Design Theories of Ship and Offshore Plant

Part II. Optimum Design

Ch. 3 Applications to Design of Ship and Offshore Plant

Fall 2016

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Determination of Optimal Principal Dimensions of a Bulk Carrier

☑ **Criteria for determining optimal principal dimensions (Objective function)**
- **Minimization of shipbuilding cost or Minimization of hull structure weight or Minimization of operation cost**

☑ **Given (Ship owner's requirements)**
- **Deadweight (DWT)**
- **Cargo hold capacity (CC_{req})**
- **Maximum draft (T_{max})**
- **Ship speed (V)**

☑ **Find (Design variables)**
- **Length (L)**
- **Breadth (B)**
- **Depth (D)**
- **Block Coefficient (C_B)**

☑ **Constraints**
- **Constraint about the displacement·weight equilibrium condition**
- **Constraint about the required cargo hold capacity**
- **Constraint about the required freeboard condition**

Formulation for Determining Optimal Principal Dimensions of a Bulk Carrier

Find (Design variables) L, B, D, C_B
Length Breadth Depth Block coefficient

Given (Ship owner's requirement) $DWT, CC_{req}, T_{\max}(=T), V$
Deadweight, Cargo hold capacity, Maximum draft, Speed

Displacement-Weight equilibrium condition (Equality constraint)

$$L \cdot B \cdot T \cdot C_B \cdot \rho_{sw} \cdot C_\alpha = DWT_{given} + LWT(L, B, D, C_B)$$
$$= DWT_{given} + C_s \cdot L^{1.6}(B+D) + C_o \cdot L \cdot B + C_{ma} \cdot NMCR$$
$$= DWT_{given} + C_s \cdot L^{1.6}(B+D) + C_o \cdot L \cdot B + C_{power} \cdot (L \cdot B \cdot T \cdot C_B)^{2/3} \cdot V^3$$

Required cargo hold capacity condition (Inequality constraint)

$$CC_{req} \le C_{CH} \cdot L \cdot B \cdot D$$

Required freeboard condition (Inequality constraint)

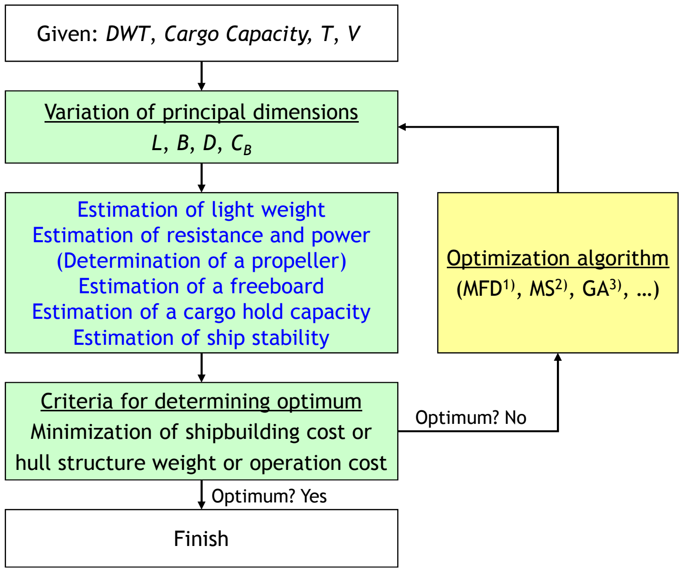
$$D \ge T + C_{FB} \cdot D$$

Criteria for determining optimal principal dimensions (Objective function)

$$Building\ Cost = C_{PS} \cdot C_s \cdot L^{1.6}(B+D) + C_{PO} \cdot C_o \cdot L \cdot B + C_{PM} \cdot C_{ma} \cdot NMCR$$

➡ Optimization problem having 4 unknowns, 1 equality and 2 inequality constraints

Process for Determining Optimal Principal Dimensions of a Bulk Carrier Using an Optimization Algorithm



1) MFD: Method of Feasible Directions, 2) MS: Multi-Start local optimization method, 3) GA: Genetic Algorithm

Given Information for Optimal Principal Dimensions of a Bulk Carrier

Principal particulars of a deadweight 150,000 ton bulk carrier (parent ship) and ship owner's requirements

Item		Parent Ship	Design Ship	Remark
Principal Dimensions	L_{OA}	abt. 274.00 m	max. 284.00 m	
	L_{BP}	264.00 m		
	B_{mld}	45.00 m	45.00 m	
	D_{mld}	23.20 m		
	T_{mld}	16.90 m	17.20 m	
	T_{scant}	16.90 m	17.20 m	
Deadweight		150,960 ton	160,000 ton	at 17.20 m
Speed		13.5 kts	13.5 kts	90 % MCR (with 20 % SM)
M/E	TYPE	B&W 5S70MC		
	NMCR	17,450 HP×88.0 RPM		Derating Ratio = 0.9
	DMCR	15,450 HP×77.9 RPM		E.M = 0.9
	NCR	13,910 HP×75.2 RPM		
FOC	SFOC	126.0 g/HP.H		
	TON/DAY	41.6		Based on NCR
Cruising Range		28,000 N/M	26,000 N/M	
Midship Section		Single Hull Double Bottom/Hopper /Top Side Wing Tank	Single Hull Double Bottom/Hopper /Top Side Wing Tank	
Capacity	Cargo	abt. 169,380 m^3	abt. 179,000 m^3	Including Hatch Coaming
	Fuel Oil	abt. 3,960 m^3		Total
	Fuel Oil	abt. 3,850 m^3		Bunker Tank Only
	Ballast	abt. 48,360 m^3		Including F.P and A.P Tanks

Optimization Result for Optimal Principal Dimensions of a Bulk Carrier

Minimization of Shipbuilding Cost

		Unit	MFD[1]	MS[2]	GA[3]	HYBRID[4] w/o Refine	HYBRID[4] with Refine
GIVEN	DWT	ton	160,000				
	Cargo Capacity	m^3	179,000				
	T_{max}	m	17.2				
	V	knots	13.5				
L		m	265.54	265.18	264.71	264.01	263.69
B		m	45.00	45.00	45.00	45.00	45.00
D		m	24.39	24.54	24.68	24.71	24.84
C_B		-	0.8476	0.8469	0.8463	0.8427	0.8420
D_P		m	8.3260	8.3928	8.4305	8.4075	8.3999
P_i		m	5.8129	5.8221	5.7448	5.7491	5.7365
A_E/A_O		-	0.3890	0.3724	0.3606	0.3618	0.3690
Building Cost		$	59,889,135	59,888,510	59,863,587	59,837,336	59,831,834
Iteration No		-	10	483	96	63	67
CPU Time[5]		sec	4.39	209.58	198.60	184.08	187.22

1) MFD: Method of Feasible Directions, 2) MS: Multi-Start local optimization method, 3) GA: Genetic Algorithm
4) HYBRID: Global-local hybrid optimization method, 5) 테스트 시스템: Pentium 3 866Mhz, 512MB RAM

Determination of Optimal Principal Dimensions of a Naval Ship

☑ **Criteria for determining optimal principal dimensions (Objective function)**
- **Minimization of a power (BHP) or Fuel Consumption (FC) of a main engine (f_1)**

or
- **Minimization of hull structure weight (f_2)**

☑ **Given (Ship owner's requirements)**
- **Δ: Displacement**
- **V: Speed**

☑ **Find (Design variables)**
- **L: Length**
- **B: Moulded breadth**
- **D: Moulded depth**
- **T: Draft**
- **C_B: Block coefficient**

☑ **Constraints**
- **Constraint about the displacement·weight equilibrium condition**
- **Constraint about the required speed and power**

Formulation for Determining Optimal Principal Dimensions of a Naval Ship

Find L, B, D, T, C_B — **Design Variables**

Minimize $BHP[HP]$(or $FC[kg/h]$) **or** $Hull\ Structure\ Weight[LT]$ — **Objective Function**

Subject to — **Constraints**

* Equilibrium condition of displacement and weight

$$L \cdot B \cdot T \cdot C_B \cdot \rho \cdot (1+\alpha) = \Delta = LWT + VL$$

* Requirements for displacement(9,000ton class)

$$8{,}900\ [LT] \le \Delta \le 9{,}100\ [LT]$$

* Requirements for speed-power

$$P/(2\pi n) = \rho \cdot n^2 \cdot D_P{}^5 \cdot K_Q$$

$$R_T/(1-t) = \rho \cdot n^2 \cdot D_P{}^4 \cdot K_T$$

$$A_E / A_O \ge K + \frac{(1.3+0.3Z)\cdot T_h}{D_P{}^2 \cdot (p_o + \rho \cdot g \cdot h - p_v)}$$

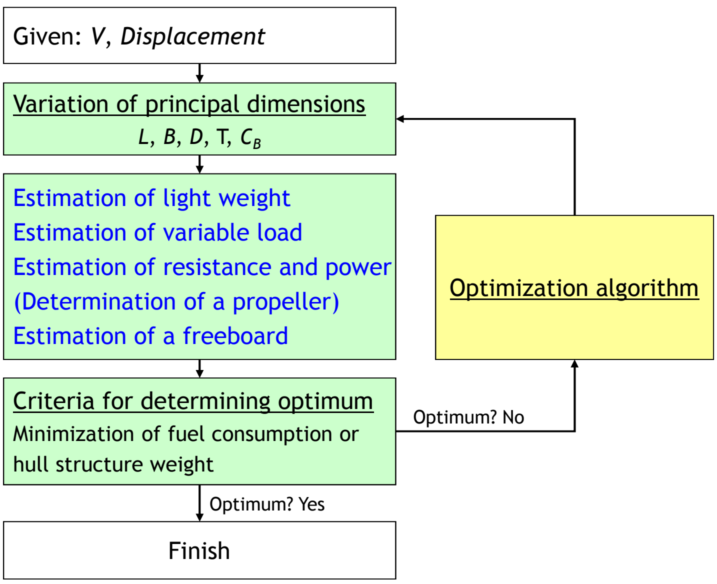
* Miscellaneous design requirements

$$L^l \le L \le L^u,\ B^l \le B \le B^u,\ D^l \le D \le D^u,\ C_B{}^l \le C_B \le C_B{}^u$$

$$0.98\,(L/B)_{parent} \le L/B \le 1.02\,(L/B)_{parent}$$

➡ Optimization problem having 5 unknowns, 3 equality constraints, and 7 inequality constraints

Process for Determining Optimal Principal Dimensions of a Naval Ship Using an Optimization Algorithm



Optimization Result for the Minimization of Fuel Consumption

CASE 1: Minimize fuel consumption (f_1)

	Unit	DDG-51	MFD	MS	GA	HYBRID w/o Refine	HYBRID with Refine
L	m	142.04	157.68	157.64	157.60	157.79	157.89
B	m	17.98	20.11	19.69	19.47	19.60	19.59
D	m	12.80	12.57	12.67	12.79	12.79	12.74
T	m	6.40	5.47	5.57	5.69	5.68	5.63
C_B	-	0.508	0.520	0.506	0.506	0.508	0.512
P_i	m	8.90	9.02	9.38	9.04	9.06	9.06
A_E/A_O	-	0.80	0.80	0.65	0.80	0.80	0.80
n	rpm	88.8	97.11	94.24	96.86	96.65	96.64
F.C (f_1)	kg/h	3,391.23	3,532.28	3,526.76	3,510.53	3,505.31	3,504.70
H.S.W	LT	3,132	3955.93	3901.83	3910.41	3942.87	3,935.39
Δ	LT	8,369	9,074	8,907	8,929	9,016	9,001
Iteration No	-	-	6	328	97	61	65
CPU Time	sec	-	3.83	193.56	195.49	189.38	192.02

Optimization Result for the Minimization of Hull Structure Weight

CASE 2: Minimize hull structure weight (f_2)

	Unit	DDG-51	MFD	MS	GA	HYBRID w/o Refine	HYBRID with Refine
L	m	142.04	157.22	155.92	155.78	155.58	155.56
B	m	17.98	20.09	20.09	20.12	20.10	20.09
D	m	12.80	12.72	12.66	12.63	12.66	12.67
T	m	6.40	5.64	5.63	5.61	5.65	5.66
C_B	-	0.508	0.510	0.506	0.508	0.508	0.508
P_i	m	8.90	8.98	9.42	9.04	9.46	9.45
A_E/A_O	-	0.80	0.80	0.65	0.80	0.65	0.65
n	rpm	88.8	97.40	94.06	97.29	93.93	93.98
F.C	kg/h	3,391.23	3,713.23	3,622.40	3,618.71	3,603.89	3,602.60
H.S.W (f_2)	LT	3,132	3,910.29	3,855.48	3,850.56	3,844.43	3,844.24
Δ	LT	8,369	9,097	9,014	9,008	9,004	9,003
Iteration No	-	-	7	364	95	64	68
CPU Time	sec	-	3.91	201.13	192.32	190.98	192.41

Optimization Result for the Minimization of Fuel Consumption and Hull Structure Weight

CASE 3: Minimize fuel consumption (f_1) & hull structure weight (f_2)

* $w_1 = w_2 = 0.5$

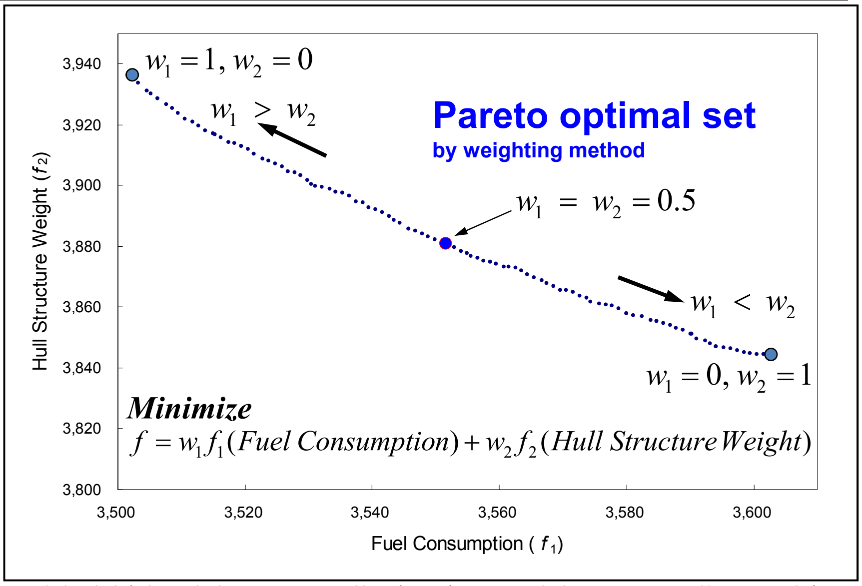
	Unit	DDG-51	MFD	MS	GA	HYBRID w/o Refine	HYBRID with Refine
L	m	142.04	157.37	157.02	156.74	156.54	156.51
B	m	17.98	19.99	19.98	19.82	19.85	19.82
D	m	12.80	12.70	12.69	12.73	12.82	12.84
T	m	6.40	5.61	5.62	5.67	5.77	5.80
C_B	-	0.508	0.510	0.506	0.506	0.508	0.508
P_i	m	8.90	9.02	9.51	9.33	9.50	9.05
A_E/A_O	-	0.80	0.80	0.65	0.65	0.65	0.65
N	rpm	88.8	97.11	93.49	94.53	93.52	93.51
F.C (f_1)	kg/h	3,391.23	3,589.21	3,583.56	3,556.15	3,551.98	3,551.42
H.S.W (f_2)	LT	3,132	3,931.49	3,896.54	3,891.45	3,880.74	3,880.18
$w_1f_1 + w_2f_2$	-	3,261.62	3,760.35	3,740.05	3,723.80	3,716.36	3,715.80
Δ	LT	8,369	9,074	9,048	9,004	9,001	9,001
Iteration No	-	-	7	351	93	65	68
CPU Time	sec	-	3.99	201.63	191.28	190.74	193.22

Summary of Optimization Results

	Unit	DDG-51	CASE 1 Minimize f_1 (fuel consumption)	CASE 2 Minimize f_2 (hull structure weight)	CASE 3 Minimize $w_1f_1+w_2f_2$
L	m	142.04	157.89	155.56	156.51
B	m	17.98	19.59	20.09	19.82
D	m	12.80	12.74	12.67	12.84
T	m	6.40	5.63	5.66	5.80
C_B	-	0.508	0.512	0.508	0.508
P_i	m	8.90	9.06	9.45	9.05
A_E/A_O	-	0.80	0.80	0.65	0.65
n	rpm	88.8	96.64	93.98	93.51
F.C	kg/h	3,391.23	3,504.70	3,602.60	3,551.42
H.S.W	LT	3,132	3,935.39	3,844.24	3,880.18
Objective	-	-	3,504.70	3,844.24	3,715.80
Δ	LT	8,369	9,001	9,003	9,001
Iteration No	-	-	65	68	68
CPU Time	sec	-	192.02	192.41	193.22

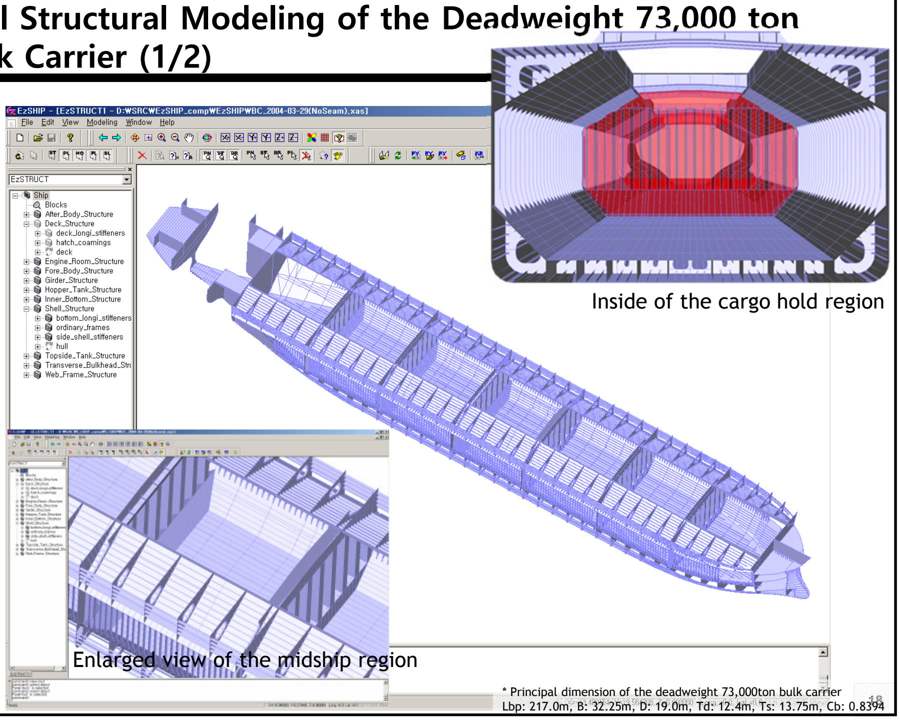
* Above results are performed by the hybrid optimization method (with Refine).

Review of Optimization Results



* Weighting method: Method of solving multi-objective optimization problems after transforming into single-objective optimization problems using weight factors

Hull Structural Modeling of the Deadweight 73,000 ton Bulk Carrier (1/2)

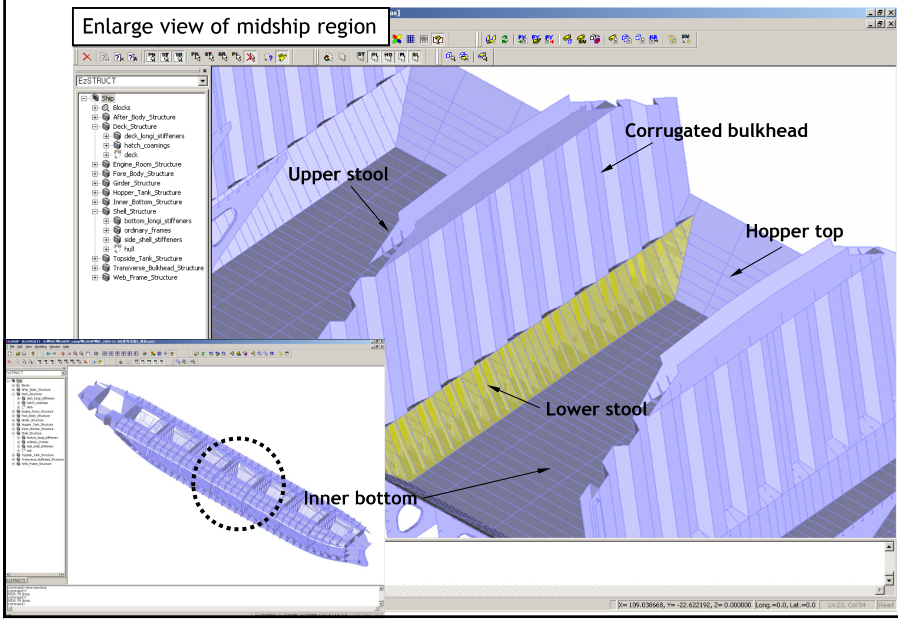


Inside of the cargo hold region

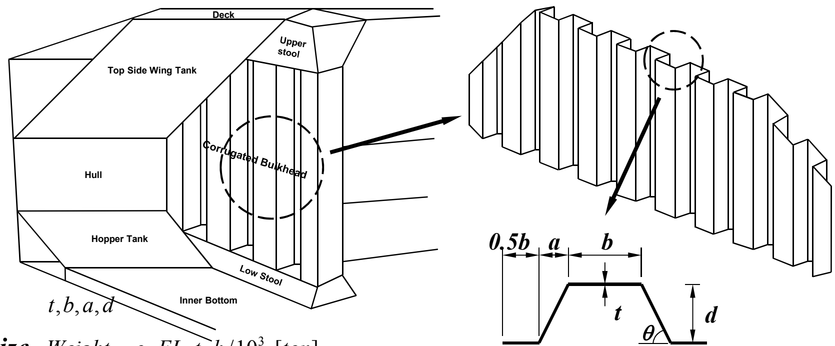
Enlarged view of the midship region

* Principal dimension of the deadweight 73,000ton bulk carrier
Lbp: 217.0m, B: 32.25m, D: 19.0m, Td: 12.4m, Ts: 13.75m, Cb: 0.8394

Hull Structural Modeling of the Deadweight 73,000 ton Bulk Carrier (2/2)



Corrugated Bulkhead Design for the Minimization of Hull Structure Weight



Find t, b, a, d

Minimize $Weight = \rho \cdot EL \cdot t \cdot h / 10^3 \ [ton]$

➡ Optimization problem having 4 unknowns and 5 inequality constraints

Subject to

$b/t - 60\sqrt{k} \le 0$: **buckling of the plate**

$40^\circ - \theta \le 0$: **minimum inclined angle of the plate**

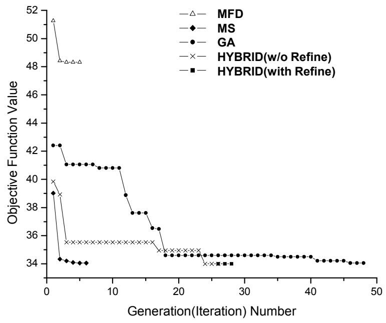
$t_{\min} - t \le 0$: **minimum plate thickness by lateral load**

$Z_{\min} - Z \le 0$: **minimum section modulus by lateral load**

$\dfrac{b + \sqrt{b^2 + a^2}}{500} + \dfrac{B}{2} - \left\lfloor \dfrac{500B}{b+a} \right\rfloor \cdot \dfrac{b+a}{1{,}000} - 4.4 \le 0$: **maximum plate breadth for 4-point bending process**

Optimization Result for Corrugated Bulkhead Design for the Minimization of Hull Structure Weight

	Unit	MFD	MS	GA	HYBRID	
					w/o Refine	with Refine
Weight	*ton*	48.321498	34.056518	34.056518	34.001399	34.001399
t	*mm*	13.780558	10.000000	10.000000	10.000000	10.000000
b	*mm*	748.804856	500.000000	500.000000	500.000000	500.000000
a	*mm*	788.425480	630.000000	630.000000	640.000000	640.000000
d	*mm*	848.562871	1620.000000	1,660.000000	1,720.000000	1,720.000000
Iteration No	-	5	245	48	26	28
CPU Time	*sec*	0.16	8.03	6.41	6.16	6.38

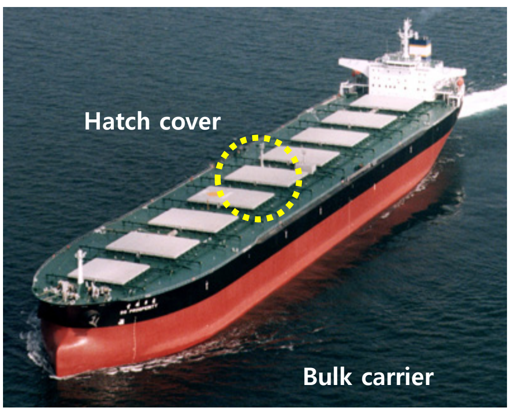


* MFD: Method of feasible directions, MS: Multi-start local optimization method, GA: Genetic algorithm, HYBRID: Global-local hybrid optimization method

Hatch Cover of a Bulk Carrier as Optimization Target (1/2)

☑ **Bulk carrier: Dry cargo ship of transporting grains, ores, coals, and so on without cargo packaging**

☑ **Hatch: Opening for loading and off-loading the cargo**



Hatch Cover of a Bulk Carrier as Optimization Target (2/2)

☑ Hatch cover

- Cover plate on the hatch for protecting the cargo
- Having a structure of stiffened plate which consists of a plate and stiffeners
- In general, the cost of hatch cover equipment is accounting for 5~8% of shipbuilding cost.
- In spite of the importance of the hatch cover in the B/C, it has hardly been optimized. Thus, the hatch cover was selected as an optimization target for the lightening of the ship weight in this study.

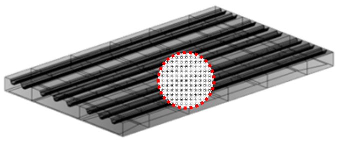
Idealization of Hatch Cover of a Bulk Carrier

☑ The hatch cover has a structure of stiffened plate which consists of a plate and stiffeners and looks like a corrugated plate.

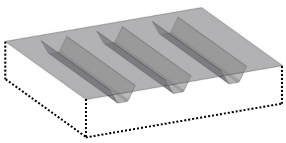
☑ The hatch cover can be idealized for the effective optimization.

☑ Thus, the idealized model will be used as the optimization target.

Real model



3D CAD model



Idealized model

Determination of Optimal Principal Dimensions of a Hatch Cover - Problem Definition

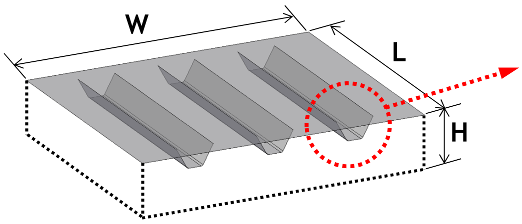
☑ **Criteria for determining optimal principal dimensions (Objective function)**
- Minimization of the weight of hatch cover

☑ **Given**
- Length (L), width (W), height (H) of hatch cover
- Total number of girders and transverse web frames
- Load (p_H) on the hatch cover
- The largest span of girders (l_g)
- Materials of the hatch cover

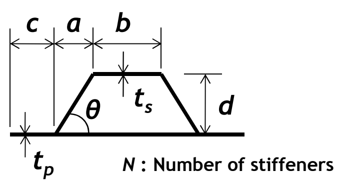
☑ **Find (Design variables)**
- Plate thickness (tp), stiffener thickness (ts), stiffener size (b, a, d), and number of stiffeners (N)

☑ **Constraints**
- Constraints about the maximum permissible stress and deflection
- Constraint about the minimum thickness of a top plate
- Constraints about the minimum section modulus and shear area of stiffeners
- Constrains about geometric limitations

Determination of Optimal Principal Dimensions of a Hatch Cover - Problem Formulation (Summary)



Idealized model



Stiffener section

Find t_p, t_s, b, a, d, N

Minimize $Weight = \left[\rho_p \cdot L \cdot W \cdot t_p + \rho_s \cdot L \cdot \left\{(2a \cdot (\cos\theta)^{-1} + b + c) \cdot N + c\right\} \cdot t_s\right] \cdot 10^{-3}\ [ton]$

Subject to

Requirement for maximum permissible stress by CSR (Common Structural Rules)

$\sigma_v \le 0.8 R_{eH}\ [N/mm^2]$

Requirement for maximum permissible deflection by CSR

$f \le 0.0056 \cdot l_g\ [m]$

Requirements for minimum thickness of a top plate

$t_{\min} \le t_p\ [mm]$

Requirements for minimum section modulus and shear area of stiffeners

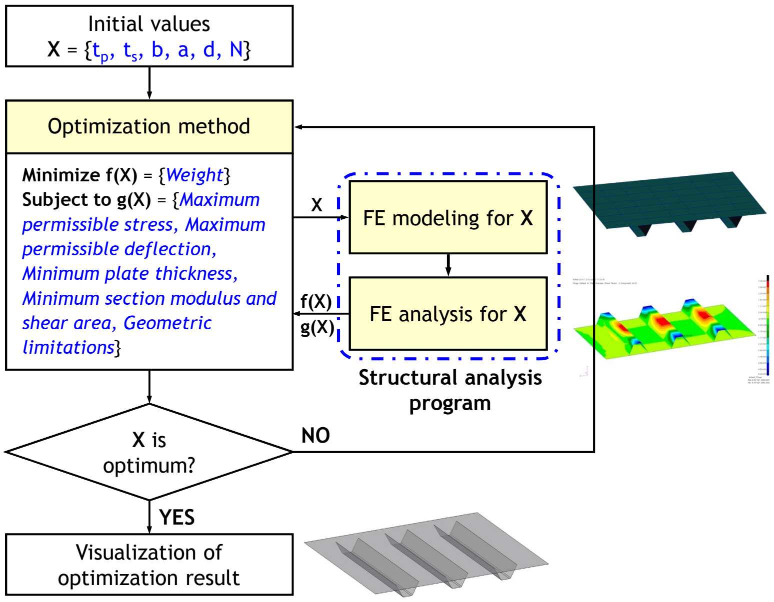
$M_{\min} \le M_{net}\ [cm^3] \qquad A_{\min} \le A_{net}\ [cm^2]$

Limitations on geometry

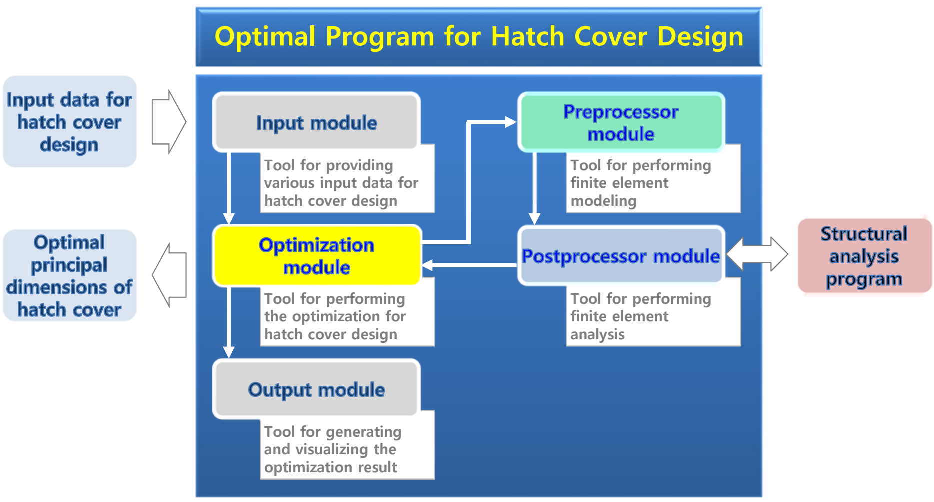
$N(2a+b) < W \qquad d \le H \qquad 0^\circ \le \theta \le 90^\circ$

➡ **Optimization problem having 6 design variables (unknowns) and 8 inequality constraints**

Process for Determining Optimal Principal Dimensions of a Hatch Cover Using an Optimization Algorithm

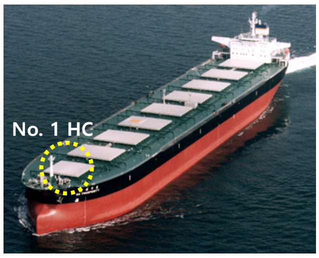


Optimization Program for the Hatch Cover Design - Configuration

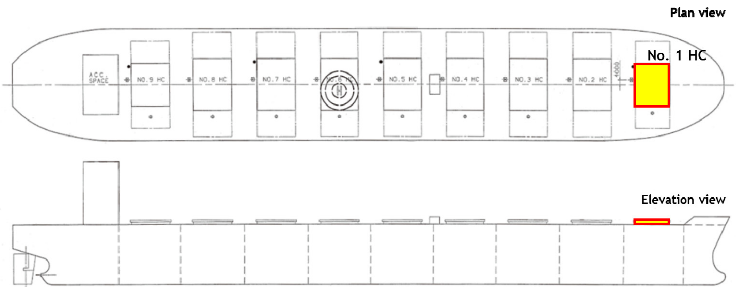


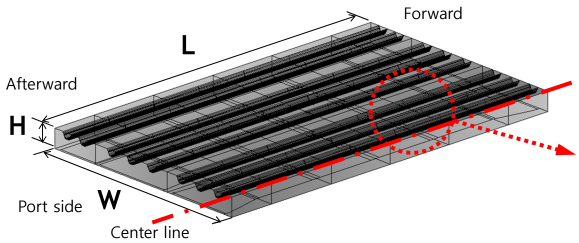
Hatch Cover Design of a Deadweight 180,000 ton Bulk Carrier - Input Data (1/2)

- ☑ Target ship: Deadweight 180,000 ton B/C
- ☑ Dimensions of the ship: Length 283.5 m, Breadth 45.0 m, Depth 24.7 m
- ☑ Input data of No. 1 HC for optimization of the hatch cover
  - Length (L) of the hatch cover: 14.929 m
  - Width (W) of the hatch cover: 8.624 m (actually, half width of No. 1 HC)
  - Height (H) of the hatch cover: 0.880 m
  - The largest span of girders (l_g) in the hatch cover: 3.138 m
  - Load (p_H) on the hatch cover by CSR: 86.28 kN/m^2
  - Materials of the hatch cover: AH32
  - Specific gravity of plate and stiffeners (ρ_p, ρ_s): 7.8 ton/m^3

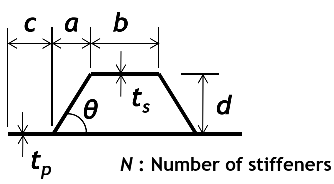


Hatch Cover Design of a Deadweight 180,000 ton Bulk Carrier - Input Data (2/2)





Idealized half model



Stiffener section

Hatch Cover Design of a Deadweight 180,000 ton Bulk Carrier - Mathematical Formulation

Find t_p, t_s, b, a, d, N

Minimize $Weight = \left[\rho_p \cdot L \cdot W \cdot t_p + \rho_s \cdot L \cdot \left\{(2a \cdot (\cos\theta)^{-1} + b + c) \cdot N + c\right\} \cdot t_s\right] \cdot 10^{-3}\ [ton]$

$$= \left[7.85 \cdot 14.929 \cdot 8.624 \cdot t_p + 7.85 \cdot 14.929 \cdot \left\{(2a \cdot (\cos\theta)^{-1} + b + c) \cdot N + c\right\} \cdot t_s\right] \cdot 10^{-3}$$

: weight of top plate and stiffeners

Subject to

$\sigma_v \le 0.8 \cdot 315\ [N/mm^2]$: maximum permissible stress

$f \le 0.0056 \cdot 3.138\ [m]$: maximum permissible deflection

$t_{\min} \le t_p\ [mm]$: minimum thickness of a top plate

$M_{\min} \le M_{net}\ [cm^3]$: minimum section modulus of stiffeners

$A_{\min} \le A_{net}\ [cm^2]$: minimum shear area of stiffeners

$N(2a + b) < W$: geometric limitation

$d < H$: geometric limitation

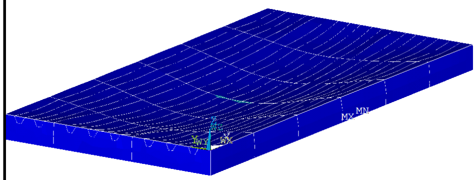
$0^\circ < \theta \le 90^\circ$: geometric limitation

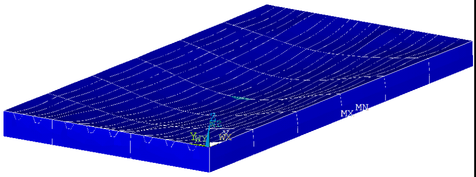
➡ **Optimization problem having 6 design variables and 8 inequality constraints**

Hatch Cover Design of a Deadweight 180,000 ton Bulk Carrier - Optimization Result (1/2)

Item	Unit	Manual design	Optimization result
t_p	mm	16	14
t_s	mm	8	8
b	m	0.170	0.160
a	m	0.120	0.111
d	m	0.220	0.198
N	-	8	8
Weight	ton	26.225	23.975
Maximum stress	MPa	218	252
Maximum deflection	mm	5.532	6.388

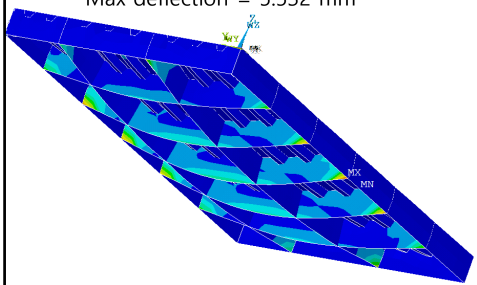
Hatch Cover Design of a Deadweight 180,000 ton Bulk Carrier - Optimization Result (2/2)

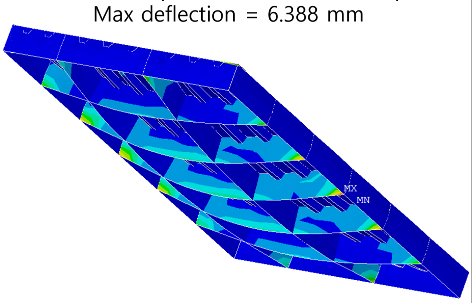




Max equivalent stress = 218 Mpa
Max deflection = 5.532 mm

Max equivalent stress = 252 Mpa
Max deflection = 6.388 mm





Before optimization (manual design)

After optimization (this study)

Midship Section Design for the Minimization of Shipbuilding Cost

Find $x_i, i = 1, \cdots, 16$

Minimize *Building Cost*

Subject to

$$t_{i,\min} - x_i \le 0,\ i = 6, \cdots, 16$$

: minimum plate thickness

$$Z_{\min}^{deck} - Z^{deck} \le 0$$

: minimum section modulus at deck

$$Z_{\min}^{bottom} - Z^{bottom} \le 0$$

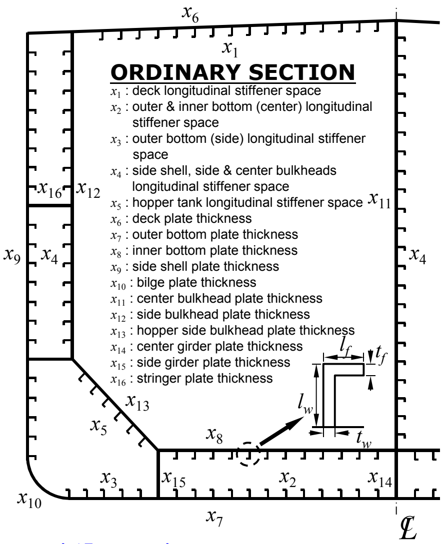
: minimum section modulus at bottom

$$\sigma^{deck} - \eta^{deck} \sigma_c^{deck} \le 0$$

: critical buckling stress at deck

$$\sigma^{bottom} - \eta^{bottom} \sigma_c^{bottom} \le 0$$

: critical buckling stress at bottom



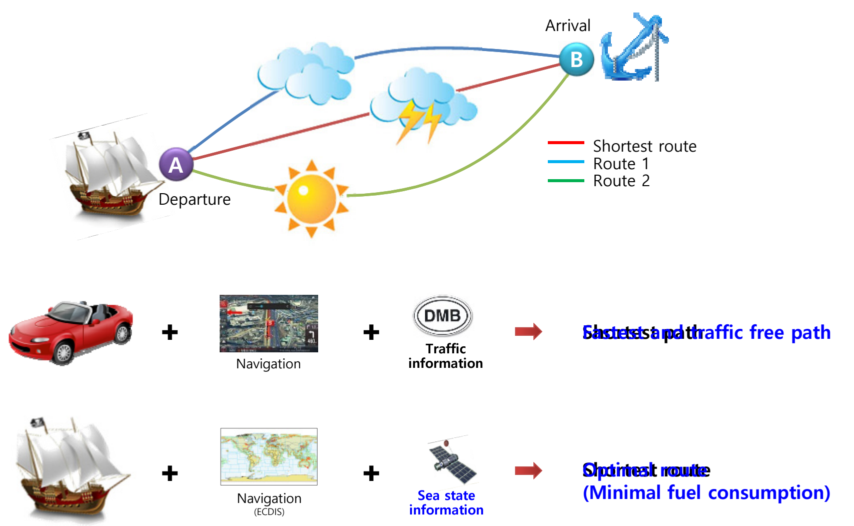
➡ Optimization problem having 16 unknowns and 15 inequality constraints

Optimization Result for Midship Section Design for the Minimization of Shipbuilding Cost

	Unit	Actual Ship	MFD	MS	GA	HYBRID	
						w/o Refine	with Refine
Building Cost	*$/m*	-	21,035.254748	20,637.828634	20,597.330090	20,422.478135	20,350.286893
x_1	*mm*	800.0	787.038274	811.324938	780.000000	810.000000	810.3701321
x_2	*mm*	800.0	762.891023	799.038243	750.000000	800.000000	800.1282732
x_3	*mm*	780.0	743.313979	787.034954	770.000000	790.000000	789.0923943
x_4	*mm*	835.0	814.142029	833.909455	820.000000	830.000000	834.838424
x_5	*mm*	770.0	756.434513	772.349435	790.000000	780.000000	780.002092
x_6	*mm*	16.5	16.983723	16.203495	16.000000	16.000000	16.390923
x_7	*mm*	16.0	16.829142	16.043803	16.500000	16.000000	15.989044
x_8	*mm*	15.5	16.020913	15.390394	16.000000	15.500000	15.432091
x_9	*mm*	17.0	17.329843	17.039439	16.500000	16.500000	17.139433
x_{10}	*mm*	14.5	15.001923	14.324335	15.000000	15.000000	14.780908
x_{11}	*mm*	13.5	14.192834	14.240495	14.000000	13.500000	13.550214
x_{12}	*mm*	14.5	15.123051	15.403945	14.500000	14.500000	14.500130
x_{13}	*mm*	17.0	16.902832	16.849387	16.500000	17.000000	17.010902
x_{14}	*mm*	14.0	14.784034	14.739454	15.500000	14.500000	14.309324
x_{15}	*mm*	14.0	15.129430	14.448504	15.500000	14.500000	14.588917
x_{16}	*mm*	14.5	14.824045	14.940584	15.000000	15.000000	14.789992
Iteration No	-	-	8	912	93	64	70
CPU Time	*sec*	-	2.90	293.28	272.91	265.06	267.92

* Adjustment (e.g., rounding a figure) is necessary to use optimum values for plate thickness and stiffener space in the aspect of considering productivity.

Concept of Optimal Ship Route



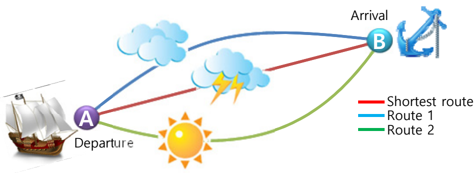
* DMB: Digital Multimedia Broadcasting
* ECDIS: Electronic Chart Display and Information System

Determination of Optimal Ship Route
- Problem Definition

☑ **Criteria for determining optimal ship route (Objective function)**
- Minimization of the fuel consumption of ship

☑ **Given (Input)**
- Positions of departure and arrival
- Required arrival time
- Information on ship and sea state
- Geographic information

☑ **Find (Design variables)**
- Optimal ship route

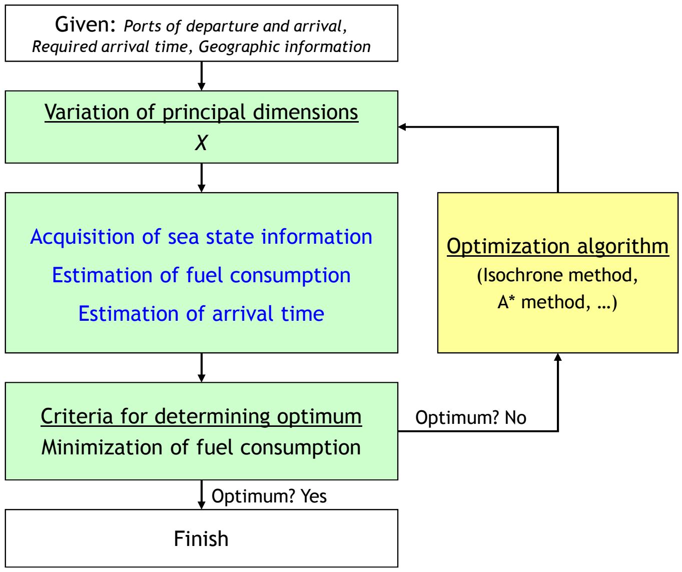


Determination of Optimal Ship Route
- Problem Formulation

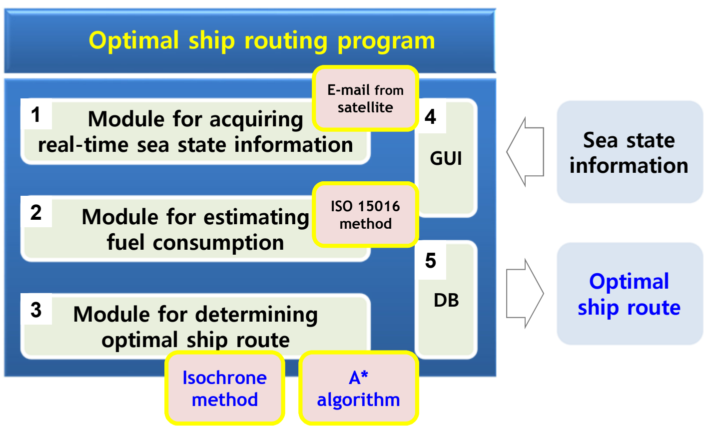
Find	$\mathbf{X}$	Route	Design Variables
Minimize	$TFOC(\mathbf{X})$	Total fuel consumption	Objective Function
Subject to	$ETA_{\min} - ETA(\mathbf{X}) \le 0$	Requirement for the minimum arrival time	Constraints
	$ETA(\mathbf{X}) - ETA_{\max} \le 0$	Requirement for the maximum arrival time	

➡ Optimization problem having 1 unknown and 2 inequality constraints

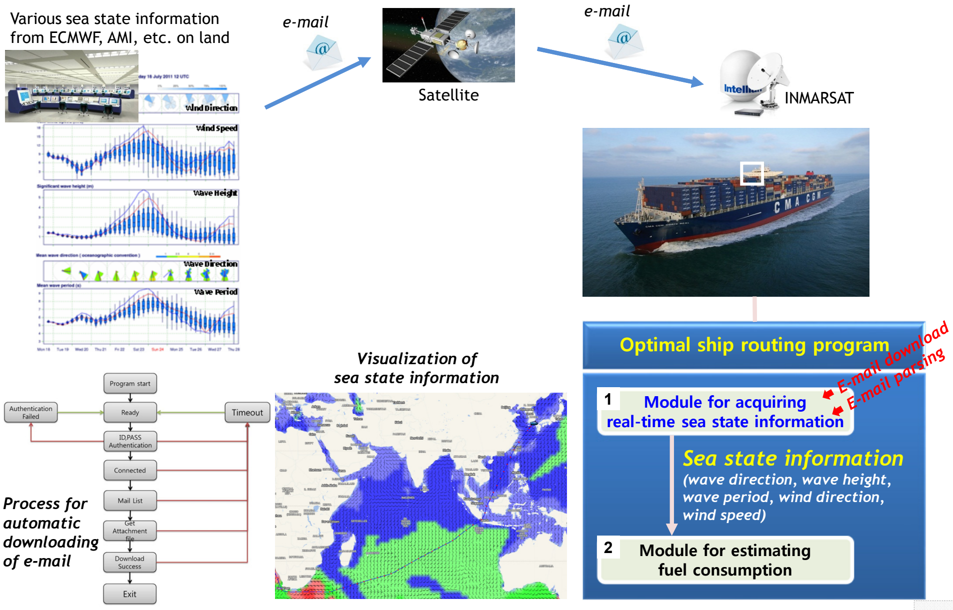
Process for Determining Optimal Ship Route Using an Optimization Algorithm



Optimization Program for the Ship Route Design - Configuration



Acquisition of Real-time Sea State Information



* ECMWF: European Center for Medium range Weather Forecasting, AMI: Aerospace & Marine International

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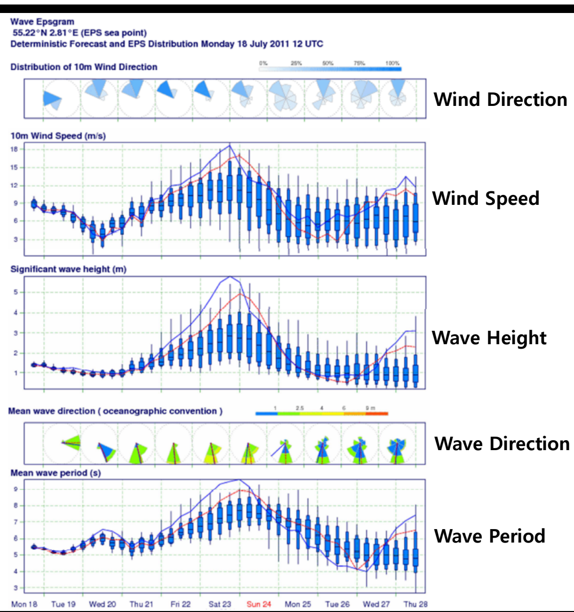
Sea State Information from ECMWF*



* ECMWF: European Center for Medium range Weather Forecasting, AMI: Aerospace & Marine International

Design Theories of Ship and Offshore Plant, September 2016, Myung-Il Roh

sydlab SEOUL NAT'L UNIV.

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Scenario of the change in Ship Performance According to the Sea State

Sea state

↓

Increase of ship's resistance
according to sea state

→ *The increased amount of ship's resistance should be calculated.*

↓

Reduction of ship's speed
according to additional resistance

→ *The reduced amount of ship's speed should be calculated.*

↓

Increase of ship's horse power
to compensate for the ship's speed

→ *The increased amount of ship's horse power should be calculated.*

↓

Increase of ship's fuel consumption
according to the increase in horse power

→ *Additional fuel consumption according to the increase in horse power should be calculated.*

Estimation of Fuel Consumption by ISO 15016 Method

Sea state information

↓

Increase of ship's resistance
according to sea state

↓

Reduction of ship's speed
according to additional resistance

↓

Increase of ship's horse power
to compensate for the ship's speed

↓

Increase of ship's fuel consumption
according to the increase
in horse power

Scenario of the change in ship performance according to the sea state

ISO 15016 method

$$\delta R = \delta R_{wave} + \delta R_{wind} + \delta R_{\delta\delta} + \delta R_{\beta\beta} + \delta R_{AS} + \delta R_{ADIS}$$

δR: increased amount of ship's resistance
δR_{wave}: added resistance by wave
δR_{wind}: added resistance by wind
$\delta R_{\delta\delta}$: added resistance by steering
$\delta R_{\beta\beta}$: added resistance by drift
δR_{AS}: added resistance by seawater condition
δR_{ADIS}: added resistance by displacement

$$\delta V = \delta V_{wave} + \delta V_{wind} + \delta V_{AC} + \delta V_{AS}$$

δV: reduced amount of ship's speed
δV_{wave}: reduced amount of ship's speed by wave
δV_{wind}: reduced amount of ship's speed by wind
δV_{AC}: reduced amount of ship's speed by current
δV_{AS}: reduced amount of ship's speed by shallow water

$$\frac{\delta P_1}{P_0} = \frac{\delta V}{V_0} \cdot (n+1)$$

$$\delta P_2 = 2\pi / 75(N_{0p}\delta Q_p + Q_{0p}\delta N_p + \delta Q_p \delta N_p)$$

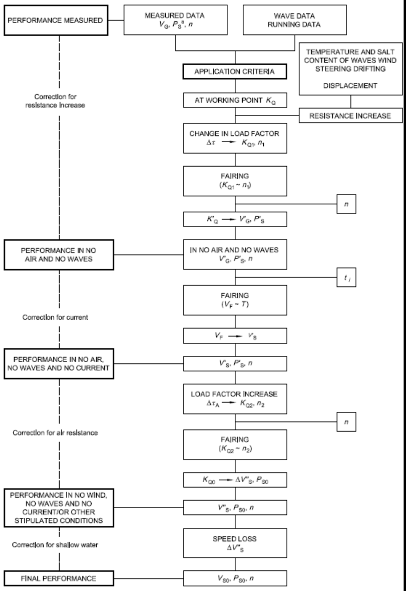
$$\delta P = (\delta P_1 + \delta P_2)/2$$

δP: increased amount of ship's horse power
P_0 : ship's horse power at speed of V_0
δV: reduced amount of ship's speed
V_0 : ship's speed in calm sea
n: coefficient according to ship's type
N_{0p} : propeller RPM at speed of V_0
δN_p: increase of propeller RPM
Q_{0p} : propeller torque at speed of V_0
δQ_p: increase of propeller torque

$$TFOC = FOC + \delta FOC$$

$$\delta FOC = SFOC \cdot \delta P \cdot ETA$$

TFOC: total fuel consumption
FOC: fuel consumption at speed of V_0
δFOC: additional fuel consumption according to δP
δP: increased amount of ship's horse power
SFOC: Specific Fuel Oil Consumption
ETA: Estimated Time of Arrival



Flowchart of speed trial analysis

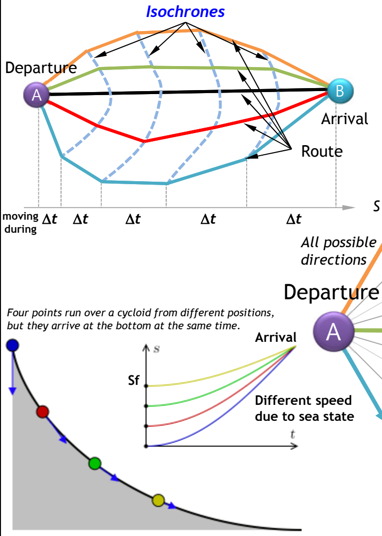
* ISO, "Guidelines for the Assessment of Speed and Power Performance by Analysis of Speed Trial Data", ISO/DIS 15016, pp. 1-45, 2002

Determination of Optimal Ship Route by Isochrone Method

Isochrone method

Isochrone is a set of connected points that a ship can reach within given time limit starting from one point and going in all possible directions.

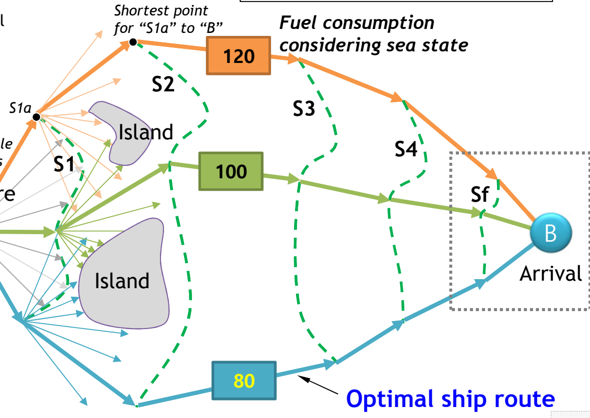
Definition of an isochrone



Improved isochrone method

- Considering sea state
- Considering obstacles such as islands

Given: Time(Δt), Sea state
Find: Position, Fuel consumption



Determination of Optimal Ship Route by A* Algorithm

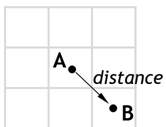
A* algorithm

A* algorithm is widely used in path finding between nodes.

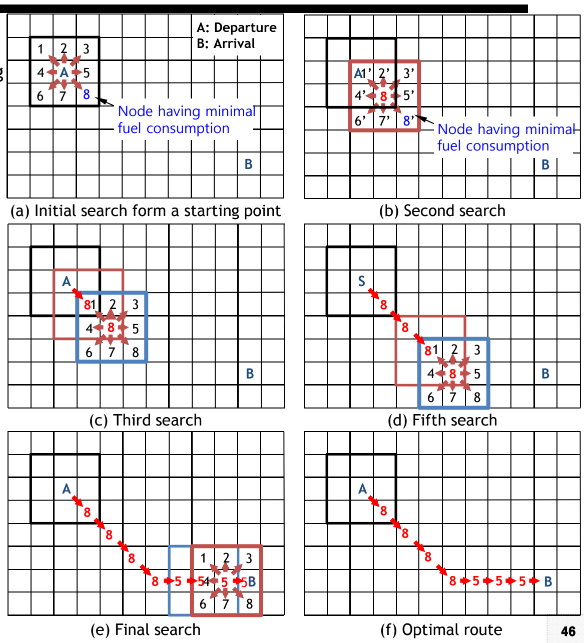
Improved A algorithm*

- Considering sea state
- Considering obstacles such as islands

Given: Position, Sea state
Find: Time, Fuel consumption

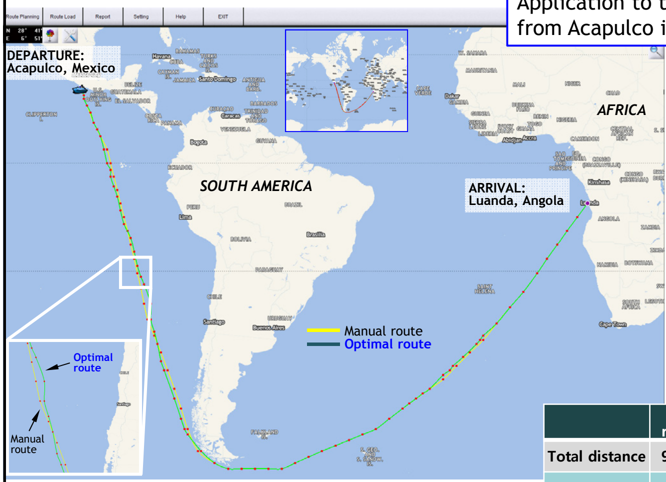


- *Calculation of the required time from A to B considering sea state*
- *Calculation of fuel consumption from A to B considering sea state*



Example of Determination of Optimal Ship Route

Application to the route
from Acapulco in Mexico to Luanda in Angola



- 4,600TEU container ship
- Lbp: 237.0m
- B: 37.5m
- D: 22.0m
- T_d/T_s: 12.4/13.4m
- C_B: 0.6600
- V: 22knots

3.0% fuel consumption
were reduced for this route.

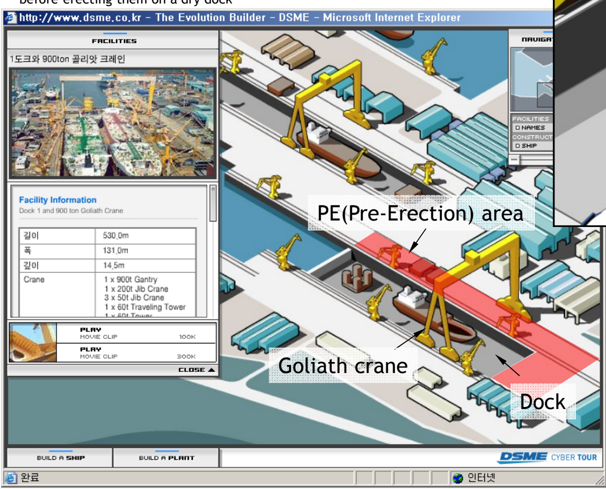
	Manual route [A]	Optimal route [B]	Reduction (B-A)	Ratio (B/A)
Total distance	9,381NM	9,395NM	-13NM	100.1%
Total time	447h 42m	437h 58m	9h 44m	97.8%
Fuel consumption[1]	1,720ton ($860,000)	1,669ton ($834,500)	51ton ($25,500)	97.0%
EEOI[2]	6.651	6.303	0.348	94.8%

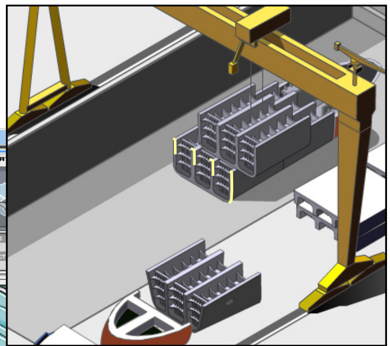
* 1: Fuel cost for HFO(Heavy Fuel Oil): $500/ton, 2: Energy Efficiency Operational Indicator

Block Erection Using a Goliath Crane

* Reference: DSME Co., Ltd.

* PE(Pre-Erection) area: Area for temporarily placing erection blocks before erecting them on a dry dock





Erection process

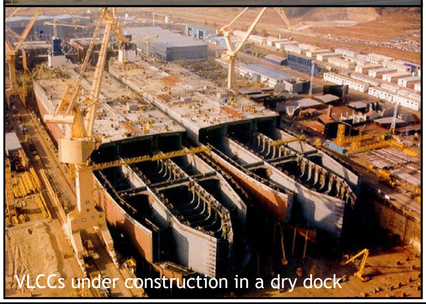
1. Start the erection of the block (or block lifting).
2. Start welding between adjacent erection blocks.
3. Repeat Steps 1 and 2 for each erection block.

Some Images of the Block Erection

* Reference: DSME Co., Ltd.

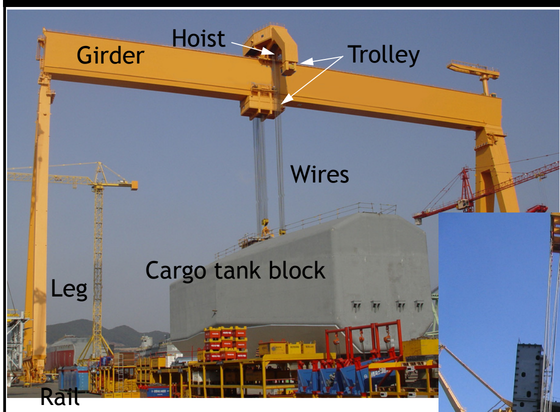
During the block erection

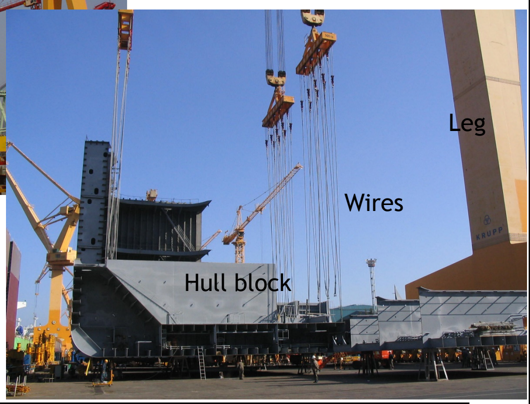
Before the block erection



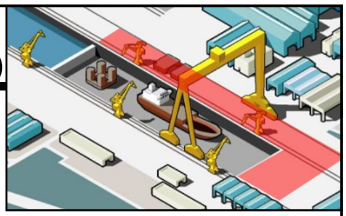
VLCCs under construction in a dry dock

Example of a Gantry Crane for Lifting Blocks





Travel Distance of a Unloaded Crane According to the Lifting Sequence (1/2)

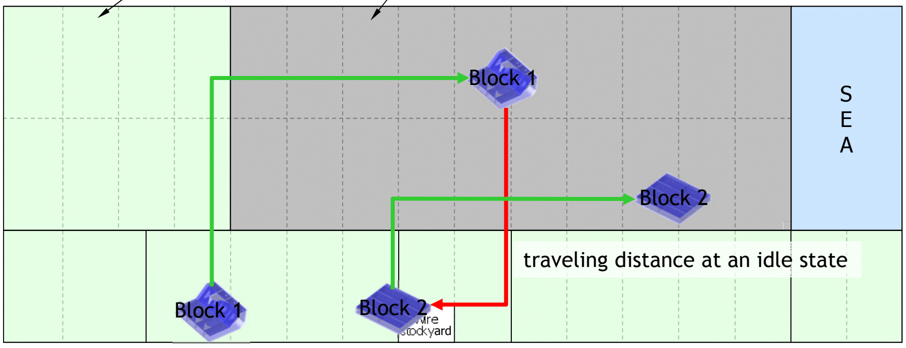


“Block 1” lifting ➡ “Block 2” lifting

PE(Pre-Erection) Area

Dock

Plan view

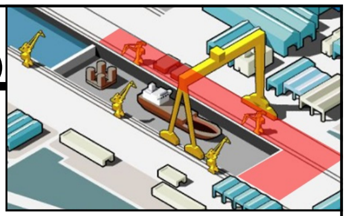


Travel of a loaded crane

Travel of a unloaded crane

* PE(Pre-Erection) area: Area for temporarily leaving erection blocks before erecting them on the dock
* Daily working time of a crane: 20hours, Moving speed of a crane: 30m/min

Travel Distance of a Unloaded Crane According to the Lifting Sequence (2/2)

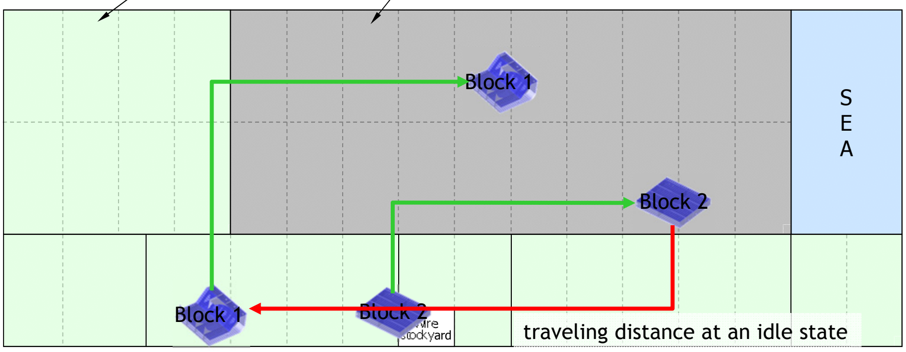


“Block 2” lifting ➡ “Block 1” lifting

PE(Pre-Erection) Area

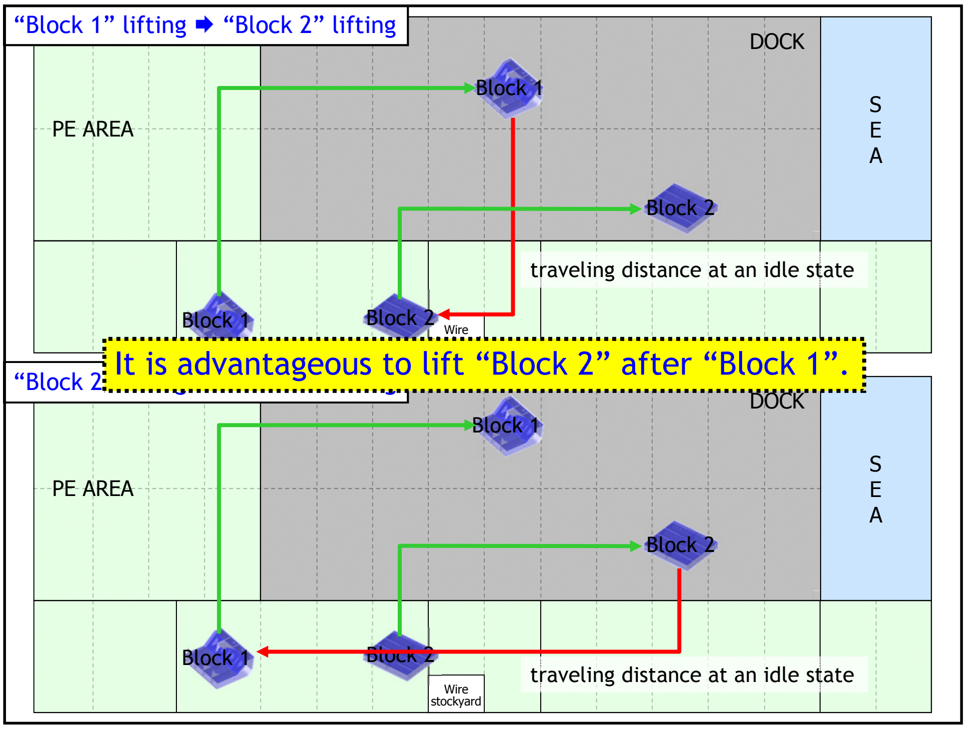
Dock

Plan view



Travel of a loaded crane

Travel of a unloaded crane

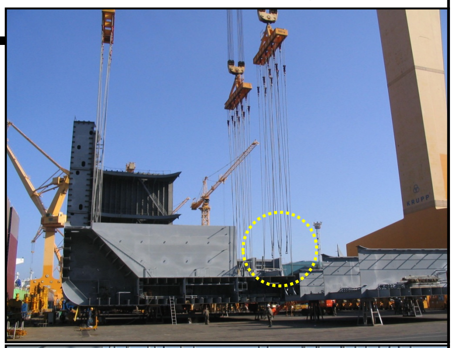


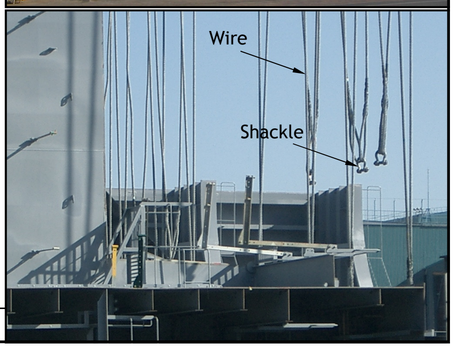
Problem for the Determination of the Optimal Lifting Sequence of Erection Blocks

☑ **Objective**
- **Minimization of the travel distance without load of a crane**

☑ **Input (“Given”)**
- **Before and after positions of each erection block**
- **Priority for lifting of each erection block per ship number**
- **Available earliest and latest time for lifting of each erection block**
- **Required time for lifting of each erection block**
- **Specification and number of wires and shackles for lifting each erection block**

☑ **Output (“Find”)**
- **Optimal lifting sequence of erection blocks**





Formulation of a Problem for the Determination of the Optimal Lifting Sequence of Erection Blocks

Find x_i — Lifting time for each block — **Design Variables**

Minimize $F_1 = \sum_{i=0}^{N-1} \{(1 - r_{i,i+1}) \cdot t_{i,i+1} + r_{i,i+1} \cdot (t_{i,W} + t_{W,i+1})\}$

Total travel time without block — **Objective Function**

Minimize $F_2 = \sum_{i=0}^{N-1} (r_{i,i+1} \cdot T_r)$

Total time for wires and shackles replacement

Subject to — **Constraints**

$g_1 = l_i - s_i \le 0$ — Constraints about the start of the lifting time

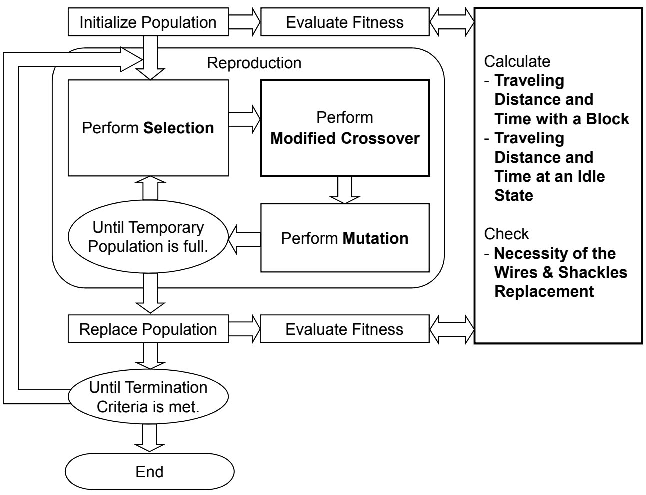
$g_2 = f_i - u_i \le 0$ — Constraints about the end of the lifting time

$g_3 = p_j - p_k \le 0$ — Constraints about the priority for lifting

$g_4 = f_N - T_e \le 0$ — Constraints about the total lifting time

$for\ i = 0, \cdots, N-1 \text{ and } j, k = 1, \cdots, N$

Proposed Algorithm for Scheduling of Block Lifting of a Gantry Crane

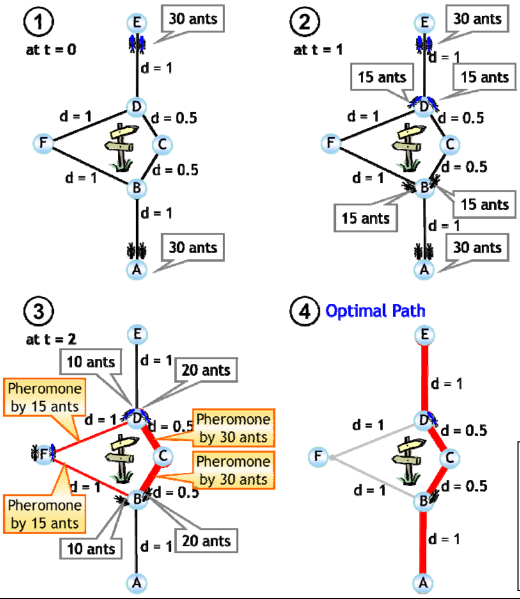


Example of a Deadweight 600 ton Transporter for Moving Blocks in Shipyards

(a) Transporter with loading (b) Transporter without loading

Specifications	• Length : 23.3 m • Breadth : 6.6 m • Height : Avg. 2.2 m (1.55 ~ 2.2 m, adjustable) • Lightweight : 126 ton • Speed : without loading 15 km/h, with loading 10 km/h • Number of wheels : 88
Purpose	Moving blocks, deck houses, main engines, large pipe equipments, etc.
Features	• Moving forward and backward, 360° at the current position • Two control rooms at the front and back • Two signalmen are required for ensuring against risks

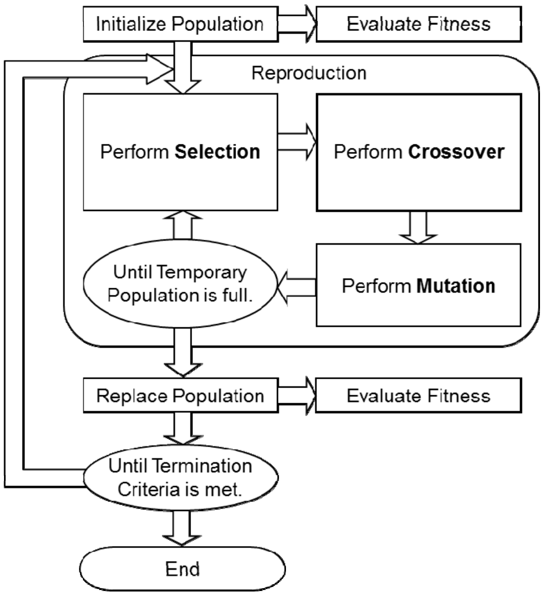
Example of Ants Finding an Optimal Path



Assumptions

- 30 ants start from A and E every unit time ('t') 1, respectively.
- The ants move by the distance ('d') 1 during the time 1 with a constant speed.

Schematic diagram of the Genetic Algorithms



Problem for the Determination of the Optimal Transporting Sequence of Erection Blocks

☑ **Objective**
- **Minimization of the travel distance without block of transporters**

☑ **Input ("Given")**
- **Total number of blocks and transporters**
- **Weight of each block and specifications of each transporter**
- **Before and after positions of each block**
- **Priority for transporting of blocks**
- **Available earliest and latest time for transporting of blocks**
- **Roads in shipyard for the block transportation**

☑ **Output ("Find")**
- **Optimal route and transporting sequence of blocks**

Detailed Input Data for the Determination of the Optimal Transporting Sequence of Erection Blocks

- ☑ Data on the transporters
  - Total number and ID of the transporters
  - Specifications (e.g., the speed, maximum deadweight, service time, etc.) of each transporter
  - Initial position of each transporter
- ☑ Data on the blocks
  - Total number and ID of the blocks to be moved by the transporters
  - Weight of each block
  - Initial position and target position after moving each block
  - Transportation time limit (lower and upper bounds) of each block
  - Priority for the transportation among the blocks
- ☑ Miscellaneous data
  - Information on the shipyard roads for the block transportation

Formulation of a Problem for the Determination of the Optimal Transporting Sequence of Erection Blocks

Design Variables

Find x_i — Transporting time for each block

Objective Function

Minimize $F_1 = \sum_{i=1}^{B}\sum_{k=1}^{T} x_i^k (e_i^k / V^k)$ *and* — Total transporting time

Minimize $F_2 = \sum_{i=2}^{B}\sum_{j=1}^{i-1}\sum_{k=2}^{T}\sum_{l=1}^{k-1} x_i^k x_j^l c_{kl}$ — Total number of interferences between transporters

Constraints

Subject to

$g_1 = w_i - t_k \le 0$ — Constraints about the maximum deadweight of transporter

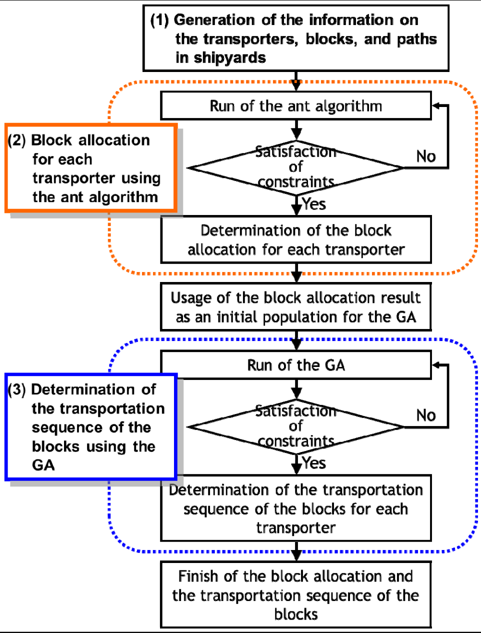
$g_2 = r_i - p_i^k \le 0$ — Constraints about the start of the transporting time

$g_3 = d_i^k - s_i \le 0$ — Constraints about the end of the transporting time

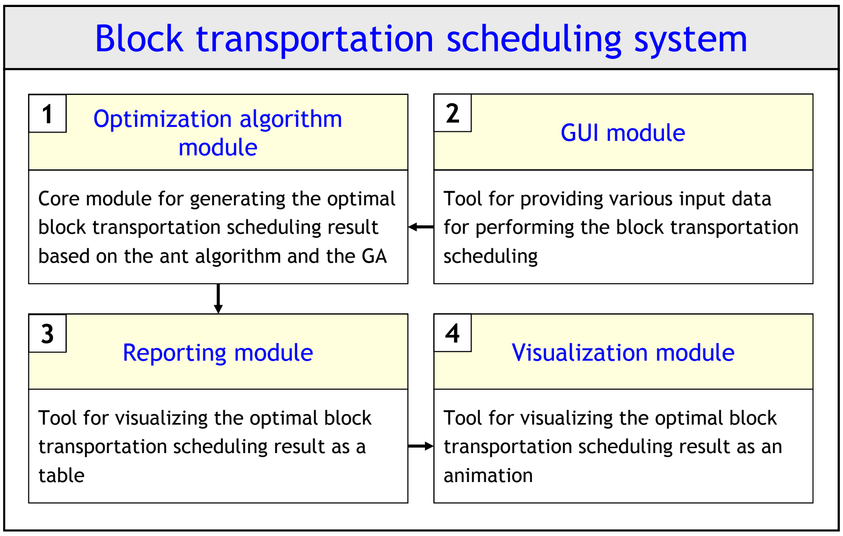
$g_4 = p_i - p_j \le 0$ — Constraints about the priority for transporting

$for\ i, j = 1, \cdots, B \text{ and } k, l = 1, \cdots, T$

Proposed Algorithm for Scheduling of Block Transporting of Multiple Transporters



Configuration of the Block Transportation Scheduling System



Comparison of the Performance Resulting from Manual Scheduling and Automatic Scheduling by the Developed System

		Manual scheduling	Genetic algorithm	Proposed algorithm
Total transportation time		14 hr 16 min	12 hr 24 min	**12 hr 13 min**
Total transportation time without loading		6 hr 10 min	4 hr 18 min	**4 hr 7 min**
No. of interferences between the transporters during the transportation		7	2	**1**
No. of allocated blocks for each transporter	T_1	11 blocks	12 blocks	**13 blocks**
	T_2	34 blocks	34 blocks	**32 blocks**
	T_3	24 blocks	25 blocks	**27 blocks**
	T_4	28 blocks	26 blocks	**25 blocks**

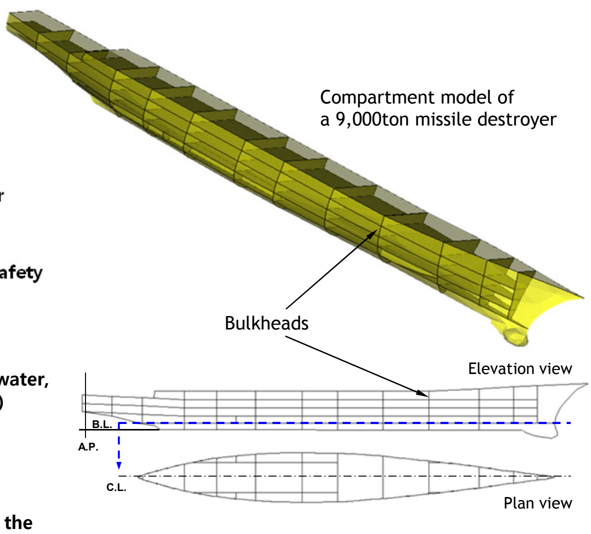
Optimal Compartment Layout Design of a Naval Ship

☑ **Design variables (Output)**
- **Positions of transverse bulkheads**

☑ **Objective function**
- **Maximization of space for weapons and equipment (= Minimization of space for liquid cargos)**

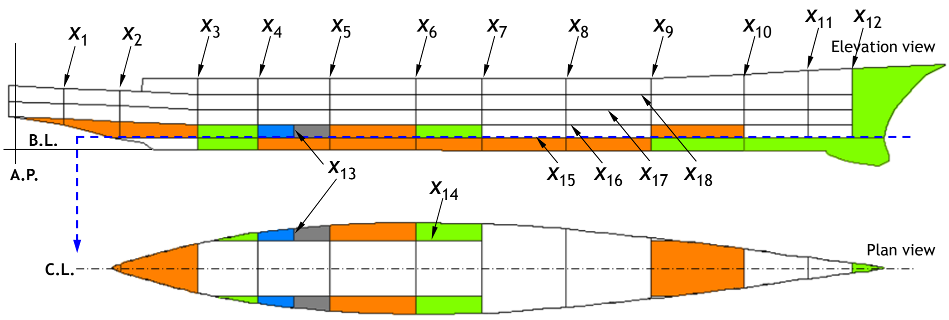
and
- **Maximization of structural safety**

☑ **Constraints**
- **Requirements for space for liquid cargos(fuel oil, fresh water, ballast water, lubrication oil)**
- **Requirements for damage stability condition by international regulations**
- **Requirements for the position(draft, trim, heel) at the damaged state**



Design Variables of an Optimal Facility Layout Problem of a Naval Ship

General arrangement of a parent ship* and design variables

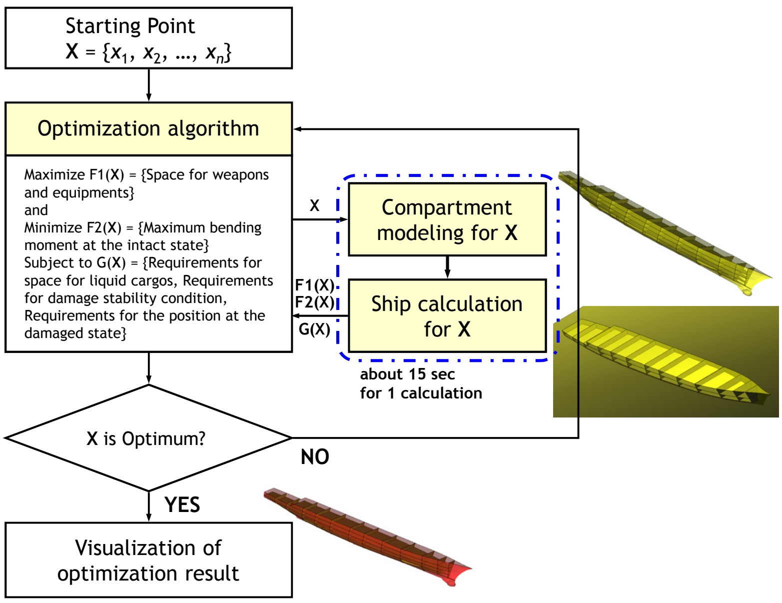


Fuel Oil Tank
Fresh Water Tank
Water Ballast Tank
Lubrication Oil Tank

- Design variables for bulkheads in x-direction: x_1 ~ x_{13} [13]
- Design variables for bulkheads in y-direction: x_{14} [1]
- Design variables for bulkheads in z-direction: x_{15} ~ x_{18} [4]

* Missile destroyer of US Navy, "Arleigh Burke DDG-51"

Process for Determining an Optimal Compartment Layout Design of a Naval Ship Using an Optimization Algorithm



* F1(X), F2(X), G(X): Objective and constraints values for each design variables X

Optimization Result for the 9,000 ton Missile Destroyer - Comparison with a Parent Ship (1/2)

Item		Unit	Parent ship		Optimization result		Note
$V_{W.B.T}$		m^3	1,181.4		1,050.6		Objective function (Minimize)
BM_1	BM_2	$kN{\cdot}m$	74,694.3	50,401.1	67,254.7	47,325.6	Objective function (Minimize)
$\phi_{0,1}$	$\phi_{0,2}$	°	0.000	0.038	0.000	0.038	Requirements for damage stability condition by international regulations
$A_{2,1}/A_{1,1}$	$A_{2,2}/A_{1,2}$	-	40.871	40.544	40.874	40.666	
T_1	T_2	m	6.919	6.884	6.819	6.787	
t_1	t_2	m	0.192	0.396	0.309	0.589	
ϕ_1	ϕ_2	°	1.243	1.336	0.839	0.896	

➡ **Decrease of space for liquid cargos as compared with a parent ship**
(= Increase of space for weapons and equipment)
& Increase of structural safety

* $V_{W.B.T}$: Total volume of ballast tank
* BM_i: Maximum bending moment at the ith loading condition
* $\phi_{0,,j}$: Initial heel angle at the jth damage case
* $A_{1,j}$, $A_{2,j}$: Areas of the negative and the positive righting moment from a statistical stability curve and a heeling arm curve at the jth damage case
* T_j, t_j: Equivalent draft and trim at the jth damage case
* ϕ_j: Equivalent heel angle considering beam wind at the jth damage case

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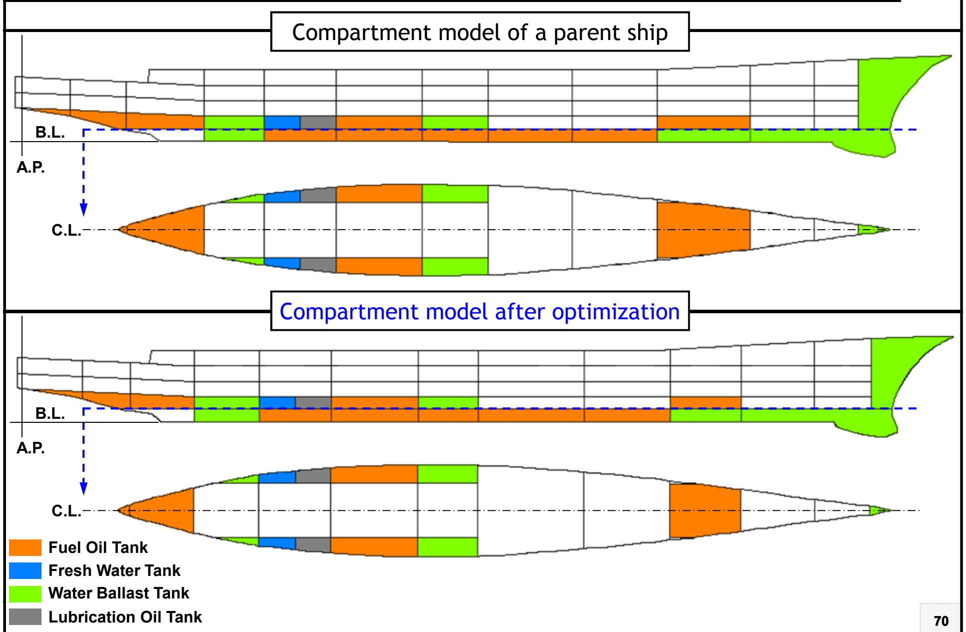
Optimization Result for the 9,000 ton Missile Destroyer - Comparison with a Parent Ship (2/2)



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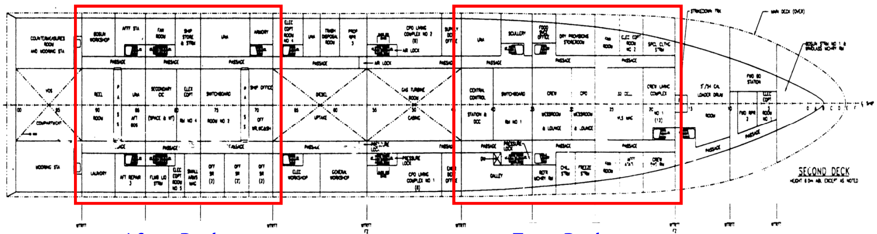
Optimal Facility Layout Problem of a Naval Ship

- ☑ Fore body (Fr. no. 68~92)
  - Rectangular boundary shape
  - 20 compartments, 2 watertight transverse bulkheads, 2 vertical passages, 2 horizontal passages
- ☑ After body (Fr. no. 17~44)
  - Curved boundary shape
  - 20 compartments, 2 watertight transverse bulkheads, 1 vertical passage, 2 horizontal passages

2nd Deck of the FF-21

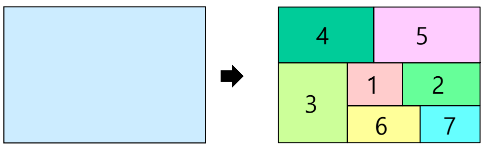


After Body (Fr. no. 68~92)

Fore Body (Fr. no. 17~44)

Facility Layout Problem (FLP)

- ☑ Facility Layout Problem
  - Given: Available area, the required area for each facility, material flow between facilities, etc.
  - Find: Best facility layout which minimizes total cost of transporting materials between facilities
  - Applications: Factory layout, equipment layout in the factory, office layout in the building, etc.
- ☑ Limitation of Existing Algorithms
  - Limited to a rectangular boundary shape
  - No consideration for inside side wall
  - No consideration for passages between facilities



A given bounded area

Best layout of 7 facilities

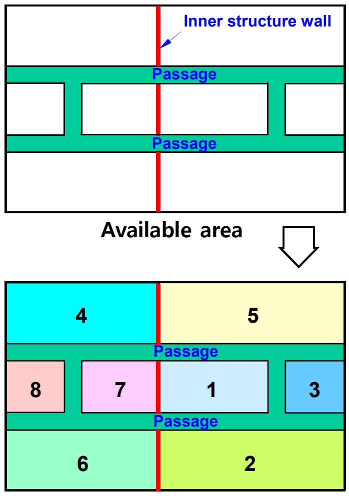
Facility Layout Problem Having Inner Structure Walls and Passages

☑ **Given**

- Number of facilities to be allocated to the available area
- Available area and its boundary shape
- Number and positions of inner structure walls
- Number and widths of each vertical and horizontal passage
- Upper and lower bounds of the required area for each facility
- Upper and lower bounds of the required aspect ratio for each facility
- Material flows between facilities
- Upper and lower bounds of the position of each vertical and horizontal passage

☑ **Find**

- Best facility layout which minimizes total cost of transporting materials between facilities



Best layout plan of facilities (1-8)

Formulation of the Optimal Facility Layout Problem Having Inner Structure Walls and Passages

Objective Function

Minimize

$$F = \sum_{i=1}^{M}\sum_{j=1}^{M} f_{ij} \times d_{ij}$$

Total cost of transporting materials

Constraints

Subject to

$$g_1 = \alpha_k^{\min} - \alpha_k \le 0$$
$$g_2 = \alpha_k - \alpha_k^{\max} \le 0$$

Constraints about the required aspect ratio of each compartment

$$g_3 = a_k^{\min} - a_k \le 0$$
$$g_4 = a_k - a_k^{\max} \le 0$$

Constraints about the required area of each compartment

$$g_5 = \sum_{k=1}^{M} a_k - A_{allowable} \le 0$$

Constraints about the total area of all compartments

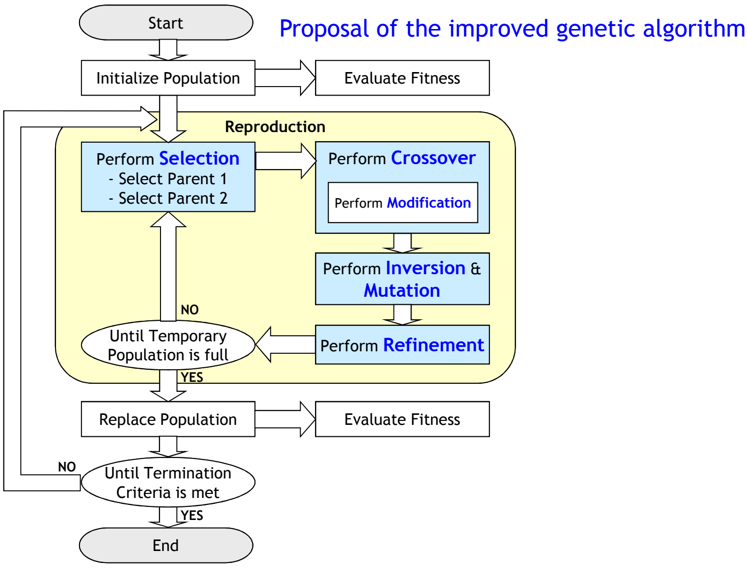
$$g_6 = x_i^r - x_s^{i.s.w} \le 0$$
$$g_7 = x_s^{i.s.w} - x_j^l \le 0$$

Constraints about the position of each compartment

$$for\ i, j, k = 1, \cdots, M \ \&\ s = 1, \cdots, P$$

f_{ij}: Material flow between the facility i and j
d_{ij}: Distance between centroids of the facility i and j

Proposed Algorithm for the Facility Layout Problem Having Inner Structure Walls and Passages



* 유전 알고리즘(Genetic Algorithm): 자연계에 있어서 생물의 유전과 진화의 메카니즘을 공학적으로 모델화하는 것에 의해 생물이 갖는 환경에서의 적응능력을 취급하는 것이고, 1975년에 John Holland 가 저서 "Adaptation on Natural and Artificial Systems"에 처음 소개한 자연 도태의 원리를 기초로 한 최적화 방법

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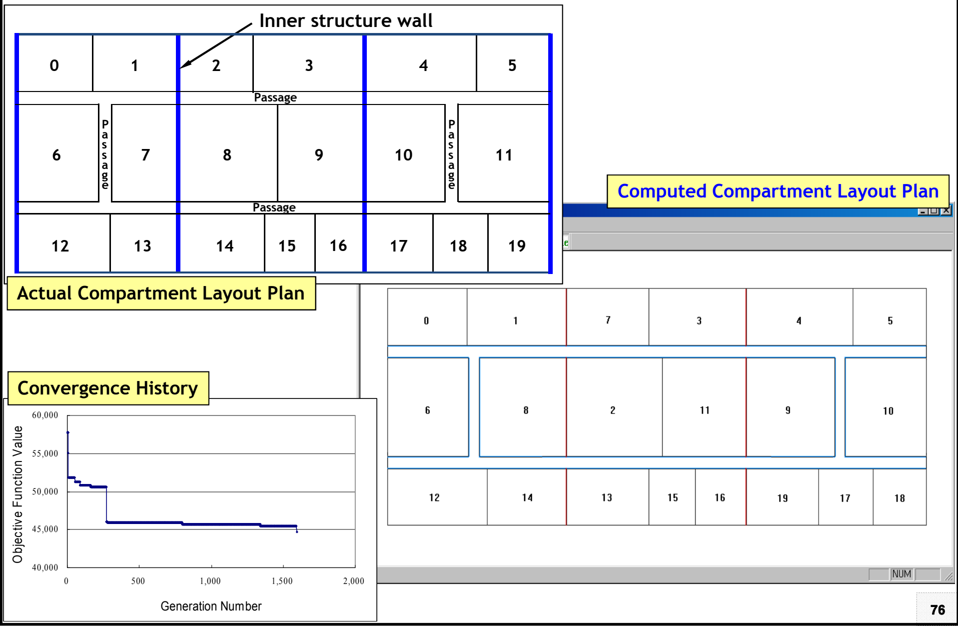
Optimal Facility Layout Problem of a Naval Ship - Optimization Result of the After Body



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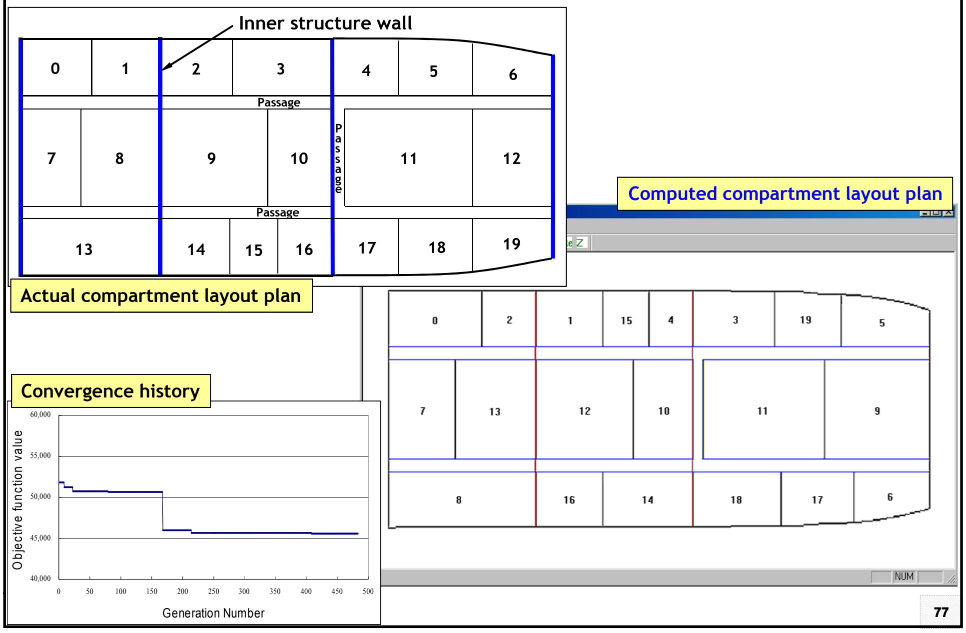
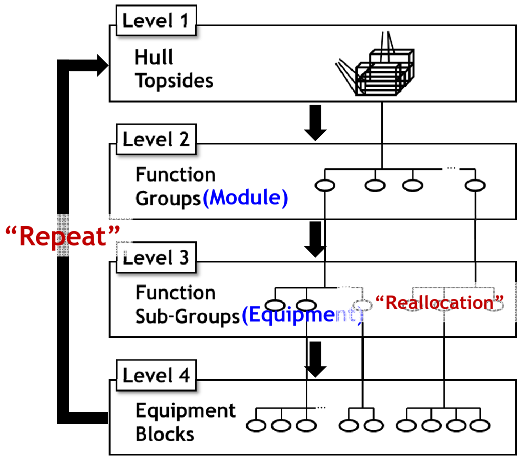
Optimal Facility Layout Problem of a Naval Ship - Optimization Result of the Fore Body



3.2 Applications to Offshore Plant Design

Existing Method for Topsides Layout (1/2)

Hierarchical Approach (Top-Down Approach)



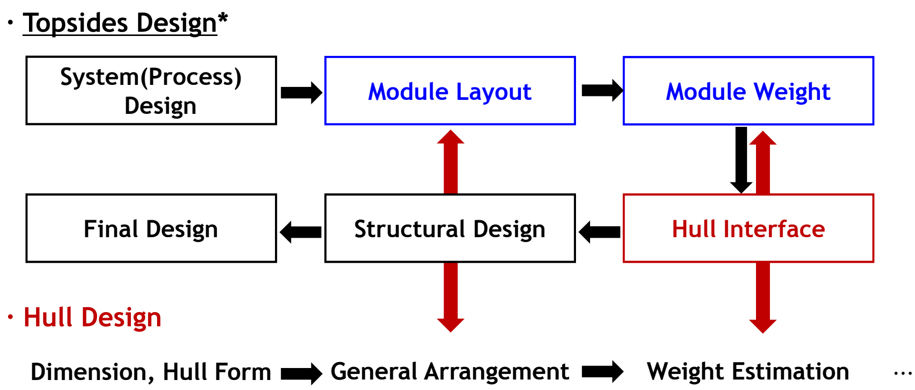
Considerations for layout

- Antagonisms
- Affinities
  - Engineering affinities
  - Manning affinities

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

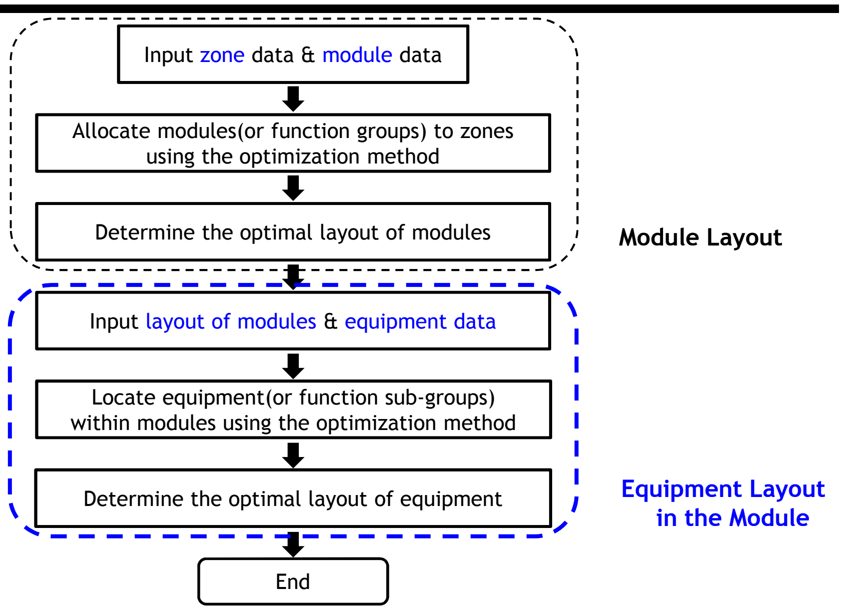
* Reference: PETRONAS, "Layout Considerations for Offshore Topsides Facilities", 1990

Existing Method for Topsides Layout (2/2)



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

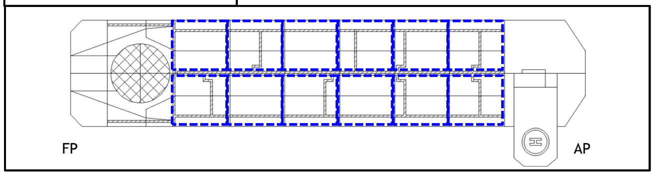
Optimal Layout of Topsides Using Optimization Technique



Optimal Module Layout of Topsides of Offshore Plant

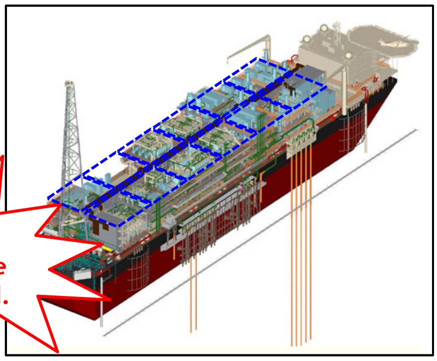
Necessity of Optimal Module Layout

Plan view of the FPSO*



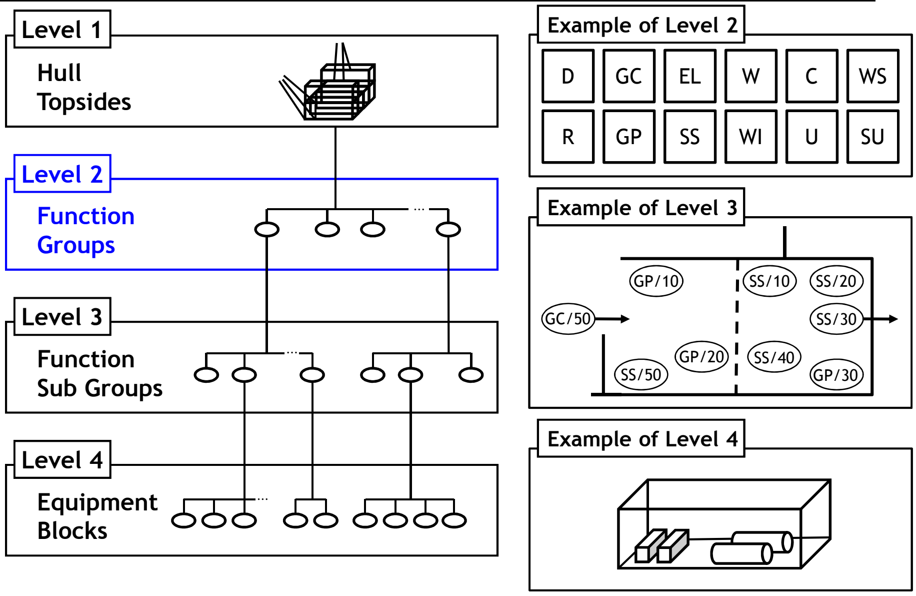
No of modules	No of design alternatives
8	40,320
10	3,628,800
12	479,001,600
14	8.72×10^{10}
16	2.09×10^{13}
18	6.40×10^{15}
…	⋮

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

☑ **Antagonisms**: 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.")

☑ **Affinities**: 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		REACTIVE / ACTIVE	W	D	SS	GP	GC	R	F	LQ	C	WS	MH	U	SU	EL	TS	WI
			3	3	3	3	2	3	3	3	3	2	2	2	3	3	3	2
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 ix

FUNCTION GROUP		LUND	W	D	SS	GP	GC	R	F	LQ	C	WS	MH	U	SU	EL	TS	WI
			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

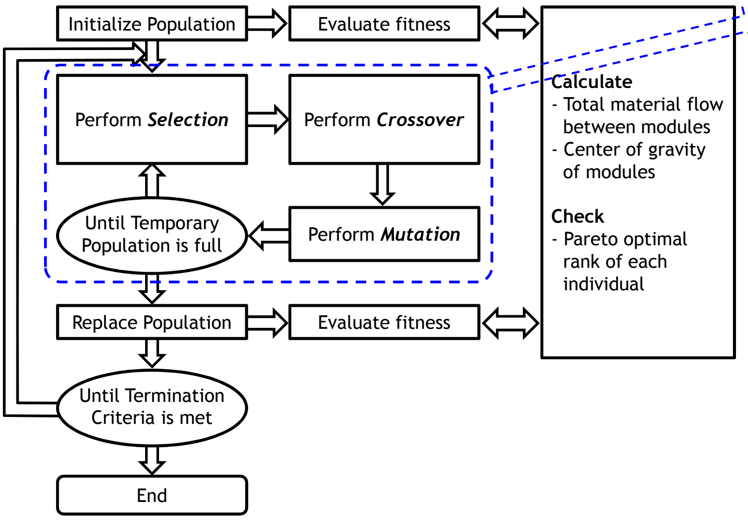
$$Minimize \quad F_1 = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (q_{i,j} \cdot d_{i,j}) \qquad \text{; Total material flow}$$

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

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

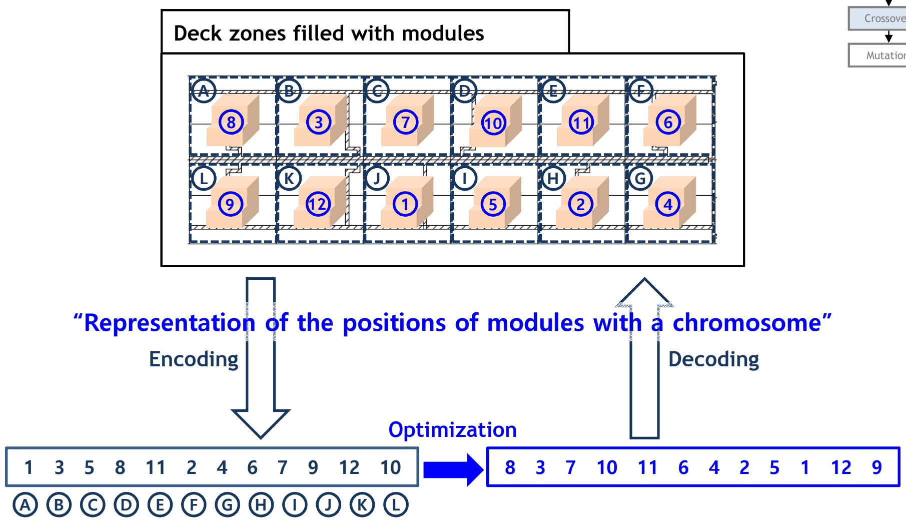
Proposal of an Algorithm for Optimal Module Layout
- Algorithm for Optimal Module Layout

Overview
Layout Representation
Selection
Crossover
Mutation



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

Overview
Layout Representation
Selection
Crossover
Mutation



Proposal of an Algorithm for Optimal Module Layout - Selection (Roulette Wheel Selection)

Overview → Layout Representation → Selction → Crossover → Mutation

Individual	C_1	C_2	C_3	C_4	C_5	C_6	C_7
F	460,136	323,287	406,656	317,550	587,101	350,094	496,949
Ft	2.17×10^{-6}	3.09×10^{-6}	2.46×10^{-6}	3.15×10^{-6}	1.70×10^{-6}	2.86×10^{-6}	2.01×10^{-6}
$P_{selection}$	12.5%	17.7%	14.1%	18.0%	9.8%	16.4%	11.5%

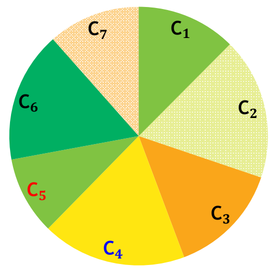
Fitness (Ft) Calculation

$$Ft = -F \text{ or } Ft = \frac{1}{F} \ (if\ F > 0)$$

Probability of Selection

$$P_{selection}(i) = \frac{Ft(i)}{\sum_i Ft(i)}$$

Roulette Wheel



* **Fitness**: Quantitative value for measuring the quality of each individual. The higher fitness, the better individual. The fitness is usually the value of the objective function in the optimization problem being solved.

Proposal of an Algorithm for Optimal Module Layout - Crossover (PMX: Partially Mapped Crossover*)

Overview → Layout Representation → Selection → Crossover → Mutation

1st Parent(P_1)

8	7	1	0	6	3	4	9	5	2

2nd Parent(P_2)

0	2	4 ⋮	3	1	5 ⋮	6	7	8	9

↓

			3	1	5				
8	7	~~1~~				4	9	~~5~~	2
8	7	6				4	9	~~3~~	2

1st Child(C_1)

8	7	6 ⋮	3	1	5 ⋮	4	9	0	2

* Reference: Goldberg, D.E. and Lingle, R., 1985. Alleles, Loci and the Traveling Salesman Problem. Proceedings of the First International Conference on Genetic Algorithms, San Francisco, CA, USA. pp.154-159

Proposal of an Algorithm for Optimal Module Layout - Mutation

Overview → Layout Representation → Selection → Crossover → Mutation

1st Child(C_1) – Before mutation

8	*7*	6	*3*	1	*5*	4	9	0	*2*

1st Child(C_1) – After mutation

8	*3*	6	*7*	1	*2*	4	9	0	*5*

Example of Optimal Module Layout of FPSO - Input Data

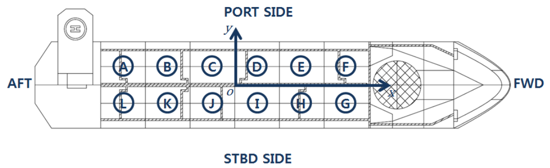
Modules to be optimized

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

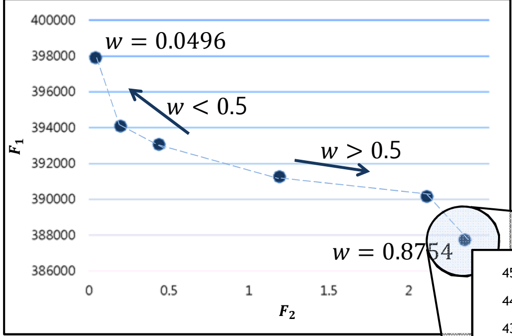
Module ID	1	2	3	4	5	6	7	8	9	10	11	12
1	-	6	6	3	2	0	0	3	3	3	3	0
2		-	3	3	2	0	0	3	3	3	3	0
3			-	3	1	0	0	3	3	3	3	0
4				-	1	0	0	3	3	3	3	0
5					-	0	0	2	2	2	2	0
6						-	3	3	1	1	3	3
7							-	3	1	1	3	2
8								-	3	3	6	2
9									-	6	3	4
10										-	3	4
11											-	3
12												-

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



Example of Optimal Module Layout of FPSO - Pareto Optimal Set[1] by Using Weight Method[2]

Pareto optimal set[2] obtained from the parametric study for the weighting factor



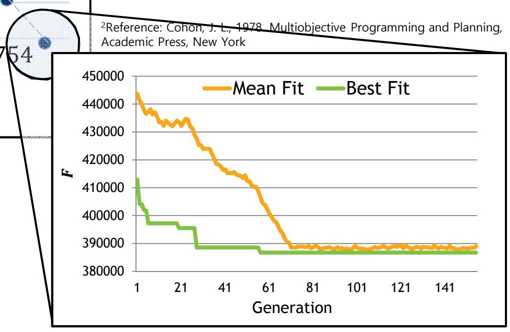
Single objective function using weighting method[1]

$$F = wF_1 + (1 - w)F_2\,, \quad 0 \le w \le 1$$

[1]Pareto optimal set: Solutions that cannot be improved in any of the objectives without degrading at least one of the other objectives. The set of Pareto optimal outcomes is often called the Pareto front or Pareto boundary.

[2]Reference: Cohon, J. L., 1978, Multiobjective Programming and Planning, Academic Press, New York

Number of population	:	100
Number of generations	:	300
Probability of crossover	:	100%
Probability of mutation	:	20%
Elitism	:	applied



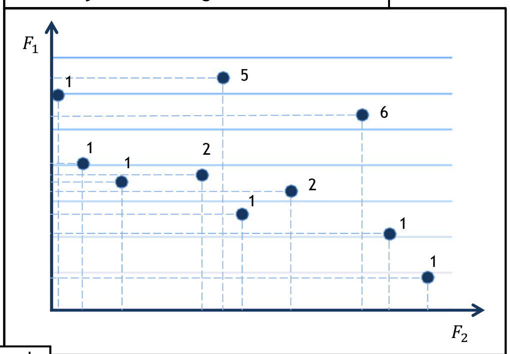
Example of Optimal Module Layout of FPSO - Pareto Optimal Set by Using Rank-based Method* (1/2)

*** Rank-based fitness assignment method: A method that determines the rank for each individual according to domination relation and calculates the fitness by using the rank.**

Determination of the rank for each individual

$$r^{(t)} = 1 + p^{(t)}$$

Multiobjective ranking for the individuals

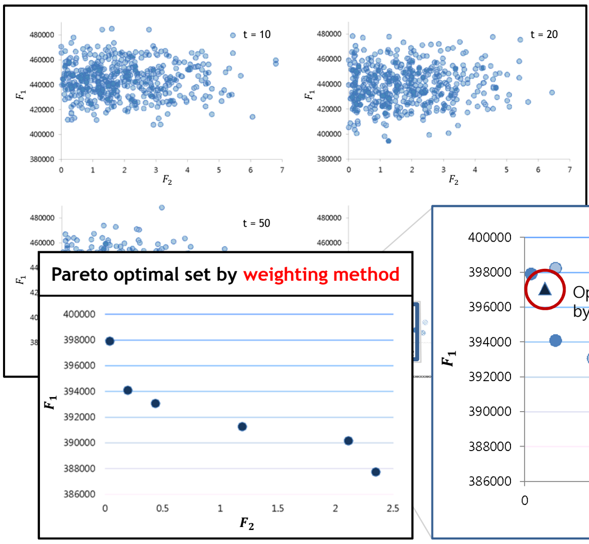


Calculation of the fitness by using the rank

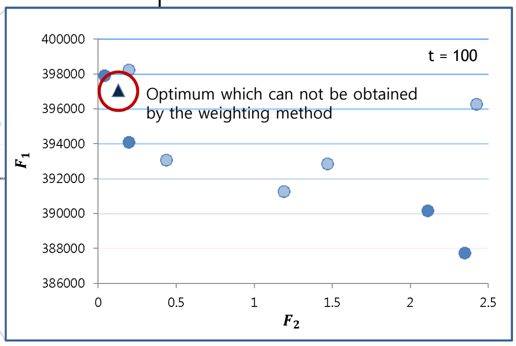
$$Ft = \begin{cases} 1/r & \text{in case of a minimization} \\ r & \text{in case of a maximization} \end{cases}$$

* Reference: Fonesca, C. H. and Fleming P. J., July 1993. Genetic Algorithms for Multiobjective Optimization: Formulation, Discussion and Generalization, Proceedings of the 5th International Conference on Genetic Algorithms

Example of Optimal Module Layout of FPSO - Pareto Optimal Set by Using Rank-based Method* (2/2)



Number of population	:	500
Number of generations	:	100
Probability of crossover	:	100%
Probability of mutation	:	20%
Elitism	:	applied



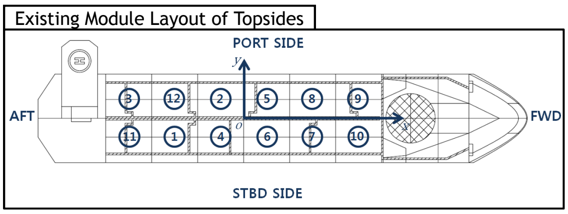
* Reference: Fonesca, C. H. and Fleming P. J., July 1993. Genetic Algorithms for Multiobjective Optimization: Formulation, Discussion and Generalization, Proceedings of the 5th International Conference on Genetic Algorithms

Example of Optimal Module Layout of FPSO - Optimization Result

Modules to be optimized

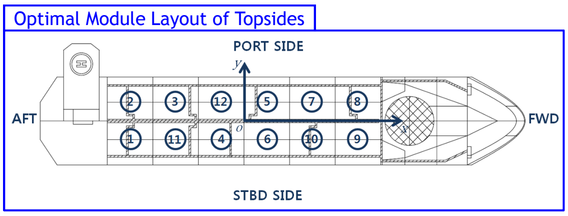
Module ID	Module name
1	Electrical BLD'G
2	Power generation
3	Water injection
4	Utilities area
5	Separation Train1
6	Separation Train2
7	Injection comp.
8	I/M metering
9	SDV platform
10	Recompressor
11	M/F dep. tower
12	Laydown area

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



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

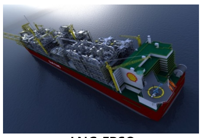
Considerations on Optimal Equipment Layout in the Liquefaction Module for Offshore Plant


<Liquefaction process system>

\+


<Exploration and Production of the Natural Gas>

=


<LNG FPSO>

☑ Safety

- 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

☑ Compactness

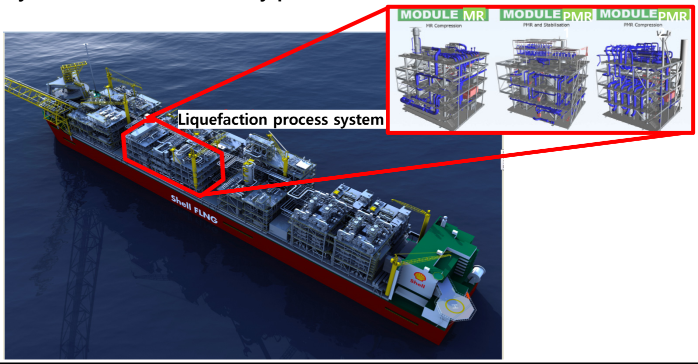
- Available area for the liquefaction cycle of offshore application is smaller than that of onshore plant.
- By determining the optimal operating conditions and doing the optimal synthesis of the liquefaction cycle, the required power for the compressors can be reduced which will result in the reduction 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

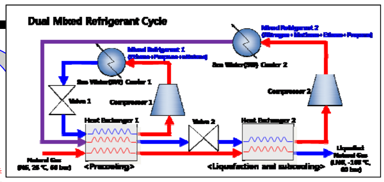
☑ **Limited Installation Area**
- Considering the limited Hull area, equipment shall be placed on the multi-floors module.
- Same functional systems shall be installed in the same module in order to reduce the piping installation space.

☑ **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.

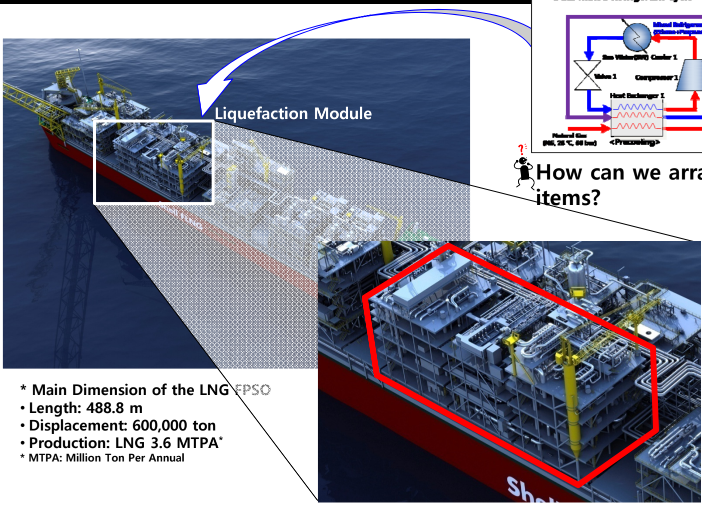


* MR: Mixed Refrigerant, PMR: Pre-Mixed Refrigerant

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 multi-deck equipment layout!

* 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)

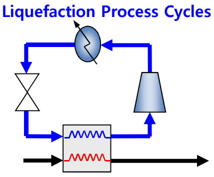
➲ Diagram that shows all data about the operating conditions, process control logic, safety and maintenance for the equipment and instruments, and vendor data about the equipment.

⑦ Plant Layout for Liquefaction Process ⟸ - 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!

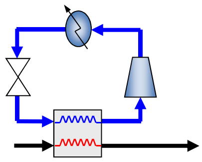
Initial Equipment Layout in Topsides Modules of Offshore Plant

Selection of Potential Liquefaction Process Cycles



Case 1

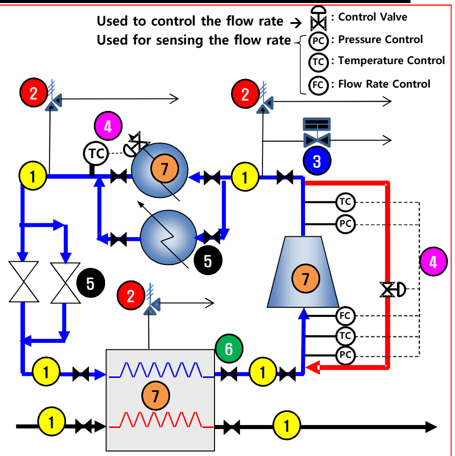
⋮



Case N

Liquefaction Cycle

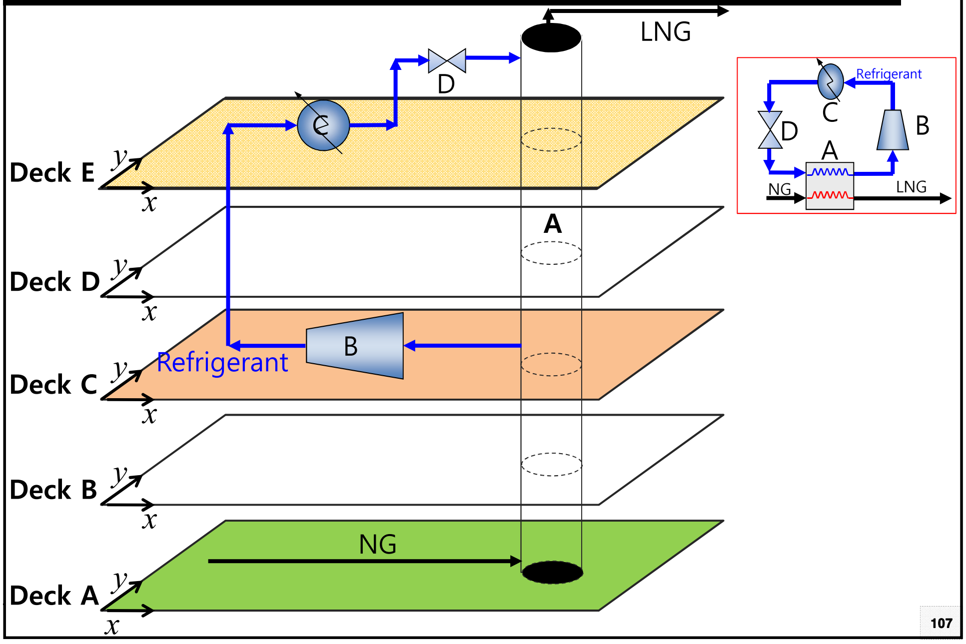
Optimal Operating Conditions (PVT) → Equipment Selection → **Initial Equipment Layout** →



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

Major Assumption and Required Data for Optimal Equipment Layout in Module (1/4)



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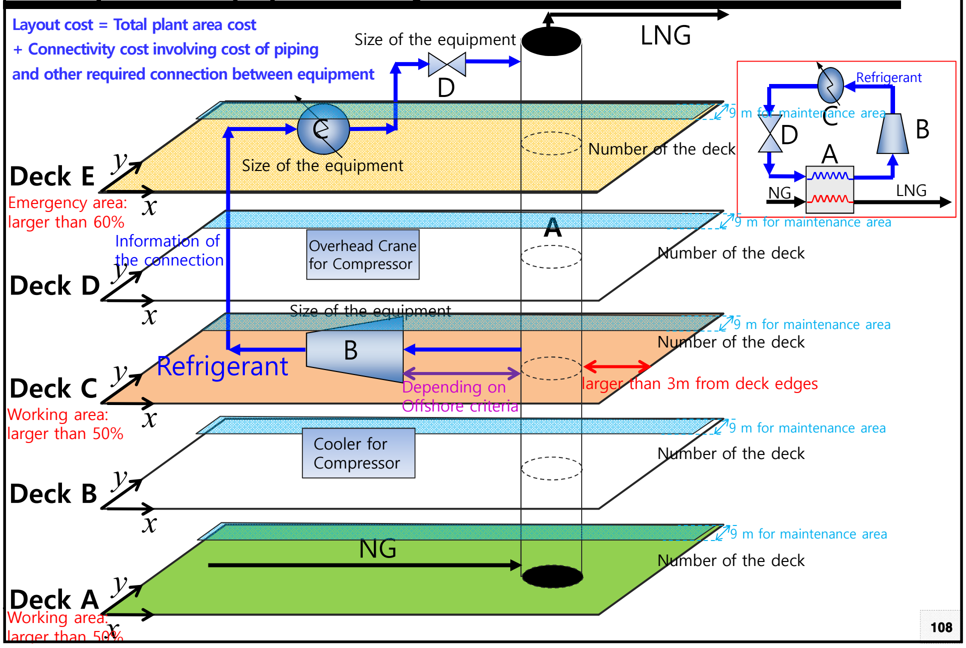
Major Assumption and Required Data for Optimal Equipment Layout in Module (2/4)



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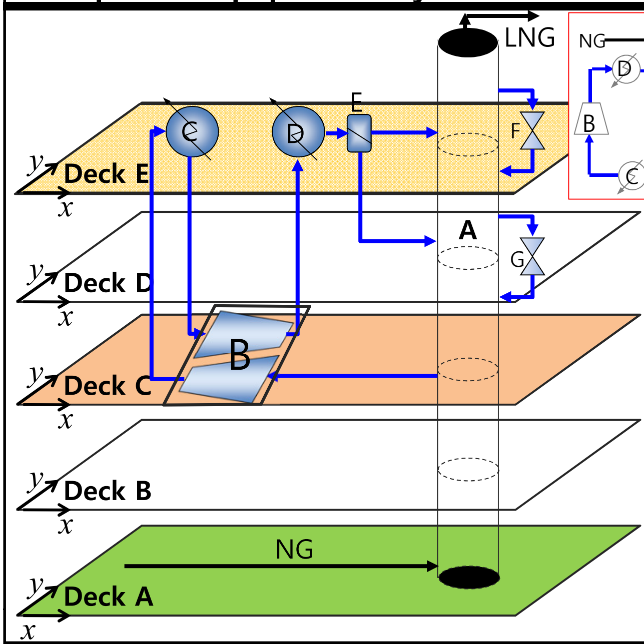
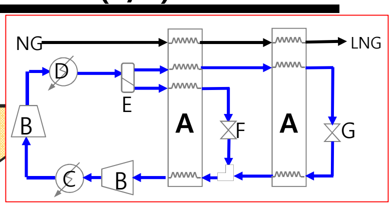
Major Assumption and Required Data for Optimal Equipment Layout in Module (3/4)





In some cases, multiple equipment can be represented as one equipment in actual design or optimization although they are represented with independent equipment in process configuration.

Ex 1) The process configuration has two compression processes (B) and the compression are actually performed two times. However, we assume that they are performed in one integrated equipment.

Ex 2) The process configuration has two liquefaction processes (A) of NG and the liquefaction are actually performed two times. However, we assume that they are performed in one integrated equipment.

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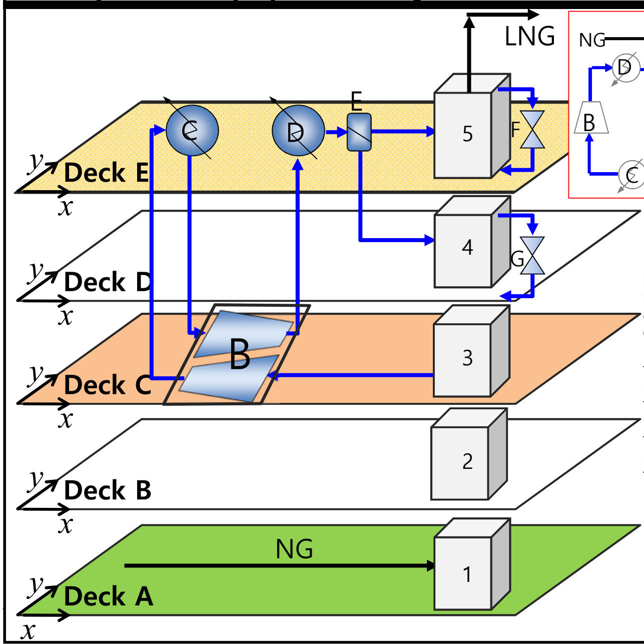
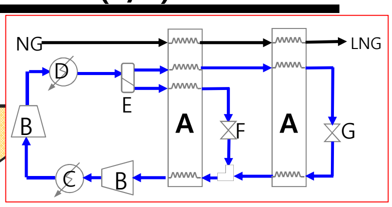
Major Assumption and Required Data for Optimal Equipment Layout in Module (4/4)





In the case of the equipment having five-deck height, we can assume that it is five equipment having one-deck height with the following constraints.

Constraints:

- The equipment "2" should be allocated over the equipment "1".
- The equipment "3" should be allocated over the equipment "2".
- The equipment "4" should be allocated over the equipment "3".
- The equipment "5" should be allocated over the equipment "4".

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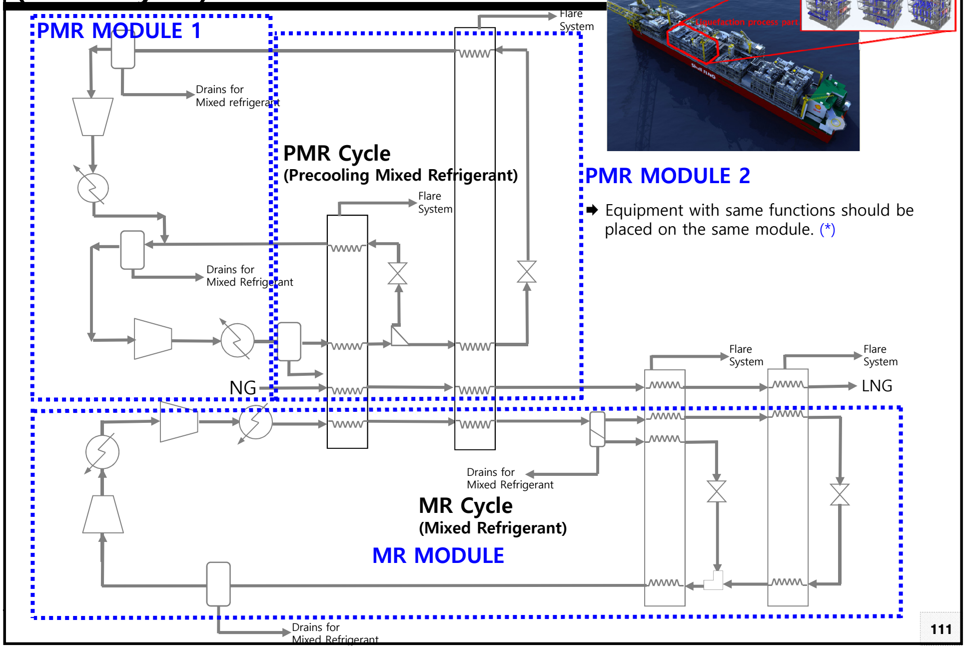
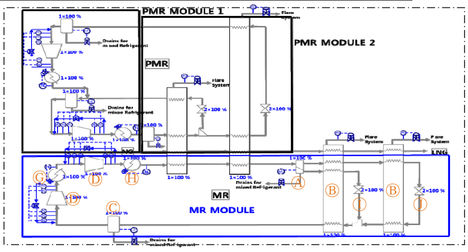
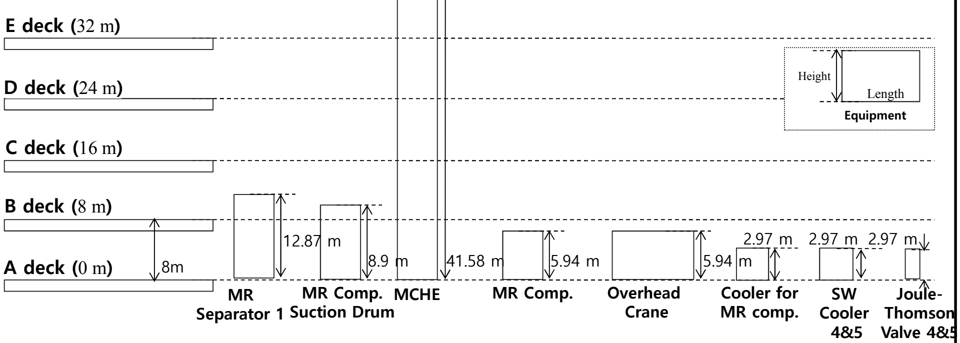
1. Multi-Deck Equipment Layout of Liquefaction Module (DMR Cycle)



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

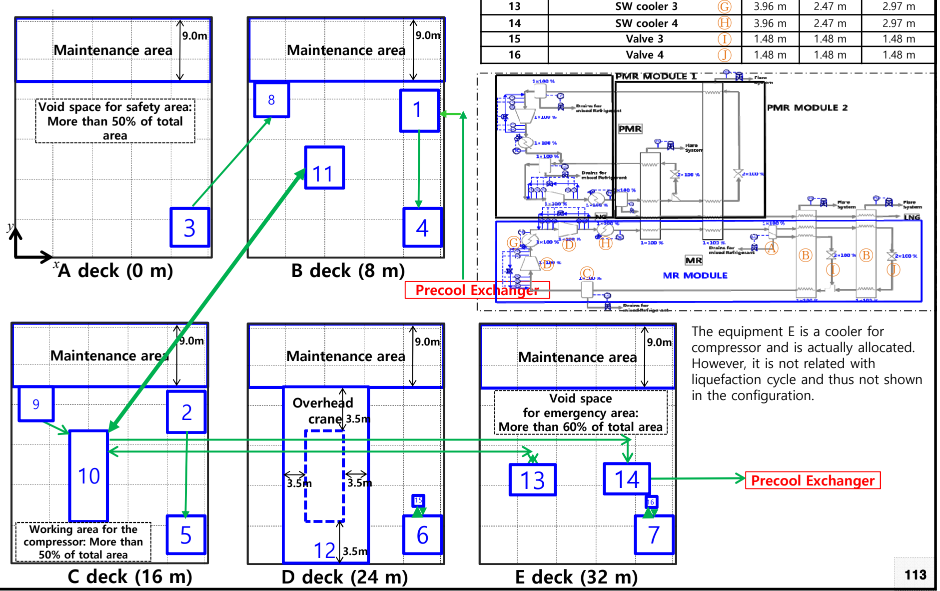
No.	Name	Dimension of the Equipment		
		Length	Breadth	Height
1, 2	MR Separator (A)	4.45 m	4.45 m	12.87 m
3,4,5,6,7	MCHE (B)	5.64 m	5.64 m	41.58 m
8, 9	MR Comp. Suction Drum (C)	5.44 m	5.44 m	8.9 m
10	MR Comp. (D)	17.12 m	5.94 m	5.94 m
11	Cooler for MR comp. (E)	2.97 m	1.98 m	2.97 m
12	Overhead crane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

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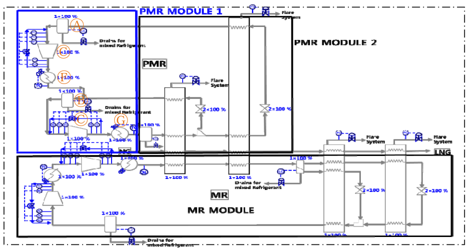
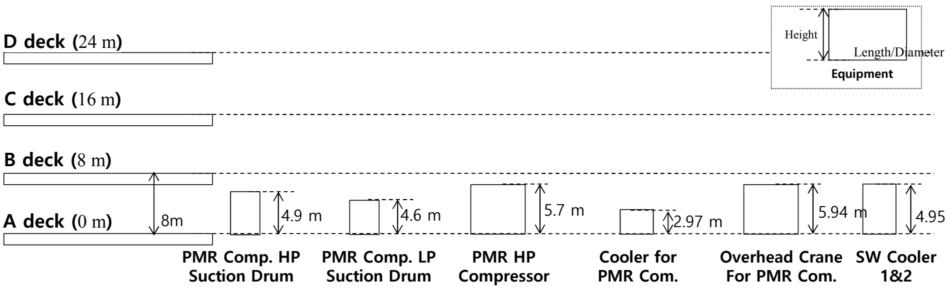
2. Problem Definition for PMR Module 1
- Given (Sizes)

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





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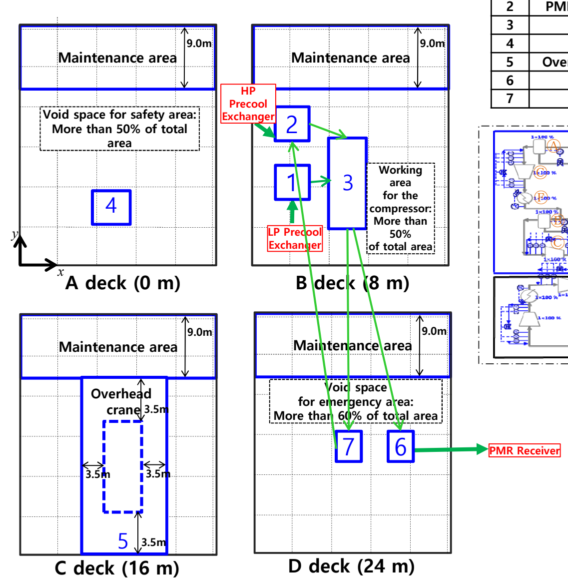
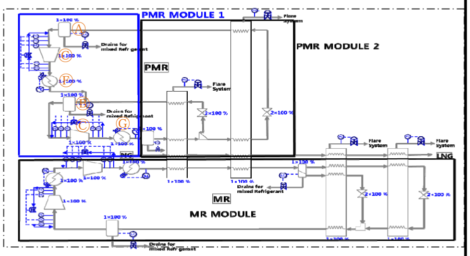
2. Problem Definition for PMR Module 1
- Given (Connection Information)

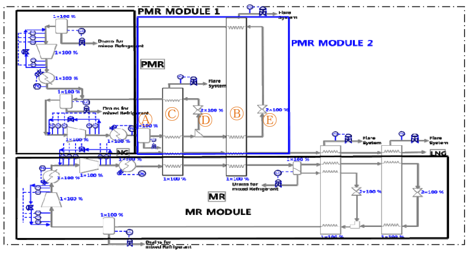
No.	Name	Dimension of the Equipment (m)		
		Length	Breadth /Diameter	Height
1	PMR comp. LP suction drum (A)	3.613	3.613	4.603
2	PMR comp. HP suction drum (B)	3.217	3.217	4.900
3	PMR Compressor (C)	18.809	5.939	5.741
4	Cooler for PMR com. (D)	2.969	1.979	2.969
5	Overhead crane for PMR com. (E)	22.769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

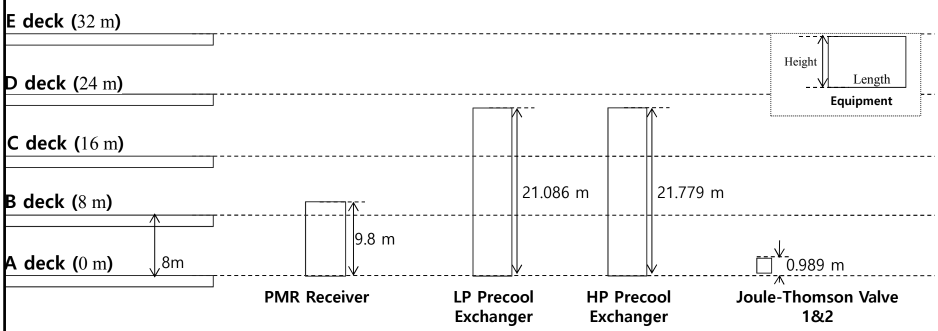




2. Problem Definition for PMR Module 2
- Given (Sizes)

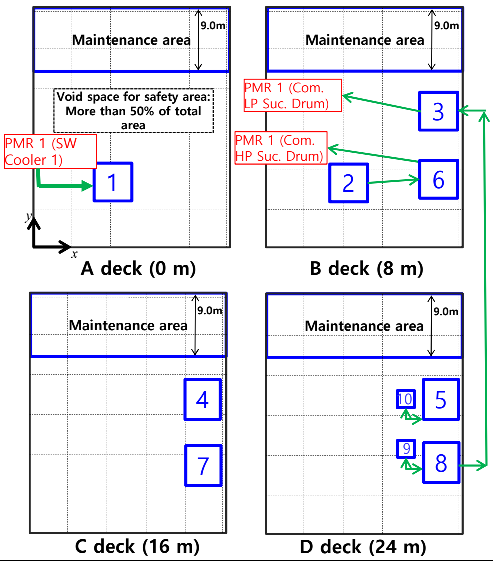
No.	Name	Dimension of the Equipment (m)		
		Length	Breadth /Diameter	Height
1,2	PMR Receiver (A)	4.157	4.157	9.800
3,4,5	LP Precool Exchanger (B)	4.157	4.157	21.086
6,7,8	HP Precool Exchanger (C)	4.355	4.355	21.779
9	Joule-Thomson Valve 1 (D)	0.989	0.989	0.989
10	Joule-Thomson Valve 2 (E)	0.989	0.989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

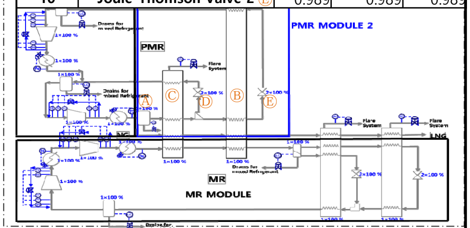




2. Problem Definition for PMR Module 2
- Given (Connection Information)

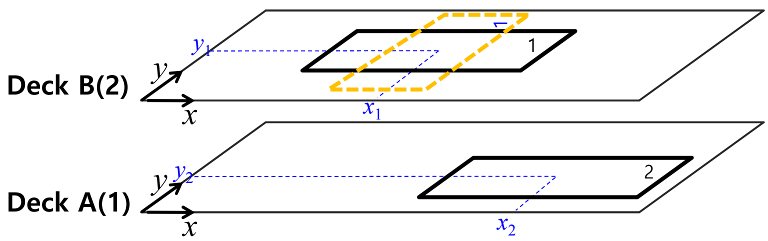
No.	Name	Dimension of the Equipment (m)		
		Length	Breadth /Diameter	Height
1,2	PMR Receiver Ⓐ	4.157	4.157	9.800
3,4,5	LP Precool Exchanger Ⓑ	4.157	4.157	21.086
6,7,8	HP Precool Exchanger Ⓒ	4.355	4.355	21.779
9	Joule-Thomson Valve 1 Ⓓ	0.989	0.989	0.989
10	Joule-Thomson Valve 2 Ⓔ	0.989	0.989	0.989





3. Mathematical Module for Multi-Deck Equipment Layout
3.1 Definition of Design Variables

- **Find:** **Layout for the Main Cooling and Precooling Modules**



1) Coordinates of the equipment item (x, y)

x_i , y_i: coordinates of geometrical center of the equipment item i [**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 [**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 [**Binary values]**

Example: In case of the above figure, $V_{1,1} = 0, V_{1,2} = 1,\ \ V_{2,1} = 1, V_{2,2} = 0$

3.2 Definition of Constraints
1) Equipment Constraints for Multi-Deck (1/3)

Each equipment item should be assigned to only one deck.

$$\sum_{k=1}^{NF} V_{i,k} = 1$$

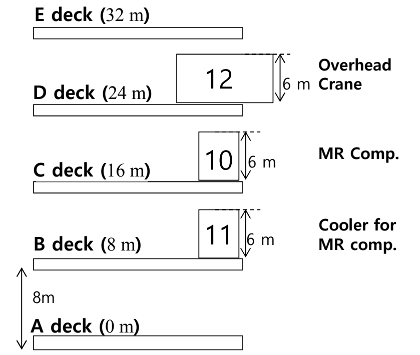
where

$V_{i,k}$: 1, if the equipment item i is assigned to the deck k; 0, otherwise

i: equipment item (=1, 2, ..., 16)

k: deck

NF: number of deck (=5)



In case of the above example

$$\sum_{k=1}^{5} V_{11,k} = V_{11,1} + V_{11,2} + V_{11,3} + V_{11,4} + V_{11,5} = 0+1+0+0+0 = 1$$

$$\sum_{k=1}^{5} V_{10,k} = V_{10,1} + V_{10,2} + V_{10,3} + V_{10,4} + V_{10,5} = 0+0+1+0+0 = 1$$

3.2 Definition of Constraints
1) Equipment Constraints for Multi-Deck (2/3)

For the equipment item whose height is larger than the height between each deck(8 m), the following constraints are considered.

MR Separator

$x_1 = x_2$

$y_1 = y_2$

$$\sum_{k=1}^{4} V_{1,k} V_{2,k+1} = 1$$

MR Comp. Suction Drum

$x_8 = x_9$

$y_8 = y_9$

$$\sum_{k=1}^{4} V_{8,k} V_{9,k+1} = 1$$

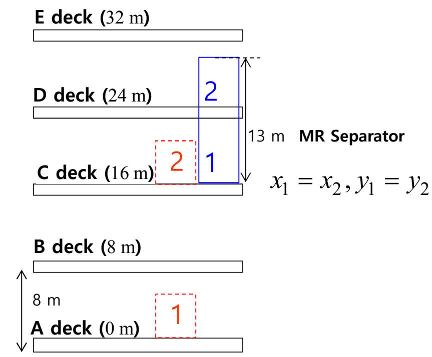
MCHE
(Main Cryogenic Heat Exchanger)

$x_i = x_{i+1}, i = 3,4,5,6$

$y_i = y_{i+1}, i = 3,4,5,6$

$V_{3,k} V_{4,k+1} V_{5,k+2} V_{6,k+3} = 1$

MR Separator: Mixed Refrigerant Separator
MCHE: Main Crygenic Heat Exchanger
MR Comp. Suction Drum: Mixed Refrigerant Compressor Suction Drum



$x_1 = x_2, y_1 = y_2$

In case of the above example

$$\sum_{k=1}^{4} V_{1,k} V_{2,k+1} = V_{1,1}V_{2,2} + V_{1,2}V_{2,3} + V_{1,3}V_{2,4} + V_{1,4}V_{2,5}$$
$$= 0\times0 + 0\times0 + 1\times1 + 0\times0 = 1$$

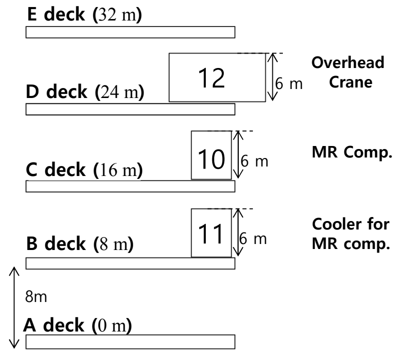
If the equipment 1 is on the 1st deck, and 2 is on 3rd deck,
then the constraint equation is not satisfied

$$\sum_{k=1}^{4} V_{1,k} V_{2,k+1} = V_{1,1}V_{2,2} + V_{1,2}V_{2,3} + V_{1,3}V_{2,4} + V_{1,4}V_{2,5}$$
$$= 1\times0 + 0\times1 + 0\times0 + 0\times0 = 0 \neq 1$$

3.2 Definition of Constraints
1) Equipment Constraints for Multi-Deck (3/3)

For the Mixed Refrigerant Compressor(MR Comp.), the cooler for the compressor is installed in the lower deck of the compressor and the overhead crane for the maintenance of the compressor is installed in the upper deck of the compressor.

$$x_{10} = x_{11}$$
$$x_{10} = x_{12}$$
$$y_{10} = y_{11}$$
$$y_{10} = x_{12}$$
$$\sum_{k=1}^{3} V_{11,k} V_{10,k+1} V_{12,k+2} = 1$$



where

x_i, y_i: coordinates of geometrical center of the equipment item i

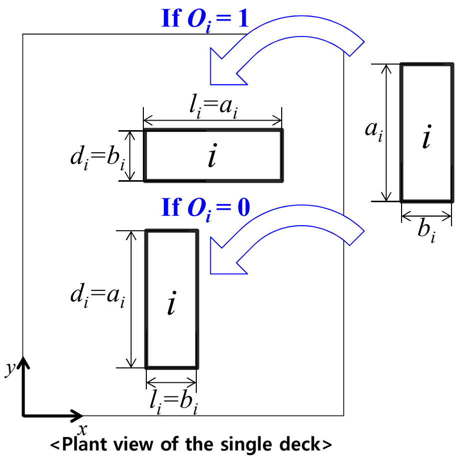
$V_{i,k}$: 1, if the equipment item i is assigned to the deck k; 0, otherwise

k: deck

In case of the above example

$$\sum_{k=1}^{3} V_{11,k} V_{10,k+1} V_{12,k+2} = V_{11,1}V_{10,2}V_{12,3} + V_{11,2}V_{10,3}V_{12,4} + V_{11,3}V_{10,4}V_{12,5}$$
$$= 0\times0\times0 \quad +1\times1\times1 \quad +0\times0\times0 \quad =1$$

3.2 Definition of Constraints
2) Non-Overlapping Constraints (1/2)



<Plant view of the single deck>

The length and the depth of the equipment item i are determined by the equipment orientation as follows:

$$l_i = a_i O_i + b_i (1 - O_i)$$
$$d_i = b_i O_i + a_i (1 - O_i)$$

where,

i: equipment item (=1, 2, ..., 16)

a_i, b_i: dimensions of the equipment item i

O_i: 1, if the length of the equipment item i is equal to a_i (i.e. parallel to x-axis); 0, otherwise

l_i: length of the equipment item i

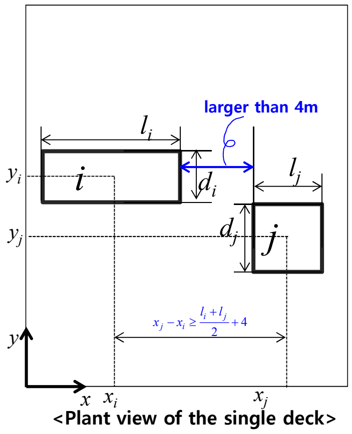
d_i: depth of the equipment item i

Design variables: O_i

If $O_i = 1$

$$l_i = a_i O_i + b_i (1 - O_i) = a_i \times 1 + b_i \times (1-1) = a_i$$
$$d_i = b_i \times 1 + a_i \times (1-1) = b_i$$

3.2 Definition of Constraints
2) Non-Overlapping Constraints (2/3)



<Plant view of the single deck>

In order to avoid situations where two equipment items i and j occupy the same physical location, appropriate constraints should be included in the model that prohibit overlapping of their equipment footprint projections, either in x or y direction.

Suppose that minimum distance between equipment = 4 m

$$|x_i - x_j| + M(1 - Z_{i,j} + E_{ij}) \geq \frac{l_i + l_j}{2} + 4 \qquad (E_{ij} = 0, Z_{i,j} = 1 \text{ ➡active})$$

$$|y_i - y_j| + M(2 - Z_{i,j} - E_{ij}) \geq \frac{d_i + d_j}{2} + 4 \qquad (E_{ij} = 1, Z_{i,j} = 1 \text{ ➡active})$$

where i: equipment item(=1, 2, ..., 15)
j: equipment item (=i+1, ..., 16)
$Z_{i,j}$: 1, if the equipment items i and j are allocated to the same deck; 0, otherwise

$$Z_{i,j} = \sum_{k=1} V_{i,k} \cdot V_{j,k}$$

$E1_{i,j}$, $E2_{i,j}$: binary parameters used for the non-overlapping constraint
M: big constant to satisfy the any inequality constraint when the total value in the bracket is positive

3.2 Definition of Constraints
2) Non-Overlapping Constraints (3/3)

$$|x_i - x_j| + M(1 - Z_{i,j} + E_{ij}) \geq \frac{l_i + l_j}{2} + 4 \qquad (E_{ij} = 0, Z_{i,j} = 1 \text{ ➡ active})$$

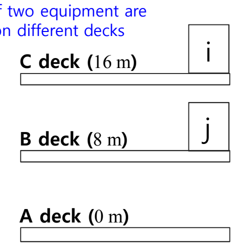
$$|y_i - y_j| + M(2 - Z_{i,j} - E_{ij}) \geq \frac{d_i + d_j}{2} + 4 \qquad (E_{ij} = 1, Z_{i,j} = 1 \text{ ➡ active})$$

where $Z_{i,j}$: 1, if the equipment items i and j are allocated to the same deck; 0, otherwise

$$Z_{i,j} = \sum_{k=1} V_{i,k} \cdot V_{j,k}$$

$E1_{i,j}$, $E2_{i,j}$: binary parameters used for the non-overlapping constraint

If two equipment are on different decks



$$Z_{i,j} = \sum_{k=1} V_{i,k} \cdot V_{j,k} = V_{i,1} \cdot V_{j,1} + V_{i,2} \cdot V_{j,2} + V_{i,1} \cdot V_{j,3} = 0 \times 0 + 0 \times 1 + 1 \times 0 = 0$$

Two constraints above are calculated as below because Z is 0.

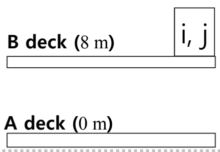
$$|x_i - x_j| + M(1 + E_{ij}) \geq \frac{l_i + l_j}{2} + 4$$

$$|y_i - y_j| + M(2 - E_{ij}) \geq \frac{d_i + d_j}{2} + 4$$

Two equations above are always satisfied regardless of values of E and positions of the equipment.

That is, we don't need to consider equipment overlapping.

If two equipment are on same decks



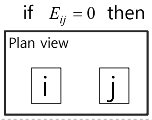
$$Z_{i,j} = \sum_{k=1} V_{i,k} \cdot V_{j,k} = V_{i,1} \cdot V_{j,1} + V_{i,2} \cdot V_{j,2} + V_{i,1} \cdot V_{j,3} = 0 \times 0 + 1 \times 1 + 0 \times 0 = 1$$

Two constraints above are calculated as below because Z is 1.

$$|x_i - x_j| + M(E_{ij}) \geq \frac{l_i + l_j}{2} + 4$$

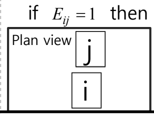
$$|y_i - y_j| + M(1 - E_{ij}) \geq \frac{d_i + d_j}{2} + 4$$

if $E_{ij} = 0$ then $|x_i - x_j| \geq \frac{l_i + l_j}{2} + 4$, $|y_i - y_j| + M(1) \geq \frac{d_i + d_j}{2} + 4$



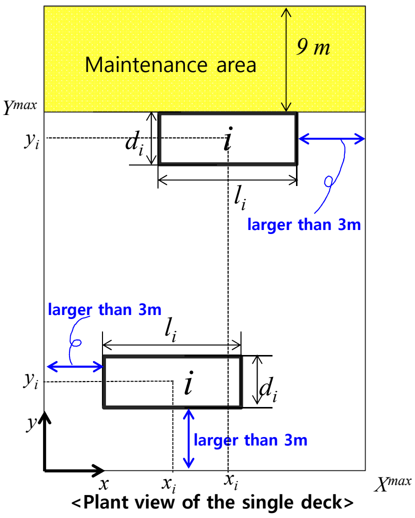
Always satisfied regardless of the y position of the equipment.
Thus, equipment overlapping in the x direction should be considered.

if $E_{ij} = 1$ then $|x_i - x_j| + M(1) \geq \frac{l_i + l_j}{2} + 4$, $|y_i - y_j| \geq \frac{l_i + l_j}{2} + 4$



Always satisfied regardless of the x position of the equipment.
Thus, equipment overlapping in the y direction should be considered.

3.2 Definition of Constraints
3) Deck Area Constraints (1/3)



<Plant view of the single deck>

The clearance between the deck edges and equipment should be larger than 3m.

$$x_i \geq \frac{l_i}{2} + 3$$

$$y_i \geq \frac{d_i}{2} + 3$$

$$x_i + \frac{l_i}{2} + 3 \leq X^{\max}$$

$$y_i + \frac{d_i}{2} \leq Y^{\max}$$

where

- i: equipment item(1, 2, ..., 16)
- l_i: length of the equipment item i
- d_i: depth of the equipment item i
- X^{max}, Y^{max}: dimensions of the deck area

3.2 Definition of Constraints
3) Deck Area Constraints (2/3)

- **Working Space Area Constraints**

For the A deck and the deck where the compressor is installed, the working space at those decks is needed more than a 50% of the deck area.

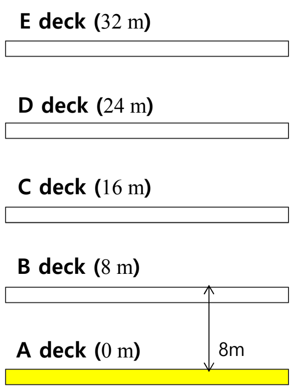
A deck

$$FA - \left(\sum_{i=1}^{16} V_{i,1} a_i b_i + X^{\max} \times 9 \right) \geq \frac{1}{2} FA$$

$$FA = X^{\max} (Y^{\max} + 9)$$

where

- i: equipment item,
- i = 10: compressor,
- k : deck(=1, 2, ..., 5)
- $V_{i,k}$: 1, if the equipment item i is assigned to the deck k; 0, otherwise
- a_i, b_i: dimensions of the equipment item i
- FA: deck area
- X^{max}: length of the deck



3.2 Definition of Constraints
3) Deck Area Constraints (3/3)

- Emergency Area Constraints

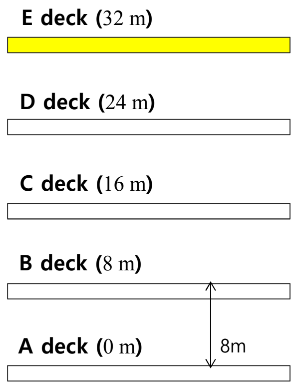
For the safety of the uppermost deck, the emergency area for installing the safety facilities at the uppermost deck is needed more than 60% of the deck area.

Uppermost deck(E deck)

$$FA - \left(\sum_{i=1}^{16} V_{i,5} a_i b_i + X^{\max} \times 9 \right) \geq 0.6 FA$$

$$FA = X^{\max} (Y^{\max} + 9)$$

where
- i: equipment item,
- i = 10: compressor,
- k: deck(=1, 2, …, 5)
- $V_{i,k}$: 1, if the equipment item i is assigned to the deck k; 0, otherwise
- a_i, b_i: dimensions of the equipment item I
- FA: deck area
- X^{max}: length of the deck



3. Mathematical Module for Multi-Deck Equipment Layout
3.3 Definition of Objective Functions (1/2)

The objective function (W) is the minimization of the plant layout cost (connectivity cost + construction cost) and distance between the heat exchanger and centerline.

$$W = \sum_i \sum_{j \neq i} \left[W_{1,ij} \cdot TD_{ij} \right] + W_2 \cdot FA + W_3 \cdot y_i$$

where
- i, j: equipment item
- TD_{ij}: total rectilinear distance between the equipment items i and j, connected each other by pipe
- FA: deck area
- y_i: distance between the heat exchanger and the centerline

$$FA = X^{\max} (Y^{\max} + 9)$$

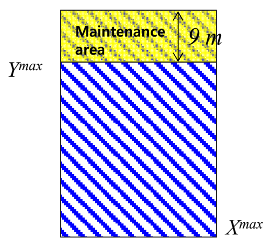
where
- X^{max}, Y^{max}: dimensions of the deck area

$$TD_{ij} = \left| x_i - x_j \right| + \left| y_i - y_j \right| + U_{ij}$$

where

$$U_{ij} = \left| H \sum_{k=1}^{NF} k \left(V_{ik} - V_{jk} \right) + z_i - z_j \right|$$

where
- k: deck number
- NF: number of decks (=5)
- H: height between decks (=8m)
- $V_{i,k}$: 1, if the equipment item i is assigned to the deck k; 0, otherwise
- $U_{i,j}$: relative distance in z coordinates between the equipment items i and j, if i is higher than j



3. Mathematical Module for Multi-Deck Equipment Layout
3.3 Definition of Objective Functions (2/2)

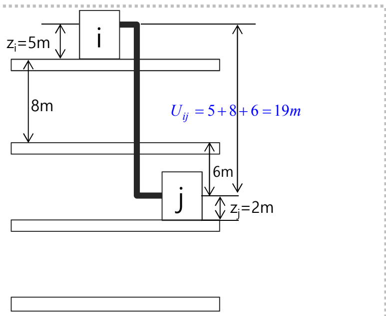
(1) Check where the equipment *i* and *j* are installed, (2) calculate the deck height, (3) and then calculate pipe length between them by considering the installation height of each equipment from bottom.

$$TD_{ij} = |x_i - x_j| + |y_i - y_j| + U_{ij}$$

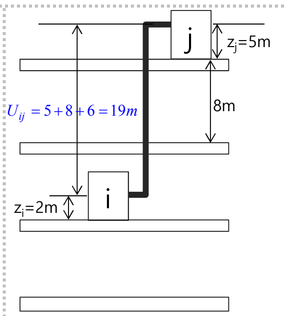
where,

$$U_{ij} = \left| H \sum_{k=1}^{NF} k \left(V_{ik} - V_{jk} \right) + z_i - z_j \right|$$

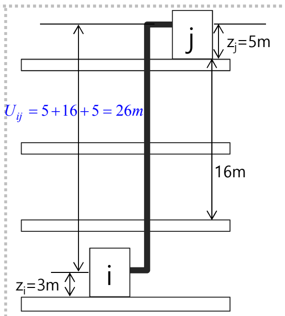
where,
- k : deck number
- NF: number of decks (=5)
- H: height between decks (=8m)
- $V_{i,k}$: 1, if the equipment item i is assigned to the deck k; 0, otherwise
- $U_{i,j}$: relative distance in z coordinates between the equipment items i and j, if i is higher than j



$$\begin{aligned} U_{ij} &= \left| H \sum_{k=1}^{NF} k \left(V_{i,k} - V_{j,k} \right) + z_i - z_j \right| \\ &= \left| H \times \{1(V_{i,1} - V_{j,1}) + 2(V_{i,2} - V_{j,2}) + 3(V_{i,3} - V_{j,3}) + 4(V_{i,4} - V_{j,4})\} + z_i - z_j \right| \\ &= |8 \times \{1(0-0) + 2(0-1) + 3(0-0) + 4(1-0)\} + 5 - 2| \\ &= |8 \times \{-2+4\} + 5 - 2| \\ &= |16 + 5 - 2| = 19 \end{aligned}$$



$$\begin{aligned} U_{ij} &= \left| H \sum_{k=1}^{NF} k \left(V_{i,k} - V_{j,k} \right) + z_i - z_j \right| \\ &= \ldots \\ &= |8 \times \{1(0-0) + 2(1-0) + 3(0-0) + 4(0-1)\} + 2 - 5| \\ &= |8 \times \{2-4\} + 2 - 5| \\ &= |-16 + 2 - 5| = 19 \end{aligned}$$



$$\begin{aligned} U_{ij} &= \left| H \sum_{k=1}^{NF} k \left(V_{i,k} - V_{j,k} \right) + z_i - z_j \right| \\ &= \ldots \\ &= |8 \times \{1(1-0) + 2(0-0) + 3(0-0) + 4(0-1)\} + 3 - 5| \\ &= |8 \times \{1-4\} + 3 - 5| \\ &= |-24 + 3 - 5| = 26 \end{aligned}$$

3. Mathematical Module for Multi-Deck Equipment Layout
3.4 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.**

➡ **Indeterminate problem (Optimization problem)**

Optimal Solution using Genetic Algorithm (GA)

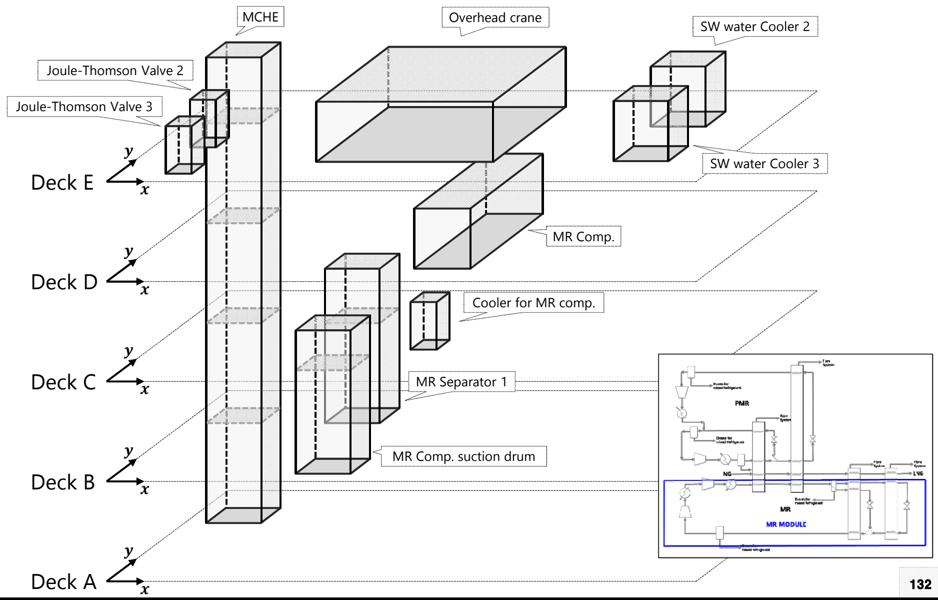
4. Result of Optimal Equipment Layout of Each Module - MR Module (1/3)

• 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

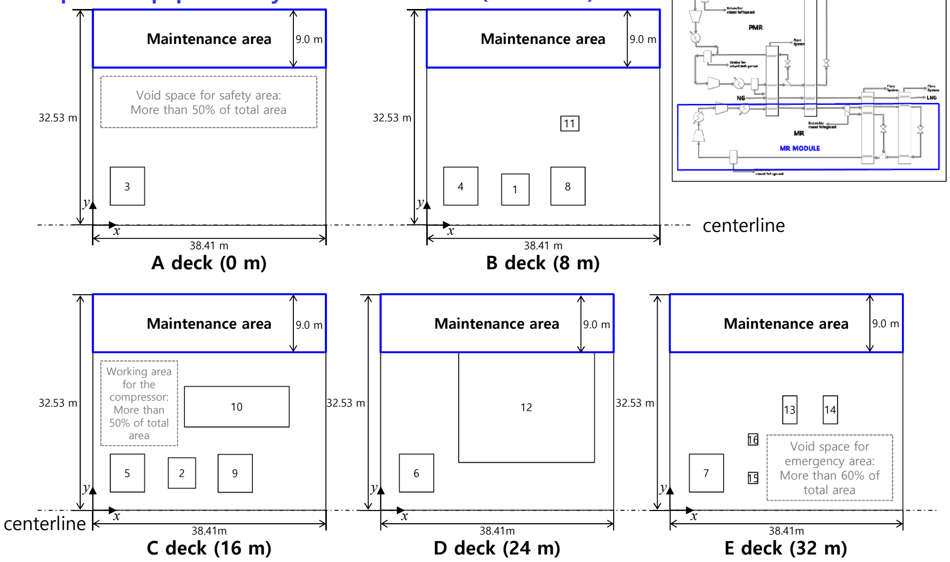
4. Result of Optimal Equipment Layout of Each Module - MR Module (2/3)

• 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)



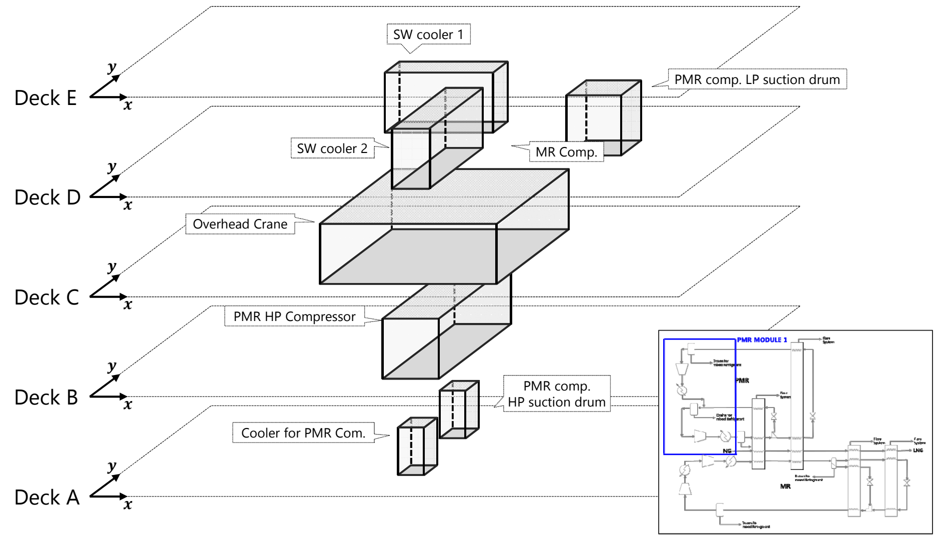
4. Result of Optimal Equipment Layout of Each Module - PMR Module 1 (1/3)

- 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

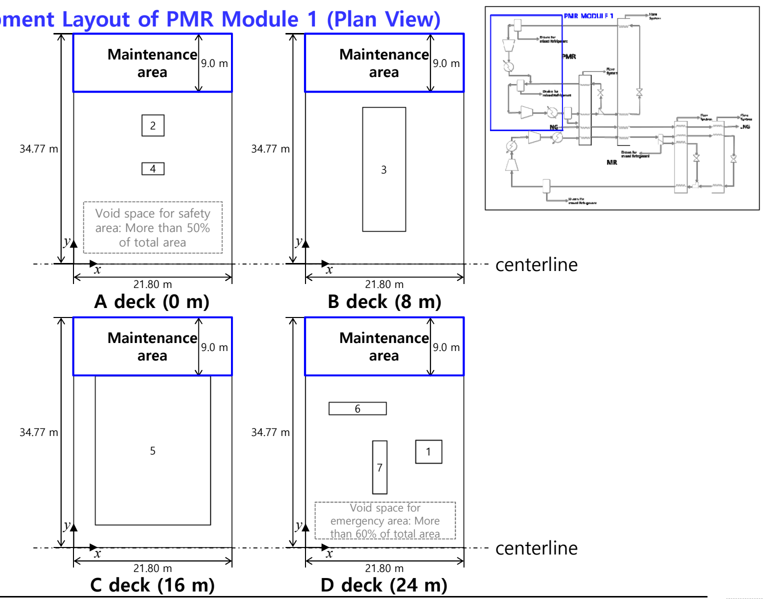
4. Result of Optimal Equipment Layout of Each Module - PMR Module 1 (2/3)

- 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)



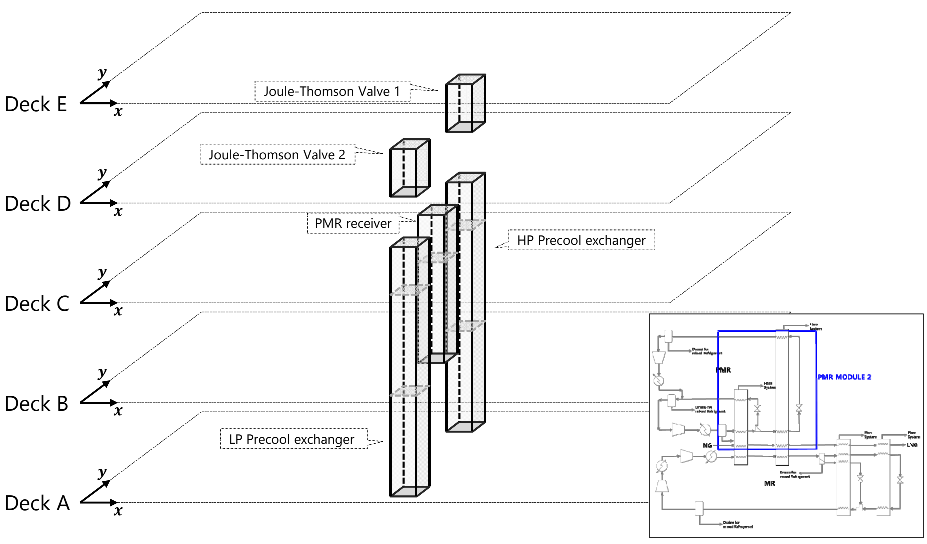
4. Result of Optimal Equipment Layout of Each Module - PMR Module 2 (1/3)

• 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

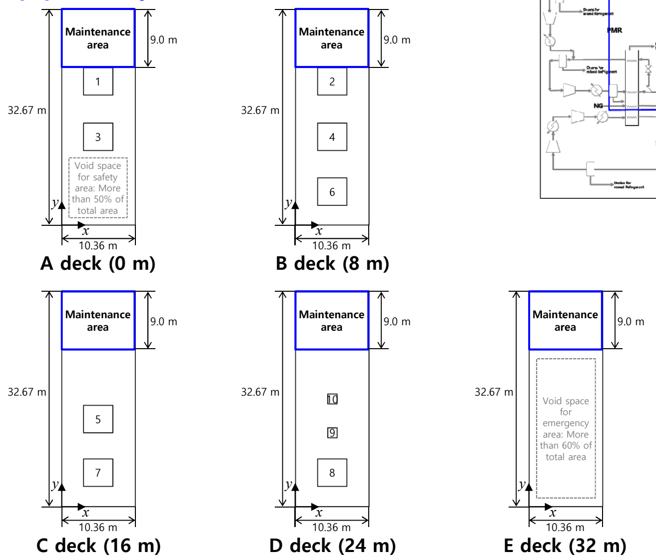
4. Result of Optimal Equipment Layout of Each Module - PMR Module 2 (2/3)

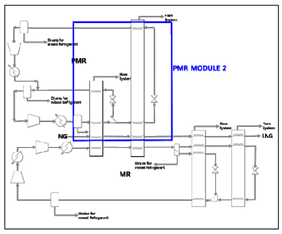
• Optimal Equipment Layout of PMR Module 2 (ISO View)



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

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



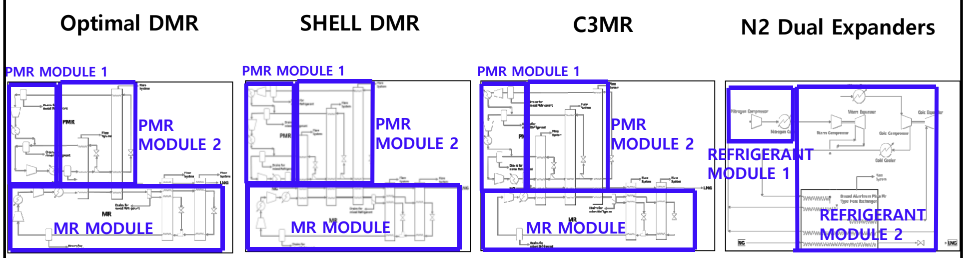


5. Installation Area by Optimal Equipment Layout of Liquefaction Module

- 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



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