AN OPTIMISATION-BASED APPROACH FOR PROCESS PLANT LAYOUT - Supporting information

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1 Multi-floor layout MILP model

The MILP model proposed by Patsiatzis and Papageorgiou[1] is presented below:

1.1 Floor constraints

Each equipment item available should be assigned to only one floor:

$$\sum_k V_{ik} = 1 \qquad \forall\ i \tag{S.1}$$

The value of N_{ij} is obtained by:

$$N_{ij} \geq V_{ik} + V_{jk} - 1 \qquad \forall\ i = 1, ..., N-1,\ j \neq i,\ k = 1, ..., K \tag{S.2}$$

$$N_{ij} \leq 1 - V_{ik} + V_{jk} \qquad \forall\ i = 1, ..., N-1,\ j \neq i,\ k = 1, ..., K \tag{S.3}$$

$$N_{ij} \leq 1 + V_{ik} - V_{jk} \qquad \forall\ i = 1, ..., N-1,\ j \neq i,\ k = 1, ..., K \tag{S.4}$$

As such, the variable N_{ij} is forced to the value of 1 if and only if item i and j are on the same floor.

An item can only be assigned to a floor that exists:

$$V_{ik} \leq W_k \qquad \forall\ i, k \tag{S.5}$$

A floor can only be available if the preceding floor is occupied:

$$W_k \leq W_{k-1} \qquad \forall\ k = 2, ..., K \tag{S.6}$$

The number of floors required for the process is then given by:

$$NF \geq \sum_k W_k \tag{S.7}$$

1.2 Equipment orientation constraints

Each equipment item is allowed rotation in the x-y plane by 90^o as deemed optimal:

$$l_i = \alpha_i O_i + \beta_i (1 - O_i) \qquad \forall\, i \tag{S.8}$$

$$d_i = \alpha_i + \beta_i - l_i \qquad \forall\, i \tag{S.9}$$

1.3 Non-overlapping constraints

The following constraints prevent items i and j from occupying the same location if they exist on the same floor ($N_{ij} = 1$). Each combination of the values of the binary variable $E1_{ij}$ and $E2_{ij}$ activates one of the four constraints, which prevents an overlap of any two equipment items.

$$x_i - x_j + BM(1 - N_{i,j} + E1_{ij} + E2_{ij}) \geq \frac{l_i + l_j}{2} \qquad \forall\, i = 1, ..., N-1,\ j = 2, ..., N \tag{S.10}$$

$$x_j - x_i + BM(2 - N_{i,j} - E1_{ij} + E2_{ij}) \geq \frac{l_i + l_j}{2} \qquad \forall\, i = 1, ..., N-1,\ j = 2, ..., N \tag{S.11}$$

$$y_i - y_j + BM(2 - N_{i,j} + E1_{ij} - E2_{ij}) \geq \frac{d_i + d_j}{2} \qquad \forall\, i = 1, ..., N-1,\ j = 2, ..., N \tag{S.12}$$

$$y_j - y_i + BM(3 - N_{ij} - E1_{ij} - E2_{ij}) \geq \frac{d_i + d_j}{2} \qquad \forall\, i = 1, ..., N-1,\ j = 2, ..., N \tag{S.13}$$

where BM is an appropriately large number.

1.4 Distance constraints

The constraints that follow determine the relative distances in the x, y, and z coordinates respectively;

$$R_{ij} - L_{ij} = x_i - x_j \qquad \forall (i,j): \; f_{ij} = 1 \tag{S.14}$$

$$A_{ij} - B_{ij} = y_i - y_j \qquad \forall (i,j): \; f_{ij} = 1 \tag{S.15}$$

$$U_{ij} - D_{ij} = FH \sum_k k(V_{ik} - V_{jk}) \qquad \forall (i,j): \; f_{ij} = 1 \tag{S.16}$$

and the total rectilinear distance between and two items i and j, connected to each other is given as:

$$TD_{ij} = R_{ij} + L_{ij} + A_{ij} + B_{ij} + U_{ij} + D_{ij} \qquad \forall (i,j): \; f_{ij} = 1 \tag{S.17}$$

1.5 Area Constraints

In order to avoid bilinear terms, the value of the floor area, FA, is selected from a set of S predefined rectangular area sizes, AR_s, with dimensions $(\overline{X}_s, \overline{Y}_s)$.

$$FA = \sum_s AR_s Q_s \tag{S.18}$$

$$\sum_s Q_s = 1 \tag{S.19}$$

The floor length and breadth is selected from the chosen rectangular area size dimensions:

$$X^{max} = \sum_s \overline{X}_s Q_s \tag{S.20}$$

$$Y^{max} = \sum_s \overline{Y}_s Q_s \tag{S.21}$$

Also, a new term NQ_s is introduced in order to linearise the cost term associated with the number of floors in the objective function.

$$NQ_s \leq K\, Q_s \qquad \forall\ s \tag{S.22}$$

$$NF = \sum_s NQ_s \tag{S.23}$$

1.6 Layout design constraints

Layout design constraints are included to avoid placement of equipment items outside of the boundary of the floor area. The lower bound constraints are:

$$x_i \geq \frac{l_i}{2} \qquad \forall\ i \tag{S.24}$$

$$y_i \geq \frac{d_i}{2} \qquad \forall\ i \tag{S.25}$$

and the upper bound:

$$x_i + \frac{l_i}{2} \leq X^{max} \qquad \forall\ i \tag{S.26}$$

$$y_i + \frac{d_i}{2} \leq Y^{max} \qquad \forall\ i \tag{S.27}$$

1.7 Objective function

The objective function minimizes the total cost given as:

$$\begin{aligned} min \sum_i \sum_{j \neq i : f_{ij}=1} [C^c_{ij} TD_{ij} + C^v_{ij} D_{ij} + C^h_{ij}(R_{ij} + L_{ij} + A_{ij} + B_{ij})] + FC1 \cdot NF \\ + FC2 \sum_s AR_s \cdot NQ_s + LC \cdot FA \end{aligned} \tag{S.28}$$

2 Case study data

2.1 Example 1: Ethylene oxide plant

Table S1: Equipment dimensions for Ethylene Oxide plant

Unit	α_i(m)	β_i(m)	γ_i(m)
1	5.22	5.22	4.50
2	11.42	11.42	2.21
3	7.68	7.68	7.42
4	8.48	8.48	2.21
5	7.68	7.68	6.40
6	2.6	2.6	3.50
7	2.4	2.4	1.20

Table S2: Parameters for the Ethylene Oxide plant

(a) Connection and pumping costs

Connection	C^c_{ij}(rmu/m)	C^h_{ij}(rmu/m)	C^v_{ij}(rmu/m)	OP_{ij}(m)	IP_{ij}(m)
(1,2)	200	400	4,000	4.5	1.11
(2,3)	200	400	4,000	1.11	3.71
(3,4)	200	300	3,000	7.42	1.11
(4,5)	200	300	3,000	1.11	3.2
(5,1)	200	100	1,000	6.40	2.25
(5,6)	200	200	2,000	0.0	1.75
(6,7)	200	150	1,500	0.0	0.60
(7,5)	200	150	1,500	1.20	4.80

(b) Other Parameters

Parameters	Value
K	3
$FC1$(rmu)	3,330
$FC2$ (rmu/m^2)	6.6
LC (rmu/m^2)	26.6
FH (m)	5

2.2 Example 2: Urea production plant

Table S3: Equipment dimensions for Urea Production plant

Unit	α_i(m)	β_i(m)	γ_i(m)
1	1.9812	1.9812	6.096
2	2.4384	2.4384	28.956
3	1.524	1.524	5.7912
4	1.0668	1.0668	14.6304
5	0.6096	0.6096	7.3152
6	0.762	0.762	3.3528
7	1.2192	1.2192	5.0292
8	1.0668	1.0668	3.6576

Table S4: Parameters for the Urea Production plant

(a) Connection and pumping costs

Connection	C^c_{ij}(rmu/m)	C^h_{ij}(rmu/m)	C^v_{ij}(rmu/m)	OP_{ij}(m)	IP_{ij}(m)
1.4	38.0	662.2	6621.8	0.0000	12.8016
4.3	161.0	513.3	5133.4	14.6304	4.6330
4.7	25.0	332.2	3321.8	0.0000	1.0058
7.8	25.0	332.2	3321.8	1.0058	2.9261
3.2	124.0	803.5	8035.1	1.1582	0.0000
2.1	103.0	803.5	8035.1	28.9560	4.5720
1.5	62.0	141.3	1413.3	6.0960	1.8288
8.6	14.0	59.0	590.0	3.6576	3.3528
6.5	13.0	59.0	590.0	3.3528	5.4864
5.3	17.0	156.2	1561.7	0.0000	4.6330

(b) Other Parameters

Parameters	Value
K	4
$FC1$(rmu)	3,200
$FC2$ (rmu/m^2)	120
LC (rmu/m^2)	420
FH (m)	8.0

2.3 Example 3: Crude distillation plant

Table S5: Equipment dimensions for Crude Distillation Plant with Preheating train

Unit	α_i(m)	β_i(m)	γ_i(m)
1	6	0.974	0.974
2	2.55	0.62	0.62
3	5.572	3.715	3.715
4	2.55	0.774	0.774
5	5.251	5.251	7.877
6	3.922	3.922	17.6
7	12.3	12.3	14.5
8	1.789	1.193	1.193
9	1.5	1.5	3.9
10	1.5	1.5	3.9
11	1.5	1.5	3.9
12	3.922	3.922	17.6
13	9.41	9.41	4.5
14	3.05	2.033	2.033
15	5.337	5.337	24.75
16	1.789	1.193	1.193
17	1.789	1.193	1.193

Table S6: Parameters for the Crude Distillation Plant with Preheating train

(a) Connection and pumping costs

Connection	C^c_{ij}(rmu/m)	C^h_{ij}(rmu/m)	C^v_{ij}(rmu/m)	OP_{ij}(m)	IP_{ij}(m)
1.2	550.3	2,481.0	24,810.0	0.000	0.620
2.3	550.3	2,481.0	24,810.0	0.000	3.715
3.4	550.3	2,481.0	24,810.0	1.857	0.774
4.5	531.4	2,395.6	23,955.8	0.000	3.938
5.6	519.2	2,340.5	23,405.0	0.000	0.000
6.7	519.2	2,340.5	23,405.0	4.280	0.750
7.1	245.3	1,106.0	11,059.9	10.000	0.974
7.2	155.0	698.9	6,988.8	6.250	0.620
7.4	161.6	728.4	7,284.1	3.750	0.774
1.7	245.3	1,106.0	11,059.9	0.000	10.750
2.7	155.0	698.9	6,988.8	0.000	6.750
4.7	161.6	728.4	7,284.1	0.000	4.250
7.8	206.1	929.2	9,291.8	14.500	0.597
8.7	102.1	460.2	4,602.0	0.000	14.250
7.9	57.4	258.6	2,586.4	10.250	3.650
9.7	11.0	49.7	496.9	3.900	10.750
9.14	67.9	306.2	3,061.9	0.000	0.000
14.9	21.6	97.2	972.4	2.033	2.650
7.10	117.5	529.8	5,297.9	6.250	3.650
10.7	17.4	78.5	785.2	3.900	6.750
7.11	31.4	141.7	1,416.6	3.750	3.650
11.7	8.0	36.0	359.6	3.900	4.250
7.12	248.3	1,119.2	11,191.6	0.000	0.000
12.13	248.3	1,119.2	11,191.6	4.280	0.250
8.15	99.0	446.2	4,462.2	0.000	12.925
15.16	50.6	228.3	2,282.8	24.750	0.597
15.17	212.7	958.7	9,587.5	0.000	0.000
16.15	30.4	137.0	1,369.7	0.000	24.475
17.15	133.9	603.8	6,038.4	1.193	0.275

(b) Other Parameters

Parameters	Value
K	7
$FC1$(rmu)	3,330
$FC2$ (rmu/m^2)	33.3
LC (rmu/m^2)	666
FH (m)	5.0

3 Layout plots

3.1 Example 1: Ethylene oxide plant

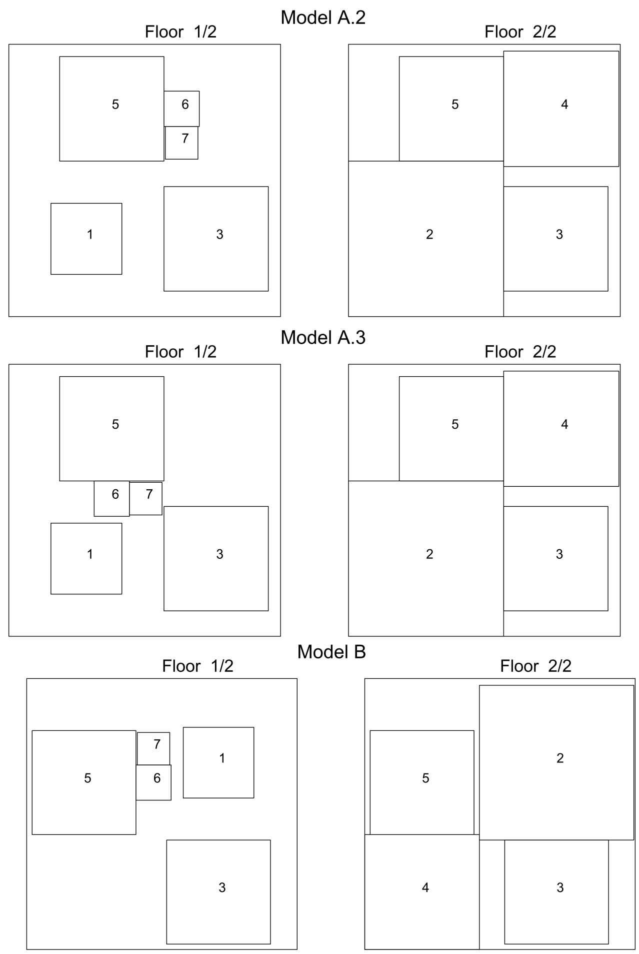

Figure S1: Example 1 layout results

3.2 Example 2: Urea production plant

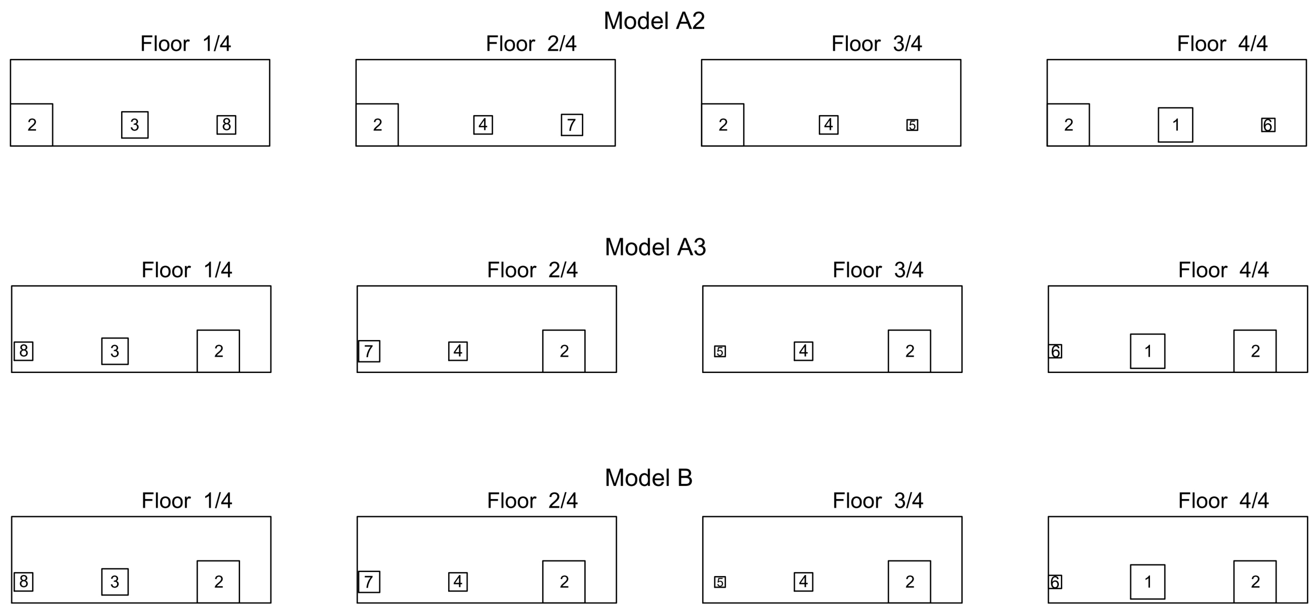

Figure S2: Example 2 layout results

3.3 Example 3: Crude distillation plant

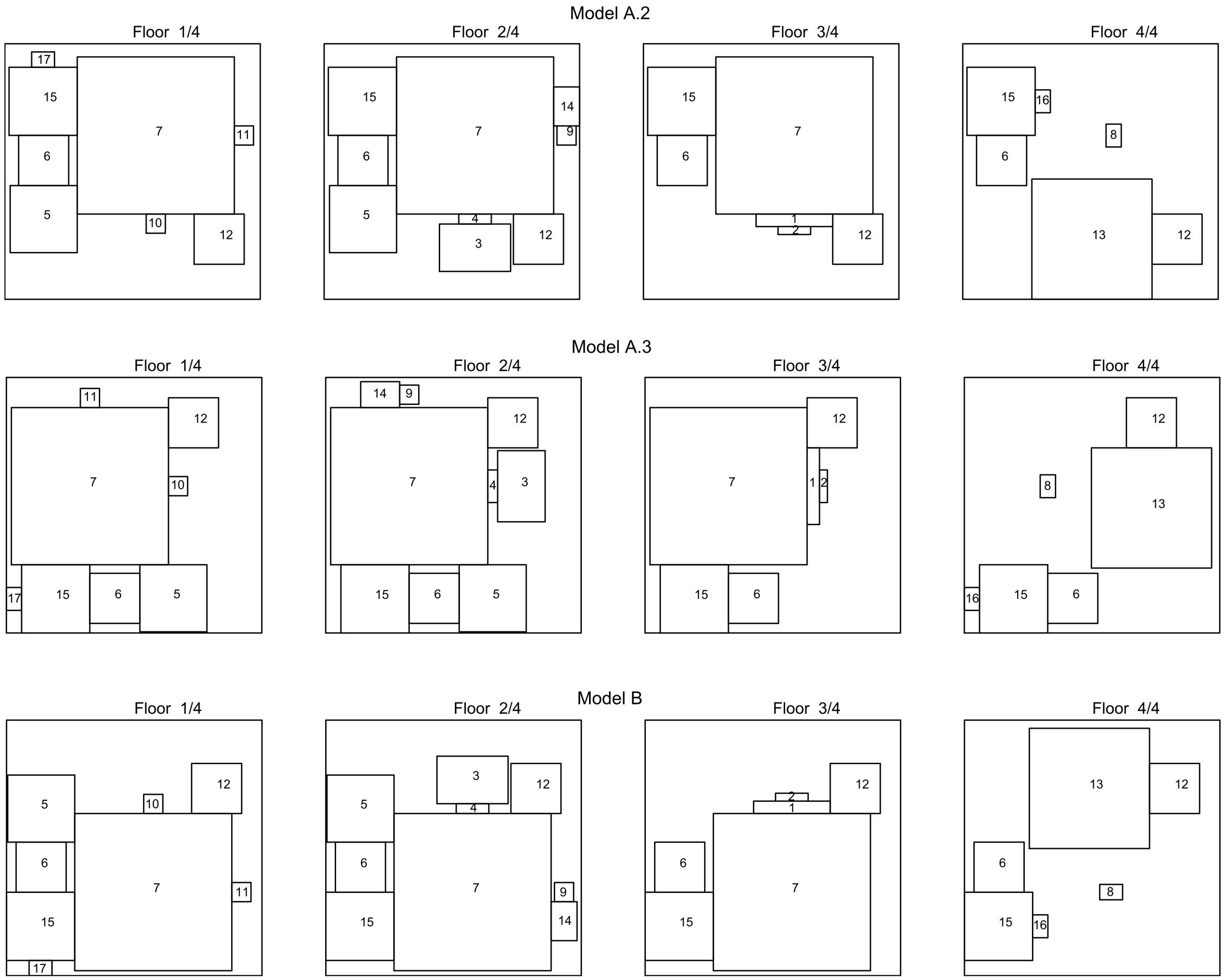

Figure S3: Example 3 layout results

References

(1) Patsiatzis, D. I.; Papageorgiou, L. G. Efficient Solution Approaches for the Multifloor Process Plant Layout Problem. *Industrial & Engineering Chemistry Research* **2003**, *42*, 811–824.