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Optimal multi-floor plant layout with consideration of safety distance based on mathematical programming and modified consequence analysis

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Abstract−A general mathematical programming formulation which also considers safety factors is presented for solving the multi-floor plant layout problem. In the presence of a risk of physical explosion, the safety distance must be considered to generate more reasonable and safe layouts. The proposed method determines detailed multi-floor process plant layouts using mixed integer linear programming (MILP). To consider the safety distance, a consequence analysis is adopted for calculating an equipment physical explosion probit. As the TNT equivalency method is used, more realistic estimations of equipment damage are possible, generating safer plant layouts. The objective function minimizes the layout cost (total plant area, floor construction costs and connection costs) and explosion damage costs for the multi-floor problem. Two illustrative examples are presented to demonstrate the applicability of the proposed method.

Key words: MILP, Plant Layout, Layout Optimization, Safety Distance

INTRODUCTION

Determining process plant layouts is an important step that demands significant engineering creativity and experience. A good layout will reduce plant construction costs, provide good maintenance accessibility and satisfy safety requirements. To do this, layouts must achieve a good balance between conflicting criterions such as safety and costs.

To solve this problem, several methods have been proposed during the last two decades. Methods based on heuristic rules were suggested [8] for the two-dimensional layout problems, but there was no guarantee that an optimal solution would be obtained. A mixed integer linear programming model (MILP) [10] was developed considering various sizes and geometries of equipment [3]. Another MILP model was developed for the multi-floor process [4] using concepts of rectangular shapes and rectilinear distances. But these methods have some limitations since they do not take safety issues into account.

A mixed integer non-linear programming (MINLP) model was developed [6] to determine the plant layout considering protective devices of equipments. An optimization using genetic algorithms with the Mond Index was also proposed [1] and proved that effective solutions could be obtained. In addition, an MILP model utilizing safety problems with Dow's fire and explosion index was proposed [5] to solve single-floor layout problems.

Since the aforementioned works focused on single floor problems only, there is a need for an improved method considering multi-floor plant layouts with safety issues as well. This paper extends previous multi-floor MILP modeling with a consideration of safety distance. To consider the safety distance of equipment, the TNT equivalency method [7] is used. The proposed method can be applied at the stage of conceptual plant design when a process flow diagram (PFD) and the dimensions of the equipment are available.

1. Safety Distance Considerations

Dow's fire and explosion index system was proposed to consider the safety distance when determining an optimal layout [5]. It is a valuable method for identifying the hazardous unit based on historic loss data and the energy potential of the processed materials. It assumes a linear correlation between the equipment damage and the distance since Dow's fire and explosion index system cannot calculate the equipment damage according to the distance.

The TNT equivalency method is a consequence analysis using the energy of explosion. It is a logical and theoretical analysis which can calculate the overpressure with respect to the distance. The overpressure can be converted to the probability of equipment damage so that can predict the equipment damage more realistically than by adopting a linear relationship assumption.

To calculate a safety distance using the TNT equivalency method, release outcomes and scenarios for the release need to be investigated. Several outcomes may occur out of a release, such as physical explosions, vapor cloud explosions (VCE), boiling liquid expanding vapor explosions (BLEVE) and confined explosions. Selecting proper scenarios for the release is another problem that is beyond the scope of this research; physical explosions are assumed as the only possible outcome of the release.

A physical explosion is related to the catastrophic rupture of a vessel containing pressurized gas. This can occur due to events like a failure of pressure relief equipment, reduction in vessel strength or an internal runaway reaction. In general, physical explosions are expected to cause less damage than other outcomes since they do not result in fire. Consequently, it can be used as the minimum guide-

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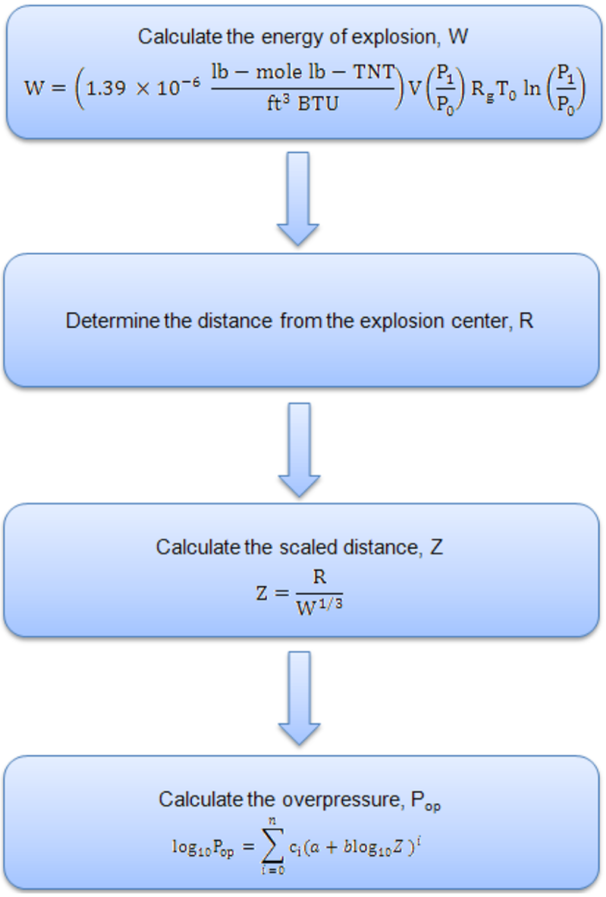

Fig. 1. Procedure for determining explosion overpressure.

line for setting a safety distance in the plant layouts.

To get damage probabilities of equipment according to the distance, overpressure should be calculated. The procedure for determining the overpressure under physical explosion [7] is shown in Fig. 1.

After the overpressure is calculated with respect to the distance, the probit can be obtained by the following equation [2]:

$$P_r=-23.8+2.92\ln P_{op} \text{ (In case of structural damage)} \tag{1}$$

Then, the probability of equipment damage under physical explosion conditions can be calculated using Eq. (2).

$$P=50\left[1+\frac{P_r-5}{|P_r-5|}\text{erf}\left(\frac{|P_r-5|}{\sqrt{2}}\right)\right] \tag{2}$$

2. Optimal Multi-Floor Plant Layout with Safety Consideration: Problem Description

The multi-floor plant layout problem with safety distance consideration can be stated as follows:

Given

1) A set of N equipment items and their dimensions
2) A set of f potential floors
3) Cost data
4) Process flow diagram
5) Floor height
6) Probabilities of damage according to the distance

Determine the detailed multi-floor layout minimizing the sum of the plant layout cost and the expected damage cost.

3. Mathematical Formulation

The mathematical formulation for the multi-floor layout problem was well presented [4] in the previous work. The objective function of that work minimized the total cost subject to floor, equipment orientation, non-overlapping, land area and distance constraints.

In this work, the proposed formulation is based on the previous research, except the addition of safety distance constraints. As a result, the objective function minimizes the total cost subject to floor, equipment orientation, non-overlapping, land area, distance and equipment damage cost constraints.

3-1. Equipment Orientation and Floor Constraints

Rectangular shapes are assumed for all equipment and allowed to rotate by 90°. The equipment orientations are determined by following equations:

$$Le_i=a_iO_i+b_i(1-O_i) \quad \forall i \tag{3}$$

$$De_i=a_i+b_i-Le_i \quad \forall i \tag{4}$$

where O_i is the binary parameter which decides equipment length and depth. If O_i is 1, then equipment length Le_i is equal to equipment dimension a_i or b_i.

Each equipment item can be located at any floor, occupying only a single floor. Two binary parameters are introduced here. The binary parameter AF_{if} has a numerical value of 1 if equipment item i is allocated to floor f; otherwise it is assigned as 0. The binary parameter Z_{ij} is equal to 1 if equipment item i and j are on the same floor, but 0 if they are not. FN is the number of floors.

$$\Sigma_f AF_{if}=1 \quad \forall i \tag{5}$$

$$Z_{ij}\ge AF_{if}+AF_{jf}-1 \tag{6}$$

$$Z_{ij}\le 1-AF_{if}+AF_{jf} \tag{7}$$

$$Z_{ij}\le 1+AF_{if}-AF_{jf} \tag{8}$$

(For i=1, …, N−1, j=i+1, …, N, f=1, …, F)

$$FN\ge\Sigma_f fAF_{if} \quad \forall i \tag{9}$$

3-2. Non-overlapping Constraints

Each equipment item that is allocated on the same floor should avoid overlapping against each other. For this, two binary parameters $E1_{ij}$, $E2_{ij}$ and one appropriate upper bound, UB, are introduced. The combination of $E1_{ij}$ and $E2_{ij}$ makes the following equations active or not. (Symbols x and y stand for the geometrical center of each equipment.)

For i=1, …, N−1, j=i+1, …, N

$$x_i-x_j+UB(1-Z_{ij}+E1_{ij}+E2_{ij})\ge\frac{Le_i+Le_j}{2} \tag{10}$$

(Activated if $E1_{ij}=0$, $E2_{ij}=0$, $Z_{ij}=1$)

$$x_j-x_i+UB(2-Z_{ij}-E1_{ij}+E2_{ij})\ge\frac{Le_i+Le_j}{2} \tag{11}$$

(Activated if $E1_{ij}=1$, $E2_{ij}=0$, $Z_{ij}=1$)

$$y_i-y_j+UB(2-Z_{ij}+E1_{ij}-E2_{ij})\ge\frac{De_i+De_j}{2} \tag{12}$$

(Activated if $E1_{ij}=0$, $E2_{ij}=1$, $Z_{ij}=1$)

$$y_j - y_i + UB(3 - Z_{ij} - E1_{ij} - E2_{ij}) \geq \frac{De_i + De_j}{2} \quad (13)$$

(Activated if $E1_{ij}=1$, $E2_{ij}=1$, $Z_{ij}=1$)

Above equations become all inactive when Z_{ij} is equal to zero, which means equipment units i and j are located on the different floors. If one equation is active, then UB makes others inactive.

3-3. Distance Constraints

All connections between the equipment can be possible through the geometry center of equipment. The rectilinear distance has been introduced to consider more realistic piping costs. The total rectilinear distance between equipment item i and j, RD_{ij}, is determined by considering relative distances in x, y, z coordinates:

$$RD_{ij}=R_{ij}+L_{ij}+A_{ij}+B_{ij}+U_{ij}+D_{ij} \quad \text{(For i=1, …, N−1, j=i+1, …, N)} \quad (14)$$

The relationships between each relative distance component in Eq. (19) are as follows:

$$R_{ij}-L_{ij}=x_i-x_j \quad (15)$$
(For i=1, …, N−1, j=i+1, …, N)

$$A_{ij}-B_{ij}=y_i-y_j$$
(For i=1, …, N−1, j=i+1, …, N) (16)

$$U_{ij}-D_{ij}=H\Sigma_f(AF_{if}-AF_{jf})$$
(For i=1, …, N−1, j=i+1, …, N, f=1, …, F) (17)

3-4. Safety Distance Constraints

The expected damage cost of unit i, DC_i, can be calculated as follows:

$$DC_i=fr_i*(PC_i+\Sigma_j P_{ij}*PC_j) \quad (\text{For } \forall i\in I^p, \forall j\neq i) \quad (18)$$

It is assumed that there are no other property damages except the purchase cost, PC, of each unit and no domino effects occur after the physical explosion. The parameter fr_i is accident-frequency of each potential unit. P_{ij} is the probability of damage of unit j when the unit i is exploded. P_{ij} varies nonlinearly with respect to the distance, for which a piecewise linearization is performed.

As the result of piecewise linearization, the rectilinear distance between unit i and unit j, RD_{ij}, is divided up into M pieces by Eq.

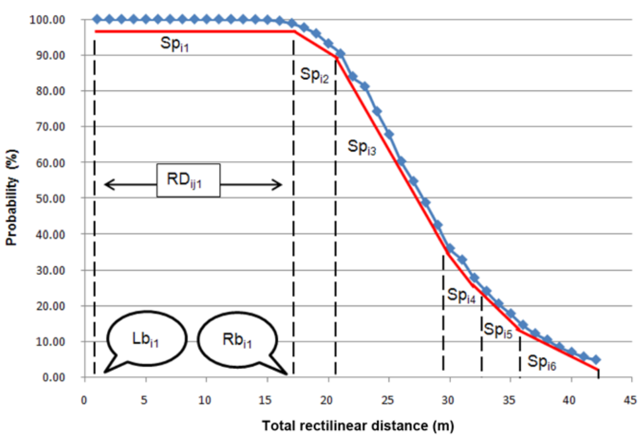

Fig. 2. An example of piecewise linearization of P_{ij}.

(4) and only one RD_{ijm} has the non-zero value due to Eqs. (5) and (6). BP_{ijm} is the binary parameter which becomes 1, if m^{th} linear section is activated; otherwise, it is 0. Finally, P_{ij} is defined by Eq. (7). Sp_{im} is the slope of m^{th} linear section and Cn_{im} is a constant corresponding to the intercept determined by the linear correlation of Lb_{im} and Ub_{im}. Fig. 2 shows an example of piecewise linearization.

For $\forall i\in I^p$, $\forall j\neq i$, m=1, …, M

$$RD_{ij}=\Sigma_m RD_{ijm} \quad (19)$$

$$Lb_{im}BP_{ijm}\leq RD_{ijm}\leq Ub_{im}BP_{ijm} \quad (20)$$

$$\Sigma_m BP_{ijm}=1 \quad (21)$$

$$P_{ij}=\Sigma_j\Sigma_m(Sp_{im}RD_{ijm}+Cn_{im}BP_{ijm}) \quad (22)$$

3-5. Objective Function

The objective function is defined as follows, minimizing the sum of pipe connection cost, pumping costs (vertical and horizontal), expected damage cost, floor construction cost, land cost and area-dependent land cost:

$$\text{Min. } \Sigma_i\Sigma_{j\neq i}[CC_{ij}*RD_{ij}+CV_{ij}*D_{ij}+CH_{ij}(R_{ij}+L_{ij}+A_{ij}+B_{ij})] + fr_iDC_i+FC*FN+LC*LA+FC2*FN*LA \quad (23)$$

The objective function should minimize the total cost, subject to floor, equipment orientation, non-overlapping, land area, distance and equipment damage cost constraints. Since Eq. (23) has nonlinearity, following equations are added to maintain the whole problem as an MILP:

$$LA=\Sigma_s AR_s*Q_s \quad (24)$$

$$\Sigma_s Q_s=1 \quad (25)$$

$$NQ_s\leq F*Q_s \quad (26)$$

$$FN=\Sigma_s NQ_s \quad (27)$$

where AR_s is a parameter for the candidate area list and NQ_s is an integer variable for the number of floors. Then, the objective function is re-written as follows:

$$\text{Min. } \Sigma_i\Sigma_{j\neq i}[CC_{ij}*RD_{ij}+CV_{ij}*D_{ij}+CH_{ij}(R_{ij}+L_{ij}+A_{ij}+B_{ij})] + fr_iDC_i+FC*FN+LC*\Sigma_s AR_s*Q_s+FC2*\Sigma_s AR_s*NQ_s \quad (28)$$

Equipment damage cost constraints, Eqs. (3)-(7), and other constraints, Eqs. (8)-(22) and Eqs. (24)-(27), are solved together to obtain the optimal solution.

4. Case Studies

The proposed MILP model was solved by GAMS coupled with CPLEX. Results for two different cases are presented.

4-1. Example 1: Ethylene Oxide (EO) Plant

The EO plant is well-known due to its recent accident histories. The EO reactor, EO absorber and the CO_2 absorber are selected as potential units of physical explosions in this case. The floor construction cost FC is assumed as 3,330/m^2; the area-dependent floor construction cost FC2 is assumed as 66.7/m^2 and the land cost LC is assumed as 26.6/m^2. Two potential floors are assumed to be available and the floor height is assumed as 5 m. Table 1 shows basic data for the case study.

Table 2 shows overpressure, probit and probabilities of damage of each pertinent unit with respect to the distance. Fig. 4 shows damage probabilities of each potential explosion unit according to the

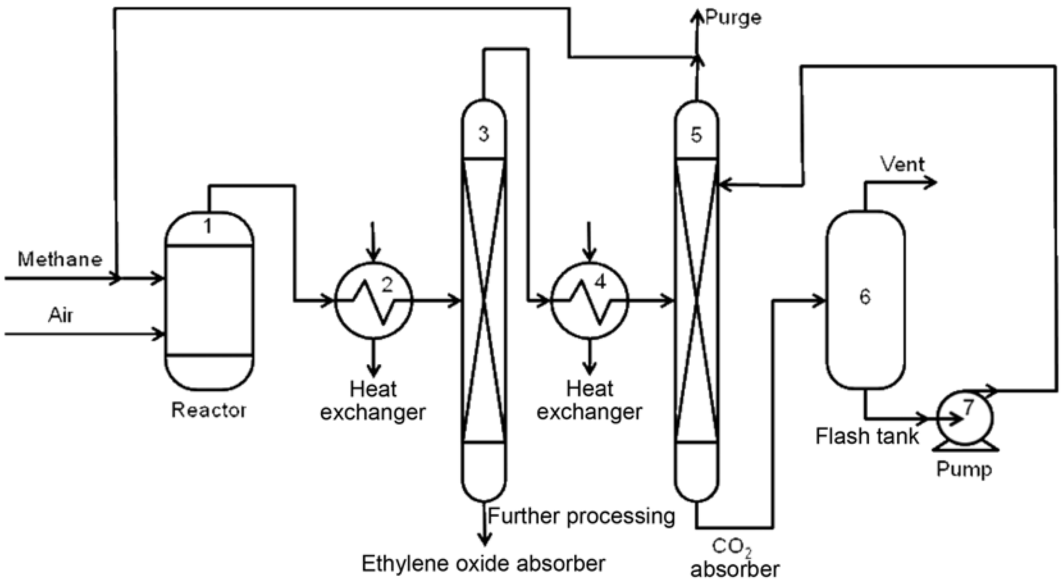

Fig. 3. A PFD for ethylene oxide plant [4].

Table 1. Basic information for example 1

Equipment number	Dimension a	Dimension b	Purchase cost	Connection	CC_{ij} (per m)	CH_{ij} (per m)	CV_{ij} (per m)
1	5.22	5.22	335,000	(1, 2)	200	400	4000
2	11.42	11.42	11,000	(2, 3)	200	400	4000
3	7.68	7.68	107,000	(3, 4)	200	300	3000
4	8.48	8.48	4,000	(4, 5)	200	300	3000
5	7.68	7.68	81,300	(5, 1)	200	100	1000
				(5, 6)	200	200	2000
6	2.60	2.60	5,000	(6, 7)	200	150	1500
7	2.40	2.40	1,500	(7, 5)	200	150	1500

Table 2. Data for each explosion potential unit, example 1

	Reactor			EO/CO_2 absorber		
Burst pressure (kPa)	1,013			1,013		
Accident frequency*	0.6/year			0.086/year		
Distance from unit (m)	Overpressure (kPa)	Probit	Prob. of damage (%)	Overpressure (kPa)	Probit	Prob. of damage (%)
1	3407.05	20.12	100	2596.44	19.33	100
4	174.19	11.44	100	125.45	10.48	100
8	43.72	7.4	99.18	33.81	6.65	95.07
12	22.63	5.48	68.40	18.11	4.83	43.18
16	14.93	4.26	23.10	12.16	3.67	9.10
20	11.04	3.38	5.29	9.06	2.81	1.41
24	8.70	2.69	1.04	7.14	2.11	0.19

*This frequency is a result of statistical analysis of past accidents, but it could be an overestimation of actual accident frequencies

distance.

Obtained results are summarized in Table 3 and Figs. 5-8. Since accident frequencies vary over operation years, operation years 1, 5, and 10 are considered as simulation cases. The accident probabilities increase as the operation year is prolonged, and consequently, the optimal layout for each year is continuously changed. Every layout which is shown at Figs. 5-8 is the result of competition between costs and safety.

Evidently, the total cost of the case which includes a safety factor is much lower than that of another case which does not consider any safety factor. In the case of no safety considerations, the layout cost is the lowest but the expected damage cost of EO reactor is significantly higher than that of the case with safety consideration. As a result, the case which considers a safety factor is regarded as

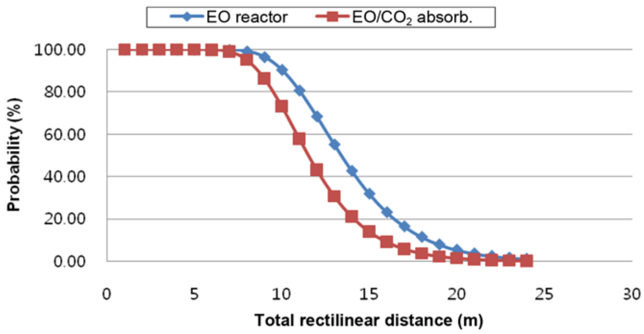

Fig. 4. Damage probabilities, example 1.

the safe plant layout since the damage cost is expected much lower than that of another case when the physical explosion could take place.

Table 3 summarizes cost changes of the case with safety consideration compared against cases without any safety considerations. The layout shown at Fig. 8 will be the best choice for the EO plant which is planned to operate for 10 years. Compared to Fig. 5, which does not consider any safety factor, it shows the layout where explosive units 1, 3, 5 are separated against each other. Thus, expected damage costs are minimized.

4-2. Example 2: Benzene Production Process

The second case is the process of benzene production via the hydrodealkylation of toluene. The PFD and basic data are shown in Fig. 9 and Table 4. The reactor, the HP separator and the LP separator are selected as potential units of physical explosions in this case. Damage probabilities of potential explosion units are shown in Fig. 10. The accident frequency of reactor is assumed as 0.6/year and the accident frequency of HP/LP separator as 2.19/year.

The benzene production process has more complexity than Exam-

Table 3. Results of Example 1

	Operation year	Expected damage cost of EO reactor	Expected damage cost of EO absorber	Expected damage cost of CO_2 absorber	Layout cost	Total cost
Without safety considerations	1 Year	326514	29698	28429	95889	480530
	5 Year	1632570	148490	142145	95889	2019094
	10 Year	3265140	296980	284290	95889	3942299
With a safety sonsideration	1 Year	225140	13635	11094	108664	358533
	5 Year	1154700	76267	56300	130134	1417401
	10 Year	2238700	131280	114210	256998	2741188

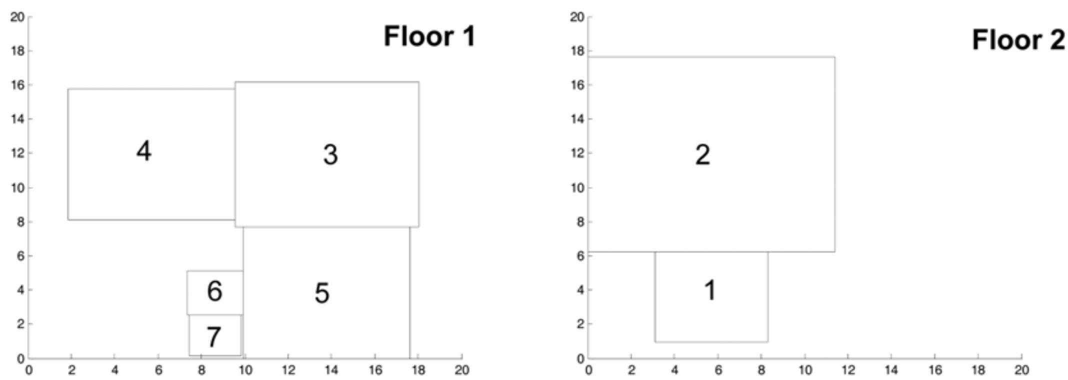

Fig. 5. Optimal layout of example 1, without safety considerations.

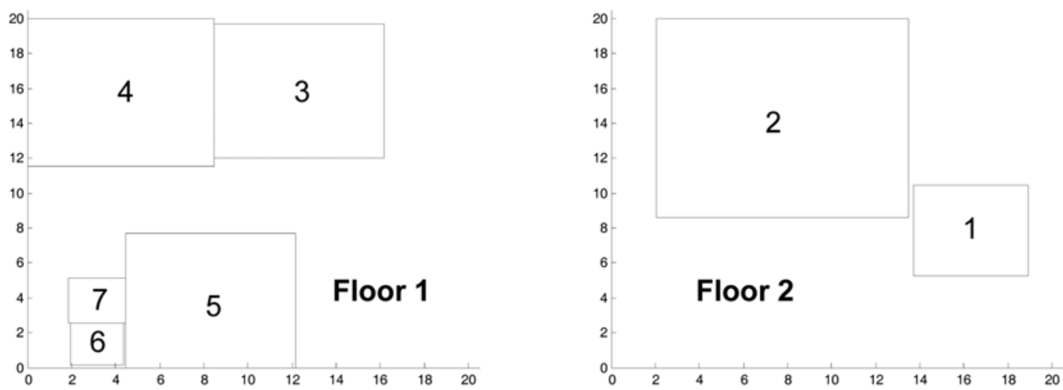

Fig. 6. Optimal layout of example 1, with safety consideration (1 year).

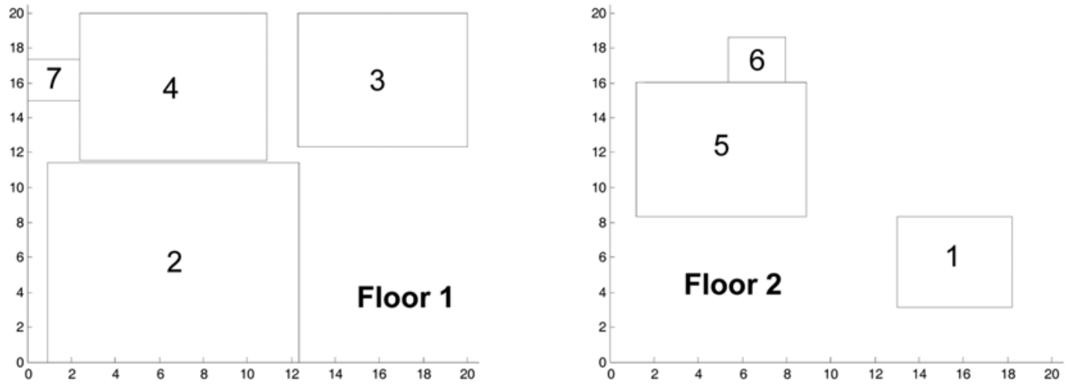

Fig. 7. Optimal layout of example 1, with safety consideration (5 year).

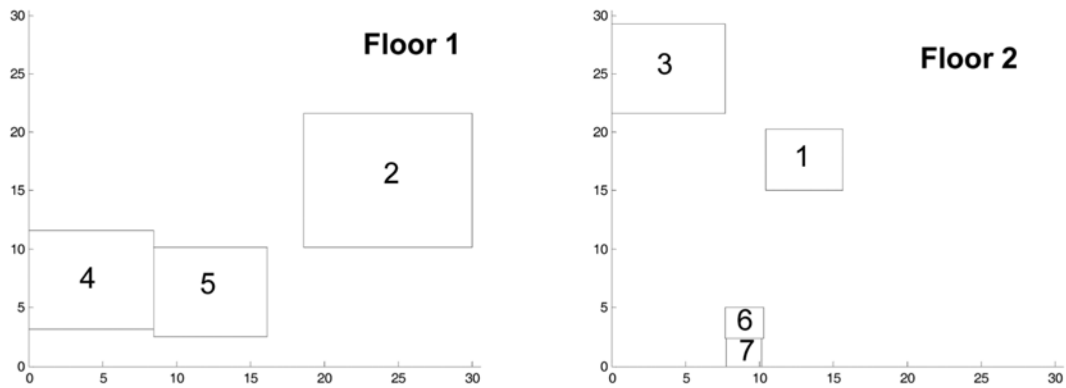

Fig. 8. Optimal layout of example 1, with safety consideration (10 year).

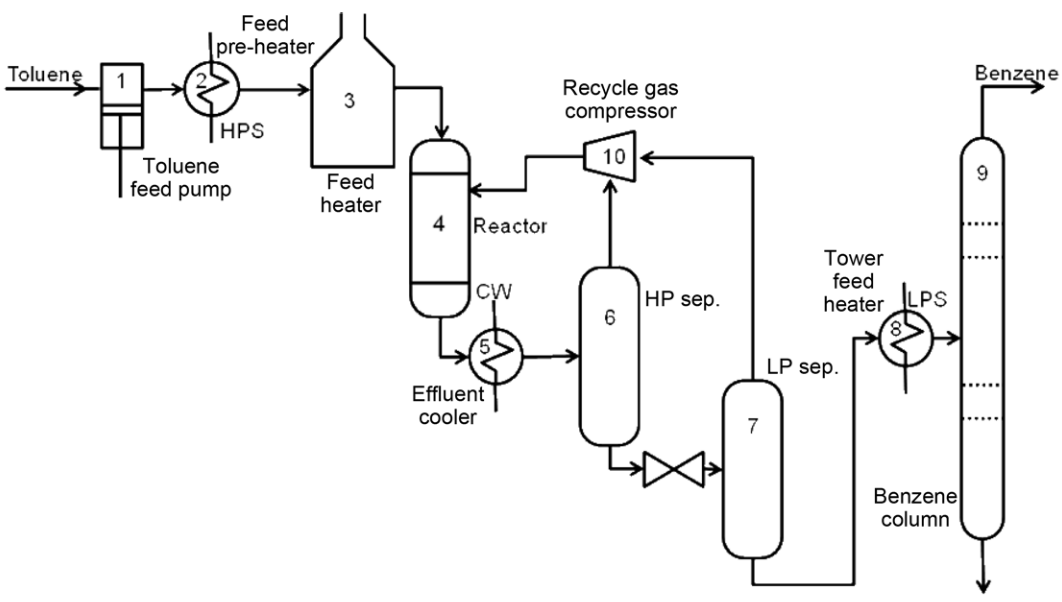

Fig. 9. PFD for the benzene production [9].

ple 1 since the number of units and connections is increased. In this case, as the optimal layout is changed according to the operation year, the plant area is also increased. As a result, the layout cost of the case which considers a safety factor is increased than another case. But, as the sum of expected damage cost is dramatically reduced, the total layout cost is also reduced more than that of another case which does not consider any safety factors.

Results are summarized at Table 5 and Figs. 11-14. The layout shown at Fig. 14 will be a proper solution for the benzene production process which is planned to operate for 10 years. Compared to Fig. 11, which does not consider any safety factor, it shows the layout where explosive units 4 and 6 are separated against each other. The

Table 4. Basic information for Example 2

Equipment number	Dimension a	Dimension b	Purchase cost	Connection	CC_{ij} (per m)	CH_{ij} (per m)	CV_{ij} (per m)
1	1	2	2,000	(1, 2)	100	250	2500
2	3	4	10,000	(2, 3)	100	250	2500
3	8	10	55,000	(3, 4)	100	250	2500
4	3	14	215,000	(4, 5)	200	250	2500
5	10	12	30,000	(5, 6)	200	250	2500
6	2	4	6,500	(6, 7)	150	30	300
				(6, 10)	30	250	2500
7	2	4	4,000	(7, 8)	150	30	300
				(7, 10)	30	30	300
8	2	3	6,000	(8, 9)	150	30	300
9	5	8	150,000				
10	3	5	9,000	(10, 4)	50	250	2500

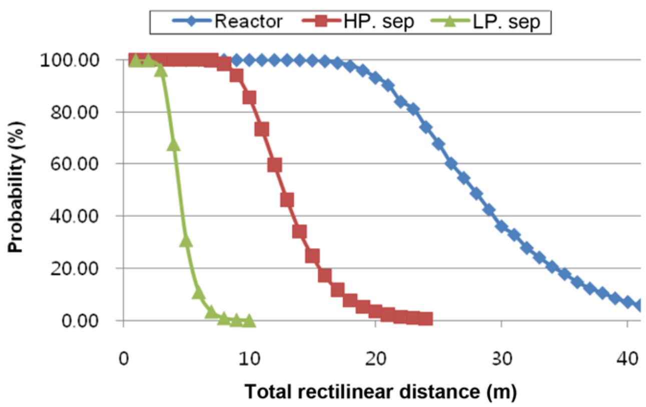

Fig. 10. Damage probabilities, example 2.

safety distance of unit 7 is allocated shorter than others since unit 7 is less explosive.

Table 6 summarizes cost changes of the case with safety consideration compared against the case without any safety considerations. In both examples, the total cost (sum of the plant layout cost and the expected damage cost) was reduced by 25-87% more than that of another case. As discussed above, the case which considers a safety factor generates more reasonable and safe layouts in the presence of the risk of the physical explosion.

CONCLUSION

An MILP model was presented to find a multi-floor optimal layout considering a safety factor. The expected damage cost must be con-

Table 5. Results of example 2

	Operation year	Expected damage cost of reactor	Expected damage cost of HP sep.	Expected damage cost of LP sep.	Layout cost	Total cost
Without safety considerations	1 year	210654	741797	507095	70655	1530201
	5 year	1053270	3708985	2535475	70655	7368385
	10 year	2106540	7417970	5070950	70655	14666115
With a safety consideration	1 year	149770	18619	10440	235649	414478
	5 year	672800	71175	43800	292464	1080239
	10 year	1290900	142350	87600	359956	1877806

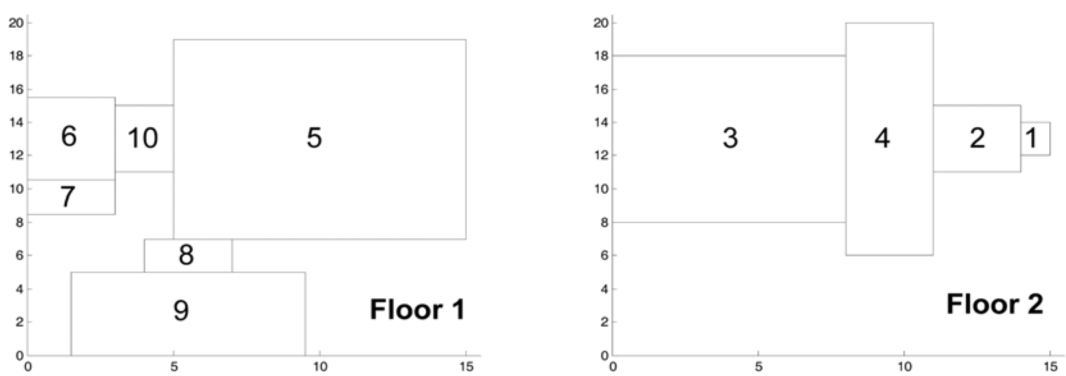

Fig. 11. Optimal layout of example 2, without safety considerations.

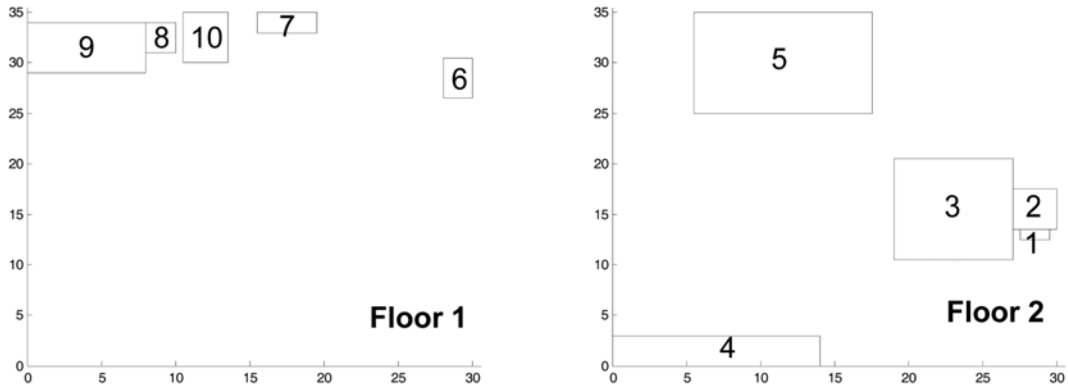

Fig. 12. Optimal layout of example 2, with safety consideration (1 year).

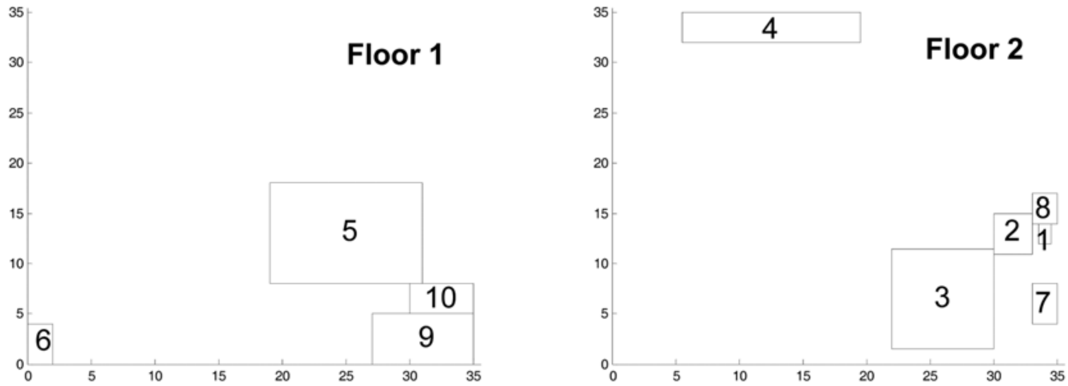

Fig. 13. Optimal layout of example 2, with safety consideration (5 year).

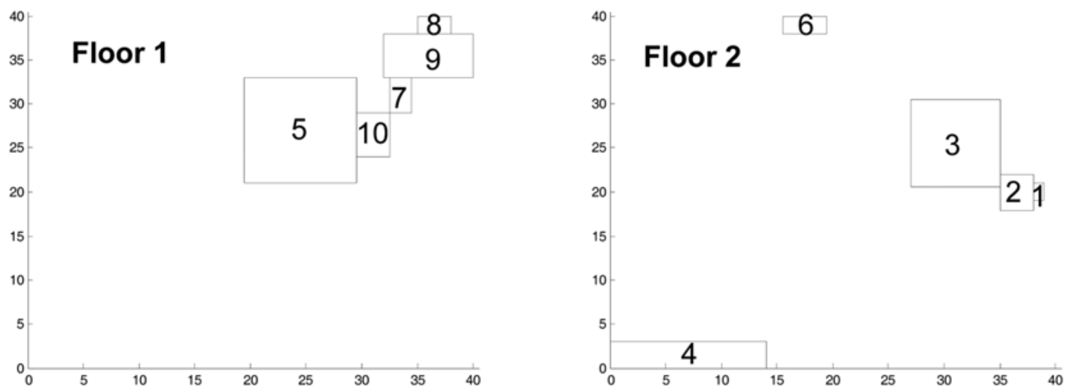

Fig. 14. Optimal layout of example 2, with safety consideration (10 year).

Table 6. Cost changes (%) relative to the case without any safety consideration

		Example 1			Example 2		
With a safety consideration	Operation year	Total costs	Expected damage costs	Layout costs	Total costs	Expected damage costs	Layout costs
	1	−25.39%	−35.04%	+13.32%	−72.91%	−87.75%	+233.52%
	5	−29.80%	−33.07%	+35.71%	−85.34%	−89.21%	+313.93%
	10	−30.47%	−35.42%	+168.02%	−87.20%	−89.58%	+409.46%

sidered to generate more reasonable and safe layouts in the presence of the risk of the physical explosion: consequence analysis was introduced and utilized for that matter. To avoid adopting a linear assumption about a relationship between the equipment damage and the distance, the presented model uses the TNT equivalency method to predict costs of equipment damage instead of using the linear correlation based on Dow's fire and explosion index system. The model successfully resolves a conflict between expected damage costs and layout costs, such as land area, floor construction and connection costs, and finds the optimal location of each unit for multi-floor layout problems. Since MILP techniques are used, the model guarantees that a global solution is obtained.

The proposed model has successfully been applied to illustrative examples and proved its applicability. Since the presented model successfully finds global optimum between safety and costs, the total layout cost including the expected damage cost is dramatically reduced in the case which considers a safety factor. This method will be valuable in finding an optimal layout of processes with safety considerations, especially ones with a low equipment number but constructed in a compact multi-floor fashion like a liquefaction process for LNG Floating Production and Storage Offloading (FPSO).

ACKNOWLEDGEMENT

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NOMENCLATURE

a : a constant −0.2144 in the case of overpressure
b : a constant 1.3503 in the case of overpressure
c_i : a constant, in the case of overpressure

i=0	2.7808	6	−0.0268
1	−1.6959	7	0.1091
2	−0.1542	8	0.0016
3	0.5141	9	−0.0215
4	0.0989	10	0.0001
5	−0.2939	11	0.0017

I^p : the set of explosion potential units
P : the probability of damage
P_{op} : the overpressure [kPa]
P_0 : the standard pressure [14.7 psia]
P_1 : the initial pressure of the compressed gas [psia]
Pr : the probit
R : the distance from the explosion center [ft]
R_g : the gas constant [1.987 Btu/lb-mole°R]
T_0 : the standard temperature [492 °R]
V : the volume of the compressed gas [ft^3]
W : the energy [lb TNT]
Z : the scaled distance

Indices
i, j : equipment item
f : potential floor
m : linear section
s : candidate area

Parameters
a_i : one dimension of unit i
AF_{if} : the binary parameter
b_i : the other dimension of unit i
BP_{ijm} : the binary parameter which equal to 1, if mth linear section is activated, otherwise 0
Cn_{im} : a constant
CC_{ij} : the connection cost between unit i and j per unit length
CH_{ij} : the horizontal pumping cost per unit length
CV_{ij} : the vertical pumping cost per unit length
$E1_{ij}$: the binary parameter
$E2_{ij}$: the binary parameter
FC : the fixed floor construction cost
FC2 : the area dependent floor construction cost
fr_i : the accident frequency
H : the floor height
Lb_{im} : the lower bound of mth linear section
LC : the land cost per unit area
O_i : the binary parameter
P_{ij} : the probability of damage of unit j when unit i is exploded
PC_i : the purchase cost of unit i
PC_j : the purchase cost of unit j
Q_s : the binary parameter
Sp_{im} : the slope of mth linear section
UB : the upper bound
Ub_{im} : the upper bound of mth linear section
Z_{ij} : the binary parameter

Variables
A_{ij} : relative distance in y coordinates between unit i and j, if i is above j
AR_s : candidate area list variable
B_{ij} : relative distance in y coordinates between unit i and j, if i is below j
D_{ij} : relative distance in z coordinates between unit i and j, if i is lower than j
DC_i : the damage cost of unit i
De_i : the depth of unit i
FN : the number of floors
L_{ij} : relative distance in x coordinates between unit i and j, if i is to the left of j
LA : the land area
Le_i : the length of unit i
NQ_s : continuous variable for the number of floors
R_{ij} : relative distance in x coordinates between unit i and j, if i is to the right of j
RD_{ij} : the total rectilinear distance between unit i and j
RD_{ijm} : the total rectilinear distance of mth linear section
U_{ij} : relative distance in z coordinates between unit i and j, if i is higher than j
x_i, y_i : coordinates of geometrical center of unit i

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