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Integrated method for layout design of LNG FPSO based on optimization technique and expert system

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LNG FPSO의 통합 배치 설계 방법

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Abstract

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The LNG FPSO is a large structure on the sea with facilities for gas and oil production, and it can be divided into hull and topside. Such facilities are grouped into several units called modules and distributed on the topside. Also, many kinds of storage tanks are arranged in the hull. The design for the offshore platform is an elaborate and difficult task because it requires many considerations such as international codes and standards, owners' requirements, operation and maintenance philosophy, and so on. At the beginning of the design, it depends heavily on designer's experience and reference projects.

In this study, the integrated design framework for LNG FPSO is proposed to obtain the optimal hull sizing, tank arrangement in the hull, module layout in the topside, and equipment layout in the topside modules that satisfy many requirements regarding safety, economics, operability, and stability.

The proposed framework consists of four components. First, the expert system is applied to computerize expert's knowledge and experience systematically and to evaluate the feasibility of alternatives for the overall design of the offshore platform. Second, the optimization method is used to yield a better design by formulating the design problem as an optimization problem with a single stage. Third, an arrangement template model is used to store the arrangement data of offshore platform. Fourth, the user interface is developed to the integrated design of the offshore platform by executing the proposed framework. A prototype program is developed to evaluate the applicability of the proposed framework.

This method was applied to the example of an LNG FPSO to verify the method, and the result shows that the proposed framework could be used for finding a better arrangement and improve the work efficiency of the design process for the offshore platform at the initial design stage.

Keywords: LNG FPSO, FLNG, Layout design, Expert system, Optimization Technique

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1. Introduction

1.1. Research background

As demand for natural gas continues to grow and the value of natural gas remains high in the major consuming markets, the impetus to monetize offshore gas resources also grows. Various offshore platforms such as FPSO for oil production at sea have been constructed, and LNG FPSO for gas production has recently appeared.

The LNG FPSO is a kind of FPSO (floating, production, storage and offloading) facility with an LNG plant, including all ancillary facilities. In contrast with commercial vessels such as LNG ship and tanker, the various parts of the process are located topside and distributed as modules that are installed on the deck. Also, many kinds of storage tanks are arranged in the hull. The design for the offshore platform is an elaborate and difficult task because it requires many considerations such as international codes and standards, owners' requirements, operation and maintenance philosophy, and so on. At the beginning of the design, it depends heavily on designer's experience and reference projects. And in terms of the design and construction of the LNG FPSO, every element of a conventional LNG facility needs to fit into an area less than one quarter the size of a land base terminal, while maintaining the utmost levels of safety and the flexibility required by LNG production.

Layout criteria for an FPSO are more stringent than onshore due to the limited footprint, the need for good weight distribution, and the need for personal refuge and escape routes. Safety is the prime consideration for the layout of LNG FPSO. The primary safety concern is the inventory of hazardous, flammable gas, and the consequence of any loss of containment.

A major contributor to safe design is to ensure that initial arrangement and layout are aimed at arriving at a design that meets operational requirements and also will be compliant with regulations.

1.2. Related works

Many scholars conducted a lot of studies on the layout design method. And the expert system has been adopted for various fields of research. In this section, a summary of the past studies, related to the layout design in the fields including naval architecture and ocean engineering, is described.

Lee et al. (2001) proposed the optimization method to solve the problem of principal dimensions of the ship using the collaborative optimization (CO) approach, one of the Multidisciplinary design optimization (MDO) methodologies. In this study, the CO approach is applied to the problem of the principal dimensions of a bulk carrier as a mathematical example to show its applicability and equivalence to standard optimization (SO) formulation.

Patisatizis et al. (2002) proposed an optimal layout method for the multi-floor process plant. Arrangement method for multi-floor process plant was formulated as an optimization problem. It applied to the five-unit instant coffee process and ethylene oxide plant.

Chung et al. (2011) proposed an optimization method of compartments in the pressure hull of a submarine with a rule-based expert system. The rule-based expert system was adopted to evaluate alternatives for the arrangement design of the submarine. The evaluation values called feasibility indices for the alternatives obtained from the expert system were used as an objective function for optimization. If a certain alternative violates a rule, a positive penalty is added to the value of the objective function of the alternative.

Park et al. (2011) proposed an optimal layout method with consideration of the safety distance based on the TNT equivalency method. The physical explosion of the pressurized vessel was considered. The proposed method was applied to the ethylene oxide plant and benzene production plant.

Mazerski (2012) proposed the optimization method to determine optimum main dimensions of the FPSO of given storage capacity concerning steel weight and strength. Multi-Objective Genetic Algorithm (MOGA) was used for optimization, and the proposed optimization method was applied to two different FPSO concept projects.

Ku et al. (2014) proposed an optimal arrangement method for a generic liquefaction system of an LNG FPSO. An arrangement problem was formulated mathematically as a constrained optimization problem, then it was applied to the liquefaction system of the LNG FPSO and solved with the genetic algorithm.

Jeong et al. (2015) proposed an optimal arrangement method for the topside of an FPSO. Optimization problems for the module arrangement and the equipment arrangement were formulated and then solved with the genetic algorithm. This study proposed the optimal arrangement method of the offshore platform topside which regards various arrangement considerations such as experts' knowledge as constraints during the optimization process. However, it is difficult to reflect additional considerations or changes on the existing problems flexibly and efficiently without the modification of the optimization problems.

Kim et al. (2017) proposed an arrangement method for the topside of an offshore platform based on an expert system and optimization technique. The arrangement design was formulated as a two-stage optimization problem for the module and the equipment that considers safety, operability, and maintainability. It was applied to the topside of the example FPSO and solved with the genetic algorithm.

The summary of the related studies is as shown in Table 1.

Table 1 Summary of the relative works and this study

	Application	Hull		Topside		Optimization
		Principal dimensions	Compartment (Tank)	Module	Equipment	
Lee et al. (2001)	Ship	O	X	X	X	O
Patsiatizs et al. (2002)	Onshore process structure	X	X	X	O	O
Chung et al. (2011)	Ship	X	O	X	X	O
Park et al. (2011)	Onshore process structure	X	X	X	O	O
Mazerski (2012)	Offshore platform (FPSO)	O	X	X	X	O
Ku et al. (2014)	Offshore platform (LNG FPSO)	X	X	X	O	O
Jung et al. (2015)	Offshore platform (FPSO)	X	X	O	O	O
Kim et al. (2017)	Offshore platform (FPSO)	X	X	O	O	O
This study	Offshore platform (LNG FPSO)	O	O	O	O	O

1.3. Target of the study

Among the various type of the offshore platform, this study proposed the integrated method of layout design of LNG FPSO. The target of the study can be divided into two main categories. One is the determination of the optimal principal dimensions of an LNG FPSO. It requires consideration of manufacturability, hull structural weight, and size of each tank. The other is to find optimal layout of hull tanks, topside modules, and equipment in each module. Considerations are adjacency, pipe length, weight distribution, and layout compatibility. In this study, the optimum layout of tanks, modules, and equipment including determination of principal dimensions of LNG FPSO is performed at the same time.

2. Integrated method for layout design of LNG FPSO

2.1. Configuration of the proposed method

This study consists of four major items as shown in Figure 1. The first item is the template model. A template model is defined as a data structure that represents and stores information. In this template model, objects needed for optimization are defined. The second item is the expert system. In this study, the rule-based expert system is used to reflect the knowledge and international regulations as a mathematical model. The third item is the optimization module. The problem is formulated so that the entire layout design of the LNG FPSO can proceed simultaneously. The fourth item is the user interface that enters the rules of the expert system and also makes it possible to perform optimization problems.

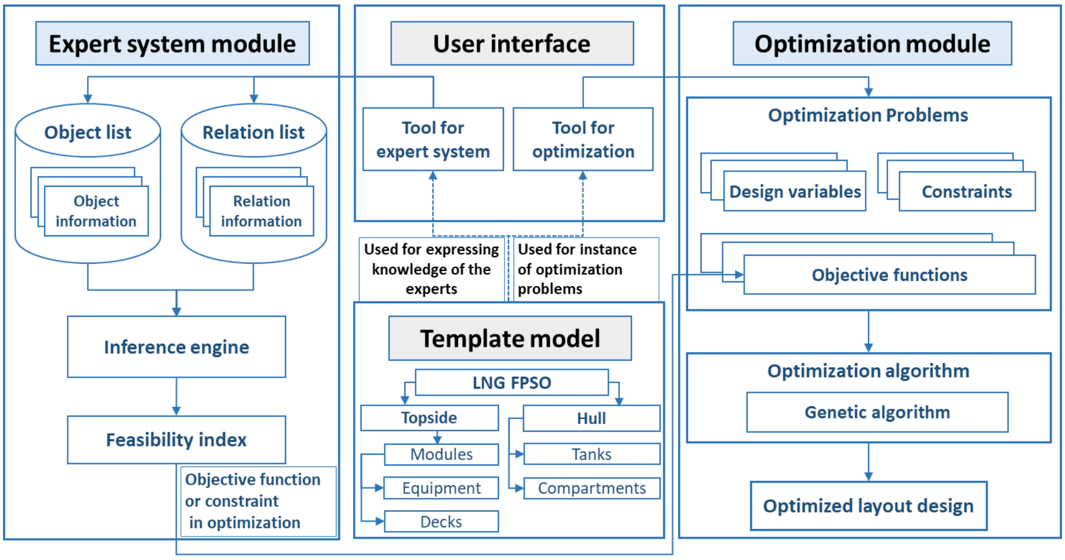

Figure 1 Configuration of the key modules in this study

2.1. Template model

Template model is designed to store the layout information and characteristics of LNG FPSO. Template model represents the hierarchical structure of a component of LNG FPSO as shown in Figure 2.

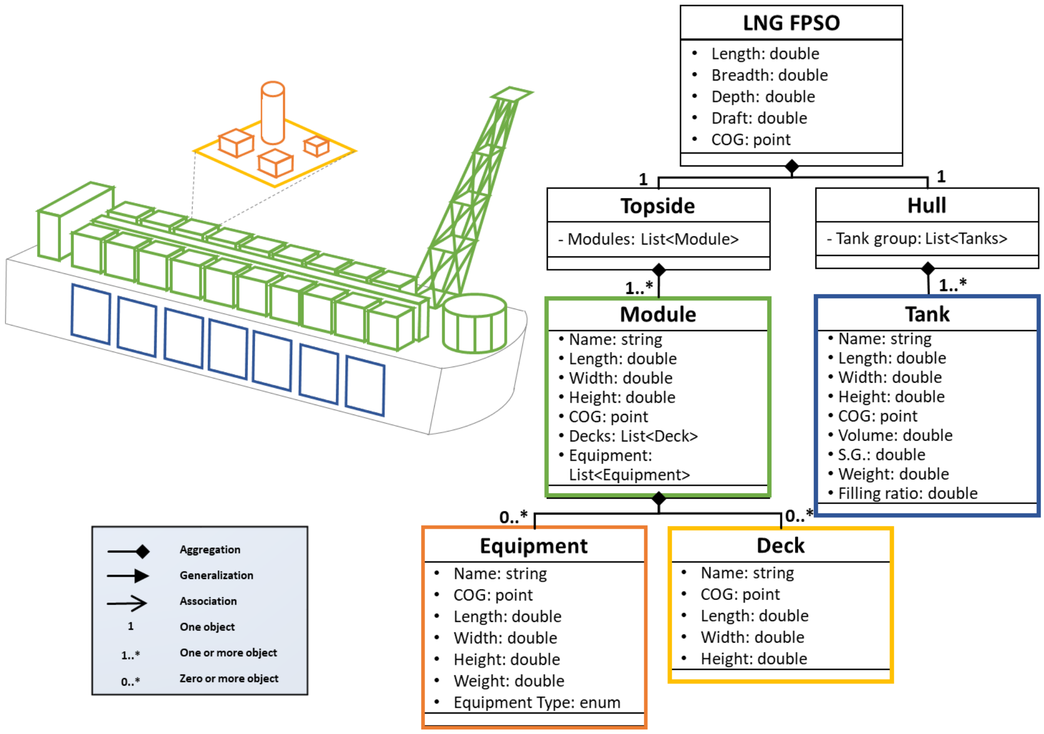

Figure 2 Template model

The overall procedure for the layout design of LNG FPSO is as follows.

First, the LNG FPSO class is defined to stores information for principal dimensions, and it consists of topside and hull as sub-objects. The topside class has module list that store information of modules such as size, weight, and location and the module class has equipment and decks. The equipment class stores size, COG, weight, and type, and the deck class has size information. The hull class has tank list containing the tank class that includes tank name, size, location, weight, and several contents for stability calculation.

Properties of each class are summarized in Table 2 to Table 8.

Table 2 Properties of the LNG FPSO class

LNG FPSO	
Properties	**Data type**
Length	Double
Breadth	Double
Depth	Double
Draft	Double
COG	Point
Topside	class
Hull	class

Table 3 Properties of the hull class

Hull	
Properties	**Data type**
Tanks	List<Tank>

Table 4 Properties of the topside class

Topside	
Properties	Properties
Modules	List<Module>

Table 5 Properties of the tank class

Tank	
Properties	**Data type**
Name	String
Length	Double
Width	Double
Height	Double
COG	Point
Volume	Double
S.G.	Double
Weight	Double
Filling ratio	Double

Table 6 Properties of the module class

Module	
Properties	**Data type**
Name	String
Length	Double
Width	Double
Height	Double
COG	Point
Decks	List<deck>
Equipment	List<equipment>

Table 7 Properties of the equipment class

Equipment	
Properties	**Data type**
Name	String
Length	Double
Width	Double
Height	Double
COG	Point
Weight	Double
Equipment type	enum

Table 8 Properties of the deck class

Deck	
Properties	**Data type**
Name	String
Length	Double
Width	Double
Height	Double
COG	Point

2.2. Expert system module

In this study, the rule-based expert system is applied. The rule-based expert system consists of the knowledge base, the database, and the inference engine as represented in Figure 3. The difference from the general rule-based expert system is that the knowledge base and the database are stored in the form of object information or relation information.

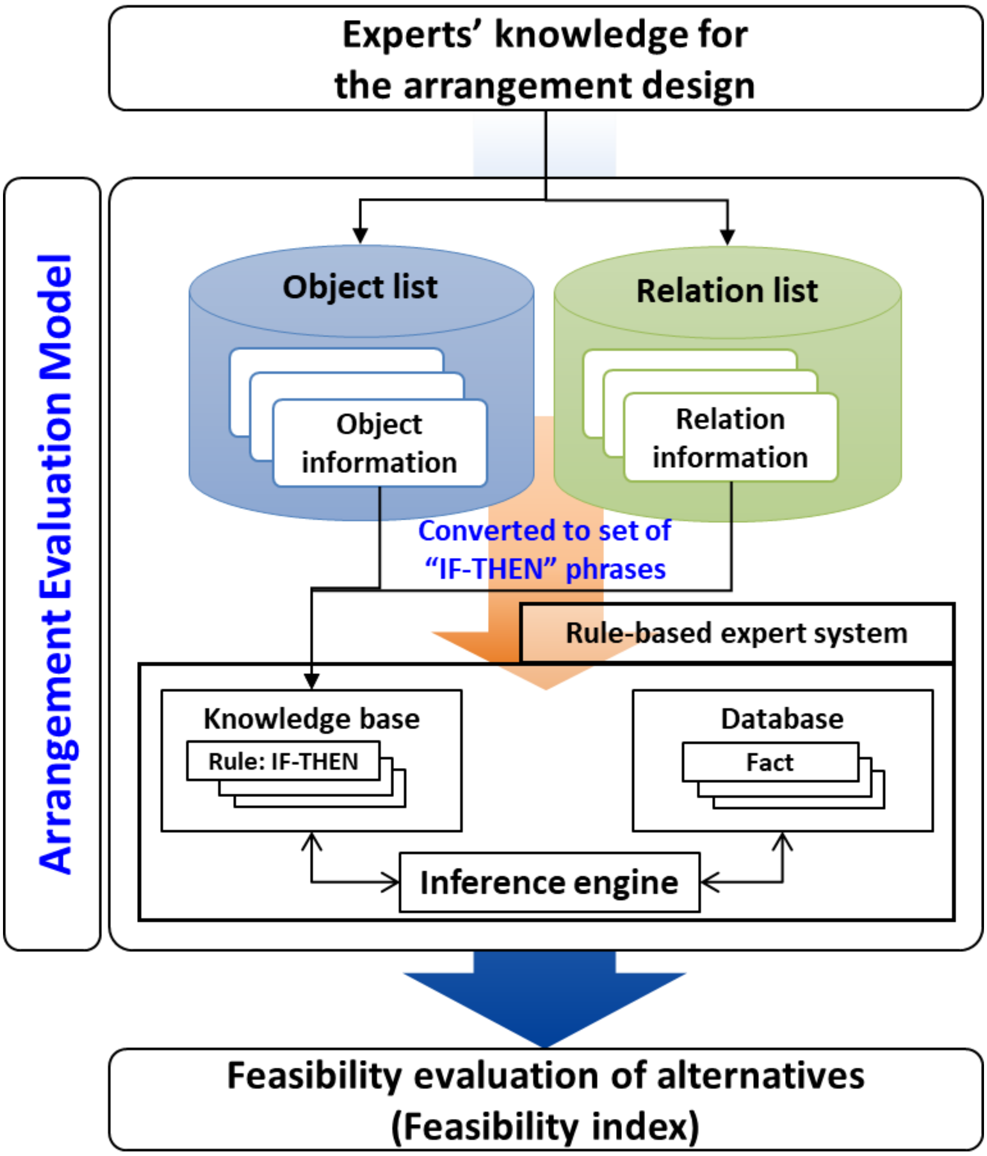

Figure 3 Configuration of the arrangement evaluation model

In the rule-based expert system, a rule is defined as the "IF-THEN" phase and stored in a knowledge base. An inference engine compares the "IF" phase of the rule in the knowledge base with the fact in a database (called pattern matching). If the "IF" part of the rule is same as the "Fact" in the database, then the "THEN" part of the rule in the knowledge base is stored in the database as a new fact.

The knowledge base, the database, and the inference engine are consolidated as the arrangement evaluation model (AEM) in this study. Rules derived from experts' knowledge or experiences are expressed as object information and relation information. The experts' knowledge about property requirements for a specific object is expressed as the object information. And the experts' knowledge about the relation between specific objects are expressed as the relation information. The object and relation information are defined as a combination of the several properties. A group of the object and relation information are named as an object list and a relation list, respectively. Thus, it can be seen that the AEM is based on the object and relation lists.

The AEM converts the object and relation information in the object and relation lists as rules of IF-THEN phrases. In this meaning, the AEM can be a kind of the rule-based expert system. Referring to the converted rules of IF-THEN phrases, a feasibility index of the given alternative for the layout design can be evaluated. The feasibility index is a certain value quantitatively scoring the compliance with the rules in the object and relation information. In this study, the AEM for the layout design of an LNG FPSO was proposed. With this model and the object and relation lists, various rules about the layout design of the LNG FPSO can be easily expressed, and the feasibility of the given design alternative can be evaluated.

As shown in Figure 3, the AEM corresponds to the knowledge base, the database, and the inference engine of the rule-based expert system. Thus, a designer does not have to consider the complicated inference process when making the rules for the layout design with the use of the AEM. In this sense, the AEM can be regarded as an extended, advanced version of the rule-based expert system for use in the layout design of an LNG FPSO.

2.2.1. Representation of object information

The object information can express experts' knowledge about requirements for a specific object in the LNG FPSO such as limitations of principal dimensions, tank capacity, location of specific module and equipment, and so on. If an expert possesses the knowledge that "The living quarters should be located outside of hazardous areas and may not be located above or below liquefied gas or condensate storage tanks or process areas", it can be represented as one objective information. The keywords in the knowledge are the object name (e.g., "Living quarter"), the object type (e.g., "Module"), the target property (e.g., "COG_X"), the attribute (e.g., "EXT"), and the target value (e.g., "25"). Adding an ID (e.g., "E001") to each distinct rule, one object information can be represented with six properties: the ID, object name, object type, target property, attribute, and target value. Here, the target value is used to give a certain value to the object. An example of object information is shown in Figure 4. The set of object information for all the objects defined in the domain is called an object list in this study.

ID	Object name	Object type	Target property	Attribute	Target value
E01	Living quarter	Module	COG_X	EXT	25

Figure 4 Configuration of the object information

To use six properties (ID, object name, object type, target property, attribute, and target value in the AEM, they have to be specified by a suitable data type for them, as shown in Figure 4. The ID, object name, and object type can be expressed by a string type to distinguish the target object for the object information. The target property represents properties of the target object, and it can be certain words like "Length", "Breadth", “Depth”, “COG_X”, “COG_Y”, “COG_Z”, “Volume”, and so on. Using an enumerator composed of those kinds of words, we can express the target property. The description of target properties of the object information is listed in Table 9.

The attribute represents the limit of the target value, and it can be certain words like “EXT” for exact value, “MAX” for maximum value, and “MIN” for minimum value. Using an enumerator composed of those kinds of words, we can express the attribute.

Table 9 Properties of the object information

Properties	Data type	Description
ID	String	ID
Object name	String	Object name
Object type	String	Hull, tank, module, equipment
Target property	Enumerator type	Length, Breadth, Depth, COG_X, COG_Y, COG_Z, Volume, …
Attribute	Enumerator type	EXT (exact), MAX (maximum), MIN (minimum), PRO (proposed)
Target value	double	

Figure 5 shows examples of representing rules as the object information. For example, the “Living quarter” should be located outside of hazardous areas and may not be located above or below liquefied gas or condensate storage tanks or process areas (ABS FLGT). This knowledge can be represented as the object information: (E01, Living quarter, Module, COG_X, EXT, 25). As another example, the “Turret” should be located with respect to safety and thruster demand (DNV-GL OTG02). This knowledge can be represented as the object information: (E02, Turret, Module, COG_X, EXT, Hull.Length-20).

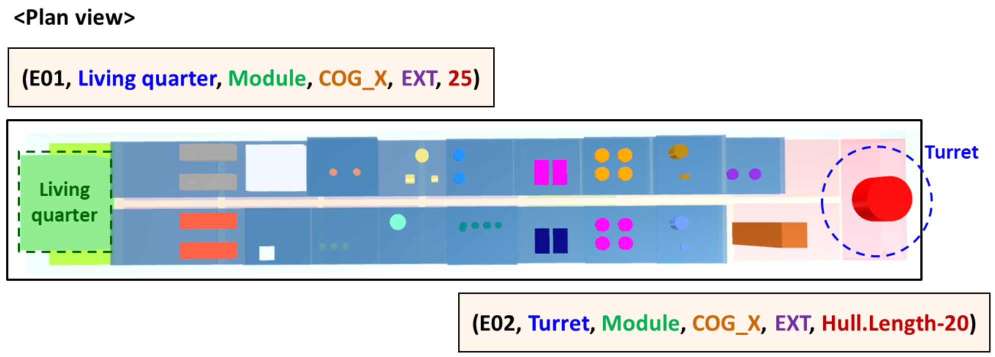

Figure 5 Examples of the object information

2.2.2. Representation of relation information

The relation information can express experts' knowledge about the relation between two objects. At this time, the measurable values are the objects of the relation. If an expert possesses the knowledge that "the laydown area A and the laydown area B should be arranged symmetrically; port and starboard", it can be represented as one relation information. The key words in such knowledge item are the object name (e.g., "Laydown area A"), the object type (e.g., "Module"), the target name (e.g., "Laydown area B"), the relation type (e.g., "GroupWith"), the target property (e.g., "COG_X"), and the target value (e.g., "0"). This example shown in Figure 6 is a knowledge item that is a relation information item, and is to distinguish the relation information from the others, an ID is additionally needed. The set of relation information for all the objects defined in the domain is called a relation list in this study.

ID	Object name	Object type	Target name	Relation type	Target property	Target value
E01	Laydown area A	Module	Laydown area B	GroupWith	COG_X	0

Figure 6 Configuration of the relation information

One relation information item has seven properties: the ID, object name, object type, target name, relation type, target property, and target value, as shown in Table 10. Here, the relation type represents the relation between two objects. The previously given an example used "GroupWith" to represent the relation. "GroupWith" can be one of the relations between two objects. Four types of relations were defined in this study to express various relations between two objects as shown in Table 11. "ConnectionTo" was used to represent the objects connected to each other along the longitudinal direction of the offshore platform. "GroupWith" was used to represent the objects connected to each other along the transverse direction of the offshore platform. "DistanceFrom" was used to represent the distance between two objects. Finally, "LevelDifference" was used to represent the vertical distance, that is, the level difference between two objects.

Table 10 Properties of the relation information

Properties	**Data type**	**Description**
ID	String	ID
Object name	String	Object name
Object type	String	Module, equipment
Target name	String	Target name
Relation type	Enumerator type	ConnectionTo, GroupWith, DistanceFrom, LevelDifference
Target property	Enumerator type	COG_X, COG_Y, COG_Z
Target value	double	

Table 11 Description of relation types of the relation information

Attributes	Description
ConnectionTo	Physical connection between two objects
GroupWith	Symmetric connection between two objects
DistanceFrom	Rectilinear distance between two objects
LevelDifference	Difference of vertical distance between two objects

To use seven properties of the relation information in the AEM, they have to be specified by a suitable data type for them, as shown in Table 12. The ID, the object name, and the target name can be expressed by a string type to distinguish the objects and subjective objects for the relation information. The relation type can be represented using an enumerator to express four types of relations. And the target value can be represented by the metric type as mentioned above. The data type and properties of the target value according to the relation types are listed in Table 12.

Table 12 Data type and properties of the target value according to the relation type

Target value	Data type	Properties according to the relation types			
		ConnectionTo	GroupWith	DistanceFrom	LevelDifference
Standard value	Double	Real value	Real value	Real value	Real value
Relation type	Enumerator type	EXT	EXT	EXT	EXT
Unit type	Enumerator type	meter (m)	meter (m)	meter (m)	meter (m)

As explained earlier, the relation information includes four relation types; "ConnectionTo", "GroupWith", "DistanceFrom", and "LevelDifference". The "ConnectionTo" type represents the physical connection of two objects; the target object and the subjective object. Using the "ConnectioTo" type, the physical connectivity of two objects along the longitudinal direction of the offshore platform can be expressed by experts. The “GroupWith” type represents the symmetric connection of two objects. Using the “GroupWith” type, the symmetrical connectivity of two objects along the transverse direction of the offshore platform can be expressed by experts. The “DistanceFrom” type represents physical distance between the target object and the subjective object. The shortest route from the target object to the subjective object is selected to calculate the value for the relation; the distance between two objects. Thus, the minimum distance between the target object and the subjective object can be calculated by using “DistanceFrom” keyword. The “LevelDifference” type represents the difference of vertical distance between the target object and the subjective object. Using the “LevelDifference” type, certain criteria for the vertical distance between two objects can be expressed by the experts.

An example of the relation information of using the “ConnectionTo” and “GroupWith” types is shown in Figure 7. In the layout design for the topside of the LNG FPSO, the “Laydown A” and “Laydown B” modules are arranged symmetrically; port and starboard side. And thus this knowledge can be represented as the relation information: (R01, Laydown area A, Module, Laydown area B, GroupWith, COG_X, 0). Also, the “Laydown A” module and the “Living quarter” module are arranged longitudinally next to each other. This knowledge can be represented as the relation information: (R02, Laydown area A, Module, Living quarter, DistanceFrom, COG_X, 30).

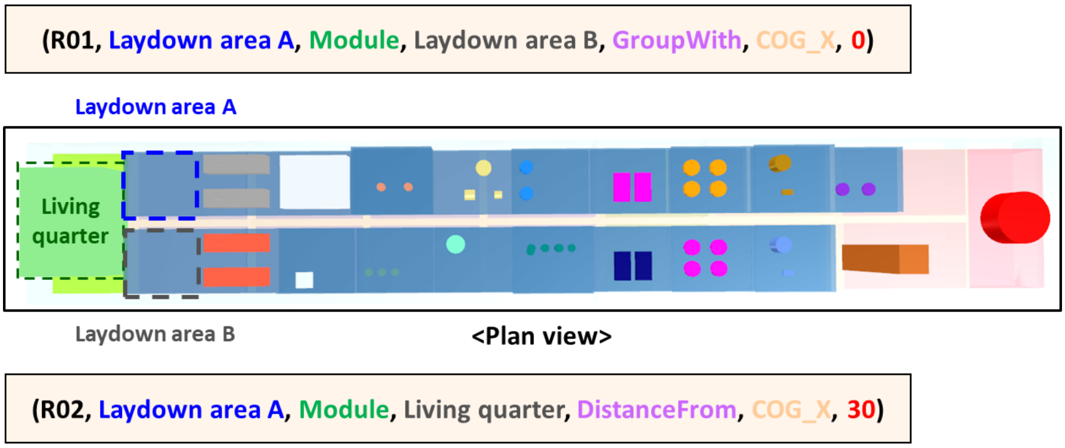

Figure 7 Example of the relation information of using the "GroupWith" and “ConnectionTo” type

2.2.3. Evaluation of rule of expert system

The body of the knowledge of experts about the layout design of an LNG FPSO is expressed with two lists: the object and relation lists. Based on these lists, rules are made, and layout design alternatives are evaluated based on such rules. As described in prior sections, specific requirements on objects to be arranged to an LNG FPSO can be expressed by the object and relation information.

The requirements on principal dimensions, properties, the location, and so on of the objects can be defined by the object information. The requirements on the connection and distance between the objects can be defined by the relation information. The object and relation information are converted to a set of IF-THEN rules, which are then used to evaluate the feasibility of the alternatives.

The object or relation information can be defined differently from one another using some boundary types for the target value, such as “EXT” for exact value, “MAX” for maximum value, “MIN” for minimum value, and “PRO” for proposed value. As for the boundary type “EXT,” if it is used, the rule is “the value of the object should be the same as the target value.” Therefore, if the value of the object is the same as the target value, the index for this rule is evaluated as “100” points, and if it is different, the index becomes “0” point. If the boundary type “MAX” is used for the target value of certain object information, the rule is “the value of the object should be lower than the maximum value.” Therefore, if the value of the object is lower than the maximum value, the feasibility index for this rule is evaluated as “100” points, and if the value is higher than the maximum value, the feasibility index for this rule is evaluated as “0” point. The boundary type “MIN” is similar to “MAX.” If the boundary type “PRO” is used, the linear-fit function evaluates the feasibility index of the object or relation information. Thus if the value of the object is the same as the target value, the index for the rule is evaluated as “100” points. The larger the difference between the value and the target value is, the lesser the index for the rule according to the linear-fit function is.

The example described in Figure 5 can be converted to the set of rules of IF-THEN phrases, as shown in Figure 8. As shown in this figure, an appropriate rule (“Rule 1” in this example) which was already made and corresponds to the object type in the object information is selected and executed. Again, an appropriate rule (“Rule 3”) which was already made and corresponds to the target property is selected and executed. And then an appropriate rule (“Rule 5”) which was already made and corresponds to the attribute is selected and executed. Finally, with the object name and the target value, appropriate rules (“Rule 7” and “Rule 8”) are automatically selected and converted, the rules are executed to calculate the feasibility index of this object information (ID of “E01”) for the given design alternative. At this time, the feasibility index can be calculated by comparing the location of the target object (“Living quarter”) for the given design alternative and the target value.

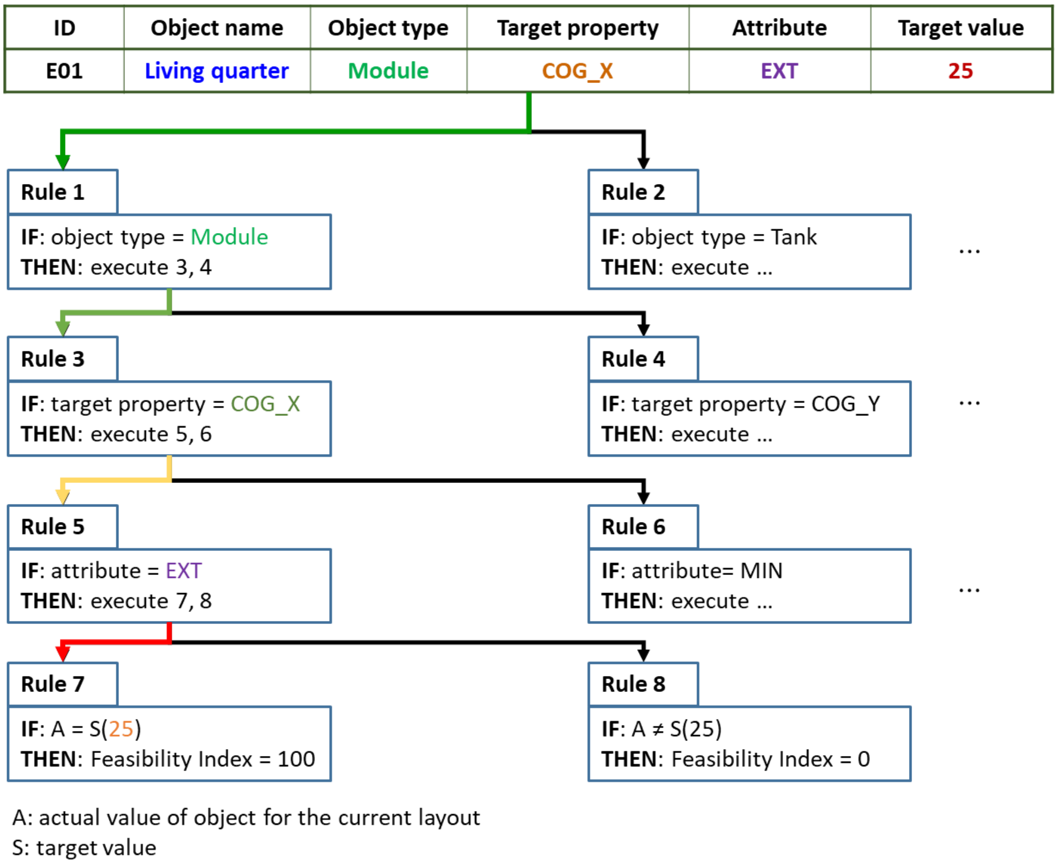

Figure 8 Example of the converting procedure of the object information to rules

Similarly, the example described in Figure 7 can also be converted to the set of rules of IF-THEN phrases, as shown in Figure 9. As shown in this figure, an appropriate rule ("Rule 1" in this example) which was already made and corresponds to the object type in the relation information is selected and executed. Again, an appropriate rule ("Rule 3") which was already made and corresponds to the target property is selected and executed. And then an appropriate rule ("Rule 5") which was already made and corresponds to the attribute is selected and executed. Finally, with the object, the target, and the target value, appropriate rules ("Rule 7" and "Rule 8") are automatically selected and converted, the rules are executed to calculate the feasibility index of this relation information (ID of "R01") for the given design alternative. At this time, the difference of longitudinal center of gravity between the object ("Laydown area A") and the target ("Laydown area B") should be calculated, and a distance calculation module based on the rectilinear method as an external module can be used for this purpose. In the case of other relation types such as "ConnectionTo", "LevelDifference", and "DistanceFrom", a suitable module for the connection or distance calculation can be used.

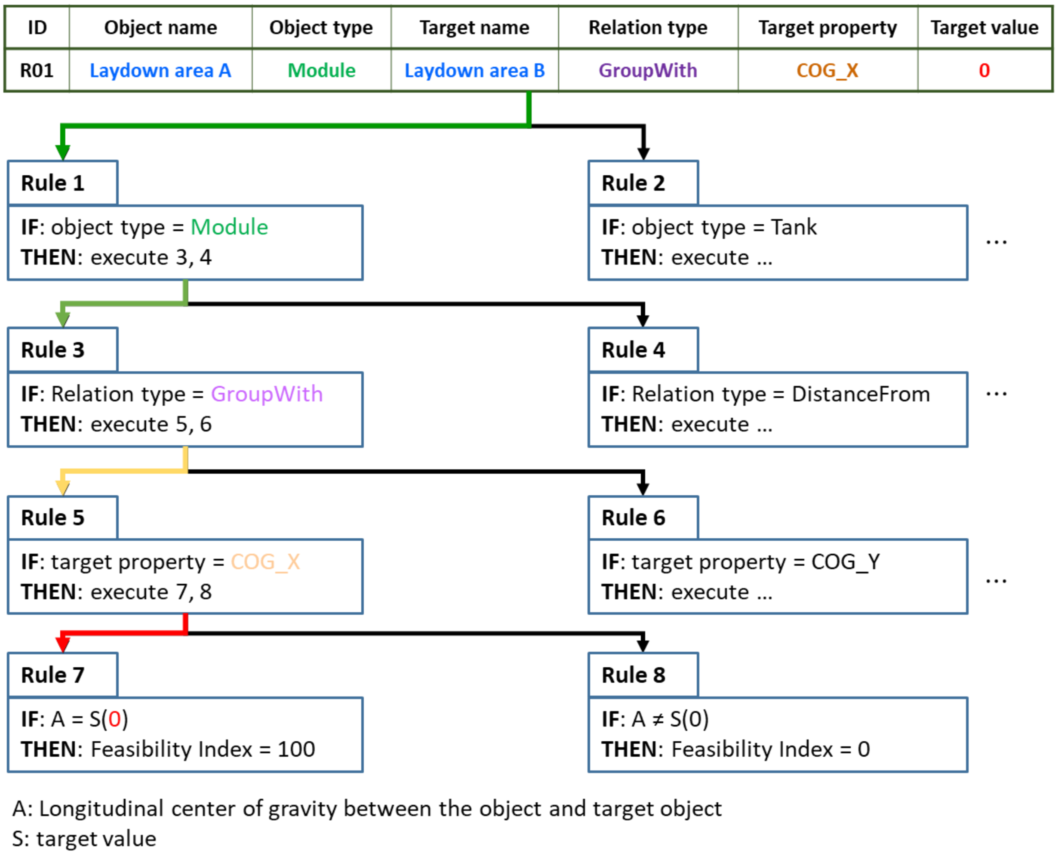

Figure 9 Example of the converting procedure for the relation information to rules

The object list and the relation list are, as mentioned above, automatically converted to the set of rules of IF-THEN" phrases. Then, according to the boundary type, the relation type, and the attribute in the object and relation information, an appropriate procedure is performed to calculate the feasibility indices for the object and the relation information included in the object and the relation lists.

2.3. Optimization module

In this study, multi-purpose optimization is performed, and the optimization problem was formulated with design variables, objective functions, and constraints. Many information and values are used in this module to get an optimized result. In this study, the formulated problem are both have many objective functions. So the algorithm for the multi-object problem was used. Through this optimization module, the optimized arrangement result can be obtained.

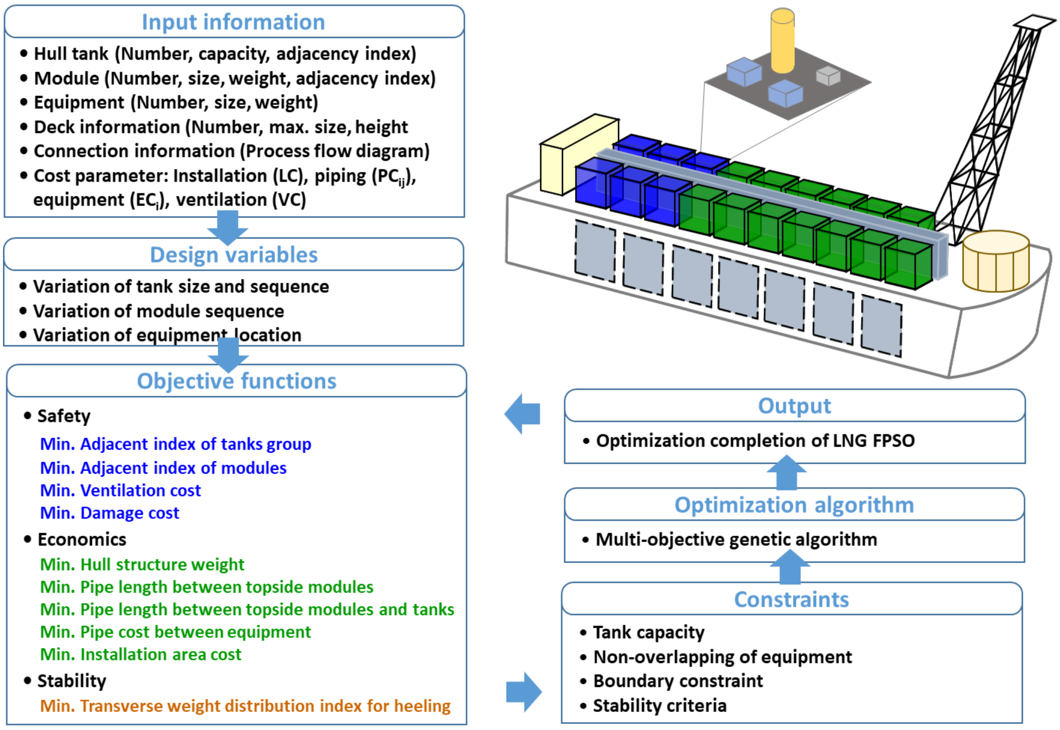

Figure 10 Flow diagram of the formulated problem

2.3.1. Input data

Input data for the layout design of LNG FPSO is summarized in Table 13.

A total number of the module in FPSO topside and id of each module is needed. Module information such as width, length, and weight of the module is also required.

Equipment information such as the total number of equipment in the module and equipment size should be provided. And deck information such as the total number of the deck and deck height is needed. Finally, piping connection information is required to calculate the piping cost. Lastly, cost parameters (PC_{ij}, LC, EC_i, VC) are needed to convert the related arrangement factors to the cost. Also, historical data such as the accident frequency of the hazardous equipment is required.

Table 13 Input data

	Input data	
Module	Total module number and ID of each module	
	Width and length of the module	d_i, l_i
	Weight of each module	
Tank	Total tank number and ID of each tank	
	Required capacity of each tank	
Equipment	Dimensions of equipment	a_i, b_i, h_i
	Total number of the deck	NF
	Deck height	H
	Piping connection information between the equipment i and j (1; if equipment i and j are connected with pipe, 0; otherwise)	f_{ij}
	Piping connection cost	PC_{ij}
	Land cost	LC
	Equipment purchase cost of equipment i	EC_i
	Probability of the potential physical explosion of equipment i (from the historical data)	fr_i
	Coefficient of the ventilation cost	VC

Adjacency coefficients between modules and tanks groups are required. Adjacency coefficient is the constant number which quantitatively represents the degree of the closeness between each object. It can be calculated from the antagonism and affinities as shown in equation 1.

$$q_{ij} = Affinity - Antagonism \qquad (1)$$

In equation 1, antagonism is the characteristics which preclude a function group being safely located near another specific function group mutually protected like fire, or blast barriers Affinities are the characteristics which make it particularly advantageous to located one function group close to another specific a function group.

2.3.2. Design variables

In this study, there are many design variables because the tank, module, and equipment arrangement are performed simultaneously with the determination of principal dimensions of LNG FPSO.

Real variables and array variables are used as design variables. Design variables are summarized in Table 14.

Table 14 Design variables

Real variables	
l_i, b_i, h_i	Dimensions of the tank i
x_i, y_i	Position of the equipment i
Array variables	
T_i	Sequence of tanks group i
M_i	Sequence of module i

First, the design variables for determining principal dimensions of the LNG FPSO through tank sizing are the length, width, and height of each cargo tank. The width and height of the cargo tanks storing LNG, LPG, Condensate, and Process liquid are the same, and the length is determined according to the required capacity. As shown in Figure 11, a midship section of the LNG FPSO is set, and the size of void spaces including cofferdams are specified.

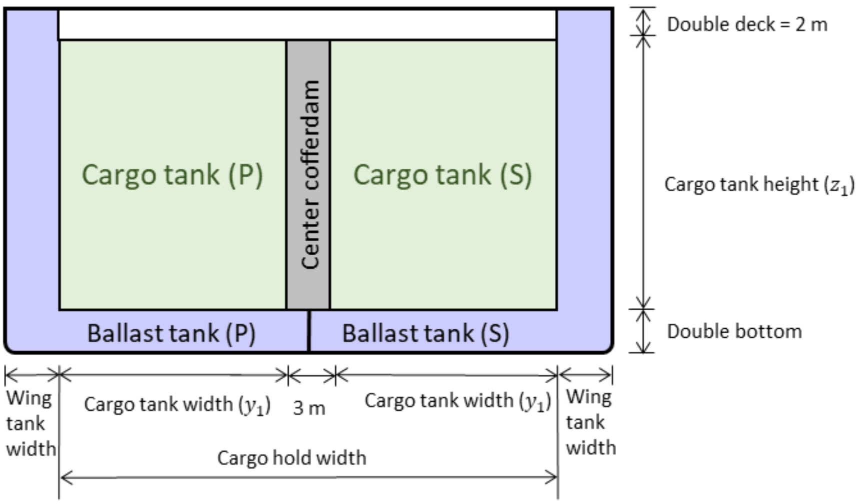

Figure 11 Midship section

The wing tank width of ballast water tanks is determined according to the size of the cargo hold as shown in Table 15.

Table 15 Determination of wing tank width

If	Wing tank width
Cargo hold width ≤ 40	3.5 m
40 < Cargo hold width ≤ 50	4.0 m
50 < Cargo hold width	4.5 m

And the double bottom height of ballast water tanks is determined according to the size of the cargo hold as shown in Table 16.

Table 16 Determination of double bottom height

If	Double bottom height
Cargo tank height ≤ 20	3.5 m
20 < Cargo tank height ≤ 25	4.0 m
25 < Cargo tank height	4.5 m

The tanks determined as above are assigned to each tank group as shown in Figure 12.

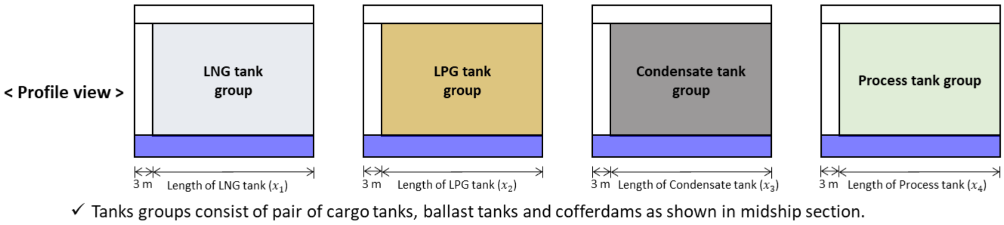

Figure 12 Profile view of tanks groups

Design variable for tanks arrangement is the arrangement sequence of the tanks groups. The locations of each tanks group and it can be represented as an array of the tanks groups "id" (encoding). After optimization, the array is converted to the arrangement of tanks groups (decoding).

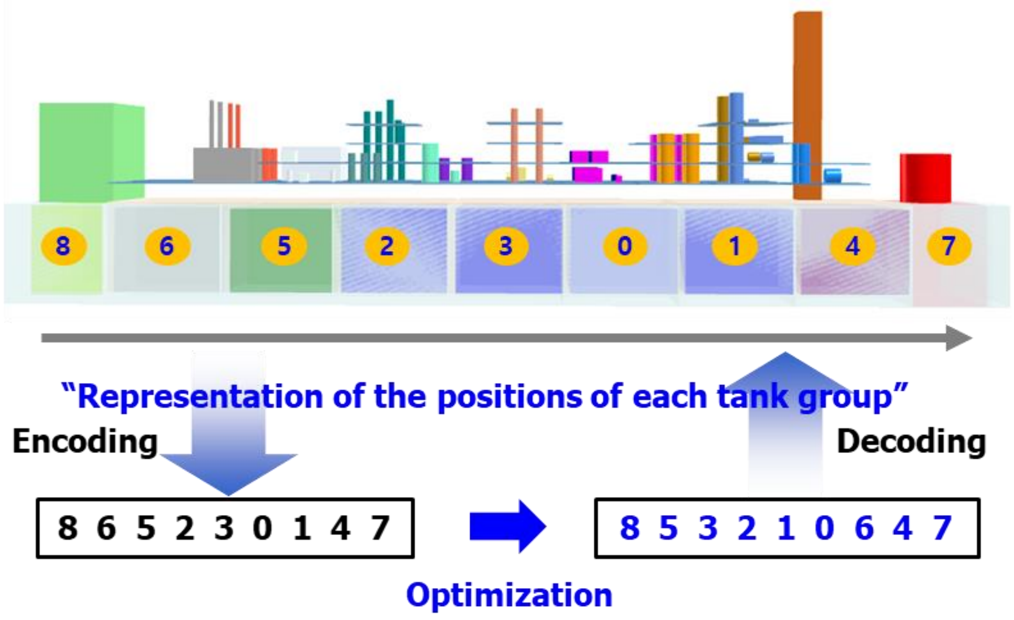

Figure 13 Representation of the positions of each tanks group

Design variable for module layout is the arrangement sequence of the module. The locations of each module can be represented as an array of the module "id" (encoding). After optimization, the array is converted to the module arrangement (decoding).

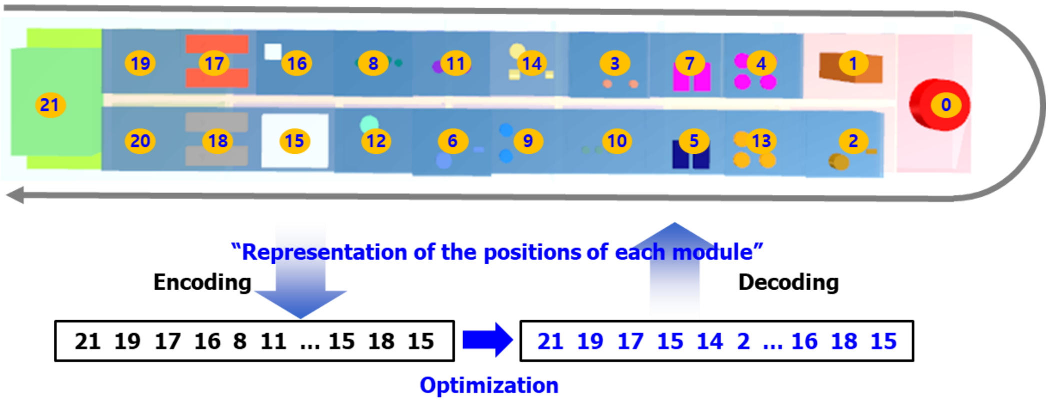

Figure 14 Representation of the positions of each module

Design variable for equipment layout is the location of equipment in each module. The locations of each equipment can be represented as real variables of “X_i” and “Y_i”.

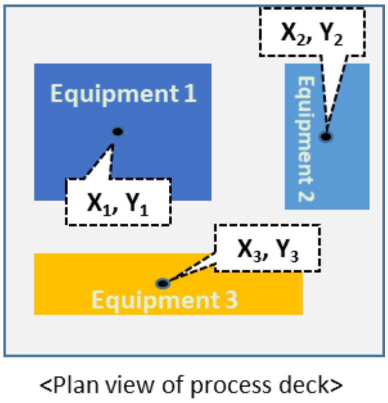

Figure 15 Design variable for equipment layout

2.3.3. Objective functions

In this study, 11 objective functions related to safety, economics, and stability are reflected. A weight factor is assigned to each objective function according to the characteristics and requirements of the LNG FPSO. All objective functions are mathematically formulated, and a multi-purpose optimization is performed. The value of each objective function is derived from -1 to 1 through generalization. Objective functions for the optimization are summarized in Table 17.

Table 17 Objective functions

Objective functions		
Hull structure weight index	Minimize	$F_1 = Hull\ length^{1.6}\ x\ (Hull\ breadth + Hull\ depth)$
Adjacency index of tanks group	Minimize	$F_2 = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (q_{i,j} \cdot d_{i,j})$
Pipe length between topside modules and tanks	Minimize	$F_3 = \sum_{i} \sum_{j \neq i / f_{ij=1}} TD_{ij}$
Adjacency index of modules	Minimize	$F_4 = \sum_{i=1}^{N-1} \sum_{j=i+1}^{n} (q_{i,j} \cdot d_{i,j})$
Transverse weight distribution index	Minimize	$F_5 = \left\lvert \sum_{i=1}^{N} (w_i \cdot y_i) \Big/ \sum_{i=1}^{N} w_i \right\rvert$
Pipe length between topside modules	Minimize	$F_6 = \sum_{i} \sum_{j \neq i / f_{ij=1}} TD_{ij}$
Installation area cost	Minimize	$F_7 = LC \cdot FA$
Piping cost	Minimize	$F_8 = \sum_{i} \sum_{j \neq i / f_{ij=1}} PC_{ij} \cdot TD_{ij}$
Ventilation cost	Minimize	$F_9 = \sum_{k=1}^{NF} VC \cdot \lvert V_{mean,empty} - V_{k,empty} \rvert$
Damage cost considering physical explosion	Minimize	$F_{10} = \sum_{i=1} \sum_{j \neq i} fr_i \cdot (EC_i + p_{ij} \cdot EC_j)$
Feasibility index from the expert system	Maximize	$F_{11} = \sum R_k$

(1) Hull structure weight index

This objective function aims to minimize the weight of the hull which occupies a large part of the hull price. The hull weight calculation is based on the simplified estimation formula.

$$Minimize\ \ F_1 = \text{Hull length1.6 x (Hull breadth + Hull depth)} \qquad (2)$$

(2) Adjacency index of tanks group

This objective function is to minimize the adjacency index among tanks groups. The adjacency index is calculated from the adjacency coefficient (qij) and distance (dij). The adjacent coefficient, “qij”, is a constant which represents the antagonism between the tanks groups. Antagonism is the characteristics which preclude a tanks group being safely located near another tanks group mutually protected like fire or explosion based on specific properties of the liquid in each cargo tank.

$$Minimize\ \ F_2 = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (q_{i,j} \cdot d_{i,j}) \qquad (3)$$

“qij” is the adjacency coefficient between tanks groups, and “dij” is the distance between tanks groups.

(3) Pipe length between topside modules and tanks

This objective function is to minimize the quantity of pipe connecting between modules and tanks. The liquid produced in the module related to the process is transferred to the storage tank inside the hull, and the pipe connected between the module and the tank is considered as shown Figure 16.

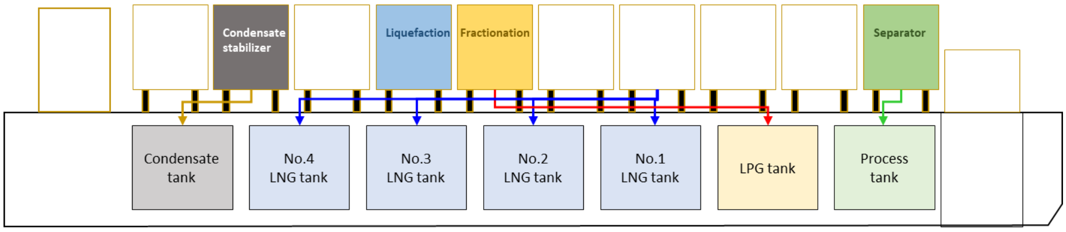

Figure 16 Connection information among modules and tanks

Pipe specifications such as diameter, thickness, and material are not considered. Only pipe length is evaluated in view of economics.

$$Minimize\ \ F_3 = \sum_{i} \sum_{j \neq i / f_{ij=1}} TD_{ij} \tag{4}$$

"TDij" is the total rectilinear distance as shown in equation 5.

$$TD_{ij} = \left|X_i - X_j\right| + \left|Y_i - Y_j\right| + \left|Z_i - Z_j\right| \tag{5}$$

(4) Adjacency index of modules

This objective function is to minimize the adjacency index among modules. The adjacency index is calculated from the adjacency coefficient (q_{ij}) and distance (d_{ij}). The adjacent coefficient, "q_{ij}", is a constant which represents the antagonism and affinities between the modules. Antagonism is the characteristics which preclude a module being safely located near another module mutually protected like fire or blast barriers. Affinities are the characteristics which make it particularly advantageous to located one module group close to another specific module.

$$Minimize\ \ F_4 = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (q_{i,j} \cdot d_{i,j}) \tag{6}$$

"qij" is the adjacency coefficient between modules, and "dij" is the distance between modules.

(5) Transverse weight distribution index

This objective function is to minimize heel due to the weight difference between modules on port side and starboard side. The weight distribution index is the coordinate of the y-axis of the center of the LNG FPSO. Trim is adjusted to make even keel through loading of the ballast water according to loading status of LNG FPSO.

$$Minimize\ \ F_5 = \left| \sum_{i=1}^{N} (w_i \cdot y_i) \ \Big/ \ \sum_{i=1}^{N} w_i \right| \tag{7}$$

"w_i" is the module weight, and "y_i" is the transverse center of gravity of module.

(6) Pipe length between topside modules

This objective function is to minimize the quantity of pipe connecting among modules. In this objective function, the modules responsible for producing LNG, LPG and Condensate are considered as shown in Figure 17. The connection between modules is to connect the outlet equipment in the module to the equipment responsible for the outlet in another module according to the process flow diagram.

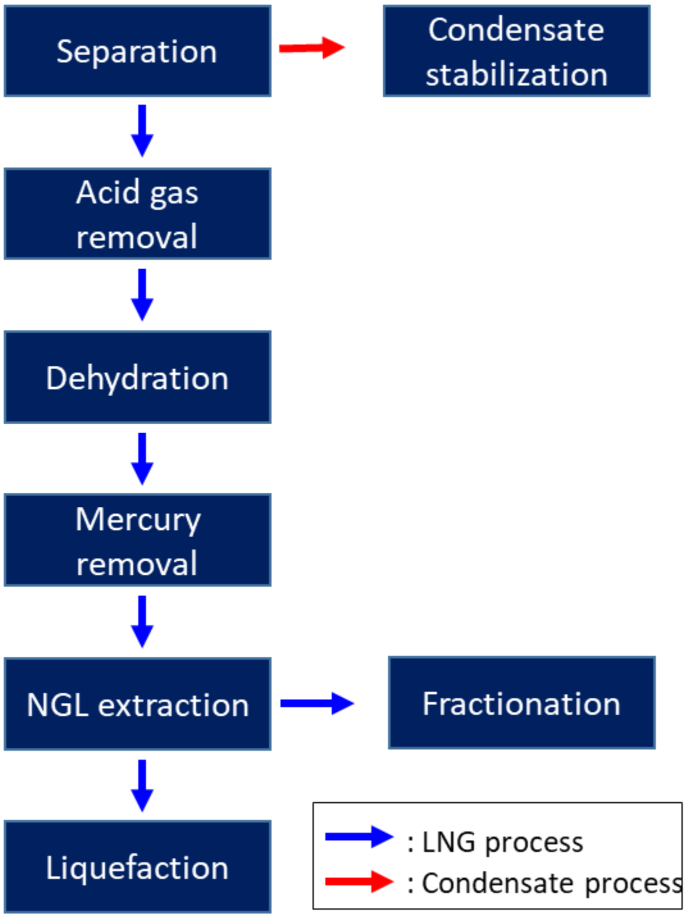

Figure 17 Connection information among modules

The pipelines between modules are connected through pipe racks as shown in Figure 18.

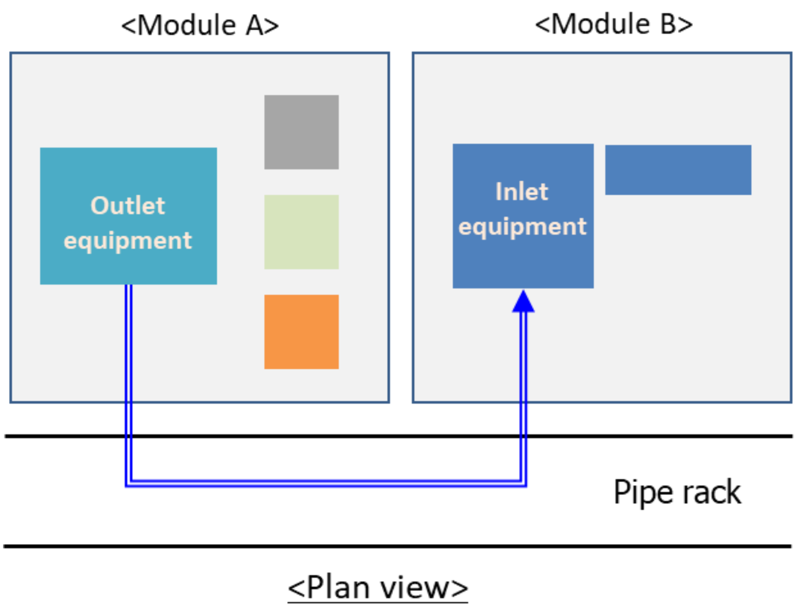

Figure 18 Piping connection between modules

$$Minimize\ \ F_6 = \sum_{i} \sum_{j \neq i / f_{ij=1}} TD_{ij} \tag{8}$$

"TDij" is the total rectilinear distance as shown in equation 9.

$$TD_{ij} = \left|X_i - X_j\right| + \left|Y_i\right| + \left|Y_j\right| + \left|Z_i - Z_j\right| \tag{9}$$

Pipe specifications such as diameter, thickness, and material are not considered. Only pipe length is evaluated in view of economics.

(7) Installation area cost

This objective function is to minimize the installation cost. Installation cost is the land cost which equipment are arranged. It is formulated as equation 10.

$$Minimize\ \ F_7 = LC \cdot FA \tag{10}$$

"FA" is the total installation area in the deck. It is calculated as shown in equation 11. "LC" is the cost parameter.

$$FA = X_{\max} \cdot Y_{\max} \tag{11}$$

(8) Piping cost

This objective function is to minimize the piping cost. Piping cost is calculated only in two equipment are connected by a pipe (e.g., fij = 1"). It is formulated as equation 12.

$$Minimize\ \ F_8 = \sum_{i=1}^{n-1} \sum_{j=2/f_{ij}=1}^{n} PC_{ij} \cdot TD_{ij} \tag{12}$$

"PC_{ij}" is the cost parameter of the piping from equipment i to j. "TD_{ij}" is the total rectilinear distance as shown in equation 13.

$$TD_{ij} = \left|X_i - X_j\right| + \left|Y_i - Y_j\right| + + \left|Z_i - Z_j\right| \tag{13}$$

(9) Ventilation cost

This objective function is to minimize the ventilation cost. If the deck is too congested, leaked gas will not be dispersed efficiently. To improve the ventilation of the leaked gas in each deck, it needs to arrange equipment uniformly on each deck area. This aspect is formulated as the ventilation cost as shown in equation 14. It prevents much equipment to be arranged in a specific deck intensively.

$$Minimize\ \ F_9 = \sum_{k=1}^{NF} \left| V_{mean,empty} - V_{k,empty} \right| \tag{14}$$

In equation 14 "$V_{mean,empty}$" is the mean volume of the empty spaces in each deck. "$V_{k,empty}$" is the empty volume in deck "k" as shown in Figure 19. They are calculated by equation 15 and 16.

$$V_{k,empth} = H \cdot (X_{\max} \cdot Y_{\max}) - \sum_{i=1}^{n} V_{i,k} \cdot x_i \cdot y_i \cdot z_i \tag{15}$$

$$V_{empth,mean} = \frac{1}{NF} \cdot \sum_{k=1}^{NF} V_{k,empth} \tag{16}$$

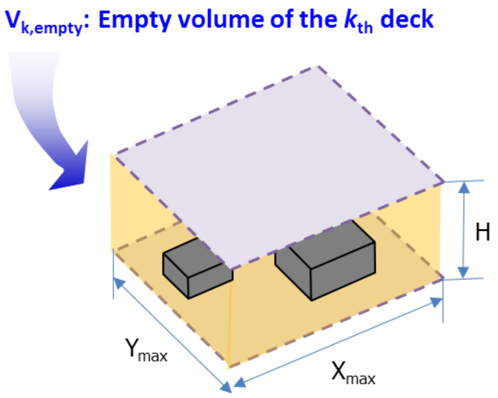

Figure 19 Empty volume of the k_{th} deck

(10) Damage cost considering the physical explosion

In this study, the physical explosion of the pressurized vessel is considered to calculate the safe distance from the hazardous equipment. Physical explosion 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 guideline for setting a safe distance in the plant layouts. The damage cost is formulated as equation 17.

$$Minimize\ \ F_9 = \sum_{i=1}^{n}\sum_{j\neq i} fr_i \cdot (EC_i + p_{ij} \cdot EC_j) \tag{17}$$

"fr_i" is the accident frequency of the hazardous equipment. It can be obtained from the historical data. "EC" is the equipment cost. "P_{ij}" is the probability of damage of the equipment j when the equipment i is exploded. It is affected by the explosion energy of the hazardous equipment and the distance from it. Calculation procedure of the "P_{ij}" is summarized in Figure 20.

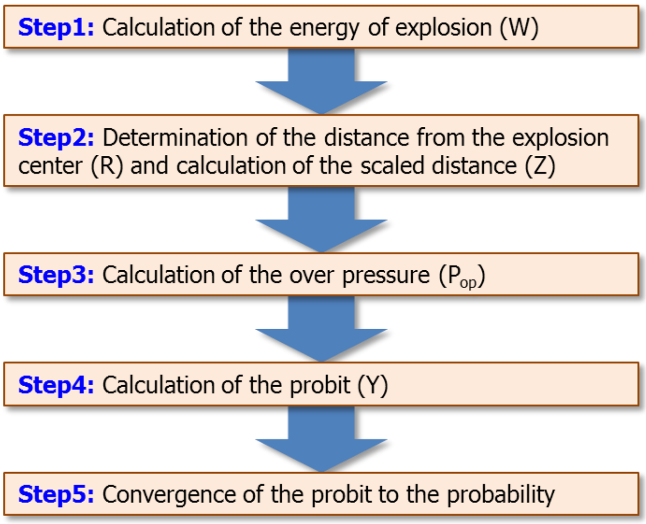

Figure 20 Calculation procedure of the probability of the damage. P_{ij} (Park, 2011)

The first step is to calculate the energy of the explosion. There are several methods which are used for calculation of a TNT equivalency method. In this study, the following equation is used.

$$\boldsymbol{W} = (1.39 \times 10^{-6}) \cdot V \cdot \left(\frac{P_1}{P_0}\right) \cdot R_g \cdot T_o \cdot ln\left(\frac{P_1}{P_2}\right) \quad (18)$$

In equation 18, “W” is the energy (lb TNT). “V” is the volume of the compressed gas (ft_3). “P_1” is the initial pressure of the compressed gas (psia). “P_2” is the final pressure of the expanded gas (psia). “P_0” is the standard pressure (14.7 psia). “T_0” is the standard temperature (492 ^oR) “R_g” is the gas constant (1.987 Btu/lb-mole-^oR). And “1.39 X 10^{-6}” is the conversion factor.

The second step is the determination of the distance from explosion center and calculation of the scaled distance. It can be calculated using equation 19.

$$\mathrm{Z} = \frac{R}{W^{1/3}} \quad (19)$$

In this equation, “W” is the explosion energy calculated by equation 18, and “R” is the distance from the explosion center.

The third step is the calculation of the overpressure (P_{op}). It is calculated using the equation 20.

$$log\boldsymbol{P_{op}} = \sum_i c_i(a + blog\boldsymbol{Z})^i \quad (20)$$

In this equation, “Z” is scaled distance calculated from equation 19. And “c_i”, “a” and “b” is the constant.

The fourth step is the calculation of the probit. In case of structural damage, probit (Y) can be calculated by equation 21.

$$\boldsymbol{Y} = -23.8 + 2.92 \cdot \ln(\boldsymbol{P_{op}}) \tag{21}$$

Lastly, calculated probit is converged to the probability using the equation 22.

$$P = 50\left[1 + \frac{\boldsymbol{Y} - 5}{|\boldsymbol{Y} - 5|} erf\left(\frac{|\boldsymbol{Y} - 5|}{\sqrt{2}}\right)\right] \tag{22}$$

In equation 23, erf is the error function formulated as follows.

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \tag{23}$$

(11) Feasibility index from the expert system

This objective function is to maximize the feasibility index from the expert system. As same as the module arrangement stage, feasibility index is returned from the expert system based on the object and relation lists.

$$Maximize \;\; F_{11} = \sum R_k \tag{24}$$

"R_k" is the evaluation score of the rule "k".

2.3.4. Constraints

When arranging the equipment, each equipment should be arranged at once. And equipment should not be overlapped. Passages around the perimeter of the deck and spaces around the equipment should be considered for operability. These aspects are formulated as constraints.

(1) Non-overlapping constraints

The equipment should not be overlapped to other equipment. Also, operation spaces should be provided to each equipment. This aspect is formulated as shown in equation 25 and 26.

$$\left|x_i - x_j\right| - \frac{\left(l_i + l_j\right)}{2} \geq \varepsilon_1 \qquad (25)$$

$$\left|y_i - y_j\right| - \frac{\left(d_i + d_j\right)}{2} \geq \varepsilon_1 \qquad (26)$$

(2) Boundary constraints

Equipment should be arranged within the deck area, "X_{max}" and "Y_{max}". Also, passages should be provided around the perimeter of the deck area. These aspects are formulated as boundary constraints as shown in from equation 27 to 30.

$$x_i - \frac{l_i}{2} \geq \varepsilon_2 \qquad (27)$$

$$y_i - \frac{d_i}{2} \geq \varepsilon_2 \qquad (28)$$

$$X_{\max} - (x_i + \frac{l_i}{2}) \geq \varepsilon_2 \qquad (29)$$

$$Y_{\max} - (y_i + \frac{d_i}{2}) \geq \varepsilon_2 \qquad (30)$$

(3) Intact stability

The intact stability was calculated and mandatory requirements in International code on intact stability, 2008 was considered to secure the stability of LNG FPSO.

The first is related to the righting lever curve properties, which are in Figure 21 and Table 18.

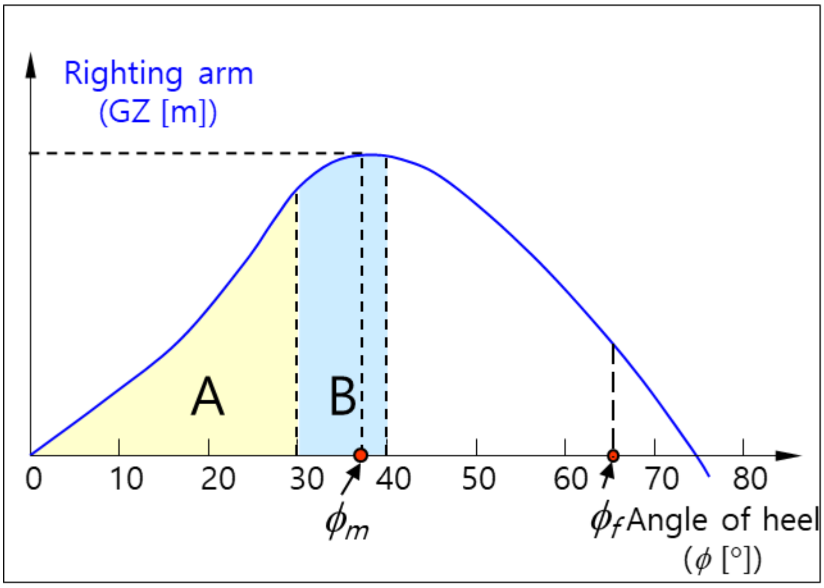

Figure 21 Righting lever properties

Table 18 Constraints for criteria regarding righting lever properties

Constraints	
Criteria regarding righting lever properties	$g_1 = Area\ A \geq 0.055\ (m{\cdot}rad)$
	$g_2 = Area\ A + B \geq 0.09\ (m{\cdot}rad)$
	$g_3 = Area\ B \geq 0.03\ (m{\cdot}rad)$
	$g_4 = GZ \geq 0.02(m)\ at\ an\ angle\ of\ heel \geq 30°$
	$g_5 = Angle\ of\ Max.\ GZ \geq\ 25°$
	$g_6 = Initial\ GoM \geq\ 0.15\ (m)$

The second is related to the combined effects of beam wind and rolling, which the LNG FPSO must be able to withstand. Details are shown in Figure 22 and Table 19.

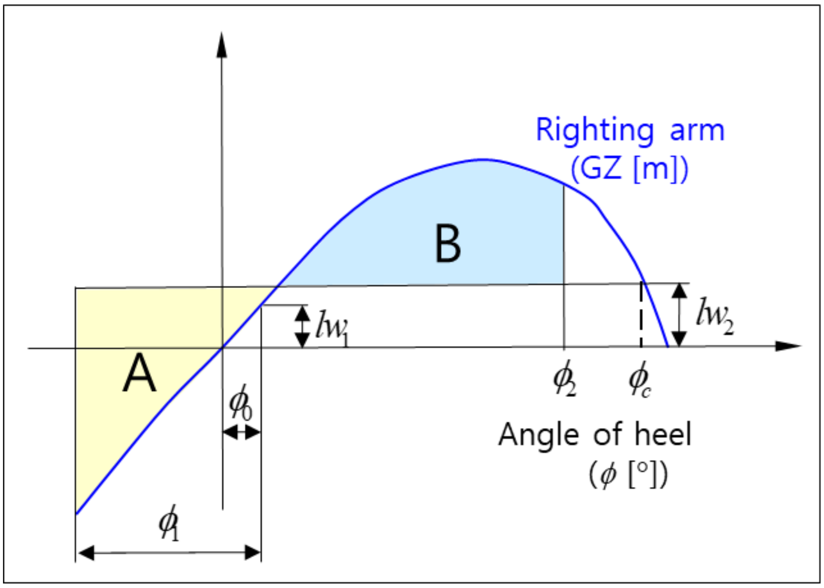

Figure 22 Severe wind and rolling

Table 19 Constraints for severe wind and rolling criterion

Constraints	
Severe wind and rolling criterion	$g_7 = \phi_0 \leq 16^o$
	$g_8 = Area\ B \geq Area\ A$

3. Prototype program

In this study, the prototype program is developed to apply the proposed method which consists of the template model, the expert system module, the optimization module, and the user interface. The prototype program was developed using C# language and WPF (Windows Presentation Foundation, http://msdn.microsoft.com/) in .Net 4.0 environment.

3.1. Configuration of prototype program

Figure 23 is a screenshot of the prototype program and shows the configuration of prototype program.

On the top, the menu bar is shown. Menu bar provides the function of execution of optimization and expert system. On the left, tree view and property view are provided. The tree view shows the hierarchy structures of the LNG FPSO. When the user selects an item in the tree view, property view shows properties of the selected item. One the center, 3D visualization shows a total view of LNG FPSO. On the right, optimization plot, stability result, and rule list are provided. The optimization plot shows optimization results in real time. The stability result show GZ curve and stability calculation results. And rule list shows a list of object information and list of relation information.

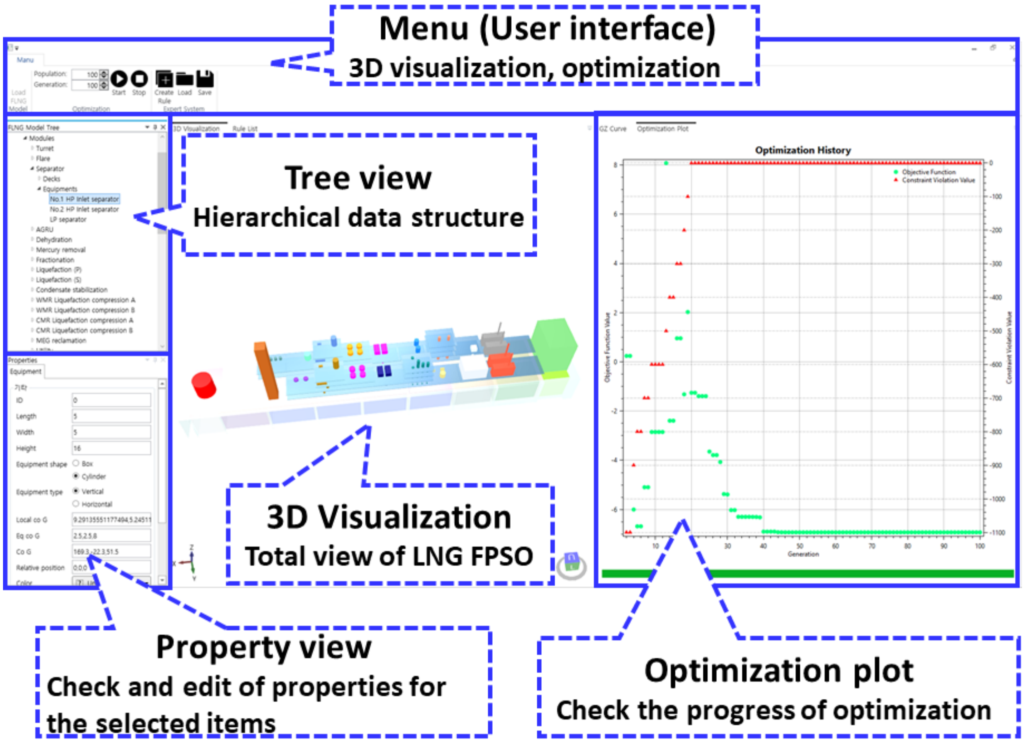

Figure 23 Configuration of prototype program

Prototype program has five components as shown in Figure 24. At first, the modeling library which expresses LNG FPSO model was developed. And the expert system library which can reflect expert's knowledge and experience, and other requirements was developed. Then, the optimization module that can optimize layout design of LNG FPSO by using optimization algorithm. Lastly, 3D visualization module that can confirm the optimum layout result by the 3D model was developed.

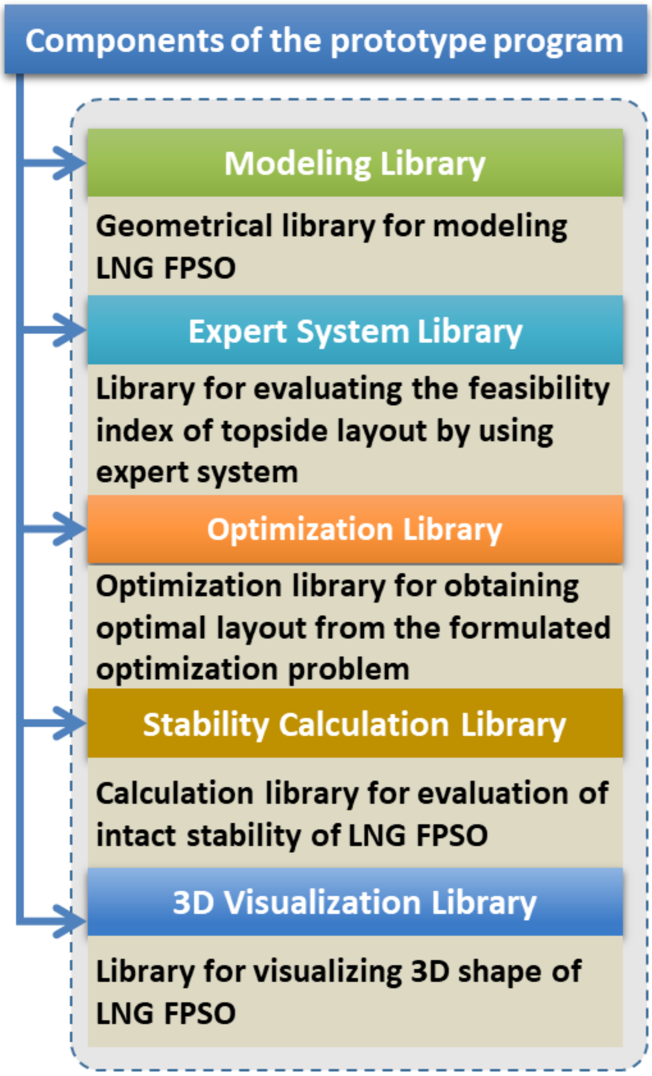

Figure 24 Components of the prototype program

3.2. Modeling library

The modeling library has a function of modeling of all parts of LNG FPSO. With design variables, it creates hull form, tanks, modules, equipment, and decks. And the layout design is completed according to the layout concept, and the properties of each component of LNG FPSO are calculated.

3.3. Expert system libraries

The expert system allows users to add object and relation information, save and load rule list. Object and relation information can be defined through the windows for the object and relation information as shown in Figure 25. Defined object and relation information are displayed in object list and relation list in Figure 26.

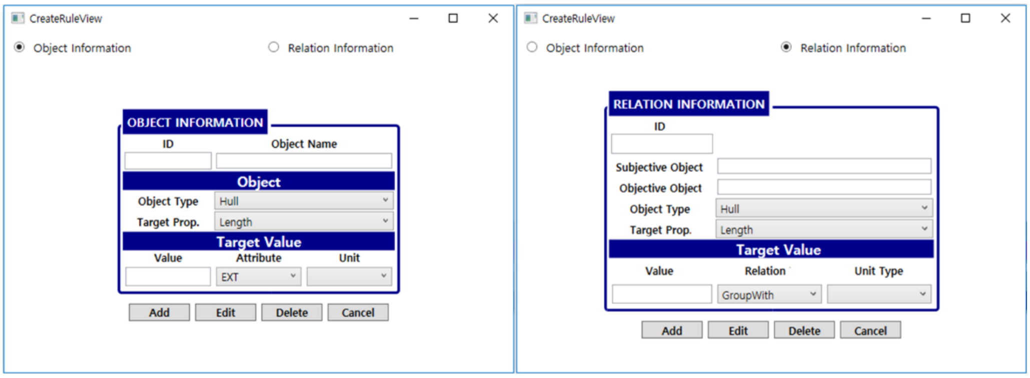

Figure 25 Screenshot of the prototype program: tool for the object and relation information

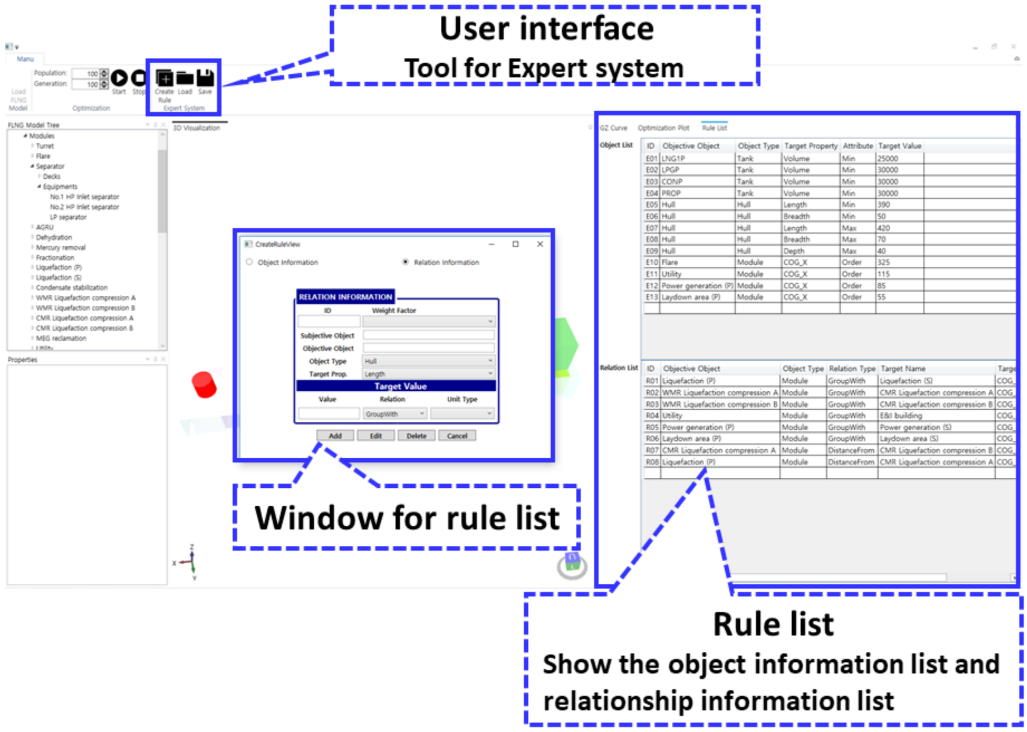

Figure 26 Screenshot of the prototype program: tool for the expert system

3.4. Optimization library

The formulated optimization problem can be solved by optimization library. The NSGA-II is used in optimization, and the algorithm is the open source library on Jmetal.NET (http://jmetal.sourceforge.net/). To solve the optimization problem consisting of various types of variables, there are several parameters according to the type of the variable, and appropriate parameters were selected and used according to each problem.

3.5. Stability calculation library

The stability calculation module performs lightweight estimation, loading condition implementation, and stability calculation according to the process as shown in Figure 27.

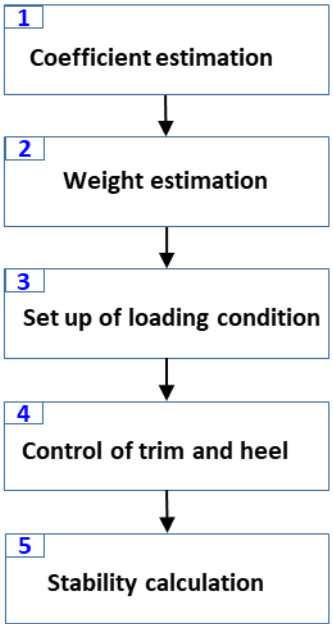

Figure 27 Stability calculation procedure

To estimate the lightweight, we first need the weight information of the reference LNG FPSO. Based on the weight information of the reference LNG FPSO, the coefficient necessary for estimating the weight of each part is calculated.

$$\text{Coefficient for hull structure weight, } C_s = \frac{W_s}{L^{1.6}\cdot(B+D)}\Big|_{Basis} \quad (31)$$

"W_s" is the hull structure weight of reference LNG FPSO. "L" is the hull length, "B" is the hull breadth, and "D" is the hull depth.

Coefficient for hull outfit weight, $C_o = \frac{W_o}{L \cdot B}|_{Basis}$ (32)

"W_o" is the hull outfit weight of reference LNG FSPO.

Coefficient for hull piping weight, $C_p = \frac{W_p}{V_{CH}}|_{Basis}$ (33)

"W_p" is the hull piping weight of reference LNG FPSO and "V_{CH}" is the cargo hold volume of reference LNG FPSO.

Coefficient for hull machinery weight, $\frac{W_m}{(L \cdot B \cdot D - V_{CH})}|_{Basis}$ (34)

"W_m" is the hull machinery weight of reference LNG FPSO.

Coefficient for hull electric weight, $C_e = \frac{W_e}{L}|_{Basis}$ (35)

"W_e" is the hull electrical weight of reference LNG FPSO.

Based on the calculated coefficients, the lightweight of LNG FPSO is estimated according to following formulas.

Hull structure weight, $W_s = C_s \cdot L^{1.6} \cdot (B + D)$ (36)

Hull outfit weight, $W_o = C_o \cdot L \cdot B$ (37)

Hull piping weight, $W_p = C_p \cdot V_{CH}$ (38)

Hull machinery weight, $W_m = C_m \cdot (L \cdot B \cdot D - V_{CH})$ (39)

The total light weight of the LNG FPSO is the sum of the hull weight and the topside weight.

$$\text{Lightweight,}\ LWT = W_s + W_o + W_p + W_m + W_e + W_a + W_t \quad (40)$$

"W_t" is the total topside weight, and it is given.

Based on the calculated lightweight, loading conditions of LNG FPSO are set up. In this study, two loading conditions are considered. One is the full load condition in which the cargo is fully loaded in the cargo hold, and the other is the ballast condition in which 2% of the cargo is loaded, and wing and bottom ballast water tanks are fully loaded. Midship section of each loading condition is shown in Figure 28.

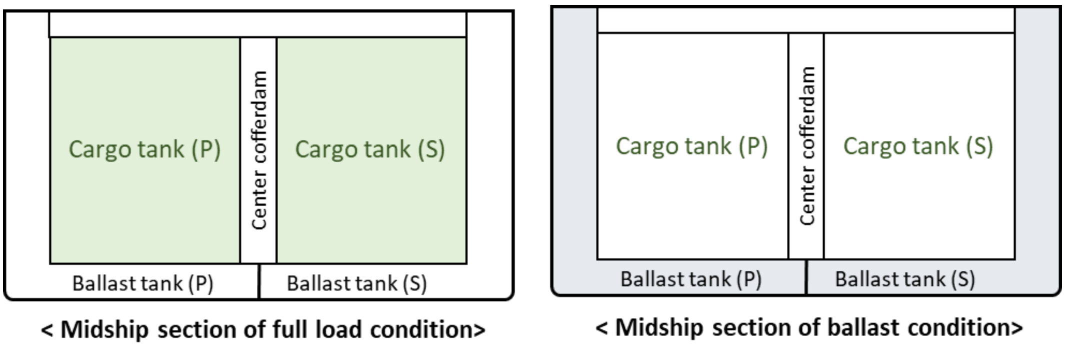

Figure 28 Midship section of each loading condition

For the process efficiency of topside modules of LNG FPSO, trim and heel shall be minimized during operation. In this study, filling ratios of a fore peak tank and a pair of aft peak tanks are automatically adjusted, so that trim and heel of LNG FPSO are closed to zero.

3.6. 3D visualization library

The 3D visualization library has a role of displaying models on the screen based on the models which were generated from the modeling library and calculated values through calculation libraries and optimization library and displaying real-time situation of optimization. They are displayed on the 3d visualization panel. For 3D visualization, an open source library WPF 3D (http://helixtoolkit.codeplex.com/) was used.

4. Application

To verify the applicability of the proposed method and prototype program, they were applied to the layout design of the LNG FPSO. Simultaneous optimization of principal dimensions, layout of hull tanks and topside modules & equipment was performed.

4.1. Input information

To use the proposed method, input information is required to be used for optimization.

4.1.1. Requirement

As shown in Table 20, we defined the requirements based on the information of the reference LNG FPSO. Main requirements are the production capacity of the topside facility and required capacity and number of each storage tank.

Table 20 Requirement

		Reference LNG FPSO	Requirements	Remark
Production rate	LNG	2.0 MTPA	2.0 MTPA	
	LPG	0.8 MTPA	0.8 MTPA	
	Condensate	0.2 MTPA	0.2 MTPA	
Tank capacity	LNG	200,000 m3	200,000 m3	100 % filling
	LPG	60,000 m3	60,000 m3	100 % filling
	Condensate	60,000 m3	60,000 m3	100 % filling
	Process liquid	50,000 m3	50,000 m3	100 % filling
Number of tanks	LNG	8	8	
	LPG	2	2	
	Condensate	2	2	
	Process liquid	2	2	
Principal dimensions	LOA	420 m		
	LBP	417.0 m		
	Bmld	68.0 m		
	Dmld	35.5 m		
POB		400	400	
Deadweight (design)		200,000 ton		
Mooring load		4,000 ton		
Displacement(design)		396,000 ton		

4.1.1. Input information

Some information is required to perform the optimization of the layout design of this study.

1) Module information of reference LNG FPSO

Module information including size and weight is shown in Table 21, and it is given from reference LNG FPSO. The module is designed to handle all the topside processes of the typical LNG FPSO.

The total number of topside modules including living quarter is 22, and the total weight of topside modules are 58,300 ton.

Table 21 Module information of reference LNG FPSO

	Name	Abbreviation	Length (m)	Width (m)	Height (m)	Weight (ton)
0	Turret	TUR	30	20	30	5,000
1	Flare	FLA	30	20	30	2,000
2	Separator	SEP	30	20	30	2,800
3	AGRU	AGR	30	20	30	2,600
4	Dehydration	DEH	30	20	30	3,400
5	Mercury removal	MER	30	20	30	2,000
6	Fractionation	FRA	30	20	30	2,100
7	Liquefaction A	LIP	30	20	30	4,200
8	Liquefaction B	LIS	30	20	30	4,200
9	Condensate stabilization	CON	30	20	30	2,500
10	Precooling liquefaction compression A	WLA	30	20	30	2,700
11	Precooling liquefaction compression B	WLB	30	20	30	2,500
12	Main liquefaction compression A	CLA	30	20	30	2,700
13	Main liquefaction compression B	CLB	30	20	30	2,700
14	MEG reclamation	MEG	30	20	30	2,000
15	Utility	UTI	30	20	30	2,300
16	E&I building	ENI	30	20	30	2,000
17	Power generation A	PGP	30	20	30	2,600
18	Power generation B	PGS	30	20	30	2,600
19	Laydown area A	LAP	30	20	30	700
20	Laydown area B	LAS	30	20	30	700
21	Living quarter	LQ	30	20	30	4,000

2) Equipment information of reference LNG FPSO

Equipment information including size, shape, and type is shown in Table 22 to Table 34, and it is given from reference LNG FPSO. The equipment is selected to handle typical process according to the schematic diagram.

Separation module has two decks, and equipment list is shown in Table 22.

Table 22 Equipment list of separation module

No.	Equipment	Length (m)	Width (m)	Height (m)	Shape	Type
1	HP Inlet separator	5	5	16	Cylinder	Vertical
2	HP Inlet separator	5	5	16	Cylinder	Vertical
3	LP separator	11	6	6	Cylinder	Horizontal

AGRU (Acid gas removal unit) module has two decks, and equipment list is shown in Table 23.

Table 23 Equipment list of AGRU module

No.	Equipment	Length (m)	Width (m)	Height (m)	Shape	Type
1	Absorber	7	7	16	Cylinder	Vertical
2	Stripper	4	4	5	Cylinder	Vertical

Dehydration module has two decks, and equipment list is shown in Table 24.

Table 24 Equipment list of dehydration module

No.	Equipment	Length (m)	Width (m)	Height (m)	Shape	Type
1	Adsorption tower	3	3	12	Cylinder	Vertical
2	Adsorption tower	3	3	12	Cylinder	Vertical
3	Adsorption tower	3	3	12	Cylinder	Vertical

Mercury removal module has two decks, and equipment list is shown in Table 25.

Table 25 Equipment list of mercury removal module

No.	Equipment	Length (m)	Width (m)	Height (m)	Shape	Type
1	Mercury absorber	5	5	10	Rectangular	Vertical
2	Mercury absorber	5	5	10	Rectangular	Vertical

Fractionation module has four decks, and equipment list is shown in Table 26.

Table 26 Equipment list of fractionation module

No.	Equipment	Length (m)	Width (m)	Height (m)	Shape	Type
1	Debutanizer column	3	3	30	Cylinder	Vertical
2	Debutanizer reboiler	1	1	2	Cylinder	Vertical
3	Deetanizer column	3	3	35	Cylinder	Vertical
4	Deetanizer reboiler	1	1	2	Cylinder	Vertical
5	Depropanizer column	3	3	25	Cylinder	Vertical
6	Depropanizer reboiler	1	1	2	Cylinder	Vertical
7	NGL extraction column	3	3	30	Cylinder	Vertical
8	NGL extraction column feed separator	3	3	10	Cylinder	Vertical
9	NGL extraction column reboiler	1	1	2	Cylinder	Vertical

Liquefaction module has four decks, and equipment list is shown in Table 27.

Table 27 Equipment list of liquefaction module

No.	Equipment	Length (m)	Width (m)	Height (m)	Shape	Type
1	Intercooler	2	11	2	Cylinder	Horizontal
2	MCHE	6	6	36	Cylinder	Vertical
3	Condenser	11	4	5	Cylinder	Horizontal
4	MR Suction drum	3	3	6	Cylinder	Vertical
5	MR separator	3	3	6	Cylinder	Vertical
6	MR Compression	10	20	3	Rectangular	Horizontal
7	MR aft cooler	4	2	2	Rectangular	Horizontal

Condensate stabilizer module has four decks, and equipment list is shown in Table 28.

Table 28 Equipment list of condensate stabilizer module

No.	Equipment	Length (m)	Width (m)	Height (m)	Shape	Type
1	No.1 Condensate stabilizer	3	3	30	Cylinder	Vertical
2	No.2 Condensate stabilizer	3	3	30	Cylinder	Vertical
3	No.1 Stabilizer reboiler	3	3	5	Cylinder	Vertical
4	No.2 Stabilizer reboiler	3	3	5	Cylinder	Vertical

Liquefaction compression A module has three decks, and equipment list is shown in Table 29.

Table 29 Equipment list of liquefaction compression A module

No.	Equipment	Length (m)	Width (m)	Height (m)	Shape	Type
1	No.1 NG Booster compressor	11	2	6	Rectangular	Horizontal
2	No.2 NG Booster compressor	4	12	4	Rectangular	Horizontal
3	NG Expander	2	6	4	Rectangular	Horizontal
4	After cooler	2	4	3	Rectangular	Horizontal
5	No.1 Lean MEG injection pump	6	11	5	Rectangular	Horizontal
6	No.2 Lean MEG injection pump	6	11	5	Rectangular	Horizontal

Liquefaction compression B module has two decks, and equipment list is shown in Table 30.

Table 30 Equipment list of liquefaction compression B module

No.	Equipment	Length (m)	Width (m)	Height (m)	Shape	Type
1	PMR receiver	6	6	20	Cylinder	Vertical
2	HP precool	6	6	20	Cylinder	Vertical
3	MP precool	6	6	20	Cylinder	Vertical
4	LP precool	6	6	20	Cylinder	Vertical

MEG regeneration module has a deck, and equipment list is shown in Table 31.

Table 31 Equipment list of MEG regeneration module

No.	Equipment	Length (m)	Width (m)	Height (m)	Shape	Type
1	Separator	8	4	4	Cylinder	Horizontal
2	Reclaimer flash drum	6	3	3	Cylinder	Horizontal
3	MEG still column	16	6	6	Cylinder	Vertical

Utility module has two decks, and equipment list is shown in Table 32.

Table 32 Equipment list of utility module

No.	Equipment	Length (m)	Width (m)	Height (m)	Shape	Type
1	Air compressor package	6	6	5	Rectangular	Horizontal
2	Nitrogen generation package	3	5	4	Rectangular	Horizontal
3	Low purity nitrogen buffer vessel	2	2	5	Cylinder	Vertical
4	High purity nitrogen buffer vessel	2	2	5	Cylinder	Vertical

E&I building module has a deck, and equipment list is shown in Table 33.

Table 33 Equipment list of E&I building module

No.	Equipment	Length (m)	Width (m)	Height (m)	Shape	Type
1	LER	25	20	15	Rectangular	Horizontal

Power regeneration module has a deck and euipment list is shown in Table 34.

Table 34 Equipment list of power regeneration module

No.	Equipment	Length (m)	Width (m)	Height (m)	Shape	Type
1	No.1 Gas turbine	23	7	14	Rectangular	Horizontal
2	No.2 Gas turbine	23	7	14	Rectangular	Horizontal
3	No.1 Gas turbine funnel	2	2	25	Cylinder	Vertical
4	No.2 Gas turbine funnel	2	2	25	Cylinder	Vertical

4.1.2. Adjacency index

The adjacency index has to be defined to obtain adjacency index. For topside modules, total 22 modules were considered, and six tanks groups for hull tank arrangement were considered as shown in Table 35 and Table 36.

Table 35 Adjacency matrix for modules

No.	Name	Abbreviation	TUR	FLA	SEP	AGR	DEH	MER	FRA	LIP	LIS	CON	WLA	WLB	CLA	CLB	MEG	UTI	ENI	PGP	PGS	LAP	LAB	LQ
0	Turret	TUR	-	9	4	2	0	-1	-1	-1	-1	2	-1	-1	-1	-1	4	-5	-5	-5	-5	-5	-5	-10
1	Flare	FLA		-	4	2	0	-1	-1	-1	-1	2	-1	-1	-1	-1	-1	-5	-5	-5	-5	-5	-5	-10
2	Separator	SEP			-	4	2	0	-1	-1	-1	4	-1	-1	-1	-1	4	-5	-5	-5	-5	-5	-5	-10
3	AGRU	AGR				-	4	2	0	-1	-1	-1	-1	-1	-1	-1	-1	-5	-5	-5	-5	-5	-5	-5
4	Dehydration	DEH					-	4	2	0	0	-1	-1	-1	-1	-1	-1	-5	-5	-5	-5	-5	-5	-5
5	Mercury removal	MER						-	4	2	2	-1	-1	-1	-1	-1	-1	-5	-5	-5	-5	-5	-5	-5
6	Fractionation	FRA							-	4	4	-1	-1	-1	-1	-1	-1	-5	-5	-5	-5	-5	-5	-5
7	Liquefaction A	LIP								-	9	-1	4	2	-1	-1	-1	-5	-5	-5	-5	-5	-5	-5
8	Liquefaction B	LIS									-	-1	-1	-1	4	2	-1	-5	-5	-5	-5	-5	-5	-5
9	Condensate stabilization	CON										-	-1	-1	-1	-1	-1	-5	-5	-5	-5	-5	-5	-5
10	WMR liquefaction compression A	WLA											-	9	9	-1	-1	-5	-5	-5	-5	-5	-5	-5
11	WMR liquefaction compression B	WLB												-	-1	-1	-1	-5	-5	-5	-5	-5	-5	-5
12	CMR liquefaction compression A	CLA													-	9	-1	-5	-5	-5	-5	-5	-5	-5
13	CMR liquefaction compression B	CLB														-	-1	-5	-5	-5	-5	-5	-5	-5
14	MEG reclamation	MEG															-	-5	-5	-5	-5	-5	-5	-5
15	Utility	UTI																-	10	10	10	10	10	4
16	E&I building	ENI																	-	10	10	10	10	4
17	Power generation A	PGP																		-	10	10	10	4
18	Power generation B	PGS																			-	10	10	4
19	Laydown area A	LAP																				-	10	10
20	Laydown area B	LAB																					-	10
21	LQ	LQ																						-

Table 36 Adjacency matrix for tanks groups

No.	Name	Abbreviation	LNG	LPG	CON	PRO	FWD	AFT
0	LNG tanks group	LNG	-	-3	-5	-5	-10	-10
1	LPG tanks group	LPG		-	-3	-3	-5	-5
2	Condensate tanks group	CON			-	-3	-3	-3
3	Process tanks group	PRO				-	-3	-3
4	FWD tanks group	FWD					-	-10
5	AFT tanks group	AFT						-

4.1.3. Expert system

To run the expert system, item for expert's knowledge is required. In this study, various requirements for activation of the expert system were established by investigating international codes and standards, experts' knowledge, and data of the reference project.

The object and relation lists for layout design of the LNG FPSO are summarized in Table 37 and Table 38, respectively.

According to requirements, the volume of each cargo tank shall be greater than or equal to required capacity. For example, the total required capacity of LNG is 2,000,000 m^3, and tank volume of each LNG tank shall be not less than 25,000 m^3 because the number of LNG tanks is eight.

E05 and E06 are for ensuring a minimum space for installation of the topside module on the main deck. To install all topside modules, the main deck requires an area of 390 meters in length and 50 meters in width.

E07, E08, and E09 are the limitations for the allowable hull size of LNG FPSO in the construction dock. To construct hull in the target construction dock, the hull length must be less than 420 meters. And the hull breadth is less than 70 meters, and the hull depth less than 40 meters shall be required based on manufacturability.

E10, E11, and E12 are related to the positioning of specific modules and are based on the reference projects.

In this study, the layout concept of the topside of LNG FPSO is to produce LNG through two liquefaction trains. Accordingly, the modules related to liquefaction are arranged in two rows and R01, R02, R03, R07, and R08 items related to this layout concept. Also, the non-hazardous modules are arranged near the living quarter by referring to the classification rules for an offshore platform. Therefore, non-hazardous modules such as power generation modules, laydown areas, utility module, and E&I building are located between the process modules and the living quarter referring to the layout concept of topside modules of reference projects.

Table 37 Object information list

ID	Object name	Object type	Target property	Attribute	Target value
E01	LNG1P	Tank	Volume	Min	25,000
E02	LPGP	Tank	Volume	Min	30,000
E03	CONP	Tank	Volume	Min	30,000
E04	PROP	Tank	Volume	Min	30,000
E05	Hull	Hull	Length	Min	390
E06	Hull	Hull	Breadth	Min	50
E07	Hull	Hull	Length	Max	420
E08	Hull	Hull	Breadth	Max	70
E09	Hull	Hull	Depth	Max	40
E10	Flare	Module	COG_X	EXT	325
E11	Utility	Module	COG_X	EXT	115
E12	Power generation A	Module	COG_X	EXT	85
E13	Laydown area A	Module	COG_X	EXT	55

Table 38 Relation information list

ID	Object name	Object type	Relation type	Target name	Target property	Target value
R01	Liquefaction A	Module	GroupWith	Liquefaction B	COG_X	0
R02	WMR liquefaction compression A	Module	GroupWith	CMR liquefaction compression A	COG_X	0
R03	WMR liquefaction compression B	Module	GroupWith	CMR liquefaction compression B	COG_X	0
R04	Utility	Module	GroupWith	E&I building	COG_X	0
R05	Power generation A	Module	GroupWith	Power generation B	COG_X	0
R06	Laydown area A	Module	GroupWith	Laydown area B	COG_X	0
R07	CMR liquefaction compression A	Module	GroupWith	CMR liquefaction compression B	COG_X	0
R08	Liquefaction A	Module	DistanceFrom	CMR liquefaction compression A	COG_X	30

4.2. Result

In this study, multi-objective optimization was performed, and the optimal solution was derived by assigning weight factors to each objective function.

The case study was conducted to investigate the influence of the weight factors for each objective function. According to the distribution of weight factors, four cases were considered as shown in Table 39. The basis case was prepared based on the layout design of the reference project. And four case studies were conducted based on safety, economics, and stability.

The case 1 focused on the safety, and the weight factor was assigned to four objective functions related to safety. In the case 2, the weight factors were given to the objective functions related to economics. In the case 3, the weight factor was given intensively to the objective function related to stability. In the case 4, weight factors were given uniformly to all objective functions. And the same weight factors were assigned to objective function for feasibility index in each case.

Table 39 List of objective functions

Objective function			Basis	Safety (Case 1)	Economics (Case 2)	Stability (Case 3)	Balance (Case 4)
Safety	F_2	Adjacent index of tanks group	-	25	0	0	10
	F_4	Adjacent index of modules	-	25	0	0	10
	F_9	Ventilation cost	-	25	0	0	10
	F_{10}	Damage cost considering physical explosion	-	25	0	0	10
Economics	F_1	Hull structure weight index	-	0	20	0	10
	F_3	Pipe length between topside modules and tanks	-	0	20	0	10
	F_6	Pipe length between topside modules	-	0	20	0	10
	F_7	Installation area cost	-	0	20	0	10
	F_8	Piping cost	-	0	20	0	10
Stability	F_5	Transverse weight distribution index	-	0	0	100	10
Expert system	F_{11}	Feasibility index	-	100	100	100	100

4.2.1. Case 1

In the case 1, weight factors were assigned to the objective functions related to safety and feasibility index. The objective functions related to safety are F_2, F_4, F_9, and F_{10}. And the optimization result summary is in Table 40.

Table 40 Optimization result of case 1

Description				Basis	Safety (Case 1)
Principal dimensions			Length (m)	417.0	419.0
			Breadth (m)	68.0	68.0
			Depth (m)	35.5	35.5
Objective functions	Safety	F_2	Adjacent index of tanks group	-0.144	-0.145 (-0.7%)
		F_4	Adjacent index of modules	-0.824	-0.849 (-3.0%)
		F_9	Ventilation cost	0.379	0.366 (-3.4%)
		F_{10}	Damage cost considering physical explosion	0.152	0.150 (-1.3%)
	Economics	F_1	Hull structure weight index	0.161	0.162 (+0.6%)
		F_3	Pipe length between topside modules and tanks	0.272	0.240 (-11.8%)
		F_6	Pipe length between topside modules	0.845	1.052 (+24.5%)
		F_7	Installation area cost	0.871	0.966 (+10.9%)
		F_8	Piping cost	0.515	0.553 (+7.4%)
	Stability	F_5	Transverse weight distribution index	0.540	0.129 (-76.1%)
	Expert system	F_{11}	Feasibility index	2,100	2,100 (0%)

In terms of principal dimensions, the changes of case 1 was 2 meters increase in length, and width and depth are the same as the basis case.

The arrangement of the hull tank changed as shown in Figure 29. As the hull length increased, the hull structure weight index (F_1) increased. The arrangement sequence of the tanks groups in the hull was the same as that of the basis case, but the adjacency index of tanks group (F_2) was improved by the change of the tank size. It is due to the change in the distance between the tanks as the size of the tank increased. And the total length of pipes connecting the modules and the tanks (F_3) was also reduced. It is because the length of the LNG pipeline is greatly reduced as the liquefaction module is moved near the LNG tanks group.

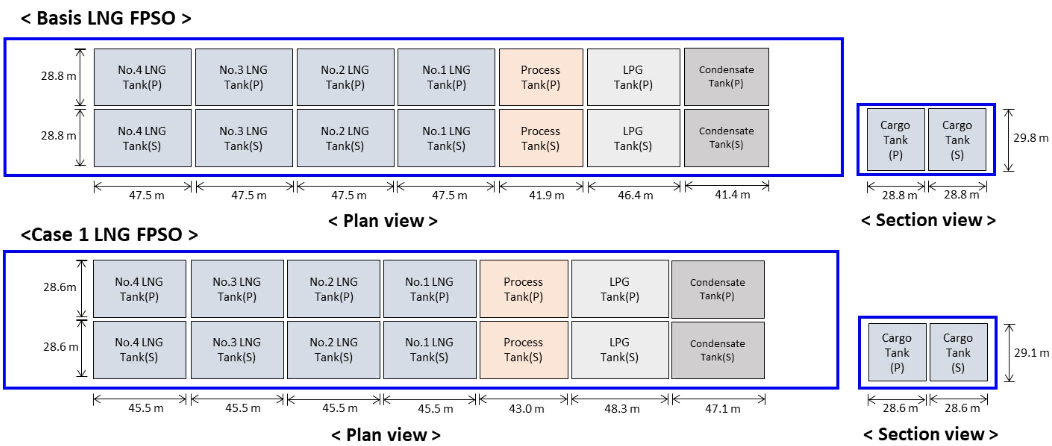

Figure 29 Hull tank arrangement of case 1

The optimization result of topside layout is shown in Figure 30. According to expert system inputs, non-hazardous modules were located near the living quarter where the person resides, and the modules responsible for the process were located near the turret. So, LNG FPSO is designed on the principle of maximizing the segregation of hydrocarbon processing area, turret area and flare system from the living quarter. Power generation and

non-hazardous utility facilities are located between the hydrocarbon processing area and living quarter.

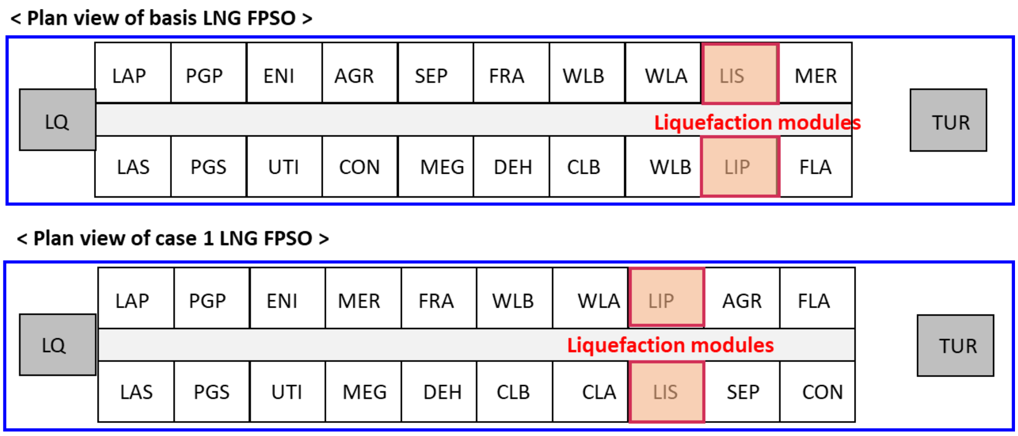

Figure 30 Module layout of case 1

The modules for liquefaction moved to the center of the main deck, and the adjacency index of modules (F_4) was improved. And the transverse weight distribution index (F_5) was improved through module rearrangement. However, the quantity of pipes connecting the modules (F_6) was increased. It is because the modules that are responsible for the LNG pre-treatment are completely separated into two parts by liquefaction and compression modules.

In the equipment layout in each module, the objective functions ventilation cost (F_9) and damage cost considering physical explosion (F_{10}) for safety were improved. It means that the equipment layout on each deck in the module is installed to facilitate ventilation and the risk of explosion damage of the pressure vessel is reduced. However, the economics related objective functions installation area cost (F_7) and piping cost (F_8) without the weight factor were worse. It means that the total deck area for arranging the equipment and the amount of pipes connecting the equipment were increased.

Finally, the all items of object information and relation information were applied through the expert system and reflected in the layout design of the LNG FPSO.

4.2.2. Case 2

In the case 2, weight factors were assigned to the objective functions related to economics and feasibility index. The objective functions related to economics are F_1, F_3, F_6, F_7, and F_8. And the optimization result summary is in Table 41.

Table 41 Optimization result of case 2

Description				Basis	Economics (Case 2)
Principal dimensions			Length (m)	417.0	398.0
			Breadth (m)	68.0	66.0
			Depth (m)	35.5	39.5
Objective functions	Safety	F_2	Adjacent index of tanks group	-0.144	-0.143 (+0.7%)
		F_4	Adjacent index of modules	-0.824	-0.831 (-0.1%)
		F_9	Ventilation cost	0.379	0.379 (0%)
		F_{10}	Damage cost considering physical explosion	0.152	0.152 (0%)
	Economics	F_1	Hull structure weight index	0.161	0.152 (-5.6%)
		F_3	Pipe length between topside modules and tanks	0.272	0.141 (-48.2%)
		F_6	Pipe length between topside modules	0.845	0.955 (+13.0%)
		F_7	Installation area cost	0.871	0.723 (-17.0%)
		F_8	Piping cost	0.515	0.508 (-1.4%)
	Stability	F_5	Transverse weight distribution index	0.540	0.437 (-19.1%)
	Expert system	F_{11}	Feasibility index	2,100	2,100

Regarding principal dimensions, the changes of case 2 were 4 meters increase in depth, and 19 meters decrease in length, and 2 meters decrease in breadth.

The arrangement of the hull tank changed as shown in Figure 31. Even though the hull depth was increased, the hull structure weight index (F_1) decreased due to a significant decrease in length and a decrease in breadth. The arrangement sequence of the tanks groups in the hull was changed. LNG tanks group was moved to forward near liquefaction modules. Due to the relocation of LNG tanks groups, objective function Pipe length between topside modules and tanks (F_3) was improved. However, adjacency index of tanks group (F_2) got worse, because the LPG tanks group was located near the FWD part where the turret is located according to adjacency matrix for tanks groups.

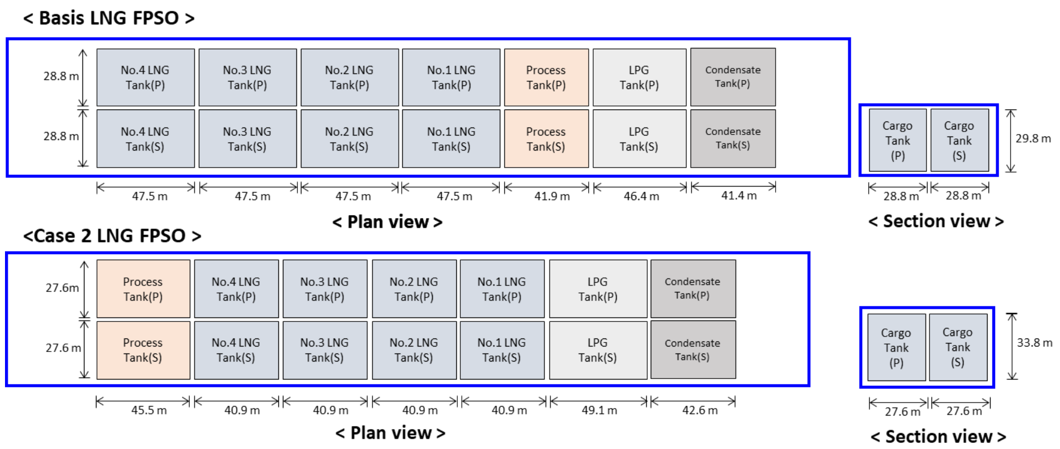

Figure 31 Hull tank arrangement of case 2

The optimization result of topside layout is shown in Figure 32. According to expert system inputs, non-hazardous modules were located near the living quarter where the person resides, and the modules responsible for the process were located near the turret. So, LNG FPSO is designed on the principle of maximizing the segregation of hydrocarbon processing area, turret area and flare system from the living quarter. Power generation and

non-hazardous utility facilities are located between the hydrocarbon processing area and living quarter.

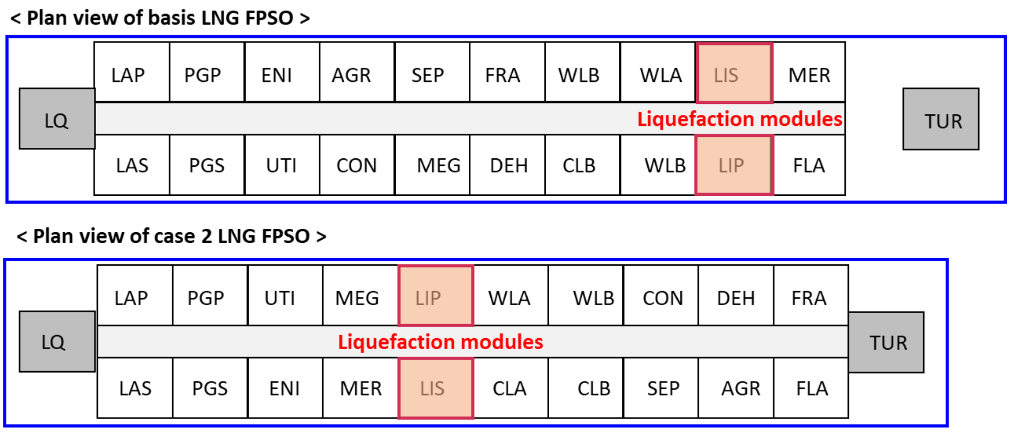

Figure 32 Module layout of case 2

The modules for liquefaction moved to the center of the LNG tanks group, and their position has a significant effect to minimize the pipe length of liquefaction modules and all LNG tanks. And modules for liquefaction and compression which deal with high pressure and low-temperature LNG were far away from the living quarters, and the adjacency index of modules (F_4) was improved. However, the movement of the liquefaction modules slightly increased the quantity of the main process pipeline among the modules.

In the equipment layout in each module, the objective functions installation area cost (F_7) and piping cost (F_8) for economics were improved. It means that the total deck area for arranging the equipment and the amount of pipes connecting the equipment were decreased. However, the safety-related objective functions ventilation cost (F_9) and damage cost considering physical explosion (F_{10}) without the weight factor were the same as the basis case.

Finally, the all items of object information and relation information were applied through the expert system and reflected in the layout design of the LNG FPSO.

4.2.3. Case 3

In the third case, weight factors were assigned to the objective function related to stability and feasibility index. The objective function related to stability is only transverse weight distribution index (F_5). And the optimization result summary is in Table 42.

Table 42 Optimization result of case 3

Description				**Basis**	**Stability (Case 3)**
Principal dimensions			Length (m)	417.0	402.0
			Breadth (m)	68.0	64.0
			Depth (m)	35.5	39.5
Objective functions	Safety	F_2	Adjacent index of tanks group	-0.144	-0.138 (+4.3%)
		F_4	Adjacent index of modules	-0.824	-0.844 (-2.4%)
		F_9	Ventilation cost	0.379	0.430 (+13.5%)
		F_{10}	Damage cost considering physical explosion	0.152	0.151 (-0.7%)
	Economics	F_1	Hull structure weight index	0.161	0.152 (-5.6%)
		F_3	Pipe length between topside modules and tanks	0.272	0.212 (-22.1%)
		F_6	Pipe length between topside modules	0.845	0.862 (+2.0%)
		F_7	Installation area cost	0.871	0.845 (-3.0%)
		F_8	Piping cost	0.515	0.550 (+6.8%)
	Stability	F_5	Transverse weight distribution index	0.540	0.180 (-66.7%)
	Expert system	F_{11}	Feasibility index	2,100	2,100 (0%)

In terms of principal dimensions, the changes of case 3 were 4 meters increase in depth, and 15 meters decrease in length, and 4 meters decrease in breadth.

The arrangement of the hull tank changed as shown in Figure 33. Even though the hull depth was increased, the hull structure weight index (F_1) decreased due to a significant decrease in length and a decrease in breadth. The arrangement sequence of the tanks groups in the hull was changed. The arrangement sequence of LNG tanks group was the same as the basis. Also, the relocation of the liquefaction modules and some tanks groups reduced the amount of pipes connecting the modules to the tanks (F_3). On the other hand, the arrangement sequence of other tanks groups was changed, and it resulted in the increase in the adjacency index of the tanks groups (F_2).

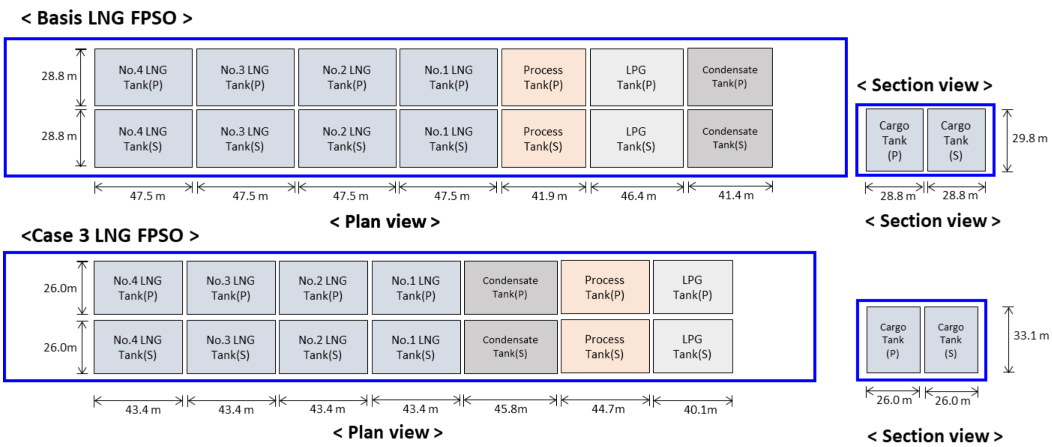

Figure 33 Hull tank arrangement of case 3

The optimization result of topside layout is shown in Figure 34. According to expert system inputs, non-hazardous modules were located near the living quarter where the person resides, and the modules responsible for the process were located near the turret. So, LNG FPSO is designed on the principle of maximizing the segregation of hydrocarbon processing area, turret area and flare system from the living quarter. Power generation and

non-hazardous utility facilities are located between the hydrocarbon processing area and living quarter.

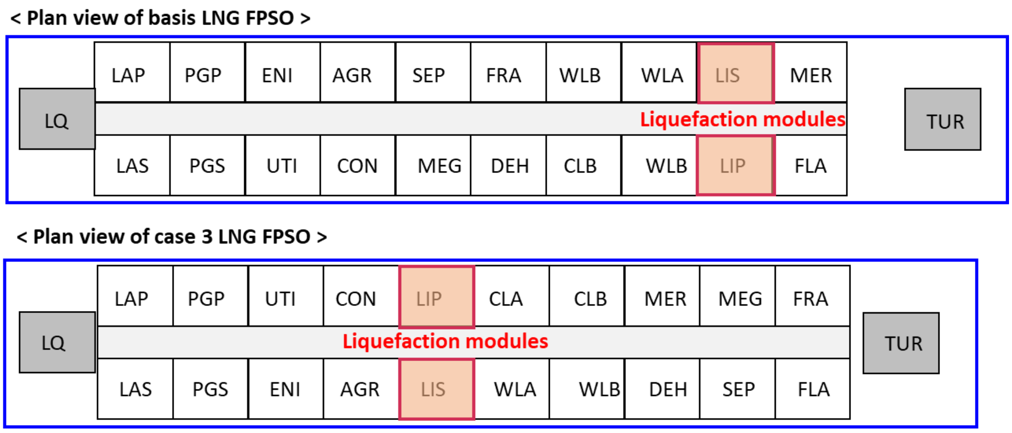

Figure 34 Module layout of case 3

The transverse weight distribution was improved through module rearrangement. The case 3 was to minimize the transverse weight difference of the topside modules, and it was considered to improve the stability performance of LNG FPSO. Since the weight factor was concentrated on the objective function F_5, this was greatly improved compared to the basis. And the modules for liquefaction moved to the center of the main deck, and the adjacency index of the modules (F_4) was improved. However, the quantity of pipes connecting the modules (F_6) was increased. This is because the distance between each production module that is responsible for the LNG pre-treatment and respective storage tanks are far away.

In the equipment layout in each module, the objective functions F_7, F_8, F_9, and F_{10} for the equipment layout had no weight factor. Compared to the basis, installation area cost (F_7) and damage cost considering physical explosion (F_{10}) were improved. It means that the total deck area for arranging the equipment and the risk of explosion damage of the pressure vessel were reduced. However, piping cost (F_8) and ventilation cost (F_9) were increased. This means the amount of pipes connecting the equipment was increased and ventilation inside the module was relatively difficult.

4.2.4. Case 4

In the case 4, weight factors were assigned to the objective functions and feasibility index. The weight factor was equally divided into the F_1, F_2, F_3, $F_{4,}$ F_5, F_6, F_7, $F_{8,}$ F_9, and $F_{10.}$ And the optimization result summary is in Table 43.

Table 43 Optimization result of case 4

Description				Basis	Balance (Case 4)
Principal dimensions			Length (m)	417.0	399.0
			Breadth (m)	68.0	64.0
			Depth (m)	35.5	39.5
Objective functions	Safety	F_2	Adjacent index of tanks group	-0.144	-0.145 (-0.7%)
		F_4	Adjacent index of modules	-0.824	-0.869 (-5.5%)
		F_9	Ventilation cost	0.379	0.366 (-3.4%)
		F_{10}	Damage cost considering physical explosion	0.152	0.151 (-0.7%)
	Economics	F_1	Hull structure weight index	0.161	0.150 (-6.8%)
		F_3	Pipe length between topside modules and tanks	0.272	0.231 (-15.1%)
		F_6	Pipe length between topside modules	0.845	0.577 (-31.7%)
		F_7	Installation area cost	0.871	0.780 (-10.4%)
		F_8	Piping cost	0.515	0.569 (+10.5%)
	Stability	F_5	Transverse weight distribution index	0.540	0.952 (+76.3%)
	Expert system	F_{11}	Feasibility index	2,100	2,100 (0%)

In terms of principal dimensions, the changes of case 4 were four meters increase in depth, and sixteen meters decrease in length, and four meters decrease in breadth.

The arrangement of the hull tank changed as shown in Figure 35. Even though the hull depth was increased, the hull structure weight index (F_1) decreased due to a significant decrease in length and a decrease in breadth. The arrangement sequence of the tanks groups in the hull was changed. Adjacency index of tanks group (F_2) was improved, because the LNG tanks group and LNG tanks group, which store the cryogenic liquid, are respectively separated from the AFT part and the FWD part. And LNG tanks group was moved to forward near liquefaction modules. Due to the relocation of LNG tanks groups, Pipe length between topside modules and tanks (F_3) was improved.

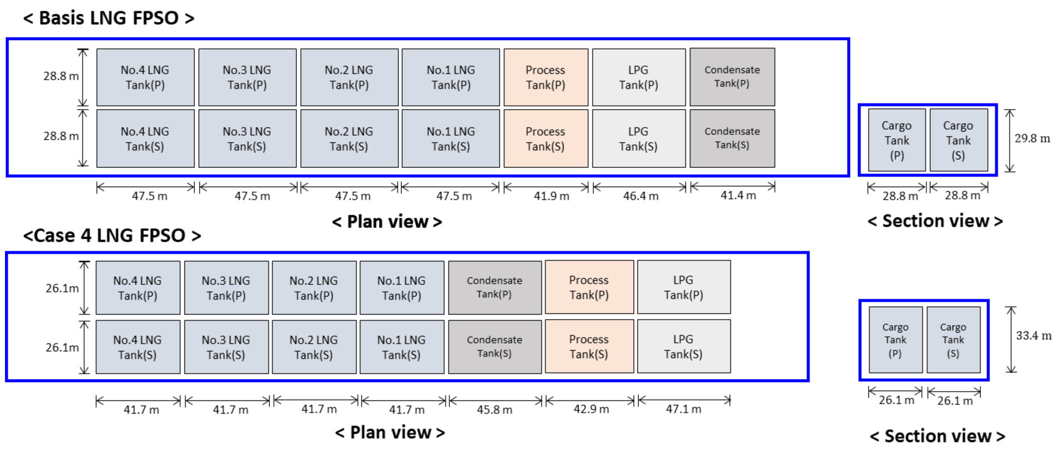

Figure 35 Hull tank arrangement of case 4

The optimization result of topside layout is shown in Figure 36. According to expert system inputs, non-hazardous modules were located near the living quarter where the person resides, and the modules responsible for the process were located near the turret. So, LNG FPSO is designed on the principle of maximizing the segregation of hydrocarbon processing area, turret area and flare system from the living quarter. Power generation and

non-hazardous utility facilities are located between the hydrocarbon processing area and living quarter.

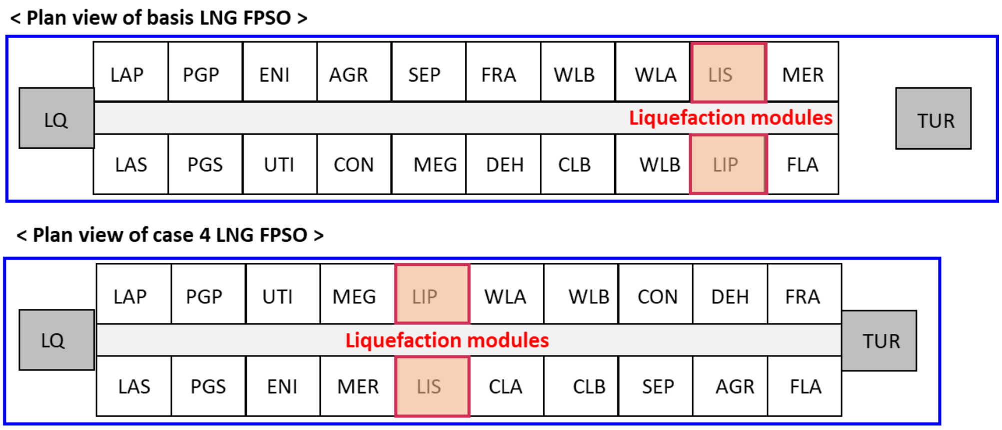

Figure 36 Module layout of case 4

The modules for liquefaction moved to the center of the main deck, and the adjacency index of the modules (F_4) was improved. And the quantity of pipes connecting the modules (F_6) was decreased. It is because the modules that are responsible for the LNG pre-treatment were arranged in the forward area. However, the transverse weight distribution (F_5) was not improved through module rearrangement.

In the equipment layout in each module, the objective functions F_7, F_9, and F_{10} were improved. It means that the total deck area for arranging the equipment (F_7), ventilation cost (F_9), and the risk of explosion damage of the pressure vessel (F_{10}) were decreased. However, the amount of pipes connecting the equipment (F_8) was increased. It means the total length among equipment were increased.

Finally, the all items of object information and relation information were applied through the expert system and reflected in the layout design of the LNG FPSO.

4.3. Summary of optimization results

In this study, we performed multi-objective optimization and tried to evaluate the effect of weight factors on each objective function. The basis case was defined based on the reference project, and four case studies were conducted according to the weight factor of the objective function.

Table 44 summarizes the optimization results. First, the results of case 1, in which the weight factor was given only to the objective function for safety, was shown that all the safety-related objective functions F_2, F_4, F_9, and F_{10} were improved. In case 2, in which the weight factor was given only to the objective function for economic efficiency, 4 out of 5 economic objective functions were improved. Case 3, in which the objective function is concentrated only on stability related objective function F_5, is shown that the value of F_5 was greatly improved. In case 4, in which the weight factor is uniformly assigned to all objective functions, 8 items out of 10 objective functions were improved.

It confirms that the design trend of the LNG FPSO changes with the weight factor value. The results of optimization show that the actual LNG FPSO can be designed according to the project characteristics and the customer's requirements when designing the actual layout.

Table 44 Summary of optimization result

Description				Basis	Safety (Case 1)	Economics (Case 2)	Stability (Case 3)	Balance (Case 4)
Principal dimensions	Length			417	419	398	402	399
	Breadth			68	68	66	64	64
	Depth			35.5	35.5	39.5	40	39.5
Objective functions	Safety	F_2	Adjacent index of tanks group	-0.144	-0.145 (-0.7%)	-0.143 (+0.7%)	-0.138 (+4.3%)	-0.145 (-0.7%)
		F_4	Adjacent index of modules	-0.824	-0.849 (-3.0%)	-0.831 (-0.1%)	-0.844 (-2.4%)	-0.869 (-5.5%)
		F_9	Ventilation cost	0.379	0.366 (-3.4%)	0.379 (0%)	0.430 (+13.5%)	0.366 (-3.4%)
		F_{10}	Damage cost considering physical explosion	0.152	0.150 (-1.3%)	0.152 (0%)	0.151 (-0.7%)	0.151 (-0.7%)
	Economics	F_1	Hull structure weight index	0.161	0.162 (+0.6%)	0.152 (-5.6%)	0.152 (-5.6%)	0.150 (-6.8%)
		F_3	Pipe length between topside modules and tanks	0.272	0.240 (-11.8%)	0.141 (-48.2%)	0.212 (-22.1%)	0.231 (-15.1%)
		F_6	Pipe length between topside modules	0.845	1.052 (+24.5%)	0.955 (+13.0%)	0.862 (+2.0%)	0.577 (-31.7%)
		F_7	Installation area cost	0.871	0.966 (+10.9%)	0.723 (-17.0%)	0.845 (-3.0%)	0.780 (-10.4%)
		F_8	Piping cost	0.515	0.553 (+7.4%)	0.508 (-1.4%)	0.550 (+6.8%)	0.569 (+10.5%)
	Stability	F_5	Transverse weight distribution index	0.540	0.129 (-76.1%)	0.437 (-19.1%)	0.180 (-66.7%)	0.952 (+76.3%)
	Expert system	F_{11}	Feasibility index	-	2100	2100	2100	2100

5. Conclusions and future works

5.1. Conclusions

This study proposes the integrated method for optimal layout design of LNG FPSO. The target of this study contains simultaneous optimization of principal dimensions, hull tanks, topside modules, and equipment, considering safety, economics, and stability. And the expert system and the optimization technique are applied to solve the problem of layout design.

The multi-purpose optimization is performed, and the optimization problem is formulated with design variables, objective functions, and constraints. Many information and values are used in this module to get an optimized result. In this study, the formulated problem has many objective functions and to solve this complicated problem efficiently optimization was used.

The prototype program was developed to confirm the effectiveness and usefulness of the proposed method. The program consists of several libraries such as modeling library, expert system library, optimization library, stability calculation library, and 3D visualization library. Through the application of this method to the program, the layout design of LNG FPSO can be performed efficiently. Also, the middle scale LNG FPSO was applied to case studies using prototype program. The optimal results and case study show that proposed method can be used as a new tool for the layout design of the LNG FPSO.

5.2. Future works

For future work, the prototype program for layout design will be refined so that the user can input more information on the program. Therefore, the program will be supplemented so that it can be applied to various kinds of offshore platform designs.

To improve the performance of the prototype program, the function of calculating the damage stability will be added. And the expert system will be improved to reflect expert's knowledge and international codes/standards more effectively

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국문 초록

최적화 기법과 전문가 시스템 기반

LNG FPSO 의 통합 배치 설계 방법

LNG FPSO 는 LNG 처리 설비를 탑재하고 있는 부유식 생산, 저장, 하역 설비로, 설계 시 가스전의 환경 조건과 운영 방식에 따라 선주의 요구 조건, 공정 흐름, 관련 국제 규정, 선급 및 발주처 자체 규정, 유사 프로젝트 데이터, 전문가의 경험과 지식 등이 복합적으로 고려되어야 한다. 특히 LNG FPSO 는 육상 LNG 플랜트의 다양한 장비와 설비를 선체 상부 (topside)의 제한된 공간에 배치해야 하므로 효율적 공간 활용을 위한 배치가 필수적이다. 또한, LNG FPSO 를 비롯한 해양 플랜트에서의 사고는 인명 및 환경, 비용적인 측면에서 큰 피해를 야기 시키므로, 폭발과 같은 안전에 위협이 되는 요소도 필히 고려하여 최적의 배치 설계를 수행해야 한다.

본 연구에서는 안정성 (stability), 안전성 (safety), 그리고 경제성 (economics)을 동시에 고려한 통합 최적 배치 설계 방법을 제안하고, 이를 LNG FPSO 의 배치 설계 예제에 적용하여 그 효용성을 검증하는 것을 목표로 한다. 본 연구의 범위는 선체 내 탱크 (tank) 크기 결정, 탱크 및 구획 배치를 통한 주요 제원 결정, 모듈 (module) 배치 및 모듈 내 장비 (equipment) 배치이며, 이들 과정을 하나의 최적화 문제로 정식화 하여 동시 최적화를 수행하고자 하였다. 또한, 배치 설계를 위한 국제 규정 및 전문가의 지식 등을 전문가 시스템의 규칙으로 구현하여 최적 배치 과정에 효과적으로 반영하고자 하였다.

본 연구에서 제안한 방법의 효용성을 평가하기 위해, LNG FPSO 최적 배치 설계 프로토타입 프로그램을 개발하였으며, 이를 중형 LNG FPSO 의 최적 배치 설계 예제에 적용하였다. 본 연구는 다목적 최적화를 수행하기 때문에 최적 해를 도출하기 위해 각 목적 함수에 가중치 (weight factor)를 부여하여 최적화를 수행하였다.

적용 결과, LNG FPSO 의 배치 설계 결과는 가중치에 따른 목적 함수에 따라 배치 설계 최적화가 되었으며, 또한 설계자가 정의한 규칙들을 만족하는 최적의 LNG FPSO 통합 배치 설계 결과를 도출할 수 있음을 확인하였다.

향후 연구 계획으로는 프로토타입 프로그램에 복원성 계산 기능을 보완하고, 다양한 전문가의 지식을 표현하기 위해 전문가 시스템을 확장하여 다양한 종류의 부유식 생산 설비에 적용할 수 있도록 연구할 예정이다.

Keywords: LNG FPSO, FLNG, 배치 설계, 전문가 시스템, 최적화 기법

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