Innovative Ship and Offshore Plant Design

Part II. Offshore Plant Design

Ch. 4 Layout Design of Topside Systems

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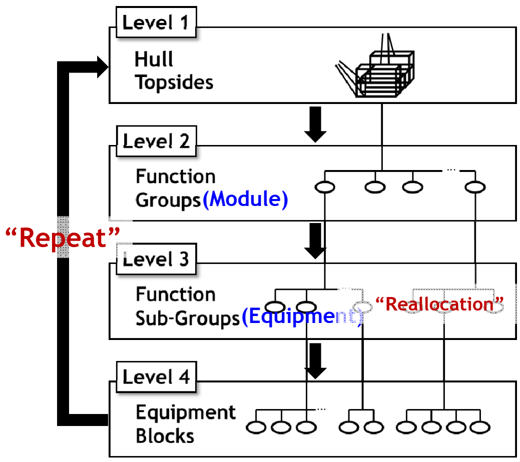
Hierarchical Approach (Top-Down Approach)



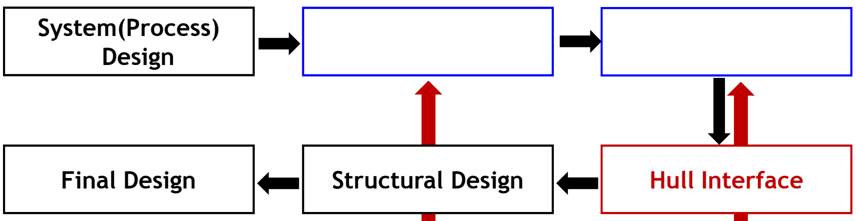
Considerations for layout
- Antagonisms
- Affinities
  - Engineering affinities
  - Manning affinities

Example of Modules of Guara FPSO(Modec/Toyo's) fabricated by Aibel

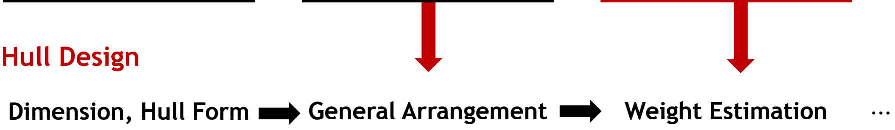
* Reference: PETRONAS, "Layout Considerations for Offshore Topsides Facilities", 1990

Existing Method for Topsides Layout (2/2)

- Topsides Design*

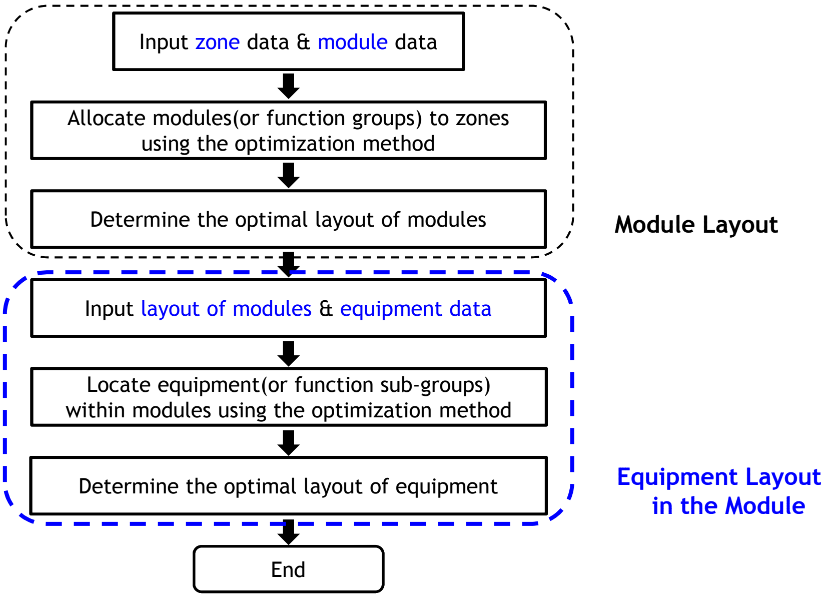


- Hull Design



* Terpstra, T., et al, "FPSO Design and Conversion: A Designer's Approach", Offshore Technology Conference, 30 April-3 May 2001, Houston, Texas

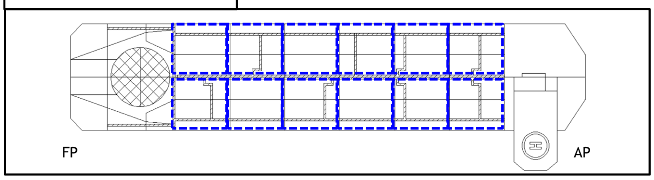
Optimal Layout of Topsides Using Optimization Technique



1. Optimal Module Layout of Topsides of Offshore Plant

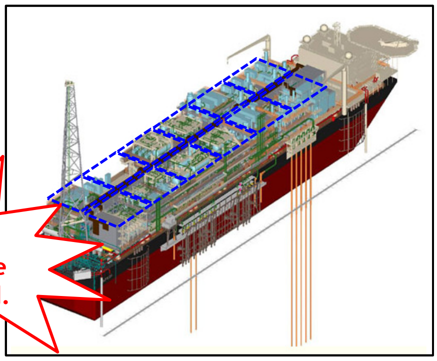
Necessity of Optimal Module Layout

Plan view of the FPSO*



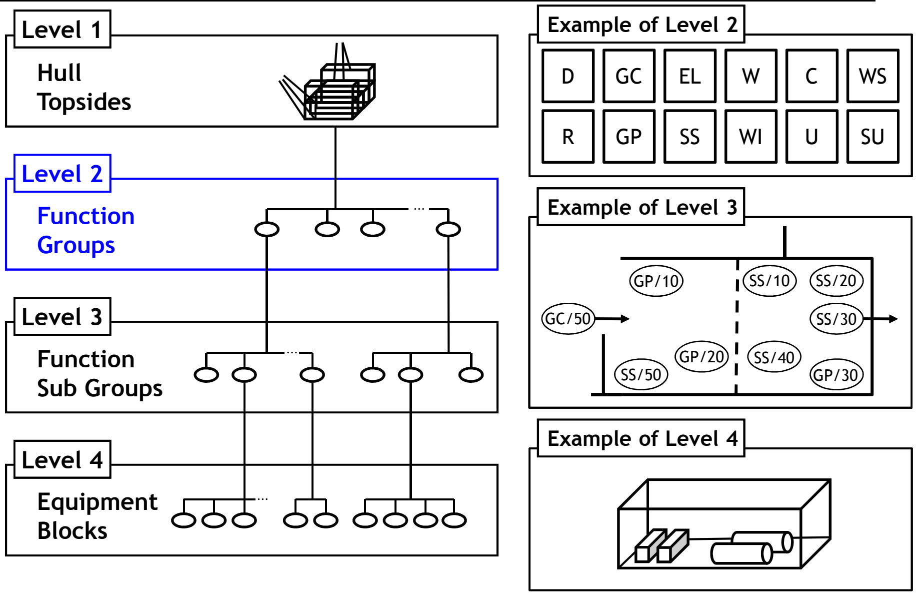
No of modules	No of design alternatives
8	40,320
10	3,628,800
12	479,001,600
14	8.72×10^{10}
16	2.09×10^{13}
18	6.40×10^{15}
…	⋮

Too many cases to be considered.



* **Reference:** (Article) MBN, 2007.12, The DSME receives an order of FPSO of 2 billion.

Hierarchical Approach of Module Layout of Topsides of Offshore Plant



* Reference: PETRONAS, "Layout Considerations for Offshore Topsides Facilities", 1990

Example of Topsides Modules (Function Groups, Function Sub Groups)

Wellhead	W
Xmas Trees	W/10
Manifold	W/20
Well Control	W/30
Conductors	W/40

Drilling	D
BOP	D/10
Drilling Derrick	D/20
Drilling Support	D/30
Mud Systems (Active)	D/40
Drilling Control	D/50

Separation/Stabilization	SS
Separation	SS/10
Stabilization	SS/20
Test Separation	SS/30
Produced Water Treatment	SS/40
Oil Export Pumping	SS/50
Oil Metering	SS/60

Gas Processing	GP
Gas Processing	GP/10
Condensate Processing	GP/20
Dehydration	GP/30
Fuel Gas	GP/40

Gas Compressing	GC
Compression Train	GC/10
Scrubber	GC/20
Coolers	GC/30
Lube Oil/Seal Oil	GC/40
Gas Metering	GC/50

Risers	R
Risers/Manifolds	R/10
ESD Valves	R/20
Pigging Facilities	R/30
Subsea Sat. Facilities	R/40

Flare System	F
Flare Knockout	F/10
Tower (incl. tip)	F/20

Living Quarter	LQ
Living Quarters	LQ/10
Living Quarters Utilities	LQ/20
Sheltered Area	LQ/30
Helideck	LQ/40

Control	C
Central Control	C/10
Local Control	C/20

Workshop/Stores	WS
Workshop - Mechanical	WS/10
Workshop - Electrical	WS/20
Stores	WS/30
Laboratory	WS/40
Storage - Standby Fuel	WS/50
Storage - Jet Fuel	WS/60
Storage - Flamm./Comb. Liquids	WS/70
Storage - Process Consumables	WS/80

Material Handling	MH
Cranes	MH/10
Laydown Areas	MH/20

Utilities	U
Seawater System	U/10
Instrument Air System	U/20
Diesel System	U/30
HVAC	U/40
Potable Water	U/50
Sewage Systems	U/60
Heating Systems	U/70
Cooling Systems	U/80

Safety Utilities	SU
Fire Water Pumps	SU/10
Emergency Generator	SU/20
Emergency Switchgear	SU/30
UPS	SU/40
Survival Craft	SU/50
Bridges	SU/60

Electrical Power Generation	EL
Driver / Power Generator	EL/10
Switchgear	EL/20

Transmission Systems	TS
Relief and Blowdown	TS/10
Drains - Open	TS/20
Drains - Closed	TS/30
Piping - Process	TS/40
Piping - Safety	TS/50
Piping - Utilities.	TS/60
Cables - Instrumentation	TS/70
Cables - Electrical	TS/80
Ducting - HVAC	TS/90

Water Injection	WI
Injection	WI/10
Treatment	WI/20

* Reference: PETRONAS, "Layout Considerations for Offshore Topsides Facilities", 1990

Characteristics for the Representation of Relationship between Topsides Modules

: Characteristics which preclude an module being safely located near another specific module unless mutually protected (e.g., “two modules should be distant from each other.”)

: Characteristics which make it particularly advantageous to locate one module close to another specific module (e.g., “two modules should be adjacent to each other.”)

Relationship between Topside Modules - Antagonisms

☑ Characteristics for defining antagonisms

- Active behavior characteristics: Probability of a module initiating major incidents
- Reactive behavior characteristics: Propensity for a module to escalate major incidents initiated elsewhere.

Antagonisms Matrix

FUNCTION GROUP			W	D	SS	GP	GC	R	F	LQ	C	WS	MH	U	SU	EL	TS	WI
		REACTIVE	3	3	3	3	2	3	3	3	3	2	2	2	3	3	3	2
		ACTIVE																
WELL HEAD	W	3	-															
DRILLING	D	3	3	-														
SEP./STABILIZATION	SS	2	3	3	-													
GAS PROCESSING	GP	2	3	3	3	-												
GAS COMPRESSION	GC	3	3	3	3	3	-											
RISERS	R	3	3	3	3	3	3	-										
FLARE SYSTEM	F	2	3	3	3	3	3	3	-									
LIVING QUARTER	LQ	0	3	3	3	3	3	3	3									
CONTROL	C	0	3	3	3	3	3	3	3	1	-							
WORKSHOP/STORES	WS	0	3	3	2	2	3	3	2	1	1	-						
MATERIAL HANDLING	MH	1	3	3	2	2	3	3	2	2	2	1	-					
UTILITIES	U	1	3	3	2	2	3	3	2	2	2	1	1	-				
SAFETY UTILITIES	SU	1	3	3	3	3	3	3	3	2	2	1	2	2	-			
ELEC. POWER GEN.	EL	3	3	3	3	3	3	3	3	3	3	2	2	2	3	-		
TRANSMISSION SYSTEMS	TS	3	3	3	3	3	3	3	3	3	3	2	2	2	3	3	-	
WATER INJECTION	WI	0	3	3	2	2	3	3	2	1	1	1	1	1	1	2	2	-

Each number (1~3) represents a quantitative value of the risk when two modules are located in adjacent zones close. The higher number, the more risk layout.

* References
- PETRONAS, “Layout Considerations for Offshore Topsides Facilities”, 1990
- Quantitative Risk Assessment, SIPM Report EP 55000-18, May 1990
- Guidelines for Risk Analysis Data, Doc. Ref F-RADS, SIPM, June 1990

Relationship between Topside Modules - Affinities

☑ Characteristics for defining affinities

- Engineering affinities: The need to locate certain modules close together, the most fundamental being the requirements of the process logic
- Manning affinities: Ways to minimize the movement of staff around the platform

Manning Affinities Matrix

FUNCTION GROUP			W	D	SS	GP	GC	R	F	LQ	C	WS	MH	U	SU	EL	TS	WI
		LUND	3	3	3	3	1	2	0	3	3	3	3	2	1	2	0	3
WELL HEAD	W	3	-	3	3	3				3	3	3	3					3
DRILLING	D	3		-	3	3				3	3	3	3					3
SEP./STABILIZATION	SS	3			-	3				3	3	3	3					3
GAS PROCESSING	GP	3				-				3	3	3	3					3
GAS COMPRESSION	GC	1					-											
RISERS	R	2						-										
FLARE SYSTEM	F	0							-									
LIVING QUARTER	LQ	3								-	3	3	3					3
CONTROL	C	3									-	3	3					3
WORKSHOP/STORES	WS	3										-	3					3
MATERIAL HANDLING	MH	3											-					3
UTILITIES	U	2																
SAFETY UTILITIES	SU	1																
ELEC. POWER GEN.	EL	2																
TRANSMISSION SYSTEMS	TS	0																
WATER INJECTION	WI	3																-

Each number (1~3) represents a quantitative value of the advantage **when two modules have frequent movement of staff each other** in the aspect of manning affinities.

* Reference: PETRONAS, "Layout Considerations for Offshore Topsides Facilities", 1990

Relationship between Topside Modules - Definition of Adjacency Factor between Modules

Adjacency Factor between Modules $Q = \begin{bmatrix} q_{11} & & \\ & \ddots & \\ & & q_{NN} \end{bmatrix}$

(= Affinities - Antagonisms)

Adjacency Factor Matrix

FUNCTION GROUP		W	D	SS	GP	GC	R	F	LQ	C	WS	MH	U	SU	EL	TS	WI
WELL HEAD	W	-	6	6	3	2	0	0	3	3	3	3	0	0	6	6	2
DRILLING	D		-	3	3	2	0	0	3	3	3	3	0	1	1	3	2
SEP./STABILIZATION	SS			-	3	3	0	0	3	3	3	3	0	5	5	6	2
GAS PROCESSING	GP				-	3	5	5	5	5	6	6	0	0	1	1	0
GAS COMPRESSION	GC					-	1	1	1	1	5	5	4	4	3	3	0
RISERS	R						-	2	2	2	2	6	6	3	3	0	0
FLARE SYSTEM	F							-	5	5	4	4	4	4	3	3	3
LIVING QUARTER	LQ								-	3	3	0	0	3	3	3	3
CONTROL	C									-	5	5	5	3	3	3	3
WORKSHOP/STORES	WS										-	3	3	6	6	6	6
MATERIAL HANDLING	MH											-	5	5	5	6	6
UTILITIES	U												-	0	0	5	5
SAFETY UTILITIES	SU													-	5	5	5
ELEC. POWER GEN.	EL														-	3	3
TRANSMISSION SYSTEMS	TS															-	3
WATER INJECTION	WI																-

Proposal of an Algorithm for Optimal Module Layout - Formulation of an Optimization Problem

Definition of a problem

Determination of module layout which minimizes total material flow (F_1) considering the magnitude of accident risk and the distance (F_2) between total COG of modules in transverse direction and centerline

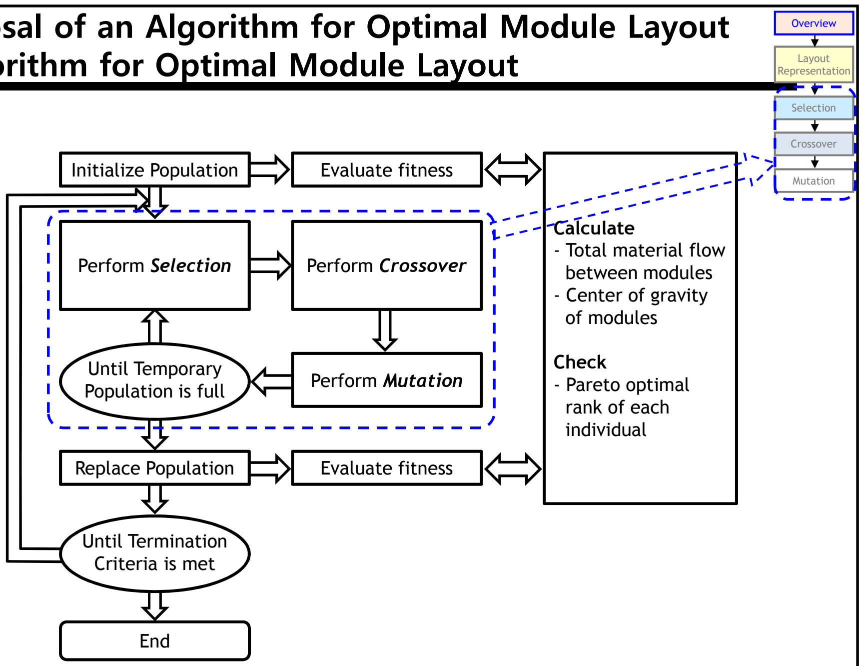
Formulation of the problem

$$Minimize \quad F_1 = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (q_{i,j} \cdot d_{i,j})$$ **; Total material flow**

$$and \quad F_2 = \left| \sum_{i=1}^{N} (w_i \cdot y_i) \Big/ \sum_{i=1}^{N} w_i \right|$$ **; Weight distribution**

N: Number of zones and modules
$q_{i,j}$: Adjacency factor between module i and module j
$d_{i,j}$: Distance between module i and module j
w_i: Weight of module i
y_i: y-coordinate (transverse position) of module i

Proposal of an Algorithm for Optimal Module Layout - Algorithm for Optimal Module Layout



Example of Optimal Module Layout of FPSO - Input Data

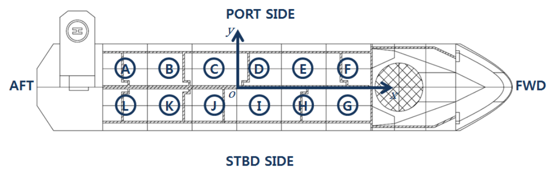
Modules to be optimized

Module ID	Module name	Module weight [*ton*]
1	Electrical BLD'G	910
2	Power generation	2,270
3	Water injection	2,240
4	Utilities area	1,700
5	Separation Train1	1,810
6	Separation Train2	2,050
7	Injection comp.	2,800
8	I/M metering	960
9	SDV platform	780
10	Recompressor	1,590
11	M/F dep. tower	1,710
12	Laydown area	105

Adjacency factor between modules

Module ID	1	2	3	4	5	6	7	8	9	10	11	12
1	-	6	6	3	2	0	0	3	3	3	3	0
2		-	3	3	2	0	0	3	3	3	3	0
3			-	3	1	0	0	3	3	3	3	0
4				-	1	0	0	3	3	3	3	0
5					-	0	0	2	2	2	2	0
6						-	3	3	1	1	3	3
7							-	3	1	1	3	2
8								-	3	3	6	2
9									-	6	3	4
10										-	3	4
11											-	3
12												-

Zone ID of FPSO topsides in this example(plan view)

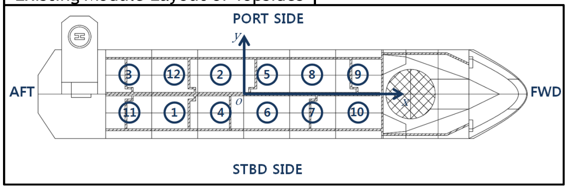


Example of Optimal Module Layout of FPSO - Optimization Result

Modules to be optimized

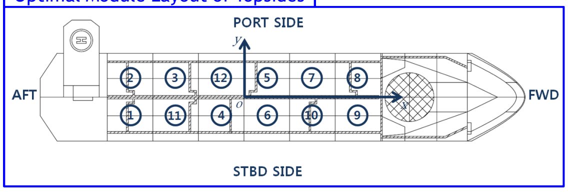
Module ID	Module name
1	Electrical BLD'G
2	Power generation
3	Water injection
4	Utilities area
5	Separation Train1
6	Separation Train2
7	Injection comp.
8	I/M metering
9	SDV platform
10	Recompressor
11	M/F dep. tower
12	Laydown area

Existing Module Layout of Topsides



	Existing	Optimization
Adjacency between Modules [F_1]	463,010	393,050 (-15.1%)
Transverse position of COG [F_2]	2.7814 *m*	0.4395 *m* (-84.2%)

Optimal Module Layout of Topsides



2. Optimal Equipment Layout in the Topsides Module of Offshore Plant (for Liquefaction Module)

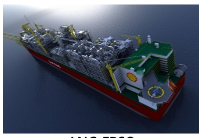
Considerations on Optimal Equipment Layout in the Liquefaction Module for Offshore Plant


<Liquefaction process system>

+


<Exploration and Production of the Natural Gas>

=


<LNG FPSO>

- Safety studies: HAZard and Operability (HAZOP), HAZard Identification (HAZID), Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA)
- Optimal layout: Maintenance, Working space area, Emergency area

- Available area for the liquefaction cycle of offshore application is smaller than that of onshore plant.
- By determining the optimal operating conditions and doing the optimal synthesis of the liquefaction cycle, the required power for the compressors can be reduced which will result in the reduction of the compressor size and the flow rate of the refrigerant. Thus, the overall sizes of the liquefaction cycle including the pipe diameter, equipment and instrument can be reduced.
- Therefore, the compactness can be achieved by optimization studies such as determination of the optimal operating condition or optimal synthesis of the liquefaction cycle.

⇨ For the optimization of the process layout, 'Compactness' & 'Safety' are the most important consideration.

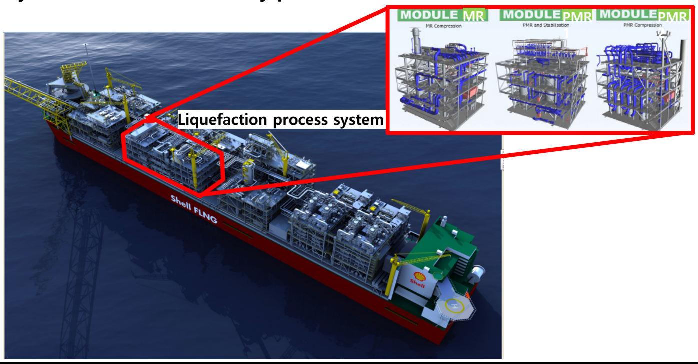
Characteristics of Equipment Layout in Topsides Modules of Offshore Plant

☑ Limited Installation Area

- Considering the limited Hull area, equipment shall be placed on the multi-floors module.
- Same functional systems shall be installed in the same module in order to reduce the piping installation space.

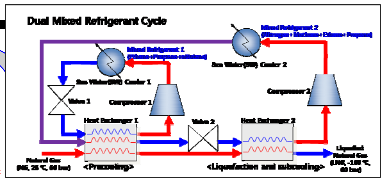
☑ Easy Installation and Maintenance

- Offshore installation shall be performed on the module basis to easily install each modules on the hull area.
- Every maintenance can be easily performed on each modules basis.

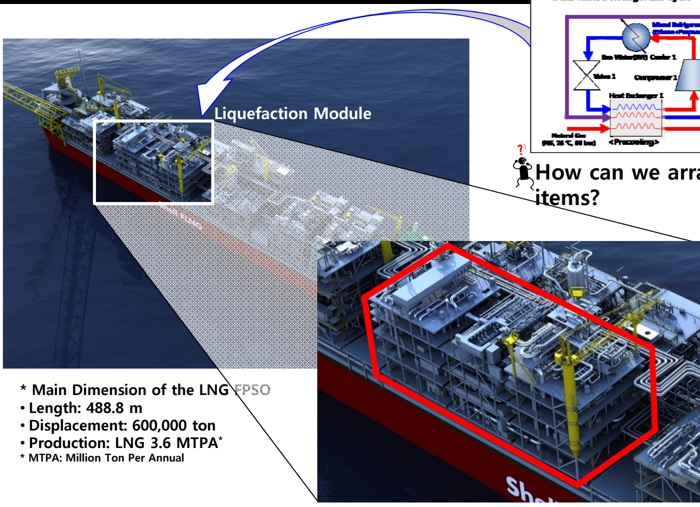


* MR: Mixed Refrigerant, PMR: Pre-Mixed Refrigerant

Necessity of Multi-Deck Layout in the Liquefaction Module of LNG FPSO



How can we arrange the equipment items?



* Main Dimension of the LNG FPSO
- Length: 488.8 m
- Displacement: 600,000 ton
- Production: LNG 3.6 MTPA*

* MTPA: Million Ton Per Annual

For the compactness, the plant layout for the liquefaction process system of the LNG FPSO is

* Reference: (Website) http://www.shell.com/home/content/innovation/feature_stories/2010/flng

Procedures of Process FEED of Liquefaction System of LNG FPSO and Importance of Optimal Equipment Layout in Module

Procedure of Construction of LNG FPSO

Exploration & Feasibility Study → Pre-FEED → **FEED** → EPCI → Commissioning

Engineering (Detail Design) → Procurement → Construction → Installation

① **Design Criteria**

➲ Well Components, Well Scale, Required Daily Production, Environment & Geographical Factor, etc.

② Process Configuration and Simulation Utility Consideration ⟸ - Determining optimal operating conditions of the liquefaction cycle of LNG FPSO

➲ Configuration of the process system and **operating conditions of each stream of the refrigerant and natural gas such as** temperature, pressure, specific volume, flow rate and mole fraction[1].

1) Mole fraction: Components of the mixed refrigerant and natural gas

③ **Process & Utility Hydraulic Calculations**

➲ Diameter of the pipe for each stream

④ **PFD** (Process Flow Diagram), **UFD** (Utility Flow Diagram)

➲ Diagram to show the safety & control logic of the topside systems and heat & material balance tables2)

⑤ **PED** (Process Equipment Datasheet), **UED** (Utility Equipment Datasheet)
PID (Process Instrument Datasheet), **UID** (Utility Instrument Datasheet)

➲ **Datasheets to show the operating conditions** and diameter of the inlet and outlet of each equipment for **performing procurement, construction, and operation of the topside process systems**

⑥ **P&ID** (Pipe & Instrument Diagram), SAC(Safety Analysis Checklist)

➲ Diagram that shows all data about the operating conditions, process control logic, safety and maintenance for the equipment and instruments, and vendor data about the equipment.

⑦ ⟸ **- Determining optimal plant layout by using the optimization technique**

➲ For the compactness, the plant layout for the liquefaction process system of the LNG FPSO is multi-floor plant layout!

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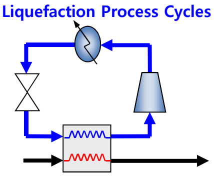
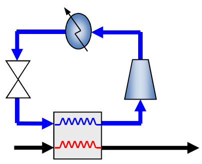
Initial Equipment Layout in Topsides Modules of Offshore Plant

Selection of Potential Liquefaction Process Cycles



Case 1

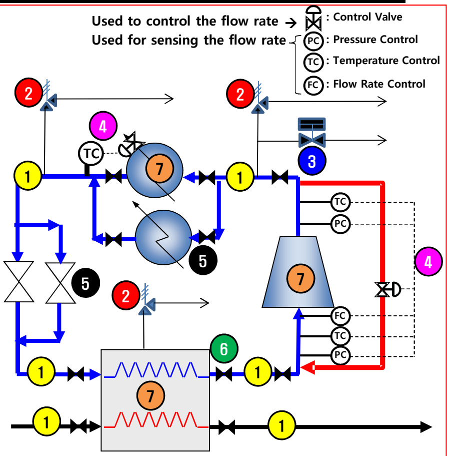
⋮



Case N

Liquefaction Cycle

Optimal Operating Conditions (PVT) → Equipment Selection → **Initial Equipment Layout** ⇒



1. **Determination of Pipe Line Sizing**
2. Safety Considerations (Pressure Safety Valve)
3. Safety Considerations (Blowdown Valve)
4. Operational Considerations
5. **Maintenance Considerations**
6. **Isolation Considerations**
7. **Vendor Data**

Liquefaction Module

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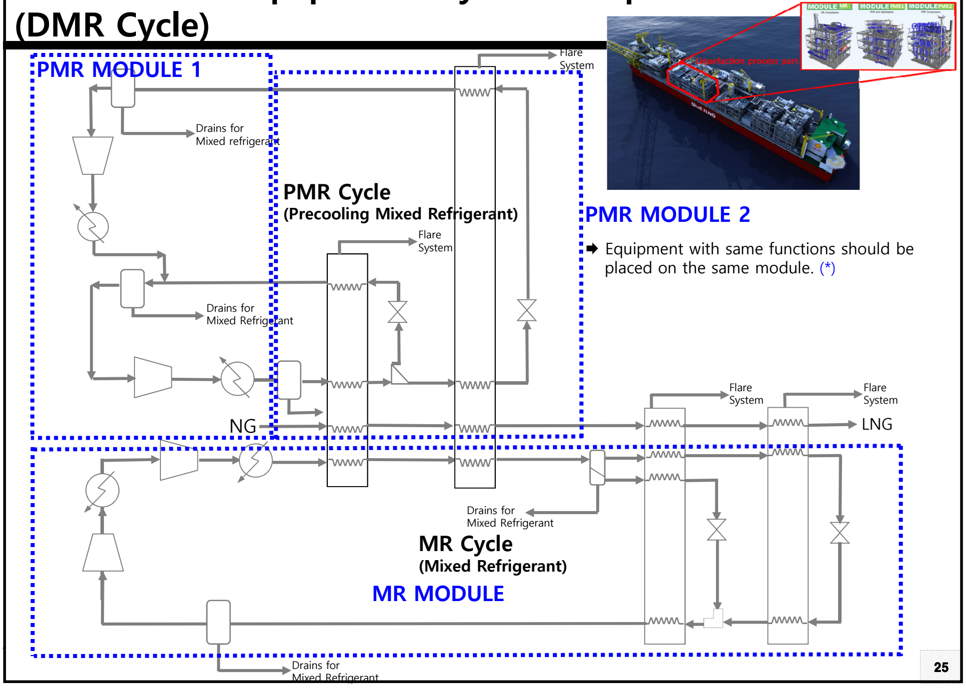
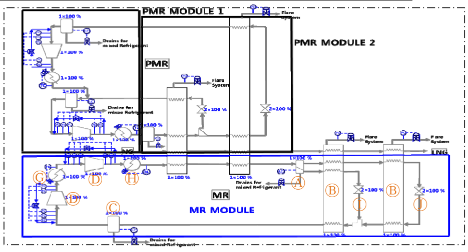
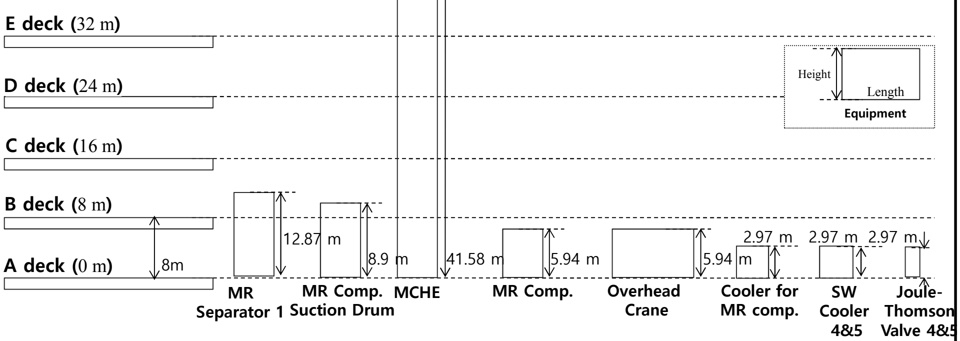
1. Multi-Deck Equipment Layout of Liquefaction Module (DMR Cycle)



2. Problem Definition for MR Module
- Given (Sizes)

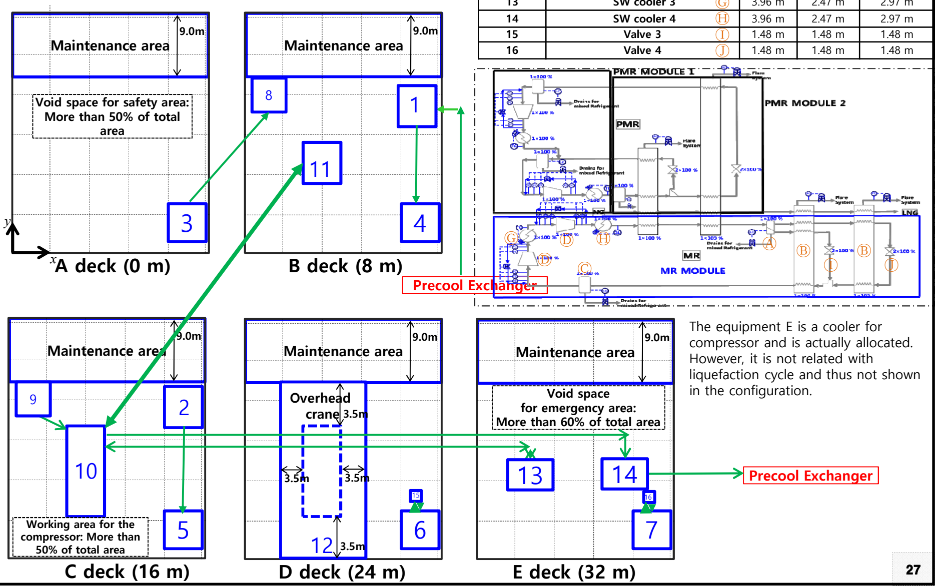
No.	Name	Dimension of the Equipment		
		Length	Breadth	Height
1, 2	MR Separator Ⓐ	4.45 m	4.45 m	12.87 m
3,4,5,6,7	MCHE Ⓑ	5.64 m	5.64 m	41.58 m
8, 9	MR Comp. Suction Drum Ⓒ	5.44 m	5.44 m	8.9 m
10	MR Comp. Ⓓ	17.12 m	5.94 m	5.94 m
11	Cooler for MR comp. Ⓔ	2.97 m	1.98 m	2.97 m
12	Overhead crane Ⓕ	22.77 m	15.84 m	5.94 m
13	SW cooler 3 Ⓖ	3.96 m	2.47 m	2.97 m
14	SW cooler 4 Ⓗ	3.96 m	2.47 m	2.97 m
15	Valve 3 Ⓘ	1.48 m	1.48 m	1.48 m
16	Valve 4 Ⓙ	1.48 m	1.48 m	1.48 m





2. Problem Definition for MR Module
- Given (Connection Information)

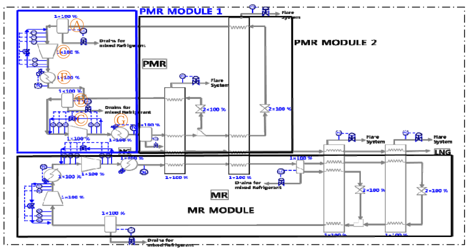
No.	Name		Dimension of the Equipment		
			Length	Breadth	Height
1, 2	MR Separator	Ⓐ	4.45 m	4.45 m	12.87 m
3,4,5,6,7	MCHE	Ⓑ	5.64 m	5.64 m	41.58 m
8, 9	MR Comp. Suction Drum	Ⓒ	5.44 m	5.44 m	8.9 m
10	MR Comp.	Ⓓ	17.12 m	5.94 m	5.94 m
11	Cooler for MR comp.	Ⓔ	2.97 m	1.98 m	2.97 m
12	Overhead crane	Ⓕ	22.77 m	15.84 m	5.94 m
13	SW cooler 3	Ⓖ	3.96 m	2.47 m	2.97 m
14	SW cooler 4	Ⓗ	3.96 m	2.47 m	2.97 m
15	Valve 3	Ⓘ	1.48 m	1.48 m	1.48 m
16	Valve 4	Ⓙ	1.48 m	1.48 m	1.48 m

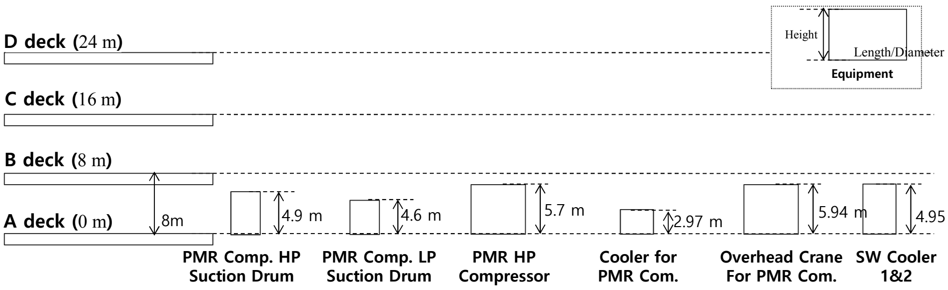


The equipment E is a cooler for compressor and is actually allocated. However, it is not related with liquefaction cycle and thus not shown in the configuration.

2. Problem Definition for PMR Module 1
- Given (Sizes)

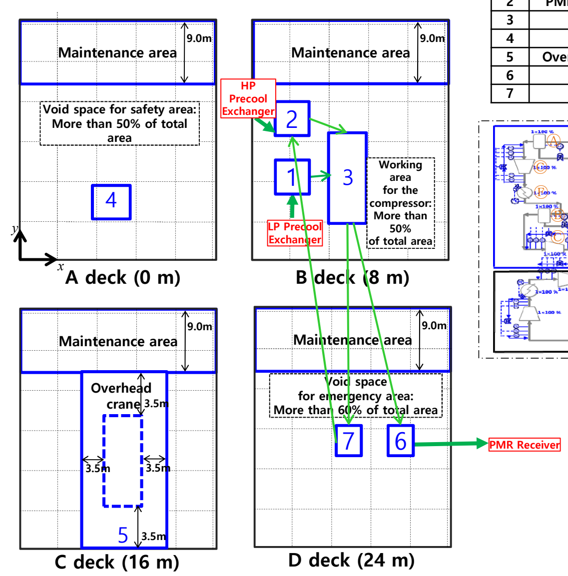
No.	Name		Dimension of the Equipment (m)		
			Length	Breadth /Diameter	Height
1	PMR comp. LP suction drum	Ⓐ	3.613	3.613	4.603
2	PMR comp. HP suction drum	Ⓑ	3.217	3.217	4.900
3	PMR Compressor	Ⓒ	18.809	5.939	5.741
4	Cooler for PMR com.	Ⓓ	2.969	1.979	2.969
5	Overhead crane for PMR com.	Ⓔ	22.769	15.839	5.939
6	SW cooler 1	Ⓕ	7.919	1.979	4.949
7	SW cooler 2	Ⓖ	7.919	1.979	4.949

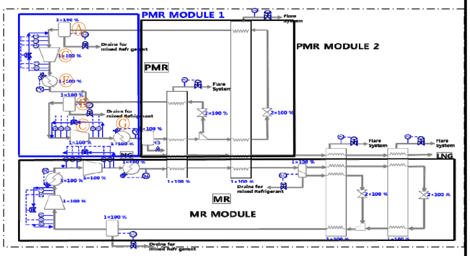




2. Problem Definition for PMR Module 1
- Given (Connection Information)

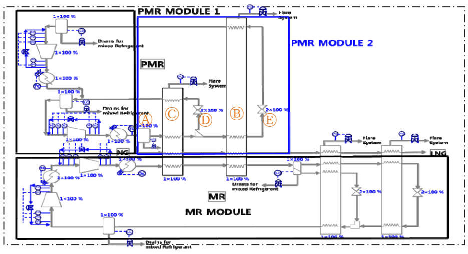
No.	Name	Dimension of the Equipment (m)		
		Length	Breadth /Diameter	Height
1	PMR comp. LP suction drum Ⓐ	3.613	3.613	4.603
2	PMR comp. HP suction drum Ⓑ	3.217	3.217	4.900
3	PMR Compressor Ⓒ	18.809	5.939	5.741
4	Cooler for PMR com. Ⓓ	2.969	1.979	2.969
5	Overhead crane for PMR com. Ⓔ	22.769	15.839	5.939
6	SW cooler 1 Ⓕ	7.919	1.979	4.949
7	SW cooler 2 Ⓖ	7.919	1.979	4.949

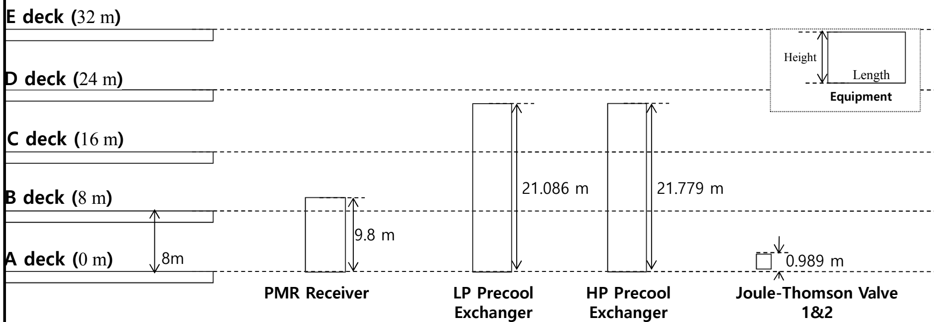




2. Problem Definition for PMR Module 2
- Given (Sizes)

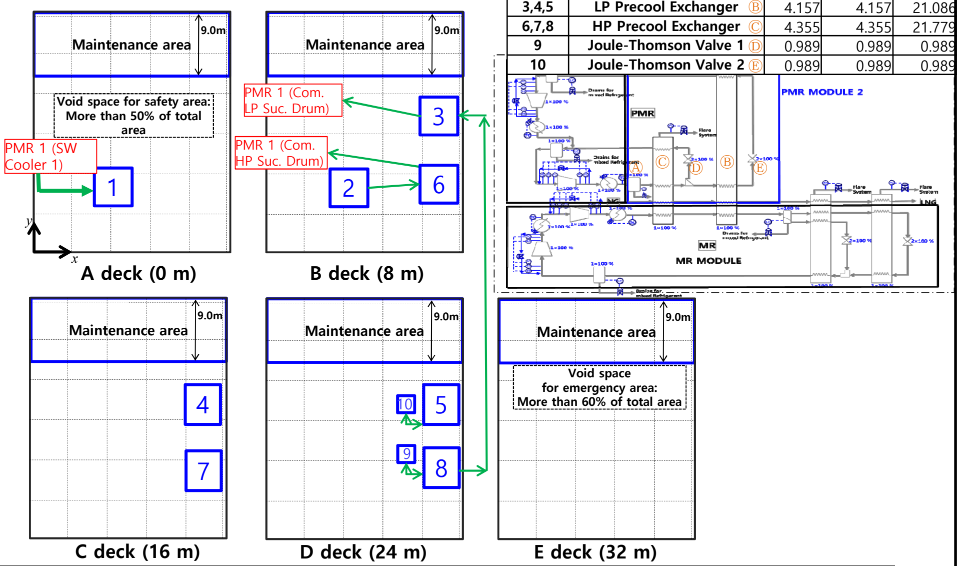
No.	Name	Dimension of the Equipment (m)		
		Length	Breadth /Diameter	Height
1,2	PMR Receiver Ⓐ	4.157	4.157	9.800
3,4,5	LP Precool Exchanger Ⓑ	4.157	4.157	21.086
6,7,8	HP Precool Exchanger Ⓒ	4.355	4.355	21.779
9	Joule-Thomson Valve 1 Ⓓ	0.989	0.989	0.989
10	Joule-Thomson Valve 2 Ⓔ	0.989	0.989	0.989





2. Problem Definition for PMR Module 2
- Given (Connection Information)

No.	Name	Dimension of the Equipment (m)		
		Length	Breadth /Diameter	Height
1,2	PMR Receiver Ⓐ	4.157	4.157	9.800
3,4,5	LP Precool Exchanger Ⓑ	4.157	4.157	21.086
6,7,8	HP Precool Exchanger Ⓒ	4.355	4.355	21.779
9	Joule-Thomson Valve 1 Ⓓ	0.989	0.989	0.989
10	Joule-Thomson Valve 2 Ⓔ	0.989	0.989	0.989



3. Mathematical Module for Multi-Deck Equipment Layout
- Model for Optimal Equipment Layout of MR Module

- **Design Variables [128]**
  - **1) Coordinate of the equipment item (x, y)**
    - x_i, y_i: coordinates of geometrical center of the equipment item i **[32 Real values]**
  - **2) Orientation of the equipment item**
    - O_i: 1, if the length of the equipment item i is parallel to x-axis; 0, otherwise **[16 Binary values]**
  - **3) Deck number of the equipment item**
    - $V_{i,k}$: 1, if the equipment item i is assigned to the deck k; 0, otherwise **[80 Binary values]**
- **Constraints [30+98=128]**
  - **1) Equipment constraints for multi-deck**
    - 30 equality constraints
  - **2) Non-overlapping constraints**
    - 32 inequality constraints
  - **3) Deck area constraints**
    - 66 inequality constraints

➡ **Number of the design variables is larger than the number of the equality constraints.**

➡

Optimal Solution using Genetic Algorithm (GA)

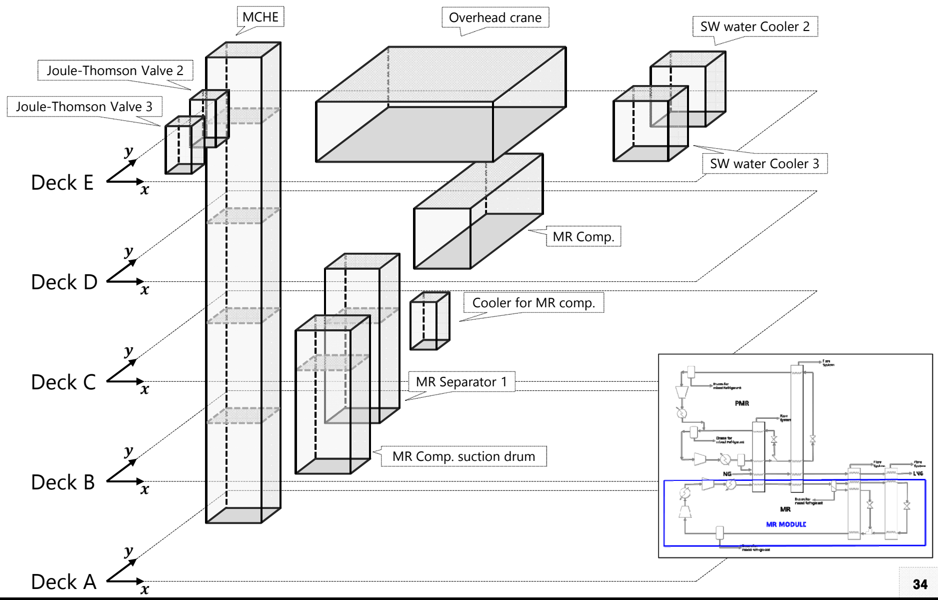
4. Result of Optimal Equipment Layout of Each Module - MR Module (1/3)

- Optimal Values of Design Variables for MR Module

Equipment		x_i	y_i	O_i	$V_{i,k}$				
No.	Name	$[m]$	$[m]$		$V_{i,1}$	$V_{i,2}$	$V_{i,3}$	$V_{i,4}$	$V_{i,5}$
1	MR Separator 1 on lower deck	17	13	1	0	1	0	0	0
2	MR Separator 1 on upper deck	17	13	1	0	0	1	0	0
3	MCHE on A deck	16	4	1	1	0	0	0	0
4	MCHE on B deck	16	4	1	0	1	0	0	0
5	MCHE on C deck	16	4	1	0	0	1	0	0
6	MCHE on D deck	16	4	1	0	0	0	1	0
7	MCHE on E deck	16	4	1	0	0	0	0	1
8	MR Comp. suction drum on lower deck	4	20	1	0	1	0	0	0
9	MR Comp. suction drum on upper deck	4	20	1	0	0	1	0	0
10	MR Comp.	8	10	0	0	0	0	1	0
11	Cooler for MR comp.	8	10	0	0	0	1	0	0
12	Overhead crane	8	10	0	0	0	0	0	1
13	SW water Cooler 2	8	8	1	0	0	0	0	1
14	SW water Cooler 3	8	14	1	0	0	0	0	1
15	Joule-Thomson Valve 2	17	9	1	0	0	0	0	1
16	Joule-Thomson Valve 3	17	9	1	0	0	0	0	1

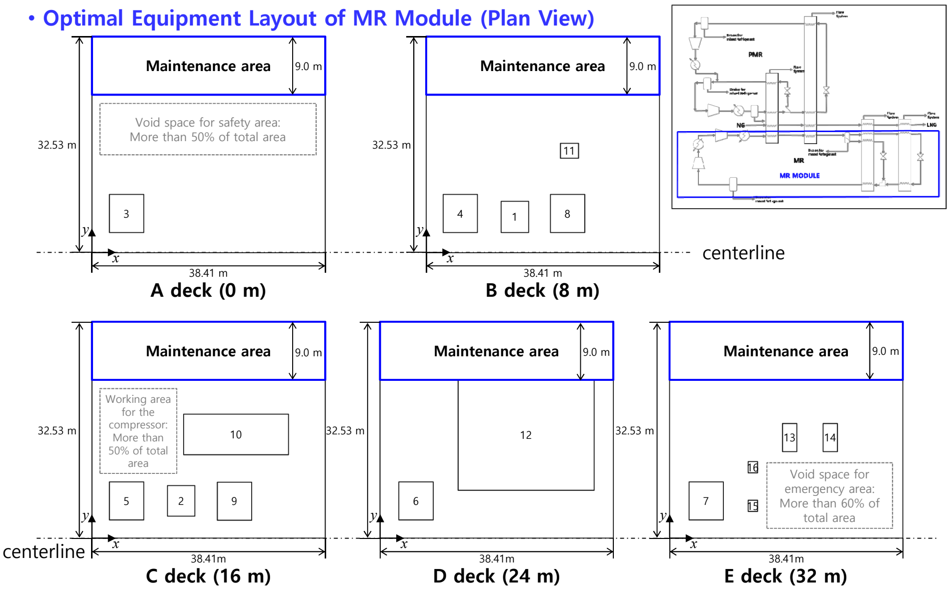
4. Result of Optimal Equipment Layout of Each Module - MR Module (2/3)

- Optimal Equipment Layout of MR Module (ISO View)



4. Result of Optimal Equipment Layout of Each Module - MR Module (3/3)

- Optimal Equipment Layout of MR Module (Plan View)



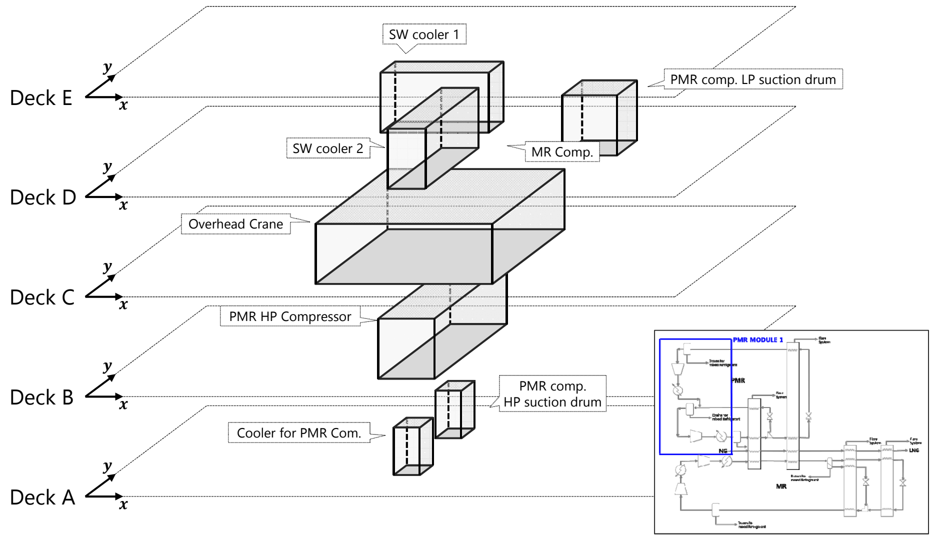
4. Result of Optimal Equipment Layout of Each Module - PMR Module 1 (1/3)

- Optimal Values of Design Variables for PMR Module 1

Equipment		x_i	y_i	O_i	$V_{i,k}$			
No.	Name	[m]	[m]		$V_{i,1}$	$V_{i,2}$	$V_{i,3}$	$V_{i,4}$
1	PMR comp. LP suction drum	10.9	7.1	0	0	0	0	1
2	PMR comp. HP suction drum	10.9	14.35	0	1	0	0	0
3	PMR HP Compressor	10.9	14.35	0	0	1	0	0
4	Cooler for PMR Com.	10.9	14.35	0	1	0	0	0
5	Overhead Crane	10.9	14.35	0	0	0	1	0
6	SW cooler 1	17.45	14.35	0	0	0	0	1
7	SW cooler 2	4.35	14.35	0	0	0	0	1

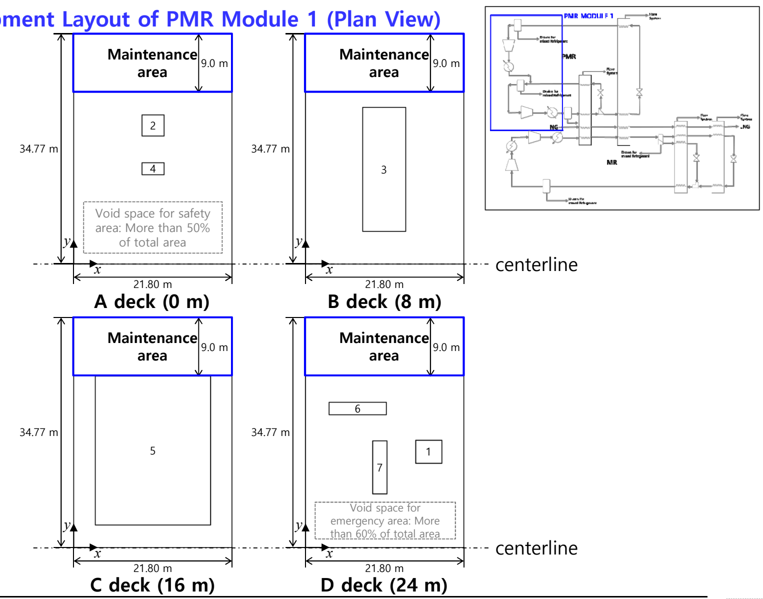
4. Result of Optimal Equipment Layout of Each Module - PMR Module 1 (2/3)

- Optimal Equipment Layout of PMR Module 1 (ISO View)



4. Result of Optimal Equipment Layout of Each Module - PMR Module 1 (3/3)

- Optimal Equipment Layout of PMR Module 1 (Plan View)



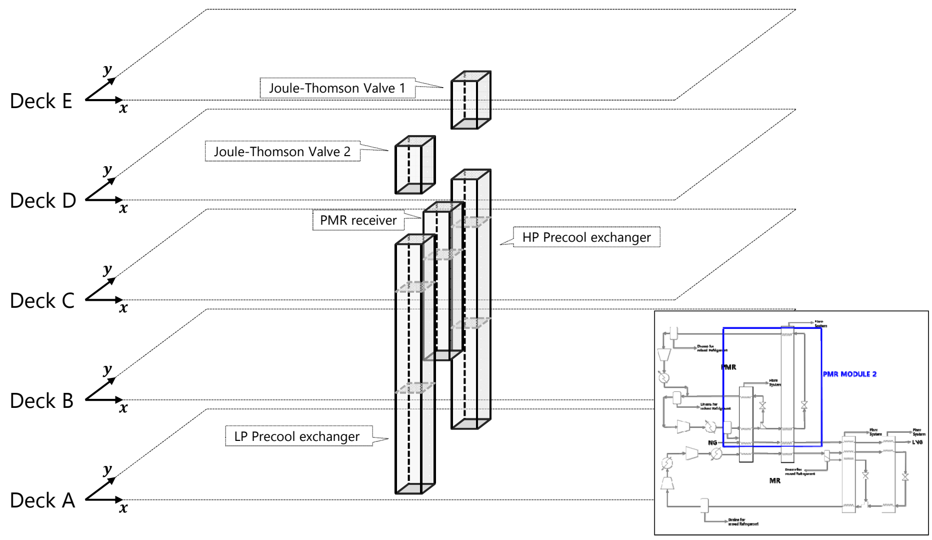
4. Result of Optimal Equipment Layout of Each Module - PMR Module 2 (1/3)

- Optimal Values of Design Variables for PMR Module 2

Equipment		x_i	y_i	O_i	$V_{i,k}$				
No.	Name	[m]	[m]		$V_{i,1}$	$V_{i,2}$	$V_{i,3}$	$V_{i,4}$	$V_{i,5}$
1	PMR receiver on lower deck	7	8	1	0	1	0	0	0
2	PMR receiver on upper deck	7	8	1	0	0	1	0	0
3	LP Precool exchanger on B deck	15	17	1	1	0	0	0	0
4	LP Precool exchanger on C deck	15	17	1	0	1	0	0	0
5	LP Precool exchanger on D deck	15	17	1	0	0	1	0	0
6	HP Precool exchanger on B deck	15	8	1	1	0	0	0	0
7	HP Precool exchanger on C deck	15	8	1	0	1	0	0	0
8	HP Precool exchanger on D deck	15	8	1	0	0	1	0	0
9	Joule-Thomson Valve 1	11	11	1	0	0	0	1	0
10	Joule-Thomson Valve 2	11	17	1	0	0	0	1	0

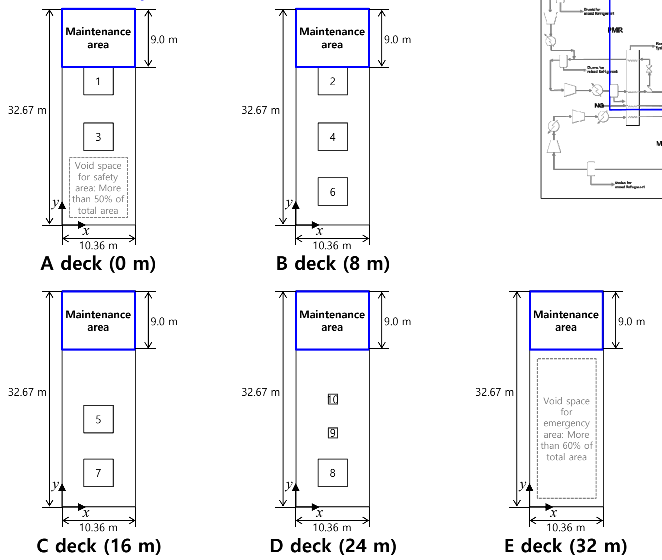
4. Result of Optimal Equipment Layout of Each Module - PMR Module 2 (2/3)

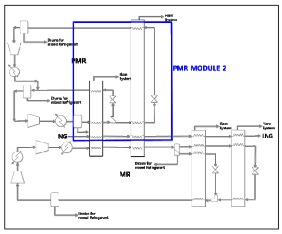
- Optimal Equipment Layout of PMR Module 2 (ISO View)



4. Result of Optimal Equipment Layout of Each Module - PMR Module 2 (3/3)

- **Optimal Equipment Layout of PMR Module 2 (Plan View)**





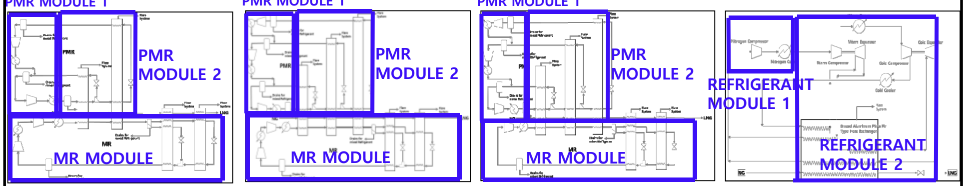
5. Installation Area by Optimal Equipment Layout of Liquefaction Module

- **Installation Area for Each Module**

Deck Area	Results	Area (m^2)	Deck Area
MR Module	38.41 m * 32.53 m	1,249.48	A Deck
	38.41 m * 32.53 m	1,249.48	B Deck
	38.41 m * 32.53 m	1,249.48	C Deck
	38.41 m * 32.53 m	1,249.48	D Deck
	38.41 m * 32.53 m	1,249.48	E Deck
PMR Module 1	21.80 m * 34.77 m	757.99	A Deck
	21.80 m * 34.77 m	757.99	B Deck
	21.80 m * 34.77 m	757.99	C Deck
	21.80 m * 34.77 m	757.99	D Deck
PMR Module 2	10.36 m * 32.67 m	338.46	A Deck
	10.36 m * 32.67 m	338.46	B Deck
	10.36 m * 32.67 m	338.46	C Deck
	10.36 m * 32.67 m	338.46	D Deck
	10.36 m * 32.67 m	338.46	D Deck
Total Area		**141,800.10**	

6. Comparison of Installation Area for Various Liquefaction Modules

Optimal DMR | SHELL DMR | C3MR | N2 Dual Expanders



Cases	Area (m^2)	Result (Constraints)
Optimal DMR	**141,800.10**	**Satisfied**
SHELL DMR	165,225.50	Satisfied
C3MR	159,599.00	Satisfied
N2 Dual Expanders	196,564.50	Satisfied