherwise $v_k=1$. For example, practical preferences of an example problem in this study are shown in **Table 1**. The weight factor of each preference is regarded as a penalty cost. It is assumed that a good plot plan is obtained by adjusting each weight factor according to the plant owner's intention and/or negotiation between engineers. Preferences and their weight factors are not always fixed through a layout work. According to negotiation between the plant owner and engineers, the plant owner's intention is put into practical preferences and weight factors by the engineers. Then a new plot plan is arranged by this method. This procedure is repeated until the plot plan is acceptable both to plant owner and to engineers. This paper proposes a method for arranging the plot plan.

f_2, a term in the piping cost, is defined as follows:

Table 1. Preferences in the example problem

	Perference	w [$]
(1)	neighboring M1 and M2	5.0×10^5
(2)	neighboring M1 and M4	1.5×10^6
(3)	neighboring M4 and M8	2.5×10^6
(4)	neighboring M2 and M3	3.0×10^5
(5)	neighboring M7 and M8	1.0×10^5
(6)	standing in line M9, M10 and M11	3.0×10^6

$$f_2=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} C_{ij} l_{ij}$$

where C_{ij} and l_{ij} are cost per unit length and length of piping between Equipment i and j. The length of piping is calculated by the following equation:

$$l_{ij}=|x_i-x_j|+|y_i-y_j|+r_{ij}$$

where x_i and y_i are x and y coordinates of Equipment i, and r_{ij} is the pipe redundancy element. The value of the redundancy element depends upon the pipe routing. f_2 is generally used as the objective function in the previous studies[1,3,7].

A term of the site area cost, f_3, is determined by the following equation:

$$f_3=S[\max\{x_i+a_i/2\}]\times[\max\{y_j+b_j/2\}] \quad (i,j=1,\cdots,n)$$

where S is the site cost per unit area, x_i and y_j are x and y coordinates of Equipment i and j, and a_i and b_j are the width and length of Equipment i and j. Fundamentally, layout problems are to determine the optimum coordinates of all equipment:

$$\min_{\boldsymbol{x},\boldsymbol{y}} F(\boldsymbol{x},\boldsymbol{y})$$

where $\boldsymbol{x}$ and $\boldsymbol{y}$ are vectors of x_i and y_i $(i=1,\cdots,n)$. However, it is difficult to solve this problem analytically, because it is MINLP. Then, this study adopts an individual formulation indicating permutations and ratios of the layout units as "modules." To search the solution efficiently, an algorithm based on an evolutionary method is developed.

2. Formulation

Input data in the proposed method are given in the forms of two lists, one an equipment list including the dimensions of each equipment unit, and the other a from-to list that indicates connecting relations between equipment units. These two lists are produced from the process flow sheet, the vendor equipment lists and the like, and **Tables 2** and **3** are the lists used in the example problem.

To reduce the calculation load, equipment such as condensers, reboilers, reactors, and columns is grouped as "modules," and the modules are further

Table 2. Equipment list in the example problem

Equipment	Dimensions			Equipment	Dimensions		
	a [m]	b [m]	h [m]		a [m]	b [m]	h [m]
R-1	2.10	2.10	4.30	V-1	4.60	12.00	6.00
R-2	2.10	2.10	4.30	V-4	1.10	3.00	2.50
R-3	13.00	7.00	13.00	V-5	2.40	6.00	3.40
R-4	3.24	3.24	9.00	V-6	0.70	3.00	2.00
R-5	3.24	3.24	9.00	P-1	2.00	6.00	2.60
E-5	2.50	10.00	3.50	C-1	3.20	5.70	2.80
E-6	1.80	7.00	2.80	C-2	3.50	6.00	3.10
E-9	1.80	7.00	2.80	C-3	16.00	12.00	8.00
E-10	2.00	8.50	3.00	C-4	9.50	12.00	7.00
E-11	1.80	6.50	2.80	C-5	6.00	9.00	5.50
E-12	1.00	3.00	2.00	D-1	2.80	2.80	21.00
E-13	1.80	7.00	2.80	D-2	6.00	6.00	28.00
E-14	0.80	2.50	1.80	D-3	2.80	2.80	10.50
E-15	1.00	3.00	2.00				
E-16	1.80	7.00	2.80				
E-17	1.00	2.50	2.00				
E-18	0.60	2.50	1.60				

Table 3. From-to list in the example problem

From	To	Cost [\$/m]
R-1	R-3	3000
R-2	R-3	3000
R-3	E-5	4000
R-3	V-1	2000
	⋮	
C-5	R-3	5000

grouped as "sections." Each module includes equipment that has spatial relations in the local area, such as a column and neighboring heat exchangers (**Fig. 1**), and its dimensions and shape are fixed. A module is dealt with as a unit in the proposed method. Modules of the example problem are shown in **Table 4**, and it is assumed that these are given.

A section is a functional group of modules, and its dimensions and shape are not fixed because they depends on the module arrangement. This grouping is useful in reduing the calculation load.

Layout problems are to determine x and y coordinates of the module, and it is usual to search the coordinates directly. However, in this study a new formulation mentioned below is developed to find the optimum module arrangement efficiently.

Module arrangement in Section i can be described in a combination of the permutation variable p_i and the partition variable r_i, where p_i and r_i respectively represent one case of permutation of modules and one way of partitioning modules into two rows, one on either side of pipe rack in Section i. In this formulation, it is assumed that the modules are installed in two rows, one on either side of the main pipe rack.

For example, if Section 1 ($i=1$) contains four modules (M1, M2, M3, M4), their arrangement can

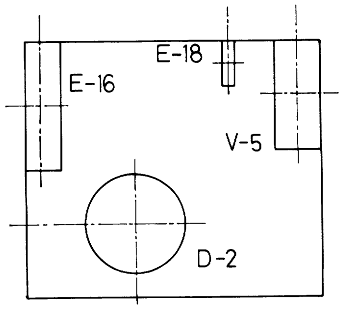

Fig. 1. Example of a module

Table 4. Module list in the example problem

Module	Size [m²]	Included equipment
M1	13.00 × 7.00	R-3
M2	22.70 × 12.00	E-5 E-6 V-1
M3	9.40 × 3.10	R-1 R-2
M4	27.10 × 12.00	C-1 C-2 C-3
M5	5.24 × 13.34	R-4 R-5
M6	14.00 × 8.50	E-9 E-10 E-11
M7	2.00 × 6.00	P-1
M8	17.90 × 12.00	C-4 C-5
M9	9.00 × 10.00	E-12 E-15 V-4 D-1
M10	15.80 × 14.00	E-13 E-16 E-18 V-5 D-2
M11	9.00 × 10.00	E-14 E-17 V-6 D-3

be indicated with two variables p_1 and r_1. In this case, p_1 and r_1 can be defined as in the following example:

$$p_1 \in \{1, 2, \cdots, 24\} ({}_4P_4 = 24)$$

$$p_1 = 1: \text{(M1-M2-M3-M4)}$$

$$p_1 = 2: \text{(M1-M2-M4-M3)}$$

......

$$p_1 = 24: \text{(M4-M3-M2-M1)}$$

and

$$r_1 \in \{1, 2, \cdots, 5\}$$

$$r_1 = 1: (4/0)$$

$$r_1 = 2: (3/1)$$

......

$$r_1 = 5: (0/4)$$

(modules in Row 1/modules in Row 2)

For example, when there are M1, M2 and M3 in Row 1, and M4 in Row 2, it follows that:

$$\text{Row } 1 = \{\text{M1-M2-M3}\}, \qquad \text{Row } 2 = \{\text{M4}\}$$

This arrangement is represented by $p_1 = 1$ and $r_1 = 2$.

If p_i and r_i in each section can be determined, a plot plan may be obtained by translation of p_i and r_i into two-dimensional coordinated of modules (**Fig. 2**). In this way the optimum arrangement of modules can be found as a solution of a combinatorial optimization

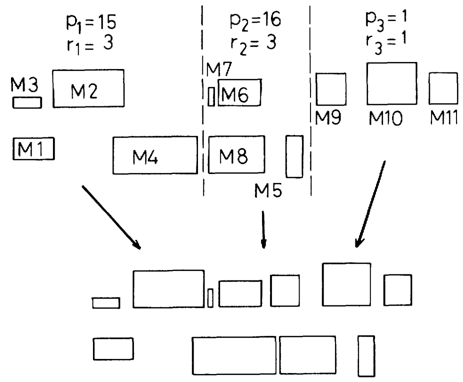

Fig. 2. Example of translation into a plot plan

problem. It is efficient to use this formulation because the number of variables is less than that of x and y coordinates.

3. Algorithm

By the above formulation, the optimum plot plan will be obtained to find the optimum values of $\boldsymbol{p}$ and $\boldsymbol{r}$, where $\boldsymbol{p}$ and $\boldsymbol{r}$ are vectors of p_i and r_i. Even though the proposed formulation is used to solve a layout problem, if the number of modules and/or sections is large, it is still difficult to find the optimum values of $\boldsymbol{p}$ and $\boldsymbol{r}$. Therefore, in this study a practical algorithm based on an evolutionary method is proposed.

The algorithm in this study is shown in **Fig. 3**. In Step 1, an initial solution is generated by optimization of p_i and r_i in Section i independently, because this initial solution may be easily found, and it may be near the optimum one provided that the grouping of modules and preferences and the weight factors appropriate.

The next part, Steps 2 to 4, is most important in this proposed algorithm. The evolution starts from the initial solution as a current one, and proceeds with evolutions about $\boldsymbol{p}$ and $\boldsymbol{r}$ separately.

In Step 2, firstly the neighbors are generated from current $\boldsymbol{p}$. Its neighbors are generated by interchanges of the adjacent elements in the permutation of modules in each section. For example, in a case where the current solution is $p_1=1$, the permutation of modules is (M1-M2-M3-M4). Its neighbors are generated by interchangings of pairs of modules:

$$p_1=2: \text{(M1-M2-M4-M3)}$$

$$p_1=3: \text{(M1-M3-M2-M4)}$$

$$p_1=7: \text{(M2-M1-M3-M4)}$$

In this case, neighbors of $p_1=1$ are $p_1=2$, 3 and 7, because the number of pairs of the adjacent modules is three. Such relations are set up also at other values of p_1 ($p_1=2, \cdots, 24$) and other sections ($p_2, p_3, \cdots$). In an evolution, neighbors of current $\boldsymbol{p}$ are generated as combinations of each current p_i and its neighbors.

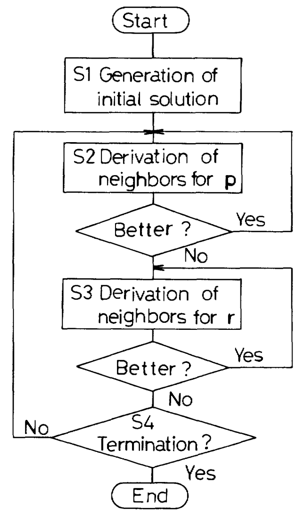

Fig. 3. Algorithm of proposed method

For example, if the numbers of modules in Section 1, 2 and 3 are respectively 4, 4 and 3, then 47 ($=4\times4\times3-1$) neighbors are generated. Each neighbor is translated into the coordinates of equipment as a plot plan, and its objective function mentioned above is estimated. If the best value of the objective function among the neighbors is better than that of the current solution, the neighbor is again kept as the current one. This procedure is repeated until no better solution occurs.

In Step 3, the evolution is repeated similarly about $\boldsymbol{r}$. For example, in the case of $r_1=3$: (2/2) its neighbors are the following:

$$r_1=2: (3/1)$$

$$r_1=4: (1/3)$$

They are obtained by increasing and decreasing a module in a row. It is also assumed that such relations are set up at other values of r_1 ($r_1=2, \cdots, 5$) and other sections ($r_2, r_3, \cdots$). This process about $\boldsymbol{r}$ is repeated in the same way as the evolutions about $\boldsymbol{p}$.

If the values of the objective function at solutions generated are not improved in either $\boldsymbol{p}$ or $\boldsymbol{r}$, this situation is regarded as convergence in this algorithm (Step 4) and the evolution is terminated. The last current solution is the best solution in this evolution.

This algorithm is a practical means of finding the best solution with ease.

4. Example Problem

The example problem in this study is to determine the plot plan of a methanol plant[2], and its flow sheet is shown in **Fig. 4**. Natural gas is fed and reformed to CO and CO_2 by steam (H_2O). This reaction proceeds in the reforming section (Section1). In the synthesis section (Section 2), methanol is synthesized from CO and CO_2 with H_2. Purification of methanol

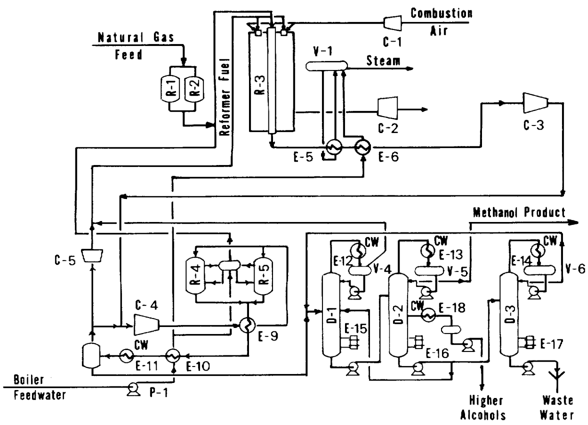

Fig. 4. Process flowsheet in the example problem

is carried out in Section 3, which contains three distillation columns because the outflow from Section 2 includes heavy alcohols and unreacted raw materials.

In this plant, the number of major equipment units is 30, excepting small ones such as some pumps and exchangers, and it is assumed in this example problem that major equipment is installed in two rows, one on either side of the main pipe rack.

At the beginning, the equipment list shown in Table 2 is made from the process flow sheet of this plant. The from-to list shown in Table 3, a document about piping relations and costs per unit length, is made from the flow sheet and piping standards.

Three sections are established by the functional groups in the way mentioned above, and eleven modules are generated from the equipment list, the from-to list, and other sources such as separation distance criteria, requirements about plant operation and so on. The separation distance criteria are taken from plant design handbooks. Modules in this problem are shown in Table 4.

Preferences in this example problem are to arrange the equipment according to the process flow, and to group equipment of the same type in the local area. These are translated into practical preferences between equipment units or modules, and are shown in Table 1.

The following is the process of evolution of this problem along the proposed algorithm, and is shown in **Table 5**. The initial solution is obtained by optimizing in each section independently; this is the starting point of the evolution.

First, the derivation about $\boldsymbol{p}$ is carried out, a neighbor that has the best value of F is selected among 47 neighbors derived from the initial solution, and it becomes a current solution repeatedly because it surpasses the initial one. At the second derivation, which generates neighbors from the current solution, no neighbor is better than the current solution, and so an evolution about $\boldsymbol{r}$ rather than $\boldsymbol{p}$ is carried out. In this problem, the evolution is terminated at the fifth derivation because F is not improved in either $\boldsymbol{p}$ or $\boldsymbol{r}$. In this problem the value of F changes from 0.995×10^7 to 0.714×10^7 dollars. **Figure 5** is the plot plan resulting from this example problem.

The evolutions in this example problem take about one minute on a SUN 3 workstation.

Table 5. Evolution process in the example problem

p_1	p_2	p_3	r_1	r_2	r_3	F [$]
0) initial solution						
15	18	1	3	3	4	0.995×10^7
1) 1st derivation of neighbors about $\boldsymbol{p}$						
15	18	6	3	3	4	0.129×10^8
15	18	2	3	3	4	0.128×10^8
15	16	1	3	3	4	0.811×10^7
15	16	6	3	3	4	0.110×10^8
			⋮			
16	24	2	3	3	4	0.142×10^8
2) 2nd derivation of neighbors about $\boldsymbol{p}$						
15	10	1	3	3	4	0.821×10^7
15	10	6	3	3	4	0.111×10^8
			⋮			
16	15	2	3	3	4	0.140×10^8
not improved						
3) 3rd derivation of neighbors about $\boldsymbol{r}$						
15	16	1	3	3	3	0.106×10^8
15	16	1	3	3	1	0.714×10^7
15	16	1	3	2	4	0.962×10^7
			⋮			
15	16	1	4	4	1	0.129×10^8
4) 4th derivation of neighbors about $\boldsymbol{r}$						
15	16	1	3	3	2	0.102×10^8
15	16	1	3	2	2	0.125×10^8
			⋮			
15	16	1	4	4	2	0.162×10^8
not improved						
5) 5th derivation of neighbors about $\boldsymbol{p}$						
15	16	6	3	3	1	0.101×10^8
15	16	2	3	3	1	0.101×10^8
			⋮			
16	18	2	3	3	1	0.129×10^8
not improved						
evolution terminates						
6) solution						
15	16	1	3	3	1	0.714×10^7

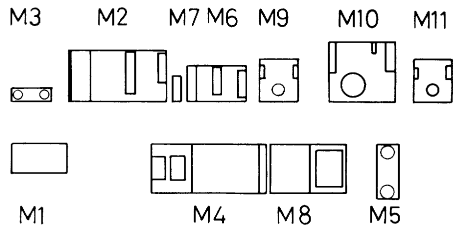

Fig. 5. A plot plan from the solution of the example problem

Conclusions

In this study a computational method for equipment layout considering both preferences and costs such as those of piping and site is proposed. Preferences are weighted as penalties according to the plant owner's intention and the results of negotiation, and are evaluated in an objective function with costs. To reduce the calculation load, "modules" are made of equipment units having spatial relations with one another in the local area, and modules are grouped into "sections" as functional groups of equipment. The module arrangement in each section is considered to be two variables which indicate the permutation and the partition of modules respectively. The algorithm is based on an evolutionary method, and the evolution is carried out about two vectors (permutation and partition) separately. In these ways the calculation load is decreased and the solution is obtained efficiently. The effectiveness of this proposed method is demonstrated through an example layout problem of a methanol plant.

Nomenclature

a_i	= width of Equipment i	[m]
b_i	= length of Equipment i	[m]
C_{ij}	= cost per unit length of piping from i to j	[$\$\cdot m^{-1}$]
h_i	= height of Equipment i	[m]
l_{ij}	= length of piping from i to j	[m]
m	= number of preferences	[—]
n	= number of equipment units	[—]
p_i	= permutation variable in Section i	[—]
$\boldsymbol{p}$	= vector of p_i	[m]
r_i	= partition variable in Section i	[—]
$\boldsymbol{r}$	= vector of r_i	[m]
S	= cost per unit area of site	[$\$\cdot m^{-2}$]
v_k	= satisfaction variable of Preference k	[—]
w_k	= weight of Preference k	[$]
x_i	= x coordinate of Equipment i	[m]
$\boldsymbol{x}$	= vector of x_i	[m]
y_i	= y coordinate of Equipment i	[m]
$\boldsymbol{y}$	= vector of y_i	[m]

⟨Subscript⟩

i, j	= equipment or section numbers
k	= preference number

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