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Risk based 3-dimensional and multifloor plant layout optimization for liquefied natural gas (LNG) liquefaction process

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Abstract−This paper presents a mathematical formulation for solving a 3-dimensional and multifloor plant layout problem with safety considerations. The presented model is formulated as a mixed integer non-linear programming (MINLP) model and quantifies risk by utilizing Dow's fire and explosion index (Dow's F&EI) system. The applicability of the model is demonstrated by an illustrative example regarding layout optimization for the C_3MR liquefaction processes.

Keywords: Risk, 3-Dimensional, Plant Layout, Optimization, LNG Liquefaction

INTRODUCTION

There has been a growing interest in liquefied natural gas (LNG) worldwide because natural gas is one of the cleanest fuels that emit low carbon dioxide, SOx, and NOx during combustion. According to the International Energy Agency (IEA), there will be an increasing demand for natural gas by 2040 [1]. Currently, more than 30 percent of natural gas trading involves LNG [2] since LNG is suitable for long-distance transportation because of its high volume reduction [3].

LNG can be produced through various LNG liquefaction processes, such as nitrogen-based expansion cycles and mixed refrigerant (MR)-based cycles. Among them, the MR-based liquefaction cycles have various types of processes, but unfortunately most of them are very complicated and dangerous. Therefore, developing a layout that considers safety aspects is very important for LNG liquefaction processes.

To achieve inherent safety for the LNG liquefaction processes, the process layout optimization problems must be studied. A good plant layout could reduce the risk of a liquefaction process, as it would separate dangerous pieces of equipment from each other. In addition, a proper layout could reduce the capital expenditure (CAPEX) of a chemical plant, as it would reduce the land cost, the floor construction cost, the connection cost, etc.

A number of studies have been conducted over the last two decades to find solutions to the optimal layout problems. Georgiadis et al. suggested the grid-based mixed integer linear programming (MILP) model to solve 3-dimensional and multifloor plant layout problems [4,5]. They used the grid information to determine the equipment location and the required land area. However, their approach cannot reflect the exact equipment dimensions and floor area since the grid-based approach is a non-continuous domain-based approach, even though its applicability was proven through various examples. Patsiatzis et al. proposed the MILP model to solve two-dimensional and multifloor layout problems [6]. Their model can reflect the exact equipment dimensions and floor area because they formulated the model based on a continuous domain. In addition, the proposed model can reflect the piping cost between equipment more precisely because they used the rectilinear distance instead of using the Euclidean distance. Xu and Papageorgiou suggested an algorithm for solving the continuous domain-based MILP model for the layout problem more efficiently by fixing some binary variables [7]. Hwang and Lee tried to find the optimal layout of various liquefaction processes for the LNG floating production, storage and offloading (FPSO) using the continuous domain-based MINLP model [8], which was suggested by Patsiatiz et al. [6]. They suggested the module based approach to solve a large scale LNG layout problem.

These studies have given insight into how to find the optimal solutions for the layout problem of the LNG liquefaction process. However, those studies cannot give a proper method that can address safety issues in the layout problem. As mentioned, safety is a crucial issue in the layout problem of the LNG liquefaction process because most LNG liquefaction processes are dangerous.

Fortunately, there have been some researches that try to address safety issues in the layout problem. Penteado and Ciric formulated the mixed integer non-linear programming (MINLP) model to solve a two-dimensional single-floor layout problem [9]. They tried to include a safety factor in the layout problem, taking into account the cost of protective devices and the financial risk. However, the proposed model in their study is difficult to apply a large size problem since the model is highly non-linear because the financial risk terms include permutations with repetition and many probability terms. In addition, their model cannot reflect exact piping cost between equipment because they adopt the Euclidean distance instead of using the rectilinear distance, and cannot handle multifloor prob-

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lems also. Patsiatzis et al. proposed the continuous domain-based MINLP model considering safety for two-dimensional and single-floor layout problems [10]. They tried to extend their MILP model, which was proposed in their previous research [6], to address safety issues as they adopted the financial risk based on Penteado and Ciric's research. However, the proposed model still includes a highly non-linear risk term so that its application is limited to simple and single-floor layout problems. To overcome the drawbacks of the previous research, Patsiatzis et al. proposed the MILP model utilizing Dow's fire and explosion index (Dow's F&EI) to quantify the risk of a process [11]. As they successfully utilized Dow's F&EI into the layout problem, they could suggest the simplified MILP model. However, their model is still good for single-floor layout problems. Park et al. formulated an MILP model to solve a two-dimensional multifloor layout problem with safety considerations using the TNT equivalent method [12]. They tried to extend the previous MILP model to address multifloor layout problems with safety considerations. However, their model cannot handle the equipment, which should assigned across several floors because of its height because they assumed all equipment heights are lower than a floor height. In addition, the risk quantification using the TNT equivalent method cannot generalize the risk in the layout problem since it considers only an explosion of equipment as potential risks.

A proper mathematical model for the layout of LNG liquefaction processes can solve a 3-dimensional and multifloor layout problem with safety considerations because an LNG liquefaction process consists of several equipment that should assigned across several floors such as main cryogenic heat exchangers, and contains flammable and explosive gases. However, there are no mathematical models to address the 3-dimensional and multifloor layout problem with safety considerations in the previous researches.

In this study, we newly propose a continuous domain-based MINLP model to solve 3-dimensional and multifloor layout problems with safety considerations. The proposed model is formulated based on the previous researches, and multifloor assignment constraints are added to handle the equipment, which should be assigned across several floors. In addition, Dow's F&EI is utilized to quantify the risk, and some mathematical model modification for Dow's F&EI has been made to reflect damage cost between equipment more accurately. The C3-MR liquefaction process is selected as an illustrative example to prove the applicability of the proposed model.

BACKGROUND THEORY

1. LNG Liquefaction Process

There are a number of liquefaction cycles that utilize an MR to liquefy the natural gas (NG), such as the propane precooled mixed refrigerant (C_3-MR) liquefaction cycle, the dual mixed refrigerant (DMR) liquefaction cycle, and the single mixed refrigerant (SMR) liquefaction cycle.

Over the last five decades, the C_3-MR liquefaction cycle has been the most popular liquefaction cycle for an onshore liquefaction plant since it has good thermodynamic efficiency, high capacity

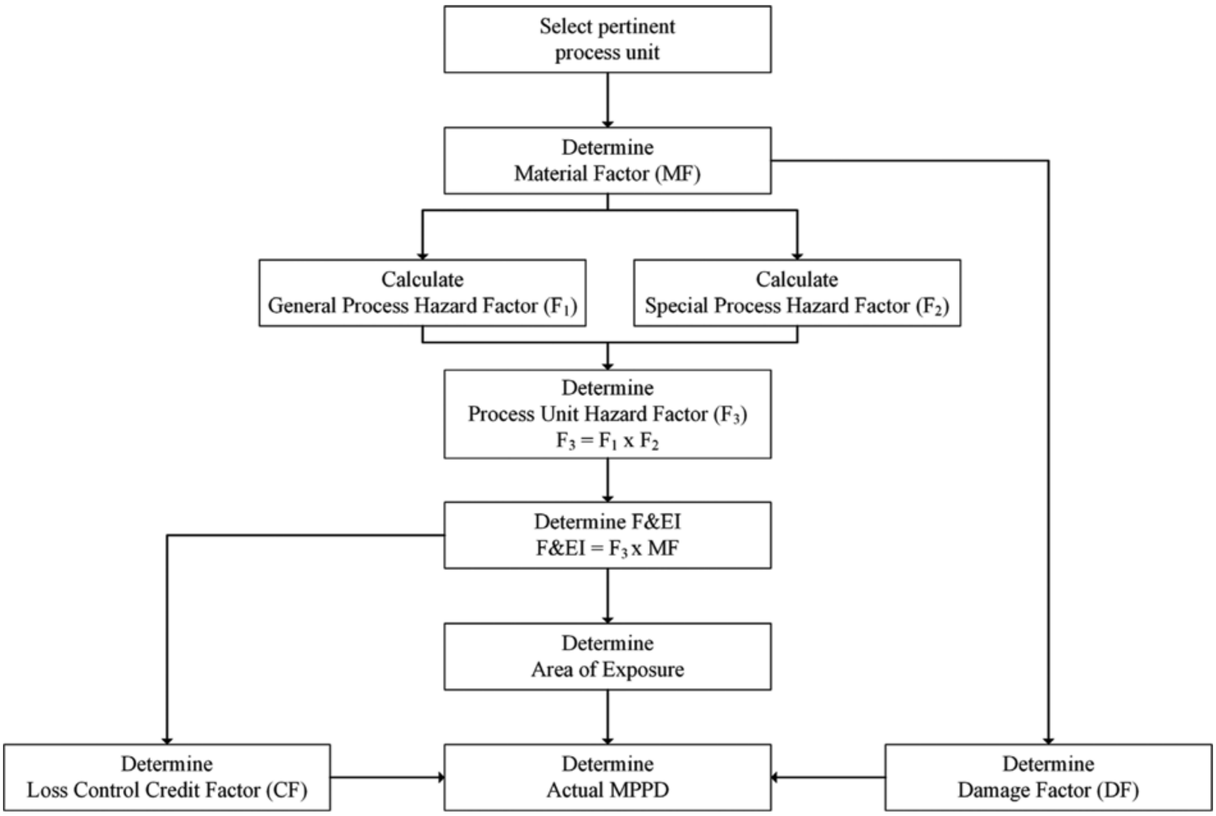

Fig. 1. A procedure for Dow's F&EI.

and good controllability [13]. Therefore, the C_3-MR liquefaction cycle is selected as an illustrative example in this paper because of its generality.

2. Dow's F&EI

Dow's F&EI fire and explosion index has been widely used over the last five decades. It is a very useful tool for determining the potential risk of chemical plants in the early design stage since it provides a systematic, easy, and quantitative method for evaluating the overall risk of a fire and/or an explosion. Several reasons why Dow's F&EI is used widely to quantify the overall risk of the liquefaction process are as follows [14-16]:

- It is easy to use and understand
- The information it requires is simple
- It can evaluate the overall risk in terms of cost
- It can estimate the effects of protective devices on the overall risk.

Dow's F&EI could become unrealistic during a detailed design stage since it is not based on consequence analyses and precise probability calculations [17]. However, in an early design stage, it can be very useful in calculating the overall risk of a process with very limited information, such as the process flow diagrams, the heat and material balances, and the rough cost data. The detailed procedure for Dow's F&EI used in this study is summarized in Fig. 1. Some modification has made from the original procedure to model the procedure.

The first step of Dows' F&EI is selecting a pertinent process unit. Pertinent process unit means a process unit that could have a severe impact on the whole plant. There are several guidelines to selecting the proper pertinent equipment in Dow's F&EI, and the following guidelines are considered in this study:

1) Chemical energy potential
2) Quantity of hazardous material in the equipment
3) Process pressure and process temperature
4) Units critical to plant operation.

The equipment which meets the above requirement tends to have high probability of fire or explosion when an emergency situation occurs.

The second step is the material factor (MF) determination. The MF, which is a measure of potential energy of materials, can be obtained from a table, which provides MFs for a number of chemical compounds, in Dow's F&EI. For instance, the MF value of natural gas, which generally contains methane more than 90 mole%, is 21.

The third step is the process unit hazard factor (F_3) calculation. The process unit hazard factor can be obtained from the general hazard factor (F_1) and the special hazard factor (F_2). The general and special hazard factors are related to the magnitude and the probability of a fire and explosion incident, respectively. Related items for each hazard factor, and scores for each item are well summarized in Dow's F&EI.

The fourth step is the fire and explosion index (F&EI) calculation. As indicated in Fig. 1, the F&EI can be obtained by the multiplication of the process unit hazard factor and the MF. The F&EI is used to estimate the degree of hazard that would result from a fire and explosion incident.

The fifth step is the area of exposure calculation. The area of exposure is the area which contains equipment that could be exposed to a fire or an explosion. The area of exposure is calculated as follows:

$$\text{Area (ft}^2) = \pi(\text{ED})^2$$

where ED stands for the radius of exposure. The radius of exposure can be determined by following equation:

$$\text{ED} = 0.84 \times \text{F\&EI}$$

The sixth step is the damage factor (DF) and the loss control credit factor (CF) determination. The DF represents the overall effect of fire and blast damage, and the DF can be obtained from the process unit hazard factor and the MF with the use of the figure in Dow's F&EI. The CF denotes the probability of reducing and preventing a particular incident, and the CF is the product of many credit factors described in Dow's F&EI. For instance, the credit factor of a pressure relief system is 0.98 and the credit factor of a gas detector is 0.94. If both safety devices are installed on an equipment, the credit factor of the equipment is 0.9212. Credit factors for various devices used in this study are summarized in Table 1.

Table 1. Credit factors for various devices [18]

Devices	Credit factors
Pressure safety valves (PSV)	0.98
Leak detection	0.94
Blow down (BD)	0.96
Emergency shut down (ESD)	0.98

The final step is the actual maximum probable property damage (MPPD), and the actual MPPD represents the possible property damage loss that could result from an incident of fire and explosion with adequate functioning of the protective devices, which are installed on the property. The calculation method for the actual MPPD is described in Section 3.7 in this study.

More detailed calculation methods and procedures for Dow's F&EI are described in Dow's Fire & Explosion Index Hazard Classification Guide, 7^{th} edition [18].

MATHEMATICAL FORMULATION

Next, the new MINLP model with safety considerations for solving 3-dimensional and multifloor layout problems of the LNG liquefaction process will be presented.

1. Problem Description

The optimal layout problem of the LNG liquefaction process can be stated as follows:

Given

1) Number of pieces of equipment and their dimensions
2) Number of floors
3) Connection information between equipment
4) Cost data
5) Floor height
6) Radius of exposure
7) Damage factor
8) Loss control credit factor.

Determine the detailed layout that minimizes the total layout cost.

2. Floor Assignment Constraints

Each piece of equipment should be assigned to one floor, and this can be expressed as follows [6]:

$$\Sigma_{k=1}^{NF} F_{i,k}=1 \quad \forall i \tag{1}$$

$$Z_{i,j} \geq F_{i,k}+F_{j,k}-1 \text{ for } i=1, 2, \cdots, N-1, j=i+1, \cdots, N \tag{2}$$

$$Z_{i,j} \leq 1-F_{i,k}+F_{j,k} \text{ for } i=1, 2, \cdots, N-1, j=i+1, \cdots, N \tag{3}$$

$$Z_{i,j} \leq 1+F_{i,k}-F_{j,k} \text{ for } i=1, 2, \cdots, N-1, j=i+1, \cdots, N \tag{4}$$

$F_{i,k}$ is a binary variable that has a numerical value of 1 if equipment i is assigned to the k^{th} floor and 0 otherwise. $Z_{i,k}$ is also a binary variable that has a numerical value of 1 if equipment i and j are assigned to the same floor and 0 otherwise. NF is the number of floors, and N is the number of equipment.

If equipment i and j are located on the same floor k, $F_{i,k}$ and $F_{j,k}$ are equal to 1. In this case, Eq. (2) is active (i.e. $Z_{i,j} \geq 1$ by Eq. (2)) and forces $Z_{i,j}$ to be equal to 1 since the range of $Z_{i,j}$ is between 0 and 1 (i.e. $0 \leq Z_{i,j} \leq 1$). Otherwise (i.e. ($F_{i,k}=1$, $F_{j,k}=0$) or ($F_{i,k}=0$, $F_{j,k}=1$)), Eq. (3) or (4) is active (i.e. $Z_{i,j} \leq 0$ by Eq. (3) or (4)) and forces $Z_{i,j}$ to be equal to 0.

3. Equipment Orientation Constraints

For the sake of convenience, it is assumed that all equipment have rectangular shapes. All equipment can be parallel to x-axis or y-axis, and the orientation of the equipment can be determined by solving the following equations [6]:

$$L_i = a_i \cdot O_i + b_i \cdot (1-O_i) \quad \forall i \tag{5}$$

$$D_i = a_i + b_i - L_i \quad \forall i \tag{6}$$

L_i is the length of equipment i, and D_i is the depth of equipment i. a_i and b_i are dimensions of equipment i. O_i is a binary variable used to determine the length of equipment i. For instance, if O_i has a numerical value of 1, L_i is equal to a_i based on Eq. (5) and D_i is equal to b_i based on Eq. (6).

4. Non-overlapping Constraints

All equipment that is assigned to the same floor should not overlap each other. To avoid overlapping, the physical location of equipment i and j should be different in x or y direction when equipment i and j are allocated to the same floor (i.e., $Z_{i,j}=1$). It can be achieved by satisfying one of the following inequalities [6]:

$$x_i - x_j + M \cdot (1 - Z_{i,j} + E1_{i,j} + E2_{i,j}) \geq \frac{L_i + L_j}{2} \tag{7}$$

for i=1, 2, ⋯, N−1, j=i+1, ⋯, N

$$x_j - x_i + M \cdot (2 - Z_{i,j} - E1_{i,j} + E2_{i,j}) \geq \frac{L_i + L_j}{2} \tag{8}$$

for i=1, 2, ⋯, N−1, j=i+1, ⋯, N

$$y_i - y_j + M \cdot (2 - Z_{i,j} + E1_{i,j} - E2_{i,j}) \geq \frac{D_i + D_j}{2} \tag{9}$$

for i=1, 2, ⋯, N−1, j=i+1, ⋯, N

$$y_j - y_i + M \cdot (3 - Z_{i,j} - E1_{i,j} - E2_{i,j}) \geq \frac{D_i + D_j}{2} \tag{10}$$

for i=1, 2, ⋯, N−1, j=i+1, ⋯, N

x_i and y_i denote the geometric center of equipment i, and M is a large, arbitrary numerical value. $E1_{i,j}$ and $E2_{i,j}$ are binary variables that have a numerical value of 1 or 0.

Note that if equipment i and j are allocated to the same floor (i.e., $Z_{i,j}=1$), only one equation from Eqs. (7) to (10) will be active depending on the numerical values of $E1_{i,j}$ and $E2_{i,j}$ and if one equation is active, M makes others inactive. For instance:

Eq. (7) is active when $E1_{i,j}=0$ and $E2_{i,j}=0$,
Eq. (8) is active when $E1_{i,j}=1$ and $E2_{i,j}=0$,
Eq. (9) is active when $E1_{i,j}=0$ and $E2_{i,j}=1$,
Eq. (10) is active when $E1_{i,j}=1$ and $E2_{i,j}=1$.

If Zi, j is equal to 0, all Eqs. from (7) to (10) will be made negligible by M.

5. Multifloor Assignment Constraints

In this section, the mathematical model to address the equipment, which should be assigned across several floors because of its height, is newly proposed.

There could be some pieces of equipment that should be assigned across several floors because of their heights. If equipment i must be located across n floors, then equipment i can be divided into n parts, such as i_1, i_2... i_n. The geometric center of each part should be the same, and each part should be assigned to a single floor sequentially. Denote a set of equipment that should be assigned across n floors as I^m. Then, the multifloor assignment constraints can be formulated as follows:

$$x_{i_1} = x_{i_2} = \cdots = x_{i_n} \quad \text{for } \forall i \in I^m, n \leq NF \tag{11}$$

$$y_{i_1} = y_{i_2} = \cdots = y_{i_n} \quad \text{for } \forall i \in I^m, n \leq NF \tag{12}$$

$$\Sigma_{k=1}^{NF-n+1} (F_{i_1,k} \cdot F_{i_2,k+1}, \cdots, F_{i_n,k+n-1}) = 1 \quad \text{for } \forall i \in I^m, n \leq NF \tag{13}$$

Eqs. (11) and (12) force the geometric centers of all divided parts of equipment i to have the same value. In addition, Eq. (13) forces each part of equipment i to be assigned to a single floor sequentially.

For instance, equipment i is assumed to be located across three consecutive floors because of its height. Thus, equipment i is divided into three parts. Then, according to Eqns. (11) and (12), the following equations are true:

$$x_{i_1} = x_{i_2} = x_{i_3} \text{ and } y_{i_1} = y_{i_2} = y_{i_3}$$

Therefore, all geometric centers of all divided parts of equipment i have the same value. In addition, if NF=4 is assumed, then according to Eq. (13), the following equation is true:

$$F_{i_1,1} \cdot F_{i_2,2} \cdot F_{i_3,3} + F_{i_1,2} \cdot F_{i_2,3} \cdot F_{i_3,4} = 1$$

Consequently, equipment i could be located on the 1^{st}, 2^{nd} and 3^{rd} floors or the 2^{nd}, 3^{rd} and 4^{th} floors.

6. Distance Constraints

Instead of using the Euclidean distance, the total rectilinear distance is used to consider the realistic piping costs of the piping used between equipment. The total rectilinear distance between two equipment can be determined by considering relative distances in x, y, and z coordinates [6]:

$$TD_{i,j} = Rt_{i,j} + Lt_{i,j} + Up_{i,j} + Dn_{i,j} + A_{i,j} + B_{i,j} \tag{14}$$

for i=1, 2, ⋯, N−1, j=i+1, ⋯, N

$$Rt_{i,j} - Lt_{i,j} = x_i - x_j \quad \text{for } i=1, 2, \cdots, N-1, j=i+1, \cdots, N \tag{15}$$

$$A_{i,j} - B_{i,j} = y_i - y_j \quad \text{for } i=1, 2, \cdots, N-1, j=i+1, \cdots, N \tag{16}$$

$$Up_{i,j} - Dn_{i,j} = H \cdot \Sigma_{k=1}^{NF} k \cdot (F_{i,k} - F_{j,k}) \quad \text{for } i=1, 2, \cdots, N-1, j=i+1, \cdots, N \tag{17}$$

$Rt_{i,j}$, $Lt_{i,j}$, $A_{i,j}$, $B_{i,j}$, $Up_{i,j}$, and $Dn_{i,j}$ indicate the relative positions of the geometric centers of equipment i and j. H is the floor height and k is an index of floors.

In addition, to make the problem feasible, one variable of each pair ($Rt_{i,j}$, $Lt_{i,j}$), ($A_{i,j}$, $B_{i,j}$) and ($Up_{i,j}$, $Dn_{i,j}$) should be zero. It can be achieved by following equations [11,12]:

$$Rt_{i,j} \le M \cdot Wx_{i,j} \quad \text{for } i=1, 2, \cdots, N-1, j=i+1, \cdots, N \tag{18}$$

$$Lt_{i,j} \le M \cdot (1 - Wx_{i,j}) \quad \text{for } i=1, 2, \cdots, N-1, j=i+1, \cdots, N \tag{19}$$

$$A_{i,j} \le M \cdot Wy_{i,j} \quad \text{for } i=1, 2, \cdots, N-1, j=i+1, \cdots, N \tag{20}$$

$$B_{i,j} \le M \cdot (1 - Wy_{i,j}) \quad \text{for } i=1, 2, \cdots, N-1, j=i+1, \cdots, N \tag{21}$$

$$Up_{i,j} \le M \cdot Wz_{i,j} \quad \text{for } i=1, 2, \cdots, N-1, j=i+1, \cdots, N \tag{22}$$

$$Dn_{i,j} \le M \cdot (1 - Wz_{i,j}) \quad \text{for } i=1, 2, \cdots, N-1, j=i+1, \cdots, N \tag{23}$$

To force one variable of each pair ($Rt_{i,j}$, $Lt_{i,j}$), ($A_{i,j}$, $B_{i,j}$) and ($Up_{i,j}$, $Dn_{i,j}$) to be zero, binary variables $Wx_{i,j}$, $Wy_{i,j}$ and $Wz_{i,j}$ are introduced. For example, if equipment i is located to the right side of equipment j (i.e. $x_i > x_j$), $Lt_{i,j}$ should be zero. When $Wx_{i,j}$ is equal to 1, $Lt_{i,j}$ is zero by Eq. (19). If equipment i is located to the left side of equipment j (i.e. $x_j > x_i$), $Rt_{i,j}$ should be zero. When $Wx_{i,j}$ is equal to 0, $Rt_{i,j}$ is zero by Eq. (18). A similar explanation is valid for Eqs. (20)-(23).

7. Safety Constraints

The purpose of including safety consideration in the layout problem is to obtain a layout, which has a good balance between the construction cost and the loss from an incident, as including the risk term in the objective function. As stated earlier, Dow's F&EI can quantify the risk systematically. Therefore, Dow's F&EI procedures are used to evaluate the risk of a liquefaction cycle in this study.

The mathematical model for Dow's F&EI is developed based on the previous research [11]; however, some mathematical modifications have been made to reflect the damage cost between equipment more precisely. In the previous research, it was assumed that damage cost between equipment linearly decreased according to the distance between equipment. However, assuming that damage cost between equipment is following the probit model (see Fig. 2) seems to be more reasonable [19,20]. Consequently, Eqs. (24)-(27) and (31)-(33) are modified based on the previous research, and Eqs. (28)-(30) are newly added in this study.

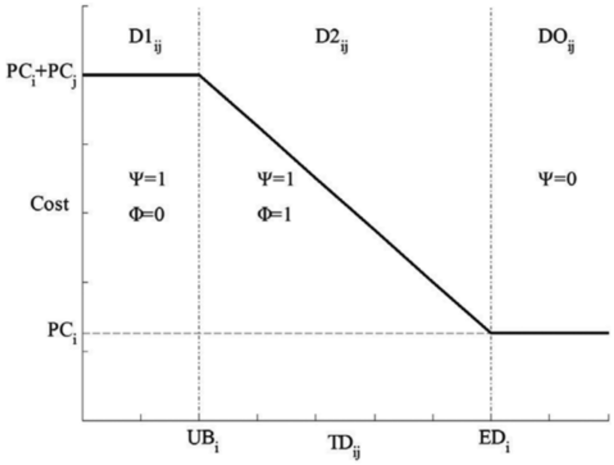

Fig. 2. Damage cost between pertinent equipment i and equipment j.

Consider a set of pertinent equipment i which has a possibility of fire or explosion denoted as I^p. If equipment j is located near equipment i, equipment j will be damaged. To quantify the damage probability of equipment j, new variables, $DI_{i,j}$ and $DO_{i,j}$, are introduced. $DI_{i,j}$ and $DO_{i,j}$ stand for the distance between equipment i and j when equipment j is located inside and outside the radius of the exposure of equipment i respectively. Then, the total rectilinear distance between the pertinent equipment i and equipment j is equal to the summation of $DI_{i,j}$ and $DO_{i,j}$ [11]:

$$TD_{i,j} = DI_{i,j} + DO_{i,j} \quad \text{for } \forall i \in I^P, j \ne i \tag{24}$$

To make the problem feasible, only one of $DI_{i,j}$ and $DO_{i,j}$ will be non-zero and it can be achieved by following equations:

$$DI_{i,j} = \psi_{i,j} \cdot (D1_{i,j} + D2_{i,j}) \quad \text{for } \forall i \in I^P, j \ne i \tag{25}$$

$$DO_{i,j} \ge ED_i \cdot (1 - \psi_{i,j}) \quad \text{for } \forall i \in I^P, j \ne i \tag{26}$$

$$DO_{i,j} \le M \cdot (1 - \psi_{i,j}) \quad \text{for } \forall i \in I^P, j \ne i \tag{27}$$

ED_i is the radius of exposure of pertinent equipment i, and $\Psi_{i,j}$ is a binary variable that has a numerical value of 1 if equipment j is located within the ED_i of pertinent equipment i and 0 otherwise. If equipment j is located inside the ED_i, then $\Psi_{i,j}$ will be equal to 1; consequently, $DO_{i,j}$ will be zero by Eqs. (26) and (27). If equipment i is located outside the ED_i, then $\Psi_{i,j}$ will be equal to 0; consequently, $DI_{i,j}$ will be zero by Eq. (25).

According to Eq. (25), $DI_{i,j}$ is equal to the summation of $D1_{i,j}$ and $D2_{i,j}$. $D1_{i,j}$ stands for the distance between equipment i and j if equipment j is allocated within the distance that makes a damage probability 100 percent. $D2_{i,j}$ stands for the distance between equipment i and j if equipment j is allocated outside the distance that makes a damage probability 100 percent.

To make the problem feasible, only one of $D1_{i,j}$ and $D2_{i,j}$ should be non-zero, and it can be formulated as follows:

$$D1_{i,j} \le UB_i \cdot (1 - \phi_{i,j}) \quad \text{for } \forall i \in I^P, j \ne i \tag{28}$$

$$D2_{i,j} \le ED_i * \phi_{i,j} \quad \text{for } \forall i \in I^P, j \ne i \tag{29}$$

$$D2_{i,j} \ge UB_i * \phi_{i,j} \quad \text{for } \forall i \in I^P, j \ne i \tag{30}$$

UB_i is the maximum distance from pertinent equipment i, at which the damage probability of equipment j is 100 percent. $\Phi_{i,j}$ is a binary variable that has a numerical value of 0 if equipment j is located within the UB_i of pertinent equipment i and 1 otherwise. For instance, if $\Phi_{i,j}$ is 0, $D2_{i,j}$ will be 0 by Eqs. (29)-(30). Consequently, equipment j will be located within the UB_i. If $\Phi_{i,j}$ is 1, $D1_{i,j}$ will be zero by Eq. (28) and equipment j will be located between UB_i and ED_i by Eqs. (29)-(30).

Then, the value of the area exposure of pertinent equipment i

(V_i), which denotes the replacement value of the piece of equipment that could be exposed to a fire or explosion, can be calculated as follows:

$$V_i = PC_i + \Sigma_{j \neq i}\left(PC_j \cdot \psi_{i,j} - PC_j \cdot \psi_{i,j} \cdot \phi_{i,j} \cdot \frac{DI_{i,j}}{ED_{i,j} - UB_i}\right) \quad \text{for } \forall i \in I^P \tag{31}$$

PC_i and PC_j are the purchase costs of equipment i and j. If equipment j is located within the UB_i of pertinent equipment i (i.e., $\Psi_{i,j}=1$ and $\Phi_{i,j}=0$), then V_i is equal to the sum of PC_i and PC_j. If equipment j is located outside the $ED_{i,j}$ of pertinent equipment i (i.e., $\Psi_{i,j}=0$), then V_i is equal to PC_i. Otherwise (i.e., $\Psi_{i,j}=1$ and $\Phi_{i,j}=1$), V_i is equal to PC_i plus some proportion of PC_j that is linearly dependent on the distance from pertinent equipment i.

Finally, the actual MPPD (Ω_i) can be calculated as follows:

$$\Omega_i = DF_i \cdot V_i \cdot \Sigma_{t \in T_i} CF_t \cdot P_{it} \quad \text{for } \forall i \in I^P \tag{32}$$

$$\Sigma_{t \in T_i} P_{it} = 1 \quad \text{for } \forall i \in I^P \tag{33}$$

DF_i stands for the damage factor of equipment i, and CF_t is the loss control credit factor of protective device configuration t. $P_{i,t}$ is a binary variable that has a numerical value of 1 if t is installed on equipment i and 0 otherwise.

Eq. (33) ensures only one protective device configuration t can be installed on pertinent equipment i, and T_i is a set of protective device configurations that can be installed on pertinent equipment i.

8. Additional Constraints

Lower and upper bound constraints on the coordinates of the geometric center are required to avoid the intersection of equipment with the origin of axes or the maximum point of axes.

$$x_i \geq \frac{L_i}{2} \quad \text{for } \forall i \tag{34}$$

$$y_i \geq \frac{D_i}{2} \quad \text{for } \forall i \tag{35}$$

$$x_i + \frac{L_i}{2} \leq X_{max} \quad \text{for } \forall i \tag{36}$$

$$y_i + \frac{D_i}{2} \leq Y_{max} \quad \text{for } \forall i \tag{37}$$

Then, the floor area (FA) can be calculated as follows:

$$FA = X_{max} \cdot Y_{max} \tag{38}$$

9. Objective Function

The objective function to be minimized is as follows:

$$\min \Sigma_i \Sigma_{j \neq i} CC_{ij} \cdot TD_{ij} + \Sigma_i \Omega_i + \Sigma_i \Sigma_{t \in T_i} DC_t \cdot P_{it} + FA \cdot (LC + FC \cdot NF) \tag{39}$$

The first term represents the connection cost. $CC_{i,j}$ is the piping cost per meter between equipment i and j if they are connected to each other. The second term is the actual MPPD, which quantifies the risk of the liquefaction cycle. The third term is the cost of protection devices installed on equipment i. DC_t is the cost of the protective device configuration t. The last term includes the land cost per square meter and the floor construction cost per square

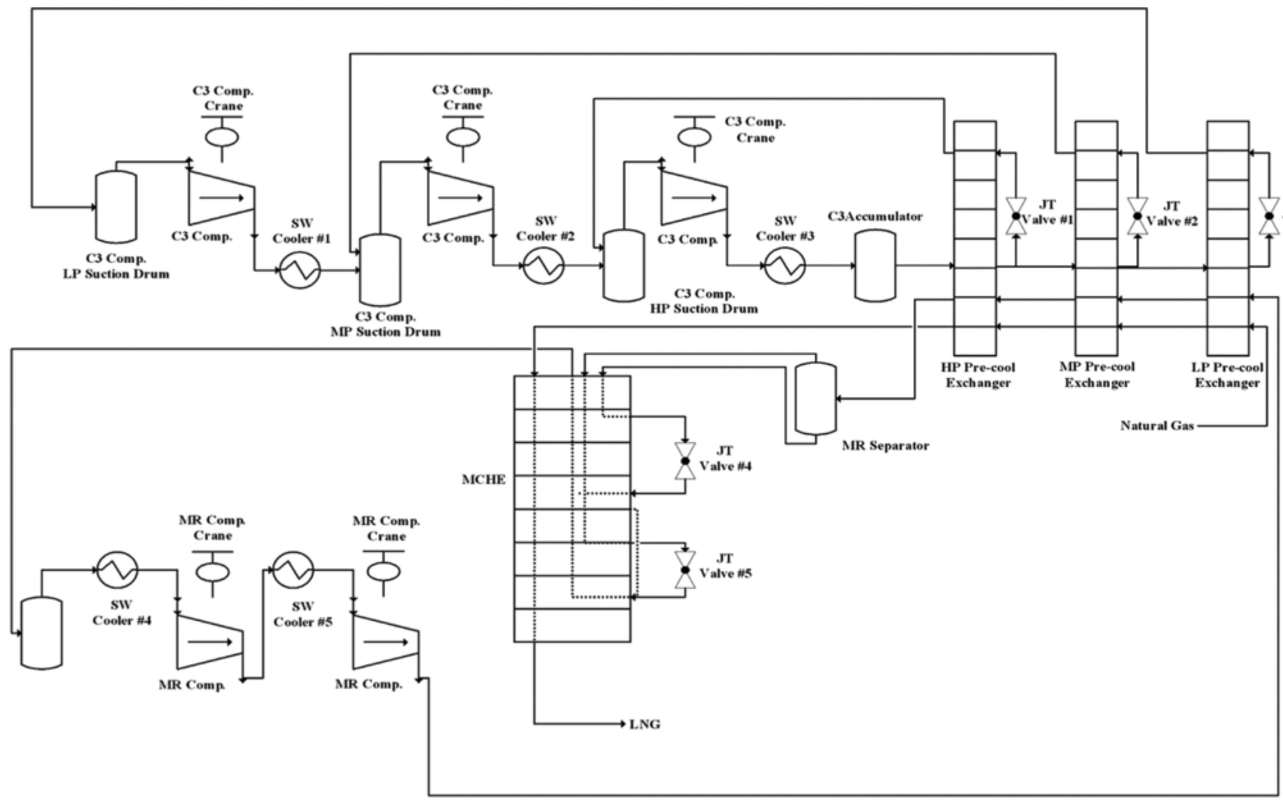

Fig. 3. Detailed drawing of the C_3-MR liquefaction cycle.

meter. LC is the land cost per square meter and FC is the floor construction cost per square meter.

CASE STUDY

Next, an illustrative example will be presented to prove that the present model can find the optimal solution for the layout optimization problem of the LNG liquefaction process. As stated earlier, the C_3-MR liquefaction cycle is selected for a case study, and the C_3-MR liquefaction cycle with 4 million tons per annum (MTPA) is used as illustrative examples.

The C_3-MR liquefaction cycle used in this research consists of two refrigerant cycles: the propane cycle and the mixed refrigerant cycle, one main cryogenic heat exchanger (MCHE), and three C_3 precoolers. A detailed drawing of the C_3-MR is shown in Fig. 3. The examples have been solved using GAMS coupled with the Dicopt solver, which is based on an outer-approximation algorithm [21].

1. Case 1: The C_3-MR Cycle with 4 MTPA

Details regarding the equipment names, numbers and sizes for the C_3-MR liquefaction cycle with 4 MTPA are summarized in Table 2.

It is assumed that the C_3-MR liquefaction cycle is divided into three separate modules. The first modularization of the C_3-MR liquefaction cycle for the layout can be found in Hwang and Lee's study [12]. Their approach is quite reasonable since all equipment in the plant can be modularized based on their function to reduce the project schedule and the construction work volume. In addition, from the viewpoint of optimization, the problem size of the layout optimization of the C_3-MR liquefaction cycle is too large to solve. Therefore, a proper modularization of the C_3-MR liquefaction cycle can help us to find the suboptimal solution to the layout problem, although it cannot guarantee the global optimal solution.

Module 1 includes the C_3 compression system, module 2 includes the precooling system, and module 3 includes the MR compression system and the MCHE. Equipment that should be installed across several floors has multiple equipment numbers, depending on their heights, as stated in section 3.5. The purchase costs for each piece of equipment are summarized in Table 3.

The radii of exposure (ED_i) and damage factors (DF_i) of the pertinent equipment are listed in Table 4. These values are calculated based on Dow's F&EI. Pertinent equipment is selected based on the guidelines stated in Section 2.2.

Possible configurations of the protective devices on pertinent equipment, their purchase costs, and the loss control credit factors are listed in Table 5. The floor height is assumed to be 8 m, the number of floors is assumed to be 5, the land cost is assumed to

Table 2. Equipment details for the C_3-MR cycle (4 MTPA) [8]

No.	Service name	Dimensions (m) (Length×Depth×Height)	Module No.
1	Propane Comp. LP Suction Drum	3.61×3.61×4.60	1
2	Propane Compressor	18.78×5.91×5.73	1
3	Overhead Crane for Propane Comp.	22.73×15.82×5.93	1
4	Sea Water Cooler #1	7.91×1.98×4.94	1
5	Propane Comp. MP Suction Drum	3.37×3.37×4.72	1
6	Sea Water Cooler #2	7.91×1.98×4.94	1
7	Propane Comp. HP Suction Drum	3.21×3.21×4.89	1
8	Sea Water Cooler #3	7.91×1.98×4.94	1
9-10	C_3 Accumulator	4.15×4.15×9.78	2
11-13	HP Precool Exchanger	4.35×4.35×21.75	2
14	JT Valve #1	0.98×0.98×0.98	2
15-17	MP Precool Exchanger	4.22×4.22×21.53	2
18	JT Valve #2	0.98×0.98×0.98	2
19-21	LP Precool Exchanger	4.15×4.15×21.05	2
22	JT Valve #3	0.98×0.98×0.98	2
23-24	MR Comp. Suction Drum	5.44×5.44×8.90	3
25	MR Compressor	17.10×5.93×5.93	3
26	Overhead Crane for MR Comp.	22.73×15.82×5.93	3
27	Sea Water Cooler #4	3.95×2.47×2.97	3
28	Sea Water Cooler #5	3.95×2.47×2.97	3
29-30	MR Separator	4.45×4.45×12.85	3
31-35	MCHE	5.63×5.63×41.52	3
36	JT Valve #4	1.48×1.48×1.48	3
37	JT Valve #5	1.48×1.48×1.48	3

Table 3. Purchase costs of equipment (4 MTPA)

No.	Service name	Purchase cost[a] (×1,000 USD)
1	Propane Comp. LP Suction Drum	195
2	Propane Compressor	17,300
3	Overhead Crane for Propane Comp.	500
4	Sea Water Cooler #1	1,100
5	Propane Comp. MP Suction Drum	195
6	Sea Water Cooler #2	1,100
7	Propane Comp. HP Suction Drum	195
8	Sea Water Cooler #3	1,100
9-10	C_3 Accumulator	600
11-13	HP Precool Exchanger	700
14	JT Valve #1	95
15-17	MP Precool Exchanger	700
18	JT Valve #2	95
19-21	LP Precool Exchanger	700
22	JT Valve #3	95
23-24	MR Comp. Suction Drum	185
25	MR Compressor	17,300
26	Overhead Crane for MR Comp.	500
27	Sea Water Cooler #4	1,100
28	Sea Water Cooler #5	1,100
29-30	MR Separator	950
31-35	MCHE	2,500
36	JT Valve #4	95
37	JT Valve #5	95

[a]The purchase cost was estimated based on the real LNG project. But, some modification for values are made

be 5,000 US dollars per square meter, and the floor construction cost is assumed to be 1,000 US dollars per square meter.

The resulting model for module #1 includes 1,189 equations, 696 decision variables (273 integers and 423 continuous variables); that for the module #2 includes 3,283 equations, 1,504 decision variables (645 integers and 859 continuous variables); and that for the module #3 includes 3,965 equations, 1,928 decision variables (798 integers and 1130 continuous variables).

For module #2, the best integer solution was found at iteration 7 and the search was stopped due to NLP worsening (an increase in the value of the objective function of the NLP sub-problem) at iteration 8. Iteration results of module #2 is shown in Fig. 4. For modules #1 and #3, the best integer solutions are found at iteration 3 and iteration 10, respectively.

The optimized layouts are shown in Fig. 5. Detailed information regarding the optimization results is listed in Tables 6 to 9. For comparison, the optimal layout of the C_3-MR liquefaction cycle without safety considerations is also shown in Fig. 6, and optimization results for a case without safety considerations are listed in Table 10.

Table 4. Radiuses of exposure and damage factors (4 MTPA)

No.	Service name	Radiuses of exposure (m)	Damage factor
1	Propane Comp. LP Suction Drum	27.6	0.737
2	Propane Compressor	48.3	0.829
5	Propane Comp. MP Suction Drum	27.8	0.740
7	Propane Comp. HP Suction Drum	29.5	0.758
9-10	C_3 Accumulator	27.9	0.741
23-24	MR Comp. Suction Drum	26.3	0.722
25	MR Compressor	53.9	0.829
29-30	MR Separator	30.0	0.762

Table 5. Configurations of protective devices, their purchase costs, and loss control credit factors (4 MTPA)

No.	Configurations	Purchase cost[a] (×1,000 USD)	Loss control credit factor
1	1. Pressure safety valves (PSV)	35	0.98
2	1. PSV 2. Leak detection	75	0.9212
3	1. PSV 2. Blow down (BD) 3. Leak detection	130	0.8844
4	1. PSV 2. Blow down (BD) 3. Leak detection 4. Emergency shut down (ESD)	190	0.8667

[a]The purchase cost was estimated based on the real LNG project. But, some modification for values are made

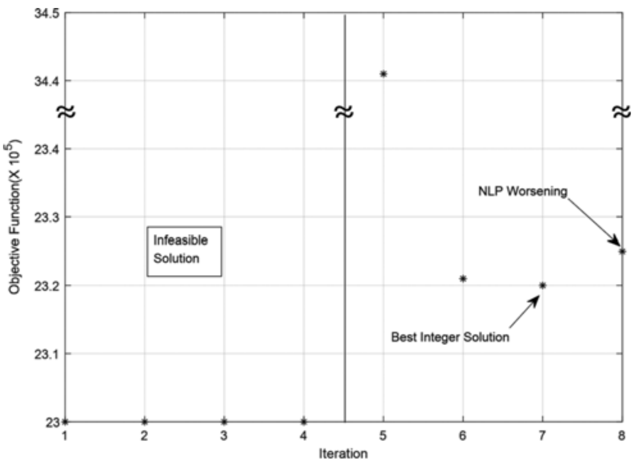

Fig. 4. Iteration results of module #1 with safety considerations (2 MTPA).

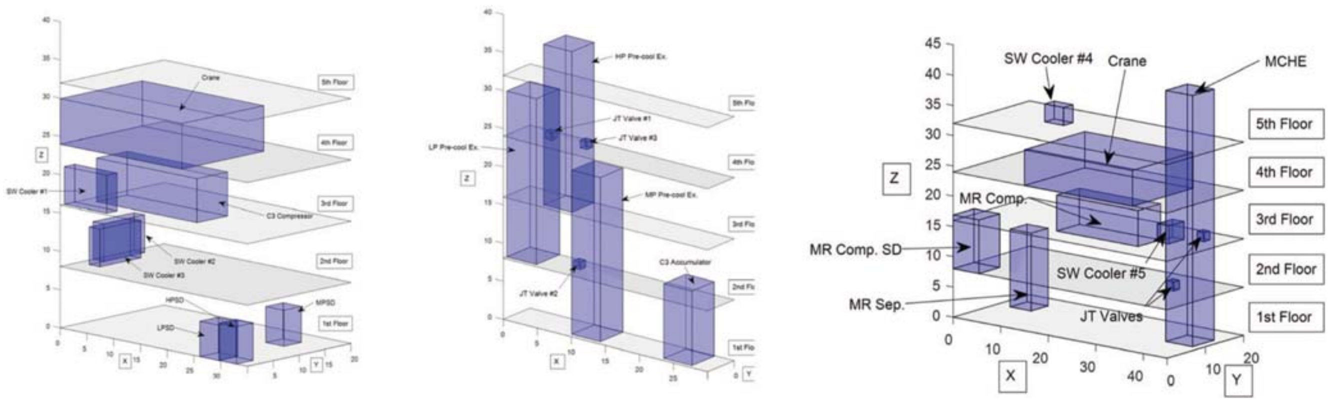

Fig. 5. Optimized layout of the 4MTPA C_3-MR process with safety considerations.

Table 6. Layout summary of module #1 with safety considerations (4 MTPA)

No.	Service name	Orientation (L×D)	Location (x, y)	Assigned floors
1	Propane Comp. LP Suction Drum	3.61×3.61	(27.9, 1.81)	1
2	Propane Compressor	18.78×5.91	(5.91, 11.37)	3
3	Overhead Crane for Propane Comp.	22.73×15.82	(15.82, 11.37)	4
4	Sea Water Cooler #1	7.91×1.98	(1.98, 3.96)	3
5	Propane Comp. MP Suction Drum	3.37×3.37	(3.37, 28.06)	1
6	Sea Water Cooler #2	1.98×7.91	(7.91, 0.99)	2
7	Propane Comp. HP Suction Drum	3.21×3.21	(3.21, 31.35)	1
8	Sea Water Cooler #3	1.98×7.91	(7.91, 2.97)	2

Table 7. Layout summary of module #2 with safety considerations (4 MTPA)

No.	Service name	Orientation (L×D)	Location (x, y)	Assigned floors
9-10	C_3 Accumulator	4.15×4.15	(2.28, 25.14)	1, 2
11-13	HP Precool Exchanger	4.35×4.35	(2.18, 2.18)	2, 3, 4
14	JT Valve #1	0.98×0.98	(2.18, 4.84)	4
15-17	MP Precool Exchanger	4.22×4.22	(2.18, 11.59)	1, 2, 3
18	JT Valve #2	0.98×0.98	(2.18, 8.99)	2
19-21	LP Precool Exchanger	4.15×4.15	(2.18, 7.41)	3, 4, 5
22	JT Valve #3	0.98×0.98	(2.18, 9.97)	4

2. Discussion

In the case of module #1, the C_3 compressor is separated from its suction drums, and the sea water coolers are located near the C_3 compressor to reduce the risk cost (actual MPPD+costs of protection devices). The radius of exposure of each suction drum is much smaller than that of the C_3 compressor; thus allocating near the C_3 compressor is definitely favorable for the sea water coolers. In the case of module #2, the only pertinent item, i.e., the C_3 accumulator, is separated from the other equipment. Thereby, the risk cost is dramatically reduced compared to other modules. For module #3, the MR separator and the MR compressor suction drum are located far away from other equipment units since the radiuses of exposure of those pieces of equipment are much smaller than that of the MR compressor.

According to the optimization results, the risk costs constitute a great part of the total costs, except for module #2. Module #2 has only one pertinent piece of equipment; thus, the risk cost can easily be reduced. However, if there are several pertinent pieces of

Table 8. Layout summary of module #3 with safety considerations (4 MTPA)

No.	Service name	Orientation (L×D)	Location (x, y)	Assigned floors
23-24	MR Comp. Suction Drum	5.44×5.44	(2.72, 2.72)	2, 3
25	MR Compressor	17.1×5.93	(26.35, 7.91)	3
26	Overhead Crane for MR Comp.	22.73×15.82	(26.35, 7.91)	4
27	Sea Water Cooler #4	3.95×2.47	(12.98, 11.53)	5
28	Sea Water Cooler #5	2.47×3.95	(36.48, 11.53)	3
29-30	MR Separator	4.45×4.45	(5.05, 13.60)	1, 2
31-35	MCHE	5.63×5.63	(40.53, 11.53)	1, 2, 3, 4, 5
36	JT Valve #4	1.48×1.48	(40.53, 15.08)	3
37	JT Valve #5	1.48×1.48	(36.98, 11.53)	2

Table 9. Optimization results summary with safety considerations (4 MTPA)

Module No.	Total cost (×1,000 USD)	Connection cost (×1,000 USD)	Risk cost (×1,000 USD)	Land cost (×1,000 USD)
1	21,163	279	15,671	5,213
2	2,119	309	626	1,184
3	24,031	739	16,435	6,857

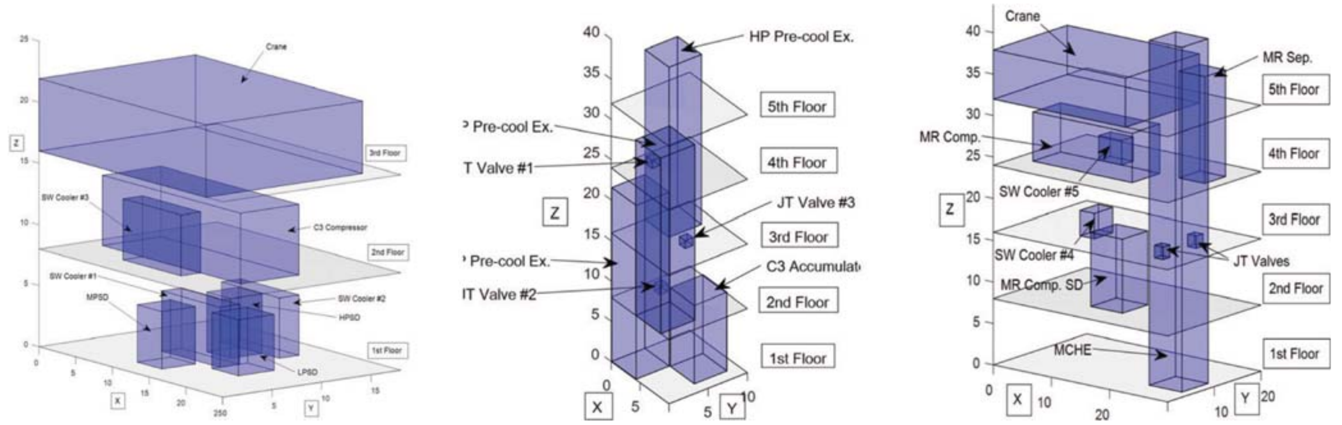

Fig. 6. Optimized layout of the 4MTPA C_3-MR process without safety considerations.

Table 10. Optimization results summary without safety considerations (4 MTPA)

Module No.	Total cost (×1,000 USD)	Connection cost (×1,000 USD)	Risk cost (×1,000 USD)	Land cost (×1,000 USD)
1	45,382	71	41,715	3,596
2	2,389	197	1,464	728
3	34,469	218	29,764	4,487

equipment, the risk costs can be noticeably increased. In the cases excluding safety constraints, the total costs are much higher than in the cases including safety constraints because of the increasing risk costs in both examples. The layout optimization without safety considerations can reduce the connection costs and land costs, but the overall costs still increase because of the further increase in the risk costs.

CONCLUSIONS

The problem of determining 3-dimensional multifloor layout with safety consideration is very complex because it involves many decision variables. Layout determination, however, is a critical issue in the early engineering design stage, as plant layouts affect plant capital expenditures and plant safety.

In this study, an MINLP model has been newly proposed to solve 3-dimensional multifloor layout with safety consideration problems. Dow's F&EI is utilized to quantify the risk cost caused by a fire or an explosion, and mathematical model modifications were made to handle 3-dimensional equipment and more accurately reflect the risks. The C_3-MR liquefaction process was adopted as an illustrative example.

The proposed model can successfully solve the layout problem of the C_3-MR liquefaction process involving more than 4,000 decision variables. And the study's results show that total layout costs without safety considerations are much higher than those with safety considerations, as safety factors play an important role in the layout determination.

The main advantage of the proposed model is that it can suggest a realistic optimal layout of complex chemical plants such as LNG liquefaction plants. The results of this study can be applied to all other processes dealing with hazardous substances.

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NOMENCLATURE

a_i, b_i : dimensions of equipment i
$A_{i,j}$: relative distance in y coordinates between equipment i and j, if equipment i is above equipment j
$B_{i,j}$: relative distance in y coordinates between equipment i and j, if equipment i is below equipment j
$CC_{i,j}$: piping cost between equipment i and j if equipment i and j are connected each other
D_i : depth of equipment i
DC_t : cost for protective device configuration t
DF_i : damage factor which represents the overall effect of fire and blast damage
$DI_{i,j}$: distance between equipment i and j if the distance is within a radius of exposure
$Dn_{i,j}$: relative distance in z coordinates between equipment i and j, if equipment i is located to a lower floor than equipment j
$DO_{i,j}$: distance between equipment i and j if the distance is outside a radius of exposure
$D1_{i,j}$: distance that makes damage probability 100 percent
$D2_{i,j}$: distance that makes damage probability follow linearity
ED_i : radius of exposure of equipment i calculated by Dow's F&EI
$E1_{i,j}$: non-overlapping binary variable
$E2_{i,j}$: non-overlapping binary variable
$F_{i,k}$: binary variable that has a numerical value of 1 if equipment i is assigned to the k^{th} floor, otherwise 0
FA : floor area
FC : floor construction cost
H : floor height
i, j : indices of equipment
I^m : set of equipment that should be assigned across n floors
I^p : set of pertinent equipment
k : index of a potential floor
L_i : length of equipment i
LC : land cost
$Lt_{i,j}$: relative distance in x coordinates between equipment i and j, if equipment i is to the left of equipment j
M : big, arbitrary numerical parameter
n : number of floors that equipment occupies
N : number of equipment
NF : number of floors
O_i : binary variable that has a numerical value of 1 if L_i is equal to a_i
$P_{i,t}$: binary variable that has a numerical value of 1 if t is installed on equipment i
PC_i : purchase cost of equipment i
$Rt_{i,j}$: relative distance in x coordinates between equipment i and j, if equipment i is to the right of equipment j
t : index of protective device configuration
T_i : set of protective device configuration that could be installed on equipment i
$TD_{i,j}$: total rectilinear distance between equipment i and j
UB_i : maximum distance that makes damage probability 100 percent
$Up_{i,j}$: relative distance in z coordinates between equipment i and j, if equipment i is located to an upper floor than equipment j
V_i : value of area exposure of a pertinent equipment i
$Wx_{i,j}$: binary variable that has a numerical value of 1 if equipment i is to the right of equipment j, otherwise 0
$Wy_{i,j}$: binary variable that has a numerical value of 1 if equipment i is above equipment j, otherwise 0
$Wz_{i,j}$: a binary variable that has a numerical value of 1 if equipment i is located to an upper floor than equipment j, otherwise 0
x_i, y_i : coordinates of geometric center of equipment i
$Z_{i,j}$: binary variable that has a numerical value of 1 if equipment i and j are assigned to the same floor
$\psi_{i,j}$: binary variable that has a numerical value of 1 if equipment j is located to the inside of a radius of exposure of pertinent equipment i, otherwise 0
$\phi_{i,j}$: binary variable that has a numerical value of 1 if equipment j is located to the outside of UB_i of a pertinent equipment i, otherwise 0
Ω_i : actual maximum probable property damage (MPPD)

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