Optimum Design

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Ch. 8 Case Study of Optimal Dimension Design

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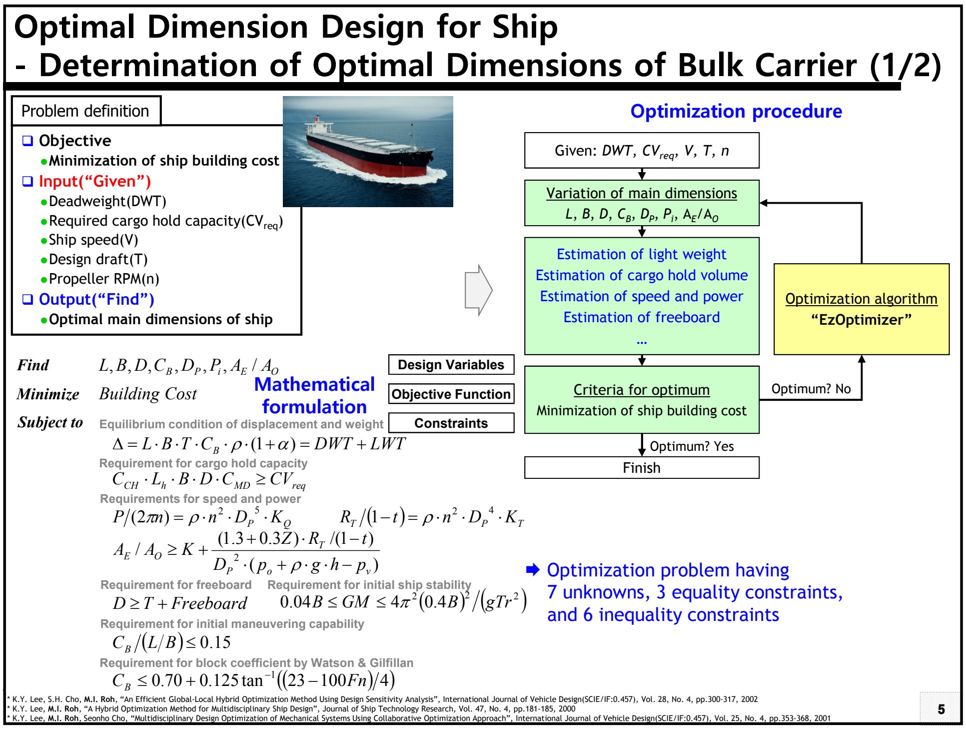
8.1 Overview



Optimal Dimension Design for Ship
- Determination of Optimal Dimensions of Bulk Carrier (1/2)

Problem definition

- ❑ Objective
  - Minimization of ship building cost
- ❑ Input("Given")
  - Deadweight(DWT)
  - Required cargo hold capacity(CV_{req})
  - Ship speed(V)
  - Design draft(T)
  - Propeller RPM(n)
- ❑ Output("Find")
  - Optimal main dimensions of ship

Optimization procedure

Given: DWT, CV_{req}, V, T, n

Variation of main dimensions
L, B, D, C_B, D_P, P_i, A_E/A_O

Estimation of light weight
Estimation of cargo hold volume
Estimation of speed and power
Estimation of freeboard
…

Optimization algorithm
"EzOptimizer"

Criteria for optimum
Minimization of ship building cost

Optimum? No

Optimum? Yes

Finish

Mathematical formulation

Find $L, B, D, C_B, D_P, P_i, A_E / A_O$ — Design Variables

Minimize Building Cost — Objective Function

Subject to — Constraints

Equilibrium condition of displacement and weight

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

Requirement for cargo hold capacity

$$C_{CH}\cdot L_h\cdot B\cdot D\cdot C_{MD} \ge CV_{req}$$

Requirements for speed and power

$$P/(2\pi n) = \rho\cdot n^2\cdot D_P{}^5\cdot K_Q \qquad R_T/(1-t) = \rho\cdot n^2\cdot D_P{}^4\cdot K_T$$

$$A_E/A_O \ge K + \frac{(1.3+0.3Z)\cdot R_T/(1-t)}{D_P{}^2\cdot(p_o+\rho\cdot g\cdot h - p_v)}$$

Requirement for freeboard

$$D \ge T + Freeboard$$

Requirement for initial ship stability

$$0.04B \le GM \le 4\pi^2(0.4B)^2/(gTr^2)$$

Requirement for initial maneuvering capability

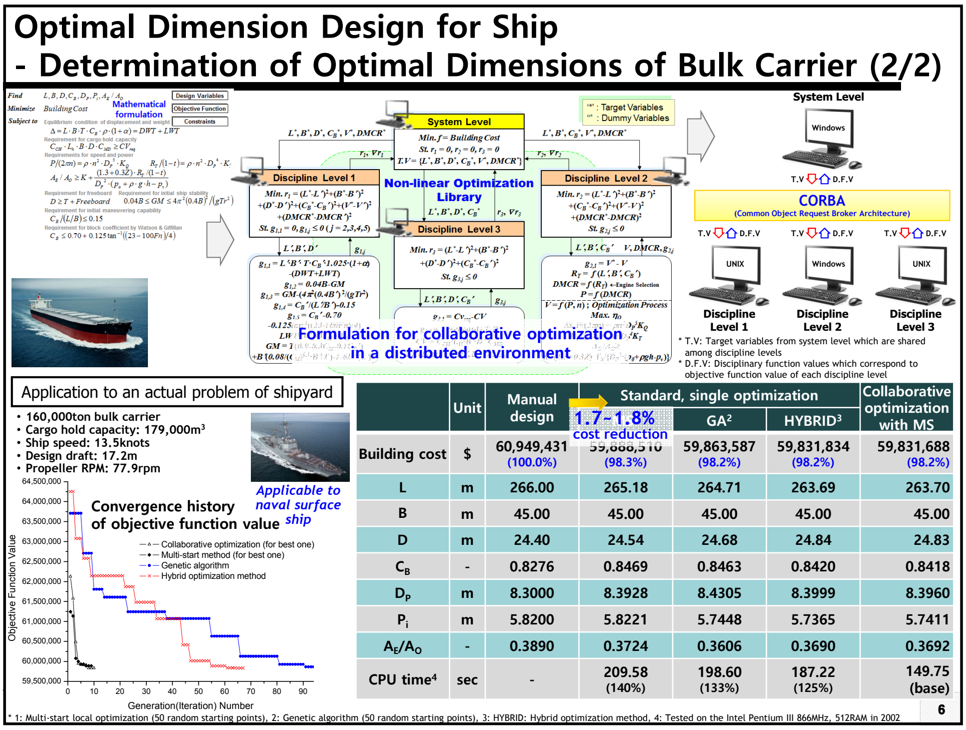
$$C_B/(L/B) \le 0.15$$

Requirement for block coefficient by Watson & Gilfillan

$$C_B \le 0.70 + 0.125\tan^{-1}((23-100Fn)/4)$$

➡ Optimization problem having 7 unknowns, 3 equality constraints, and 6 inequality constraints

* K.Y. Lee, S.H. Cho, **M.I. Roh**, "An Efficient Global-Local Hybrid Optimization Method Using Design Sensitivity Analysis", International Journal of Vehicle Design(SCIE/IF:0.457), Vol. 28, No. 4, pp.300-317, 2002
* K.Y. Lee, **M.I. Roh**, "A Hybrid Optimization Method for Multidisciplinary Ship Design", Journal of Ship Technology Research, Vol. 47, No. 4, pp.181-185, 2000
* K.Y. Lee, **M.I. Roh**, Seonho Cho, "Multidisciplinary Design Optimization of Mechanical Systems Using Collaborative Optimization Approach", International Journal of Vehicle Design(SCIE/IF:0.457), Vol. 25, No. 4, pp.353-368, 2001



Optimal Dimension Design for Ship
- Determination of Optimal Dimensions of Bulk Carrier (2/2)

Formulation for collaborative optimization in a distributed environment

CORBA
(Common Object Request Broker Architecture)

* T.V: Target variables from system level which are shared among discipline levels
* D.F.V: Disciplinary function values which correspond to objective function value of each discipline level

Application to an actual problem of shipyard

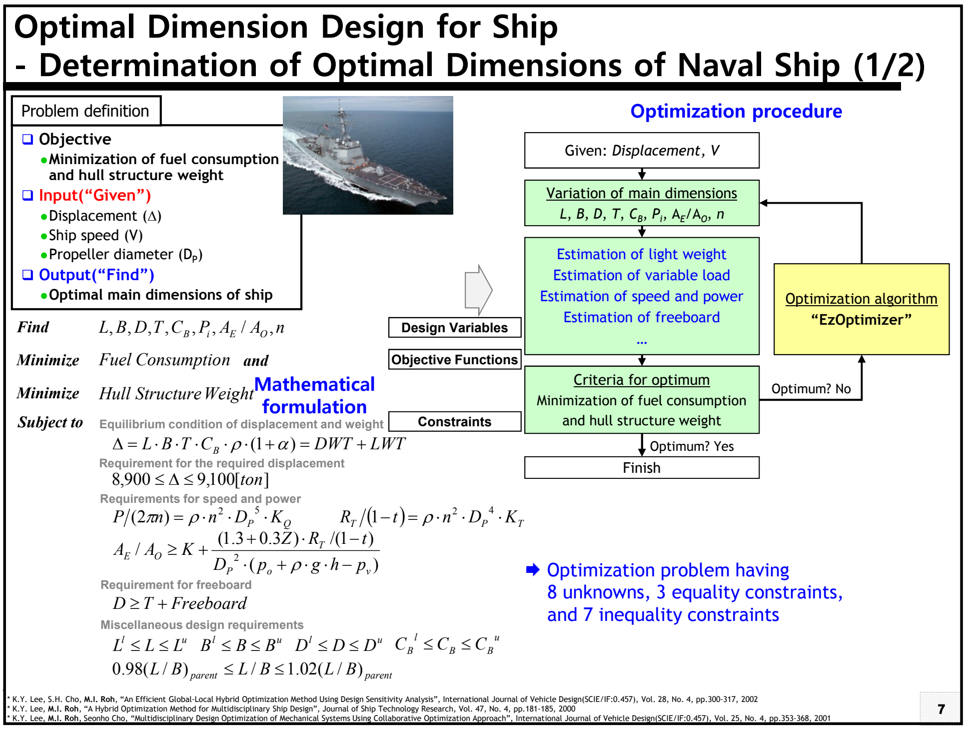
- 160,000ton bulk carrier
- Cargo hold capacity: 179,000m³
- Ship speed: 13.5knots
- Design draft: 17.2m
- Propeller RPM: 77.9rpm

Applicable to naval surface ship

Convergence history of objective function value

	Unit	Manual design	Standard, single optimization			Collaborative optimization with MS
			1.7~1.8% cost reduction	GA²	HYBRID³	
Building cost	$	60,949,431 (100.0%)	59,888,510 (98.3%)	59,863,587 (98.2%)	59,831,834 (98.2%)	59,831,688 (98.2%)
L	m	266.00	265.18	264.71	263.69	263.70
B	m	45.00	45.00	45.00	45.00	45.00
D	m	24.40	24.54	24.68	24.84	24.83
C_B	-	0.8276	0.8469	0.8463	0.8420	0.8418
D_P	m	8.3000	8.3928	8.4305	8.3999	8.3960
P_i	m	5.8200	5.8221	5.7448	5.7365	5.7411
A_E/A_O	-	0.3890	0.3724	0.3606	0.3690	0.3692
CPU time⁴	sec	-	209.58 (140%)	198.60 (133%)	187.22 (125%)	149.75 (base)

* 1: Multi-start local optimization (50 random starting points), 2: Genetic algorithm (50 random starting points), 3: HYBRID: Hybrid optimization method, 4: Tested on the Intel Pentium III 866MHz, 512RAM in 2002



Optimal Dimension Design for Ship
- Determination of Optimal Dimensions of Naval Ship (1/2)

Problem definition

- **Objective**
  - **Minimization of fuel consumption and hull structure weight**
- **Input("Given")**
  - Displacement (Δ)
  - Ship speed (V)
  - Propeller diameter (D_P)
- **Output("Find")**
  - **Optimal main dimensions of ship**

Optimization procedure

Given: *Displacement*, *V*

Variation of main dimensions
L, *B*, *D*, *T*, C_B, P_i, A_E/A_O, *n*

Estimation of light weight
Estimation of variable load
Estimation of speed and power
Estimation of freeboard
…

Criteria for optimum
Minimization of fuel consumption and hull structure weight

Optimum? No

Optimization algorithm
"EzOptimizer"

Optimum? Yes

Finish

Mathematical formulation

Find	$L, B, D, T, C_B, P_i, A_E/A_O, n$	**Design Variables**
Minimize	*Fuel Consumption* ***and***	**Objective Functions**
Minimize	*Hull Structure Weight*	
Subject to	Equilibrium condition of displacement and weight	**Constraints**

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

Requirement for the required displacement

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

Requirements for speed and power

$$P/(2\pi n) = \rho\cdot n^2\cdot D_P{}^5\cdot K_Q \qquad R_T/(1-t) = \rho\cdot n^2\cdot D_P{}^4\cdot K_T$$

$$A_E/A_O \ge K + \frac{(1.3+0.3Z)\cdot R_T/(1-t)}{D_P{}^2\cdot(p_o+\rho\cdot g\cdot h-p_v)}$$

Requirement for freeboard

$$D \ge T + Freeboard$$

Miscellaneous design requirements

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

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

➡ Optimization problem having 8 unknowns, 3 equality constraints, and 7 inequality constraints

* K.Y. Lee, S.H. Cho, **M.I. Roh**, "An Efficient Global-Local Hybrid Optimization Method Using Design Sensitivity Analysis", International Journal of Vehicle Design(SCIE/IF:0.457), Vol. 28, No. 4, pp.300-317, 2002
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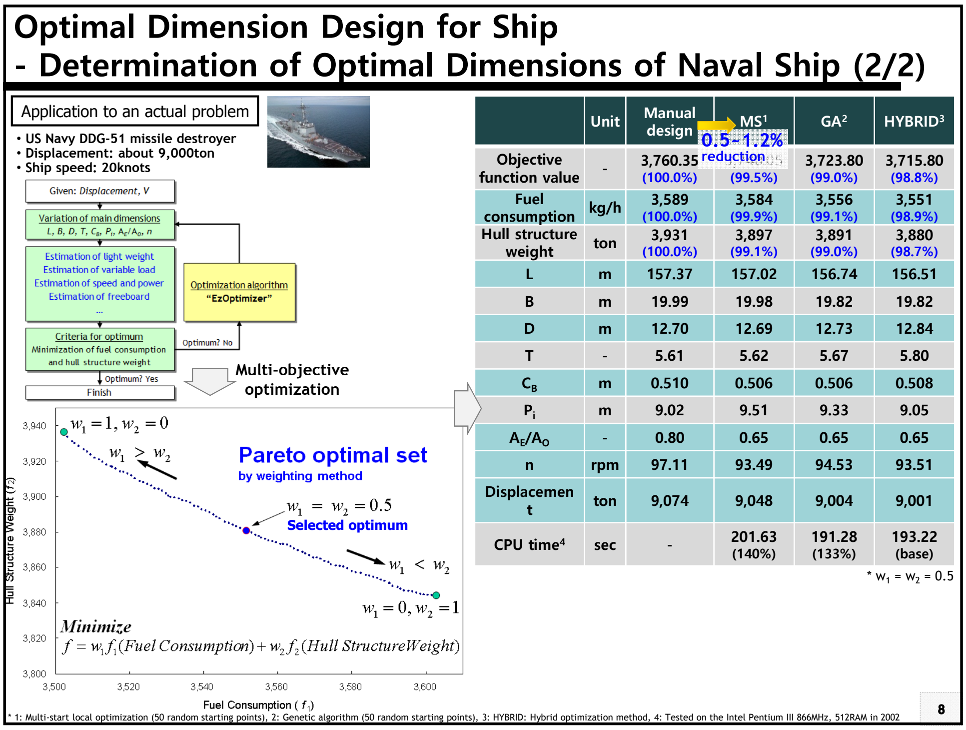


Optimal Dimension Design for Ship
- Determination of Optimal Dimensions of Naval Ship (2/2)

Application to an actual problem

- US Navy DDG-51 missile destroyer
- Displacement: about 9,000ton
- Ship speed: 20knots

Given: *Displacement*, *V*

Variation of main dimensions
L, *B*, *D*, *T*, C_B, P_i, A_E/A_O, *n*

Estimation of light weight
Estimation of variable load
Estimation of speed and power
Estimation of freeboard
…

Criteria for optimum
Minimization of fuel consumption and hull structure weight

Optimum? No

Optimization algorithm
"EzOptimizer"

Optimum? Yes

Finish

Multi-objective optimization

Minimize

$$f = w_1 f_1(Fuel\ Consumption) + w_2 f_2(Hull\ Structure Weight)$$

0.5~1.2% reduction

	Unit	Manual design	MS[1]	GA[2]	HYBRID[3]
Objective function value	-	3,760.35 (100.0%)	3,740.05 (99.5%)	3,723.80 (99.0%)	3,715.80 (98.8%)
Fuel consumption	kg/h	3,589 (100.0%)	3,584 (99.9%)	3,556 (99.1%)	3,551 (98.9%)
Hull structure weight	ton	3,931 (100.0%)	3,897 (99.1%)	3,891 (99.0%)	3,880 (98.7%)
L	m	157.37	157.02	156.74	156.51
B	m	19.99	19.98	19.82	19.82
D	m	12.70	12.69	12.73	12.84
T	-	5.61	5.62	5.67	5.80
C_B	m	0.510	0.506	0.506	0.508
P_i	m	9.02	9.51	9.33	9.05
A_E/A_O	-	0.80	0.65	0.65	0.65
n	rpm	97.11	93.49	94.53	93.51
Displacement	ton	9,074	9,048	9,004	9,001
CPU time[4]	sec	-	201.63 (140%)	191.28 (133%)	193.22 (base)

* $w_1 = w_2 = 0.5$

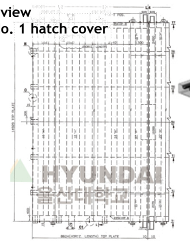
* 1: Multi-start local optimization (50 random starting points), 2: Genetic algorithm (50 random starting points), 3: HYBRID: Hybrid optimization method, 4: Tested on the Intel Pentium III 866MHz, 512RAM in 2002

Optimal Dimension Design for Ship
- Determination of Optimal Dimensions of Hatch Cover (1/2)

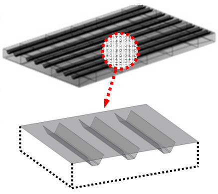
Problem definition

- ❑ Objective
  - Minimization of the weight of hatch cover
- ❑ Input("Given")
  - Length, width, height of hatch cover
  - Total number of girders and transverse web frames
- ❑ Output("Find")
  - Optimal dimensions of hatch cover

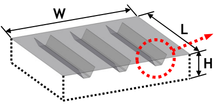
Plan view for No. 1 hatch cover

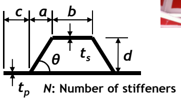


3D CAD model of hatch cover



Idealized model





N: Number of stiffeners

Find t_p, t_s, b, a, d, N **Design Variables**

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

Subject to **Constraints**

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

$\sigma_v \le 0.8 R_{eH}$ **Mathematical formulation**

Requirement for maximum permissible deflection by CSR

$\delta \le 0.0056 l_g$

Requirements for minimum plate and stiffener thickness by CSR

$t_{p,\min} \le t_p \quad t_{s,\min} \le t_s$

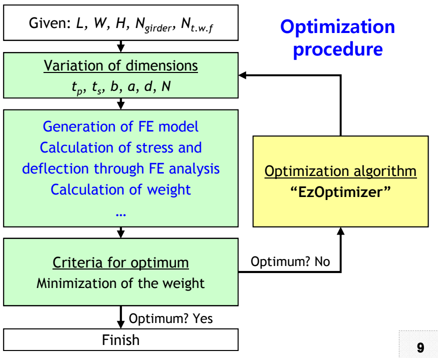
Limitations on geometry

$N(2a+b) \le W$

$d \le H$

$0^\circ \le \theta \le 90^\circ$

➡ Optimization problem having 6 unknowns and 7 inequality constraints



Optimization procedure

Given: L, W, H, N_{girder}, $N_{t.w.f}$

Variation of dimensions
t_p, t_s, b, a, d, N

Generation of FE model
Calculation of stress and deflection through FE analysis
Calculation of weight
…

Criteria for optimum
Minimization of the weight

Optimum? No

Optimization algorithm
"EzOptimizer"

Optimum? Yes

Finish

Optimal Dimension Design for Ship
- Determination of Optimal Dimensions of Hatch Cover (2/2)

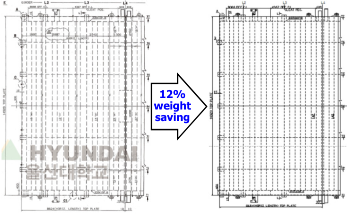
Application to an actual problem

- 180,000ton bulk carrier
- Lbp/B/D: 283.5/45.0/24.7m
- Ts: 18.2m

Optimization

	Unit	Manual design [A]	Optimization [B]	Ratio (B/A)
t_p	mm	16	14	87.5%
t_s	mm	8	8	100.0%
b	mm	170	160	94.1%
a	mm	120	111	92.5%
d	mm	220	198	90.0%
N	-	3	3	100.0%
Weight	ton	32.360	28.410	87.8%
σ_{max}	MPa	218	252	115.6%
δ_{max}	mm	5.532	6.388	115.5%

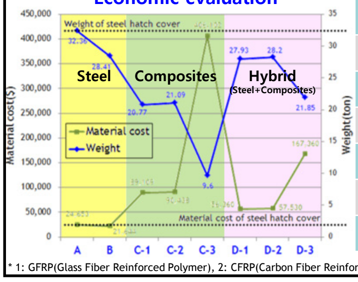
12% reduction



Before optimization
(weight = 32.36ton)

After optimization
(weight = 28.41ton)

Economic evaluation

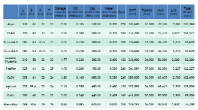


	Unit	Manual [A]	OPT [B]	Composites HC			Steel-Composites HC		
				C-1	C-2	C-3	D-1	D-2	D-3
Material	-	Steel (AH32)	Steel (AH32)	GFRP¹	GFRP	CFRP²	AH32 +GFRP	AH32 +GFRP	AH32 +CFRP
Fabrication method	-	Welding	Welding	Hand lay up	Vacuum	Vacuum	Hand lay up	Vacuum	Vacuum
Weight	ton (%)	32.36 (100.0)	28.41 (87.8)	20.77 (64.2)	21.09 (65.2)	9.60 (29.7)	27.93 (86.3)	28.20 (87.1)	21.85 (67.5)
Material cost	$ (%)	24,653 (100.0)	21,644 (87.8)	89,109 (361.5)	90,438 (366.8)	406,102 (1,647.3)	56,360 (228.6)	57,530 (233.4)	167,360 (678.9)
Fuel cost (for 25 years)	$	419,871	368,620	269,491	273,643	124,560	362,392	365,895	283,504
CO_2 emissions (for 25 years)	ton	16,088	14,124	10,326	10,485	4,773	13,885	14,020	10,863
CO_2 cost³ (for 25 years)	$	402,194	353,101	258,145	262,122	119,316	347,135	350,491	271,568
Total cost (for 25 years)	$ (%)	846,718 (100.0)	743,365 (87.8)	616,745 (72.8)	626,203 (74.0)	649,978 (76.8)	765,887 (90.5)	773,916 (91.4)	722,432 (85.3)

* 1: GFRP(Glass Fiber Reinforced Polymer), 2: CFRP(Carbon Fiber Reinforced Polymer), 3: CO_2 treatment cost

Optimal Dimension Design for Offshore Plant - Weight Estimation Model Using the Optimization Method

Past records for offshore plants



Dara acquisition from the literature

Items	Independent Parameters
Principal dimensions	L, B, D, T, H_LWT, DWT
Capacity	SC, OP, GP, WP
Miscellaneous	CREW

Extraction of initial variables

Parameters for optimization

Terminal Set
L, B, D, T, H_LWT, DWT, S_C, O_P, G_P, W_P, Crew

Parameters for terminal set

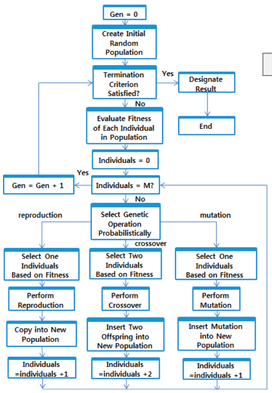
Function Set
+, -, ×, ÷, sin, cos, exp, √

Parameters for function set

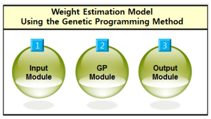
Items	Value
Population size	100
Max generation	300
Reproduction rate	0.05
Crossover probability	0.85
Mutation probability	0.10

Parameters for genetic programming

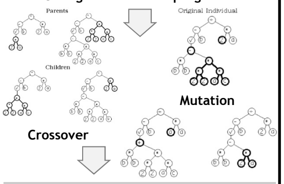
Genetic programming

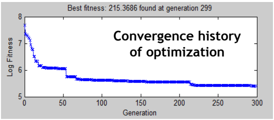


Flowchart of genetic programming



Configuration of the program



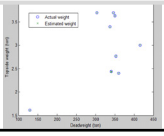


Convergence history of optimization

Generation of model for weight estimation

$$T\_LWT = 67.38 \cdot Crew + 67.38 \cdot B + 67.38 \cdot S\_C - 3059 \cdot \cos(L \cdot WP \cdot (H\_LWT - 3.838)) + 12533 \cdot \cos(\exp(\sin(S\_C))) + 0.5007 \cdot B \cdot T + 67.38 \cdot O\_P \cdot G\_P + 0.5007 \cdot D \cdot \sin(H\_LWT) \cdot L^2 - 30033$$

Verification of the model



	weight [A]	Estimated weight [B]	Ratio[A/B]
	37,000	36,951	0.999
USAN	27,700	27,672	0.999
Kizomba A	24,400	24,352	0.998
Kizomba B	24,400	24,383	0.999
Greater Plutonio	24,000	24,063	1.023
Pazflor	37,000	36,918	0.998
CLOV	36,300	36,318	1.001
Agbami	34,000	33,906	0.997
Dalia	30,000	30,059	1.002
Skarv-Idun	16,100	16,093	1.000
Mean	-	-	1.001

*Now, this model can be applied to **the weight estimation of a new offshore plant**.*

8.2 Determination of Optimal Principal Dimensions of Propeller

Generals

Mathematical Formulation and Its Solution

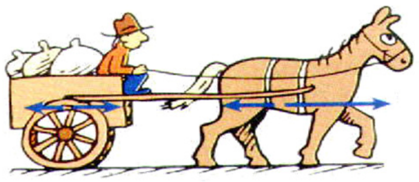
Example

Generals

Example of a Propeller

- ☑ Ship: 4,900 TEU Container Ship
- ☑ Owner: NYK, Japan
- ☑ Shipyard: HHI (2007.7.20)
- ☑ Diameter: 8.3 m
- ☑ Weight: 83.3 ton
- ☑ No of Blades: 5

Concept of the Determination of Principal Dimensions of a Propeller



Wheel design to draw the carriage with cargo by one horse for maximum speed

Given

One Horse = Main Engine

Friction Power = Resistance of a Ship

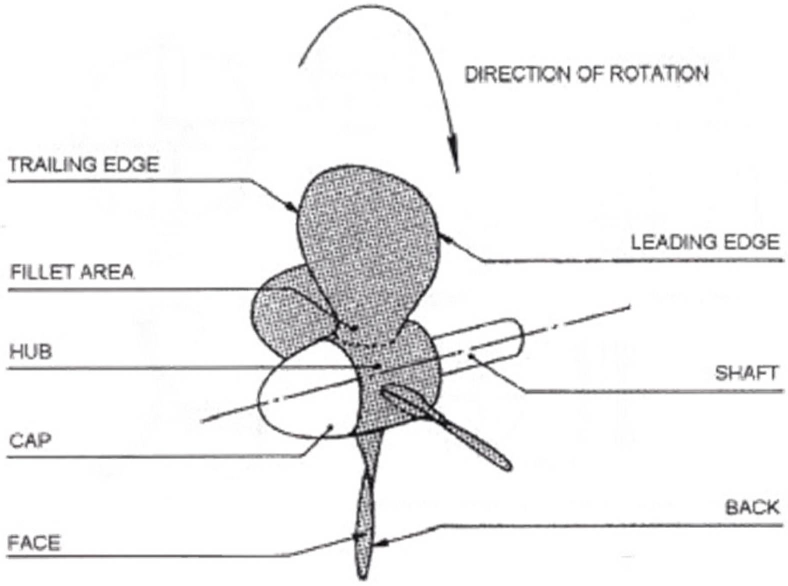
Find

Wheel Design = Propeller Design

Maximum Speed = Maximum Speed of a Ship

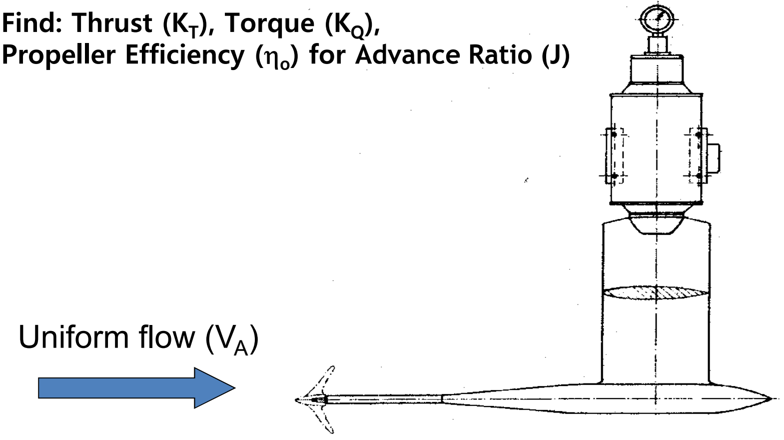
Wheel Diameter = Principal Dimensions of a Propeller

Propeller Components



Propeller Open Water (POW) Test

- ☑ **This test is carried out under ideal condition in which the propeller does not get disturbed by the hull.**
- ☑ **Given: Propeller Dimensions (D_P, P_i, A_E/A_O, z), Propeller RPM (n), Speed of Advance (V_A)**
- ☑ **Find: Thrust (K_T), Torque (K_Q),**
  Propeller Efficiency (η_o) for Advance Ratio (J)



Main Non-dimensional Coefficients of Propeller

From dimensional analysis:

① Thrust coefficient: $$\frac{T}{\rho \cdot n^2 \cdot D_P^4} = K_T$$

② Torque coefficient: $$\frac{Q}{\rho \cdot n^2 \cdot D_P^5} = K_Q$$

③ Advance ratio: $$J = \frac{v_A}{n \cdot D_P}$$
$$v_A = v \cdot (1 - w)$$

④ Propeller efficiency: (in open water) $$\eta_o = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q}$$

v: Ship Speed [m/s]
w: Wake fraction
T: Thrust of the propeller [kN]
Q: Torque absorbed by propeller [kN·m]
n: Number of Revolutions [1/s]
D_P: Propeller Diameter [m]
P_i: Propeller Pitch [m]
V_A: Speed of Advance [m/s]

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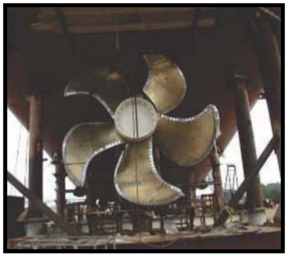
* Thrust deduction coefficient: The ratio of the resistance increase due to rotating of a propeller at after body of ship

POW Propeller Model

Actual Propeller



Model Propeller

Geometric Similarity

$$\frac{T}{\rho \cdot n^2 \cdot D_P^{\ 4}} = K_T$$

$$\frac{Q}{\rho \cdot n^2 \cdot D_P^{\ 5}} = K_Q$$

$$J = \frac{v_A}{n \cdot D_P}$$

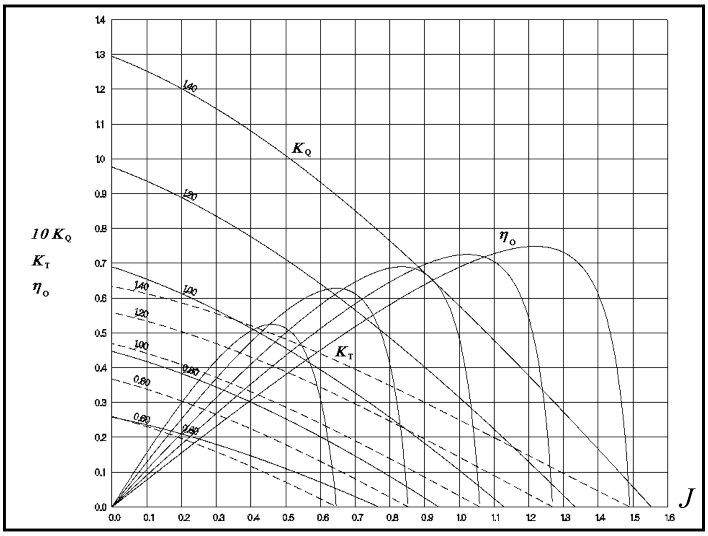
$$v_A = v \cdot (1 - w)$$

Same non-dimensional coefficient

$$\left(K_T, K_Q, J\right)$$

Propeller Open Water (POW) Curve

- Values of K_T,K_Q and η_O at different pitch ratio (P_i / D_p)



$$K_T = \frac{T}{\rho \cdot n^2 \cdot D_P^{\ 4}}$$

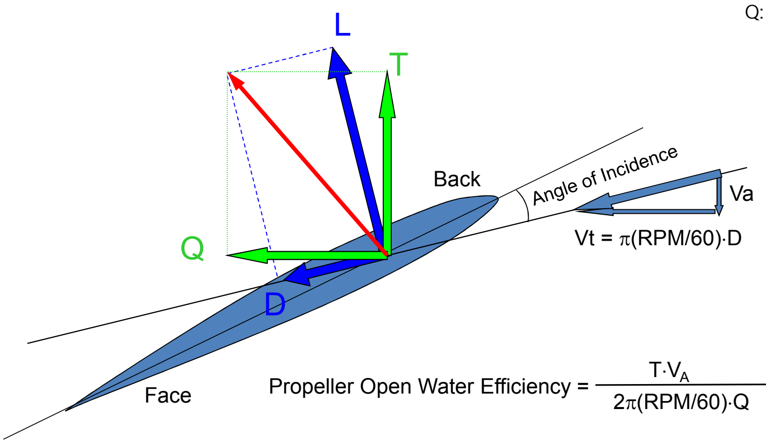
$$K_Q = \frac{Q}{\rho \cdot n^2 \cdot D_P^{\ 5}}$$

$$J = \frac{v_A}{n \cdot D_P}$$

$$\eta_o = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q}$$

Forces Acting on Propeller

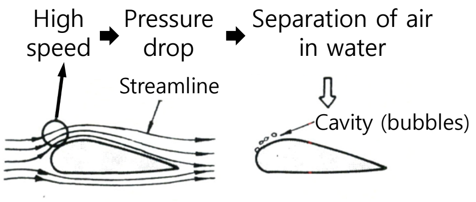
L: Lift force
D: Drag force
T: Thrust
Q: Torque

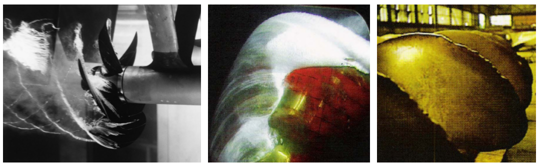


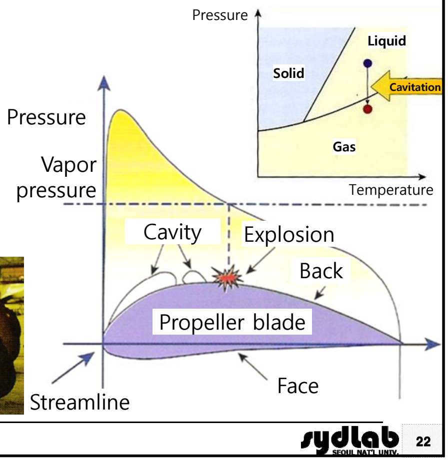
$$\text{Propeller Open Water Efficiency} = \frac{T \cdot V_A}{2\pi(RPM/60) \cdot Q}$$

Cavitation

- ☑ **Cavities (small liquid-free zones, “bubble”) are generated by the phase change of water from liquid to gas due to not temperate change but pressure change, that is, rapid change of pressure around blades of propeller.**
- ☑ **Noise and Vibration Problem, Corrosion at the back of blades**







Mathematical Formulation and Its Solution

Governing Equations for the Determination of Principal Dimensions of a Propeller (1/3)

Given	z ; P_{NCR} $[kW]$, n_{MCR} [1/s] ; $R_T(v)$ $[kN]$
Find	D_p $[m]$, P_i [m], A_E/A_O ; v [m/s]

- **Condition 1: The propeller absorbs the torque delivered by main engine.**

$$\boxed{\frac{P}{2\pi n}} = \boxed{\rho \cdot n^2 \cdot D_P{}^5 \cdot K_Q} \cdots (1)$$

Torque delivered by the main engine = Torque absorbed by the propeller

Governing Equations for the Determination of Principal Dimensions of a Propeller (2/3)

Given	z ; P_{NCR} $[kW]$, n_{MCR} [1/s] ; $R_T(v)$ $[kN]$
Find	D_p $[m]$, P_i [m], A_E/A_O ; v [m/s]

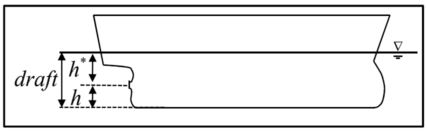
- **Condition 2: The propeller should produce the required thrust at a given ship speed.**

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

The thrust which is required to propel the ship for the given speed **=** The thrust which is produced by the propeller

Governing Equations for the Determination of Principal Dimensions of a Propeller (3/3)

Given	z ; P_{NCR} $[kW]$, n_{MCR} [1/s] ; $R_T(v)$ $[kN]$
Find	D_p $[m]$, P_i [m], A_E/A_O ; v [m/s]



- **Condition 3: Required minimum expanded blade area ratio for non-cavitating criterion can be calculated by using one of the two formulas.**

① Formula given by Keller

$$A_E / A_O \geq K + \frac{(1.3+0.3z)\cdot T}{D_P{}^2 \cdot (p_0 + \rho g h^* - p_v)}$$

K: Single Screw = 0.2, Double Screw = 0.1

P_0-P_v = 99.047 [kN/m^2] at 15℃ Sea water

h*: Shaft Immersion Depth [m]

h: Shaft Center Height (height from the baseline) [m]

T: Propeller Thrust [kN]

or ② Formula given by Burrill

$$A_E / A_O \geq F \cdot (\eta_0 / (1/J)^2) / [\{1 + 4.826(1/J)^2\} \cdot (1.067 - 0.229 \cdot P_i / D_p)]$$

$$F = \frac{\eta_R \cdot B_P^2 \cdot v_A^{1.25}}{287.4(10.18+h)^{0.625}}$$

$$\boxed{B_P = n \cdot P^{0.5} / v_A^{2.5}} \longleftarrow \boxed{v_A = v \cdot (1-w)[knots]}$$

$P = DHP \cdot \eta_R [HP]$
$n[rpm]$

Determination of the Propeller Principal Dimensions for Maximum η_0 (1/6)

By Using Optimization Method

Given	z ; P_{NCR} $[kW]$, n_{MCR} [1/s] ; $R_T(v)$ $[kN]$
Find	D_p $[m]$, P_i [m], A_E/A_O ; v [m/s]

4 Unknowns

2 Equality constraints
1 Inequality constraint

- **Condition 1: The propeller absorbs the torque delivered by main engine.**

$$\frac{P}{2\pi n} = \rho \cdot n^2 \cdot D_P^{\ 5} \cdot K_Q$$

- **Condition 2: The propeller should produce the required thrust at a given ship's speed.**

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

- **Condition 3: Required minimum expanded blade area ratio for non-cavitating criterion.**

$$A_E / A_O \geq K + \frac{(1.3+0.3z)\cdot T}{D_P^{\ 2}\cdot(p_0+\rho g h^* - p_v)}$$

⇩

Nonlinear indeterminate equation

⇩

Objective Function: Maximum η_0

$$\eta_o = \frac{J}{2\pi}\cdot\frac{K_T}{K_Q}$$

Propeller diameter(D_p), pitch(P_i), expanded blade area ratio(A_E/A_O) , and ship speed are determined to maximize the objective function by iteration.

Determination of the Propeller Principal Dimensions for Maximum η_0 (2/6)

Calculation By Hand

1 Assume the Expanded Area Ratio (A_E / A_o).

A_O: Disc area ($\pi D_P^2/4$)
A_E: Expanded propeller area

Assume that the expanded area ratio of the propeller of the design ship is the same as that of the basis ship.

2 Assume the ship speed v.

3 Express the condition 1 as $K_Q = C_1 J^5$.

Condition 1: $\frac{P}{2\pi n} = \rho \cdot n^2 \cdot D_P^{\ 5} \cdot K_Q$,

$$J = \frac{v_A}{n \cdot D_P} \Rightarrow \frac{nJ}{v_A} = \frac{1}{D_P}$$

$$K_Q = \frac{P}{2\pi n^3 \rho}\cdot\frac{1}{D_P^{\ 5}} = \frac{P}{2\pi n^3 \rho}\cdot\left(\frac{nJ}{v_A}\right)^5$$

$$= \frac{P\cdot n^2}{2\pi \rho v_A^5} J^5 = C_1 J^5, \quad \left(C_1 = \frac{P\cdot n^2}{2\pi \rho v_A^5}\right)$$

$$\boxed{K_Q = C_1 J^5}$$

Determination of the Propeller Principal Dimensions for Maximum η_0 (3/6)

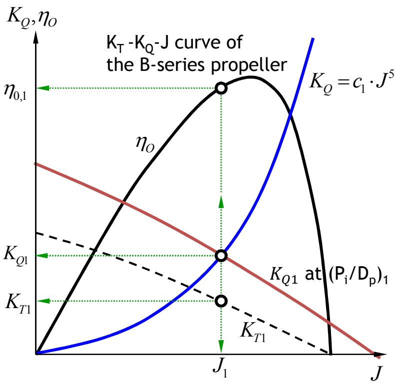
Calculation By Hand

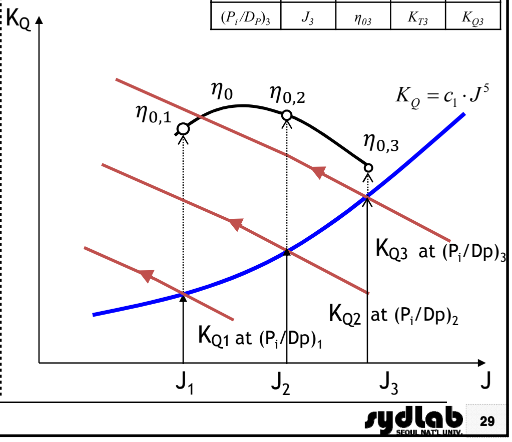
4

By using the POW-Curve (K_T -K_Q-J) of the series propeller data, for example, B-series propeller data, calculate the intersection point (J_1, K_{Q1}) between the $K_Q = c_1 \cdot J^5$ of the design propeller and the K_T -K_Q-J curve of the B-series propeller at a given pitch/diameter ratio $(P_i/D_p)_1$. And read the K_{T1} and η_{01} at J_1.

Repeat this procedure by varying pitch/diameter ratio

P_i/D_P	J	η_0	K_T	K_Q
$(P_i/D_P)_1$	J_1	η_{01}	K_{T1}	K_{Q1}
$(P_i/D_P)_2$	J_2	η_{02}	K_{T2}	K_{Q2}
$(P_i/D_P)_3$	J_3	η_{03}	K_{T3}	K_{Q3}





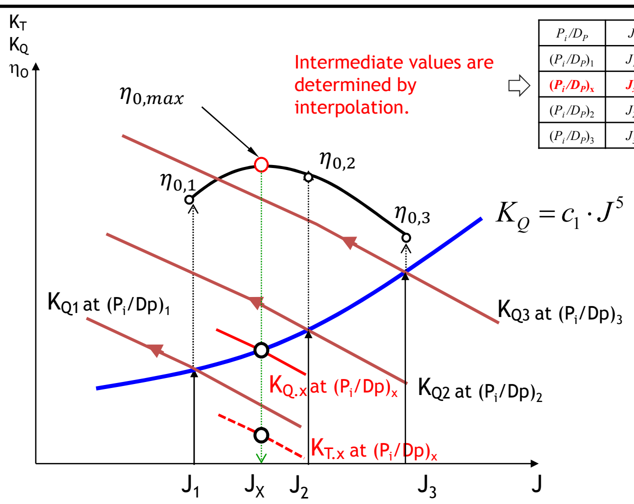
Determination of the Propeller Principal Dimensions for Maximum η_0 (4/6)

Calculation By Hand

5

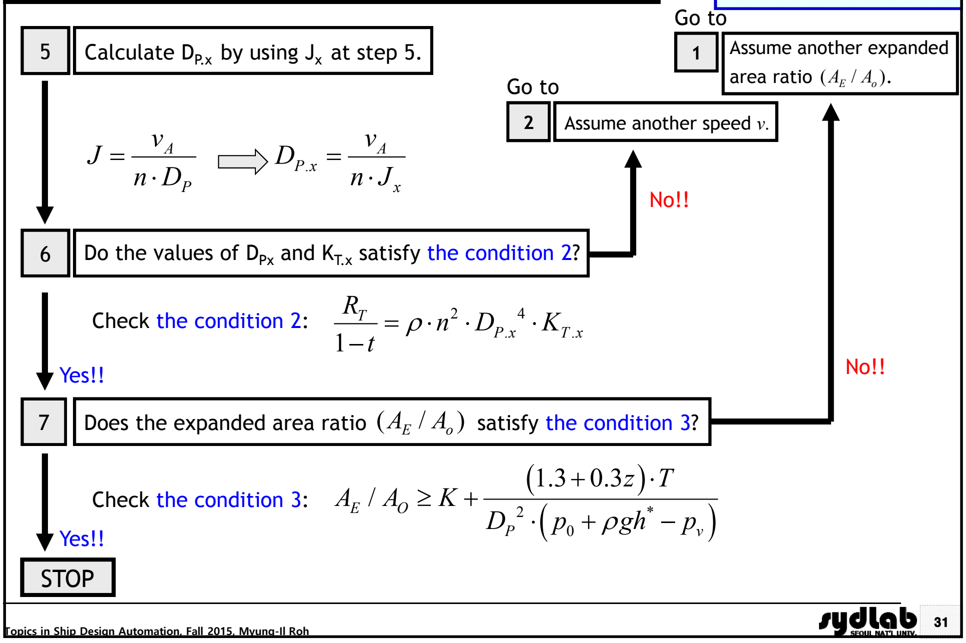
By using the set of K_T, K_Q, η_0 (varied with pitch ratio), determine J_x to maximize η_0 and pitch/diameter ratio $(P_i/D_p)_x$ at J_x .

P_i/D_P	J	η_0	K_T	K_Q
$(P_i/D_P)_1$	J_1	η_{01}	K_{T1}	K_{Q1}
$(P_i/D_P)_x$	J_x	η_{0x}	K_{Tx}	K_{Qx}
$(P_i/D_P)_2$	J_2	η_{02}	K_{T2}	K_{Q2}
$(P_i/D_P)_3$	J_3	η_{03}	K_{T3}	K_{Q3}


Intermediate values are determined by interpolation.

Determination of the Propeller Principal Dimensions for Maximum η_0 (5/6)

Calculation By Hand



5 Calculate $D_{P.x}$ by using J_x at step 5.

$$J = \frac{v_A}{n \cdot D_P} \Rightarrow D_{P.x} = \frac{v_A}{n \cdot J_x}$$

6 Do the values of D_{Px} and $K_{T.x}$ satisfy the condition 2?

No!! Go to 2 Assume another speed v.

Check the condition 2: $\frac{R_T}{1-t} = \rho \cdot n^2 \cdot D_{P.x}{}^4 \cdot K_{T.x}$

Yes!!

7 Does the expanded area ratio (A_E / A_o) satisfy the condition 3?

No!! Go to 1 Assume another expanded area ratio (A_E / A_o).

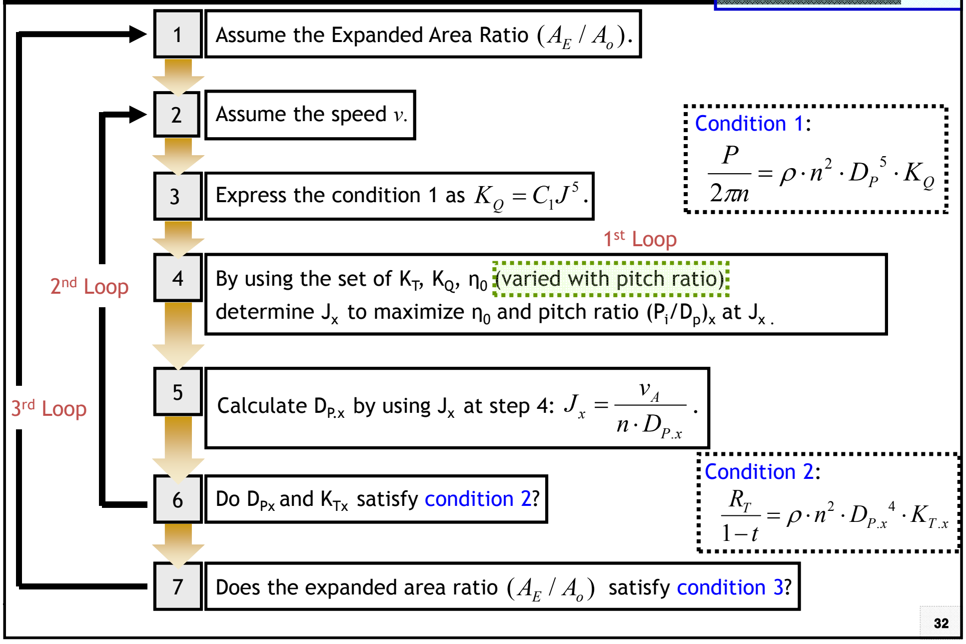
Check the condition 3: $A_E / A_O \geq K + \frac{(1.3+0.3z) \cdot T}{D_P{}^2 \cdot (p_0 + \rho g h^* - p_v)}$

Yes!!

STOP

Determination of the Propeller Principal Dimensions for Maximum η_0 (6/6): Summary

Calculation By Hand



1 Assume the Expanded Area Ratio (A_E / A_o).

2 Assume the speed v.

3 Express the condition 1 as $K_Q = C_1 J^5$.

Condition 1: $\frac{P}{2\pi n} = \rho \cdot n^2 \cdot D_P{}^5 \cdot K_Q$

1st Loop

4 By using the set of K_T, K_Q, η_0 (varied with pitch ratio), determine J_x to maximize η_0 and pitch ratio $(P_i/D_p)_x$ at J_x.

2nd Loop

3rd Loop

5 Calculate $D_{P.x}$ by using J_x at step 4: $J_x = \frac{v_A}{n \cdot D_{P.x}}$.

6 Do D_{Px} and K_{Tx} satisfy condition 2?

Condition 2: $\frac{R_T}{1-t} = \rho \cdot n^2 \cdot D_{P.x}{}^4 \cdot K_{T.x}$

7 Does the expanded area ratio (A_E / A_o) satisfy condition 3?

Determination of the Optimal Principal Dimensions of a Propeller by Using the Lagrange Multiplier (1/5)

Given $P, n, A_E / A_O, V$

Find $J, P_i / D_P$

Maximize $\eta_O = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q}$ $\longrightarrow$ **Because K_T and K_Q are a function of J and P_i/D_p, the objective is also a function of J and P_i/D_p.**

Subject to $\frac{P}{2\pi n} = \rho \cdot n^2 \cdot {D_P}^5 \cdot K_Q$

: The propeller absorbs the torque delivered by Diesel Engine

Where,

$$J = \frac{V(1-w)}{n \cdot D_P}$$

$$K_T = f(J, P_i / D_P)$$

$$K_Q = f(J, P_i / D_P)$$

P: Delivered power to the propeller from the main engine, KW
n: Revolution per second, 1/sec
D_P: Propeller diameter, m
P_i: Propeller pitch, m
A_E/A_O: Expanded area ratio
V: Ship speed, m/s
η_O: Propeller efficiency (in open water)

➡ **Optimization problem having two unknown variables and one equality constraint**

Determination of the Optimal Principal Dimensions of a Propeller by Using the Lagrange Multiplier (2/5)

$$\frac{P}{2\pi n} = \rho \cdot n^2 \cdot {D_P}^5 \cdot K_Q \quad \cdots\cdots \quad \text{(a)}$$

: The propeller absorbs the torque delivered by main engine

The constraint (a) is reformulated as follows:

$$C = \frac{K_Q}{J^5} = \frac{P \cdot n^2}{2\pi\rho \cdot {V_A}^5}$$

$$G(J, P_i / D_P) = K_Q - C \cdot J^5 = 0 \quad \cdots\cdots \quad \text{(a')}$$

Propeller efficiency in open water η_O is as follows.

$$F(J, P_i / D_P) = \eta_O = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q} \quad \cdots\cdots \quad \text{(b)}$$

The objective F is a function of J and P_i/D_p.

It is to determine the optimal principal dimensions (J and P_i/D_p) to maximize the propeller efficiency in open water satisfying the constraint (a').

Determination of the Optimal Principal Dimensions of a Propeller by Using the Lagrange Multiplier (3/5)

$$G(J,P_i/D_P)=K_Q-C\cdot J^5=0 \quad \cdots\cdots \quad (\text{a}')$$

$$F(J,P_i/D_P)=\eta_0=\frac{J}{2\pi}\cdot\frac{K_T}{K_Q} \quad \cdots\cdots \quad (\text{b})$$

Introduce the Lagrange multiplier λ to the equation (a′) and (b).

$$H(J,P_i/D_P,\lambda)=F(J,P_i/D_P)+\lambda G(J,P_i/D_P) \quad \cdots\cdots \quad (\text{c})$$

Determine the value of the P_i/D_p and λ to maximize the value of the function H.

$$\frac{\partial H}{\partial J}=\frac{1}{2\pi}(\frac{K_T}{K_Q})+\frac{J}{2\pi}\frac{\{(\frac{\partial K_T}{\partial J})\cdot K_Q-(\frac{\partial K_Q}{\partial J})\cdot K_T\}}{{K_Q}^2}+\lambda\{(\frac{\partial K_Q}{\partial J})-5\cdot C\cdot J^4\}=0\cdots(1)$$

$$\frac{\partial H}{\partial(P_i/D_P)}=\frac{J}{2\pi}\frac{\{(\frac{\partial K_T}{\partial P_i/D_P})\cdot K_Q-(\frac{\partial K_Q}{\partial P_i/D_P})\cdot K_T\}}{{K_Q}^2}+\lambda(\frac{\partial K_Q}{\partial P_i/D_P})=0 \quad \cdots \quad (2)$$

$$\frac{\partial H}{\partial\lambda}=K_Q-C\cdot J^5=0 \quad \cdots\cdots\cdots\cdots \quad (3)$$

Determination of the Optimal Principal Dimensions of a Propeller by Using the Lagrange Multiplier (4/5)

Eliminate λ in the equation (1), (2), and (3), and rearrange as follows.

$$\begin{aligned}&(\frac{\partial K_Q}{\partial(P_i/D_P)})\{J\cdot(\frac{\partial K_T}{\partial J})-4K_T\}\\&+(\frac{\partial K_T}{\partial(P_i/D_P)})\{5K_Q-J\cdot(\frac{\partial K_Q}{\partial J})\}=0 \quad \cdots\cdots \quad (4)\end{aligned}$$

$$K_Q-C\cdot J^5=0 \quad \cdots\cdots \quad (5)$$

By solving the nonlinear equation (4) and (5), we can determine J and P_i/D_p to maximize the propeller efficiency.

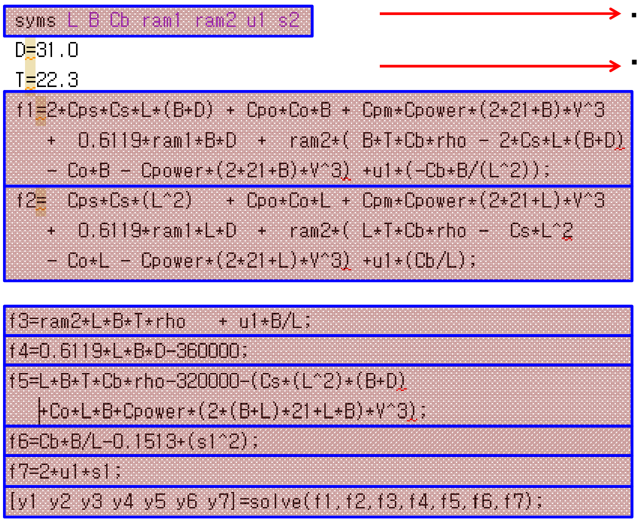
By definition $J=\frac{V(1-w)}{n\cdot D_P}$, if we have J, we can find D_p. Then P_i is obtained from P_i/D_p.

Thus, we can find the propeller diameter (D_p) and pitch (P_i).

Determination of the Optimal Principal Dimensions of a Propeller by Using the Lagrange Multiplier (5/5)

- **Programming by using the Matlab**

$L \rightarrow x_1, B \rightarrow x_2, C_B \rightarrow x_3$



```
syms L B Cb ram1 ram2 u1 s2
D=31.0
T=22.3
f1=2*Cps*Cs*L*(B+D) + Cpo*Co*B + Cpm*Cpower*(2*21+B)*V^3
   +  0.6119*ram1*B*D  +  ram2*( B*T*Cb*rho - 2*Cs*L*(B+D)
   - Co*B - Cpower*(2*21+B)*V^3) +u1*(-Cb*B/(L^2));
f2=  Cps*Cs*(L^2)    + Cpo*Co*L + Cpm*Cpower*(2*21+L)*V^3
   +  0.6119*ram1*L*D  +  ram2*( L*T*Cb*rho -  Cs*L^2
   - Co*L - Cpower*(2*21+L)*V^3) +u1*(Cb/L);

f3=ram2*L*B*T*rho    + u1*B/L;
f4=0.6119*L*B*D-360000;
f5=L*B*T*Cb*rho-320000-(Cs*(L^2)*(B+D)
   +Co*L*B+Cpower*(2*(B+L)*21+L*B)*V^3);
f6=Cb*B/L-0.1513+(s1^2);
f7=2*u1*s1;
[y1 y2 y3 y4 y5 y6 y7]=solve(f1,f2,f3,f4,f5,f6,f7);
```

- **Define the symbolic variable: 7 variables**
- **Input the constant value.**

$\frac{\partial H}{\partial x_1}$ ...(1)

$\frac{\partial H}{\partial x_2}$ ...(2)

$\partial H / \partial x_3$ ...(3)

$\partial H / \partial \lambda_1$ ...(4)

$\partial H / \partial \lambda_2$ ...(5)

$\partial H / \partial u$ ...(6)

$\partial H / \partial s$ ...(7)

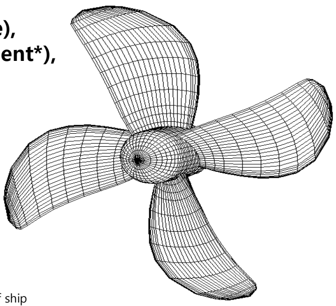
'solve' is a command for solving the simultaneous equation.

Example

Determination of Optimal Principal Dimensions of a Propeller - Problem Definition

☑ **Problem for determining optimal principal dimensions of a propeller of a 9,000ton missile destroyer (DDG)**

- **Objective**
  - **Maximization of the efficiency of propeller (η_O)**
- **Input (Given, Ship owner's requirements)**
  - **P: Delivered power**
  - **D_P: Diameter of propeller**
  - **Data related to resistance: R_T (total resistance), w (wake fraction), t (thrust deduction coefficient*), η_R (relative rotative efficiency)**
- **Output (Find)**
  - **P_i: Propeller pitch**
  - **A_E/A_O: Expanded area ratio**
  - **n: Propeller RPS (Revolution Per Second)**
  - **V: Ship speed**



* Thrust deduction coefficient: The ratio of the resistance increase due to rotating of a propeller at after body of ship

* Reference: Kyu-Yeul Lee, Myung-Il Roh, "An Efficient Genetic Algorithm Using Gradient Information for Ship Structural Design Optimization", Journal of Ship Technology Research, Vol. 48, No. 4, pp.161-170, 2001.

Determination of Optimal Principal Dimensions of a Propeller - Problem Formulation

Find $P_i, A_E / A_O, n, V$

Design Variables

Maximize $\eta_O = \frac{J}{2\pi}\cdot\frac{K_T}{K_Q}$

Objective Function

Subject to $\frac{P}{2\pi n} = \rho\cdot n^2\cdot D_P{}^5\cdot K_Q$

Constraints

: The condition that the propeller absorbs the torque delivered by main engine

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

: The condition that the propeller should produce the required thrust at a given ship's speed

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

: The condition about the required minimum expanded area ratio for non-cavitating criterion

Where $J = \frac{V(1-w)}{n\cdot D_P}, K_T = f(J, P_i / D_P, A_E / A_O, Z),$

$$K_Q = f(J, P_i / D_P, A_E / A_O, Z), T_h = R_T / (1-t)$$

➡ **Optimization problem having 4 design variables, 2 equality constraints, and 1 inequality constraint**

Determination of Optimal Principal Dimensions of a Propeller - Optimization Result

Optimization results according to optimization methods

	Unit	DDG-51	MFD	MS	GA	HYBRID w/o Refine	HYBRID with Refine
Pi	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
V*	kts	20.00	19.98	20.01	20.01	19.99	20.00
η_O	-	-	0.6439	0.6447	0.6457	0.6463	0.6528
Δ	LT	8,369	9,074	8,907	8,929	9,016	9,001
BHP	HP	13,601	14,654	14,611	14,487	14,447	14,443
Iteration No	-	-	5	267	89	59	63
CPU Time	sec	-	0.88	38.07	41.92	40.45	41.39

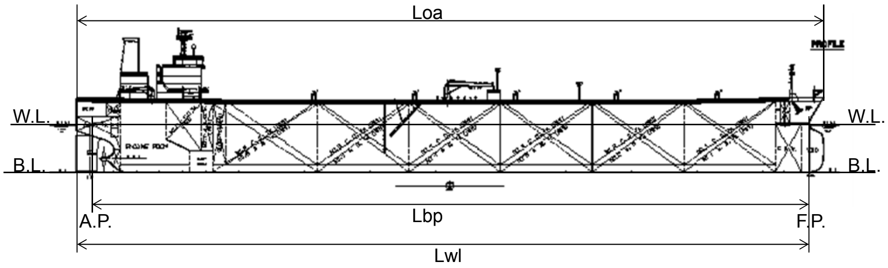
* V*: Cruising Speed
* MFD: Method of feasible directions, MS: Multi-start local optimization method, GA: Genetic algorithm, HYBRID: Global-local hybrid optimization method
* Test system: Pentium 3 866MHz, 512MB RAM

8.3 Determination of Optimal Principal Dimensions of Ship

Generals
Design Equations
Mathematical Formulation and Its Solution
Example for the Determination of Optimal Principal Dimensions of a Bulk Carrier
Example for the Determination of Optimal Principal Dimensions of a Naval Ship

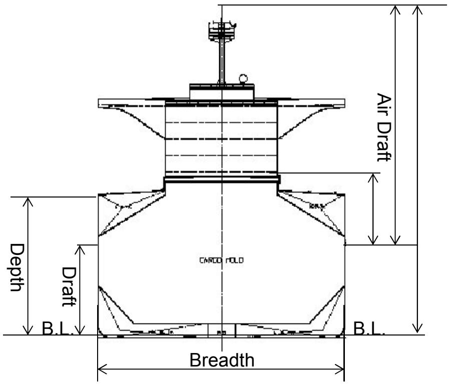
Generals

Principal Dimensions (1/2)



- ☑ LOA (Length Over All) [m]: Maximum Length of Ship
- ☑ LBP (Length Between Perpendiculars (A.P. ~ F.P.)) [m]
  - ■ A.P.: After perpendicular (normally, center line of the rudder stock)
  - ■ F.P.: Inter-section line between designed draft and fore side of the stem, which is perpendicular to the baseline
- ☑ Lf (Freeboard Length) [m]: Basis of freeboard assignment, damage stability calculation
  - ■ 96% of Lwl at 0.85D or Lbp at 0.85D, whichever is greater
- ☑ Rule Length (Scantling Length) [m]: Basis of structural design and equipment selection
  - ■ Intermediate one among (0.96 Lwl at Ts, 0.97 Lwl at Ts, Lbp at Ts)

Principal Dimensions (2/2)



- B (Breadth) [m]: Maximum breadth of the ship, measured amidships
  - B_{molded}: excluding shell plate thickness
  - $B_{extreme}$: including shell plate thickness
- D (Depth) [m]: Distance from the baseline to the deck side line
  - D_{molded}: excluding keel plate thickness
  - $D_{extreme}$: including keel plate thickness
- Td (Designed Draft) [m]: Main operating draft
  - In general, basis of ship's deadweight and speed/power performance
- Ts (Scantling Draft) [m]: Basis of structural design

- Air Draft [m]: Distance (height above waterline only or including operating draft) restricted by the port facilities, navigating route, etc.
  - Air draft from baseline to the top of the mast
  - Air draft from waterline to the top of the mast
  - Air draft from waterline to the top of hatch cover
  - …

Weight and COG (Center Of Gravity)

☑ **Displacement** [ton]
- Weight of water displaced by the ship's submerged part

☑ **Deadweight** (DWT) [ton]: Cargo payload + Consumables (F.O., D.O., L.O., F.W., etc.) + DWT Constant
= Displacement - Lightweight

☑ Cargo Payload [ton]: Weight of loaded cargo at the loaded draft

☑ DWT Constant [ton]: Operational liquid in the machinery and pipes, provisions for crew, etc.

☑ **Lightweight** (LWT) [ton]: Total of hull steel weight and weight of equipment on board

☑ Trim: difference between draft at A.P. and F.P.
- Trim = {Displacement x (LCB - LCG)} / (MTC x 100)

☑ LCB: Longitudinal Center of Buoyancy

☑ LCG: Longitudinal Center of Gravity

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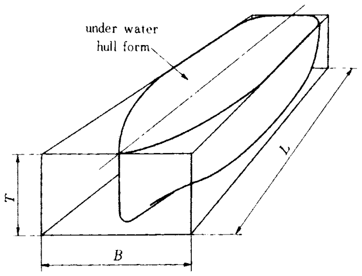
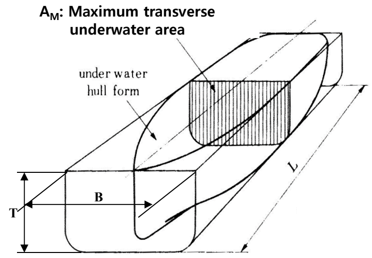
* F.O.: Fuel Oil, D.O.: Diesel Oil, L.O.: Lubricating Oil, F.W.: Fresh Water

Hull Form Coefficients (1/2)

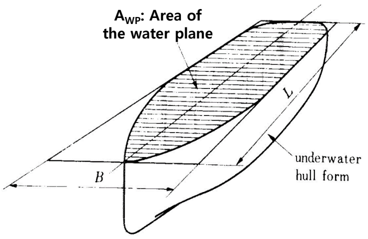


- C_B (Block Coefficient)
  = Displacement / (L x B x T x Density)
  where, density of sea water = 1.025 [Mg/m^3]



- C_M (Midship Section Coefficient)
  = A_M / (B x T)
- C_P (Prismatic Coefficient)
  = Displacement / (A_M x L x Density)

Hull Form Coefficients (2/2)



- C_{WP} (Water Plane Area Coefficient)
  = A_{WP} / (L x B)

Speed and Power (1/2)

- ☑ MCR (Maximum Continuous Rating) [PS x rpm]
  - NMCR (Nominal MCR)
  - DMCR (Derated MCR) / SMCR (Selected MCR)

- ☑ NCR (Normal Continuous Rating) [PS x rpm]

- ☑ Trial Power [PS x rpm]: Required power without sea margin at the service speed (BHP)

- ☑ Sea Margin [%]: Power reserve for the influence of storm seas and wind including the effects of fouling and corrosion.

- ☑ Service Speed [knots]: Speed at NCR power with the specific sea margin (e.g., 15%)

Speed and Power (2/2)

- ☑ DHP: Delivered Horse Power
  - Power actually delivered to the propeller with some power loss in the stern tube bearing and in any shaft tunnel bearings between the stern tube and the site of the torsion-meter

- ☑ EHP: Effective Horse Power
  - Required power to maintain intended speed of the ship

- ☑ η_D: Quasi-propulsive coefficient = EHP / DHP

- ☑ RPM margin
  - To provide a sufficient torque reserve whenever full power must be attained under unfavorable weather conditions
  - To compensate for the expected future drop in revolutions for constant-power operation

Tonnage

☑ Tonnage: normally, 100 ft^3 (=2.83 m^3) = 1 ton

- Basis of various fee and tax
- GT (Gross Tonnage): Total sum of the volumes of every enclosed space
- NT (Net Tonnage): Total sum of the volumes of every cargo space
  - GT and NT should be calculated in accordance with "IMO 1969 Tonnage Measurement Regulation".
- CGT (Compensated Gross Tonnage)
- Panama and Suez canal have their own tonnage regulations.

Unit (1/2)

☑ LT (Long Ton, British) = 1.016 [ton], ST (Short Ton, American) = 0.907 [ton], MT (Metric Ton, Standard) = 1.0 [ton]

☑ Density ➡ [ton/m^3 or Mg/m^3]

- e.g., density of sea water = 1.025 [ton/m^3], density of fresh water = 1.0 [ton/m^3], density of steel = 7.8 [ton/m^3]

☑ 1 [knots] = 1 [NM/hr] = 1.852 [km/hr] = 0.5144 [m/sec]

☑ 1 [PS] = 75 [kgf·m/s] = 75×10^{-3} [Mg]·9.81 [m/s^2]·[m/s] = 0.73575 [kW] (Pferdestarke, German translation of horsepower)

- NMCR of B&W6S60MC: 12,240 [kW] = 16,680 [PS]

☑ 1 [BHP] = 76 [kgf·m/s] = 76×10^{-3} [Mg]·9.81 [m/s^2]·[m/s] = 0.74556 [KW] (British horsepower)

Unit (2/2)

☑ SG (Specific Gravity) ➡ No dimension

- SG of material = density of material / density of water
- e.g., SG of sea water = 1.025, SG of fresh water = 1.0, SG of steel = 7.8

☑ SF (Stowage Factor) ➡ [ft^3/LT]

- e.g., SF = 15 [ft^3/LT] ➡ SG = 2.4 [ton/m^3]

☑ API (American Petroleum Institute) = (141.5 / SG) - 131.5

- e.g., API 40 ➡ SG = 0.8251

☑ 1 [barrel] = 0.159 [m^3]

- e.g., 1 [mil. barrels] = 159,000 [m^3]

Basic Functions of a Ship

☑ Going fast on the water

- Hull form: Streamlined shape having small resistance
- Propulsion: Diesel engine, Helical propeller
- The speed of ship is represented with knot(s). 1 knot is a speed which can go 1 nautical mile (1,852 m) in 1 hour.

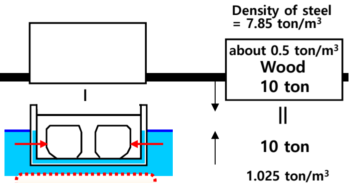
☑ Containing like a strong bowl

- Welded structure of plates (thickness of about 20 ~ 30mm), stiffeners, and brackets
- A VLCC has the lightweight of about 45,000 ton and can carry crude oil of about 300,000 ton.

☑ Navigable safely

- A ship has less motion for being comfortable and safe of passengers and cargo.
- Maneuvering equipment: Rudder

Basic Requirements of a Ship



- The basic requirements of a ship
  - (1) Ship should float and be stable in sea water

    Ship stability

    ➡ Weight of the ship is equal to the buoyancy* in static equilibrium.
  - (2) Ship should transport cargoes.

    Ship compartment design

    ➡ The inner space should be large enough for storing the cargoes.
  - (3) Ship should move fast to the destination and be possible to control itself.

    Hull form design, Ship hydrodynamics, Propeller design, Ship maneuverability and control

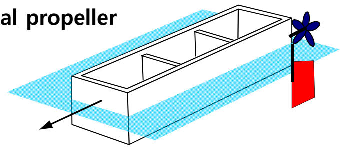
    ➡ Shape: It should be made to keep low resistance (ex. streamlined shape).

    ➡ Propulsion equipment: Diesel engine, Helical propeller

    ➡ Steering equipment: Steering gear, Rudder
  - (4) Ship should be strong enough in all her life.

    ➡ It is made of the welded structure of steel plate (about 10~30mm thickness) and stiffeners.

    Ship structural mechanics, Structural design & analysis



* Archimedes' Principle: The buoyancy of the floating body is equal to the weigh of displaced fluid of the immersed portion of the volume of the ship.

Criteria for the Size of a Ship

☑ **Displacement**
- Weight of water displaced by the ship's submerged part
- Equal to total weight of ship
- Used when representing the size of naval ships

☑ **Deadweight**
- Total weight of cargo. Actually, Cargo payload + Consumables (F.O., D.O., L.O., F.W., etc.) + DWT Constant
- Used when representing the size of commercial ships (tanker, bulk carrier, ore carrier, etc.)

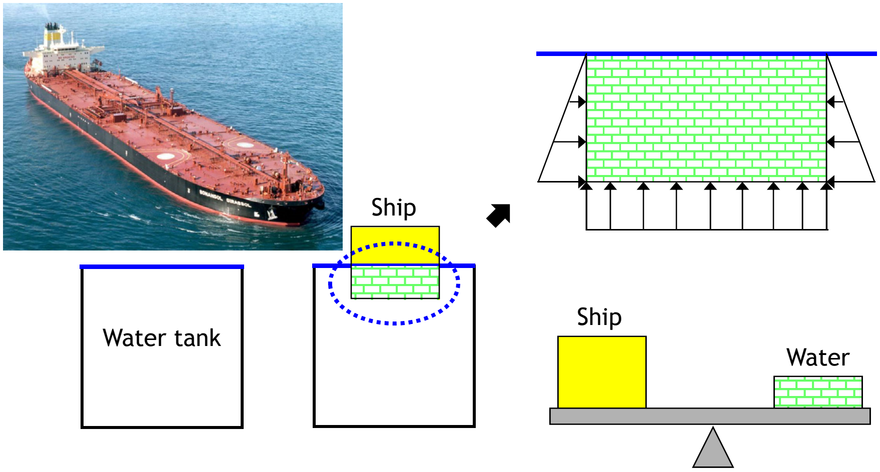
☑ **Tonnage**
- Total volume of cargo
- Basis for statics, tax, etc.
- Used when representing the size of passenger ships

* F.O.: Fuel Oil, D.O.: Diesel Oil, L.O.: Lubricating Oil, F.W.: Fresh Water

How does a ship float? (1/3)

☑ **The force that enables a ship to float** ➡ "Buoyant Force"

- **It is directed upward.**
- **It has a magnitude equal to the weight of the fluid which is displaced by the ship.**



How does a ship float? (2/3)

☑ Archimedes' Principle

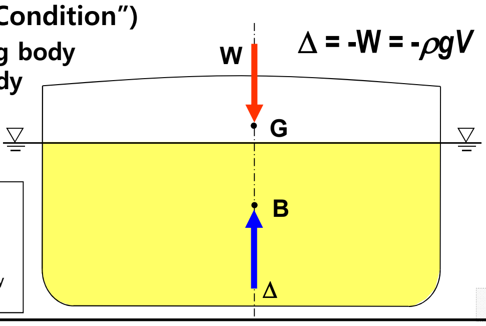
- **The magnitude of the buoyant force acting on a floating body in the fluid is equal to the weight of the fluid which is displaced by the floating body.**
- **The direction of the buoyant force is opposite to the gravitational force.**

Buoyant force of a floating body
= the weight of the fluid which is displaced by the floating body ("Displacement")
➡ Archimedes' Principle

☑ Equilibrium State ("Floating Condition")

- **Buoyant force of the floating body**
  = Weight of the floating body

$\therefore$ **Displacement = Weight**



$\Delta = -W = -\rho g V$

G: Center of gravity
B: Center of buoyancy
W: Weight, Δ: Displacement
ρ: Density of fluid
V: Submerged volume of the floating body (Displacement volume, ∇)

How does a ship float? (3/3)

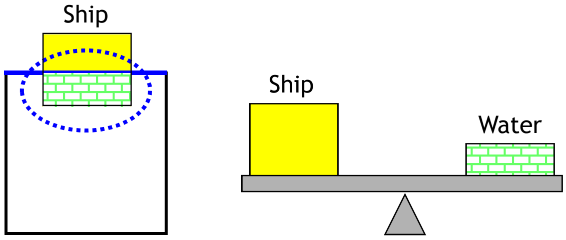
☑ **Displacement(Δ)** = **Buoyant Force** = **Weight(W)**

$$\boxed{\Delta = L \cdot B \cdot T \cdot C_B \cdot \rho}$$

$$= \boxed{W = LWT + DWT}$$

T: Draft
C_B: Block coefficient
ρ: Density of sea water
LWT: Lightweight
DWT: Deadweight

☑ **Weight = Ship weight** (Lightweight) **+ Cargo weight**(Deadweight)



What is a “Hull form”?

☑ **Hull form**

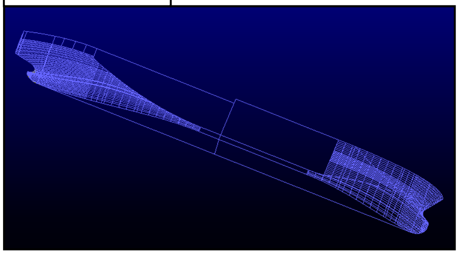
- **Outer shape of the hull** that is streamlined in order to satisfy requirements of a ship owner such as a deadweight, ship speed, and so on
- **Like a skin of human**

☑ **Hull form design**

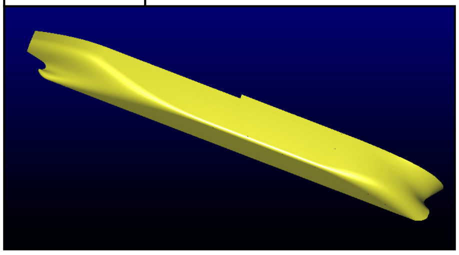
- **Design task that designs the hull form**

Hull form of the VLCC(Very Large Crude oil Carrier)

Wireframe model



Surface model



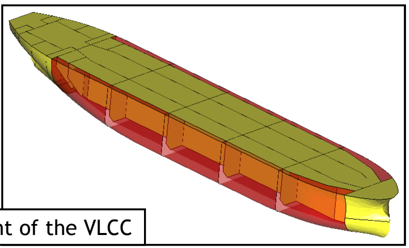
What is a "Compartment"?

☑ Compartment
- Space to load cargos in the ship
- It is divided by a bulkhead which is a diaphragm or peritoneum of human.

☑ Compartment design (General arrangement design)
- Compartment modeling + Ship calculation

☑ Compartment modeling
- Design task that divides the interior parts of a hull form into a number of compartments

☑ Ship calculation (Naval architecture calculation)
- Design task that evaluates whether the ship satisfies the required cargo capacity by a ship owner and, at the same time, the international regulations related to stability, such as MARPOL and SOLAS, or not



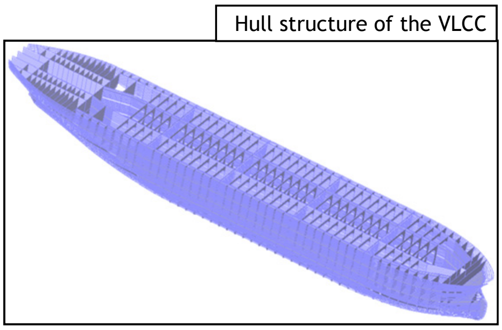
Compartment of the VLCC

What is a "Hull Structure"?

☑ Hull structure
- Frame of a ship comprising of a number of hull structural parts such as plates, stiffeners, brackets, and so on
- Like a skeleton of human

☑ Hull structural design
- Design task that determines the specifications of the hull structural parts such as the size, material, and so on

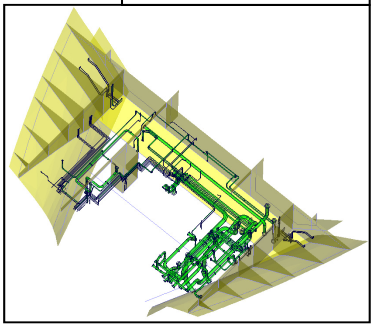
Hull structure of the VLCC



What is a “Outfitting”?

- ☑ Outfitting
  - ■ All equipment and instrument to be required for showing all function of the ship
    - ● Hull outfitting: Propeller, rudder, anchor/mooring equipment, etc.
    - ● Machinery outfitting: Equipment, pipes, ducts, etc. in the engine room
    - ● Accommodation outfitting: Deck house (accommodation), voyage equipment, etc.
    - ● Electric outfitting: Power, lighting, cables, and so on
  - ■ Like internal organs or blood vessels of human
- ☑ Outfitting design
  - ■ Design task that determines the types, numbers, and specifications of outfitting

Pipe model of the VLCC



Design Equations

(1) Owner's Requirements

Owner's Requirements

☑ Owner's Requirements
- Ship's Type
- Deadweight (DWT)
- Cargo Hold Capacity (V_{CH})
  - Cargo Capacity: Cargo Hold Volume / Containers in Hold & on Deck / Car Deck Area
  - Water Ballast Capacity
- Service Speed (V_s)
  - Service Speed at Design Draft with Sea Margin, MCR/NCR Engine Power & RPM
- Dimensional Limitations: Panama canal, Suez canal, Strait of Malacca, St. Lawrence Seaway, Port limitations
- Maximum Draft (T_{max})
- Daily Fuel Oil Consumption (DFOC): Related with ship's economy
- Special Requirements
  - Ice Class, Air Draft, Bow/Stern Thruster, Special Rudder, Twin Skeg
- Delivery Day
  - Delivery day, with (   )$ penalty per delayed day
  - Abt. 21 months from contract
- The Price of a Ship
  - Material & Equipment Cost + Construction Cost + Additional Cost + Margin

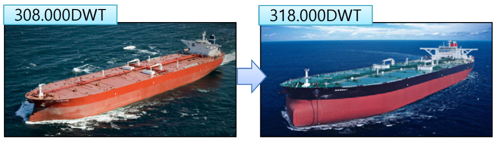
Principal Particulars of a Basis Ship

At early design stage, there are few data available to determine the principal particulars of the design ship.

Therefore, initial values of the principal particulars can be estimated from the basis ship (called also as 'parent ship' or 'mother ship'), whose main dimensional ratios and hull form coefficients are similar with the ship being designed.

The principal particulars include main dimensions, hull form coefficients, speed and engine power, DFOC, capacity, cruising range, crew, class, etc.

Example) VLCC (Very Large Crude oil Carrier)

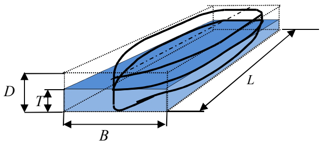


Principal Dimensions & Hull Form Coefficients

The principal dimensions and hull form coefficients decide many characteristics of a ship, e.g. stability, cargo hold capacity, resistance, propulsion, power requirements, and economic efficiency.

Therefore, the determination of the principal dimensions and hull form coefficients is most important in the ship design.

The length L, breadth B, depth D, immersed depth (draft) T, and block coefficient C_B should be determined first.



(2) Design Constraints

Design Constraints

In the ship design, the principal dimensions cannot be determined arbitrarily; rather, they have to satisfy following design constraints:

1) Physical constraint

- **Floatability: Hydrostatic equilibrium ➡ "Weight Equation"**

2) Economical constraints

- **Owner's requirements**
  Ship's type, Deadweight (*DWT*) [*ton*],
  Cargo hold capacity (*V_{CH}*) [*m^3*], ➡ **"Volume Equation"**
  Service speed (*V_S*) [*knots*], ➡ **Daily fuel oil consumption(DFOC)**[*ton/day*]
  Maximum draft (*T_{max}*) [*m*],
  Limitations of main dimensions (Canals, Sea way, Strait, Port limitations
  : e.g. Panama canal, Suez canal, St. Lawrence Seaway, Strait of Malacca,
  Endurance [*N/M*[1)]],

3) Regulatory constraints

International **M**aritime **O**rganization [**IMO**] regulations,
International Convention for the **S**afety **O**f **L**ife **A**t **S**ea [**SOLAS**],
International Convention for the Prevention of **Mar**in **Pol**lution from Ships [**MARPOL**],
International **C**onvention on **L**oad **L**ines [**ICLL**],
Rules and Regulations of **Classification** Societies

1) N/M: Nautical Mile
1 N/M = 1.852 km

(3) Physical Constraints

Physical Constraint

- **Physical constraint**
  - **Floatability**

For a ship to float in sea water, the total weight of the ship (W) must be equal to the buoyant force (F_B) on the immersed body
➡ **Hydrostatic equilibrium**:

$$F_B \overset{!}{=} W \quad ...(1)$$

$$\boxed{W = LWT + DWT}$$

***Lightweight**(*LWT*) reflects the weight of vessel being ready to go to sea without cargo and loads. And lightweight can be composed of:
LWT = Structural weight + Outfit weight + Machinery weight

***Deadweight**(*DWT*) is the weight that a ship can load till the maximum allowable immersion(at the scantling draft(T_s)).
And deadweight can be composed of:
DWT= Payload+ Fuel oil + Diesel oil+ Fresh water +Ballast water + etc.

Physical Constraint

- **Physical constraint : hydrostatic equilibrium** $F_B = W$ ...(1)

$W = LWT + DWT$

∇ : the immersed volume of the ship.

ρ : density of sea water = 1.025 Mg/m^3

(L.H.S) **What is the buoyant force (F_B)?**
According to the Archimedes' principle,

the buoyant force on an immersed body has the same magnitude as the weight of the fluid displaced by the body.

$$\boxed{F_B = \underbrace{g \cdot \underbrace{\rho \cdot \underbrace{V}_{\text{Volume}}}_{\text{Mass}}}_{}}$$

Buoyant Force is the weight of the displaced fluid.

In shipbuilding and shipping society, those are called as follows :

- **Displacement volume** ∇
- **Displacement mass** Δ_m
- **Displacement** Δ

In shipbuilding and shipping society, **buoyant force** is called in another word, **displacement (Δ)**.

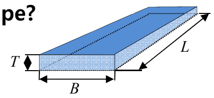
---

(4) Weight Equation

Block Coefficient (C_B)

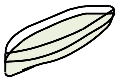
V : immersed volume
V_{box} : volume of box
L : length, B : breadth
T : draft

Does a ship or an airplane usually have box shape?



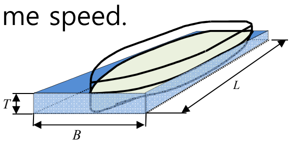
No!

They have a streamlined shape.



Why does a ship or an airplane has a streamlined shape?

They have a streamlined shape **to minimize the drag force** experienced when they travel, so that the propulsion engine needs a smaller power output to achieve the same speed.



Block coefficient(C_B) is **the ratio of the immersed volume to the box bounded by L, B, and T.**

$$C_B \equiv \frac{V}{V_{box}} = \frac{V}{L \cdot B \cdot T}$$

Shell Appendage Allowance

$$C_B = \frac{V}{L \cdot B \cdot T}$$

V : immersed volume
V_{box} : volume of box
L : length, B : breadth
T : draft
C_B : block coefficient

The immersed volume of the ship can be expressed by block coefficient.

$$V_{molded} = L \cdot B \cdot T \cdot C_B$$

In general, we have to consider the **displacement of shell plating and appendages such as propeller, rudder, shaft, etc.** additionally.
Thus, The total immersed volume of the ship can be expressed as following:

$$V_{total} = L \cdot B \cdot T \cdot C_B \cdot (1+\alpha)$$

Where the hull dimensions length L, beam B, and draft T are the **molded** dimensions of the immerged hull to the inside of the shell plating,

thus α is a fraction of the shell appendage allowance which adapts the **molded volume to the actual volume** by accounting for the volume of the shell plating and appendages (typically about 0.002~0.0025 for large vessels).

$$\boxed{F_B = g \cdot \rho \cdot V_{total} = \rho \cdot g \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha)}$$

Design Equations
- Weight Equation

- **Physical constraint:** **hydrostatic equilibrium** $F_B = W$ ...(1)
  (R.H.S) $W = LWT + DWT$
  (L.H.S) $F_B = \rho \cdot g \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha)$

ρ : density of sea water = 1.025 Mg/m^3
α : displacement of shell, stern and appendages
C_B : block coefficient
g : gravitational acceleration

$$\boxed{\rho \cdot g \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha) = LWT + DWT \text{...(2)}}$$

The equation (2) describes the physical constraint to be satisfied in ship design,

Unit of the Lightweight and Deadweight

- **Physical constraint**: hydrostatic equilibrium
  $F_B = W$ ...(1)

$$\boxed{\rho \cdot g \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha) = LWT + DWT \quad \text{...(2)}}$$

What is the unit of the lightweight and deadweight?

Design Equations
- Mass Equation

- **Physical constraint** : hydrostatic equilibrium

$$F_B = W \qquad ...(1)$$

In shipping and shipbuilding world, "ton" is used instead of "Mg (mega gram)" for the unit of the lightweight and deadweight in practice.

Actually, however, the weight equation is "mass equation".

$$\boxed{\rho \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha) = LWT + DWT \qquad ...(3)}$$

"Mass equation"

where, ρ = 1.025 Mg/m^3

---

(5) Volume Equation

Economical Constraints: Required Cargo Hold Capacity ➡ Volume Equation

- Economical constraints

  - Owner's requirements (Cargo hold capacity[m^3])
  - The main dimensions have to satisfy the required cargo hold capacity (V_{CH}).

$$\boxed{V_{CH} = f(L, B, D)}$$

: Volume equation of a ship

- It is checked whether the depth will allow the required cargo hold capacity.

---

(6) Service Speed & DFOC (Daily Fuel Oil Consumption)

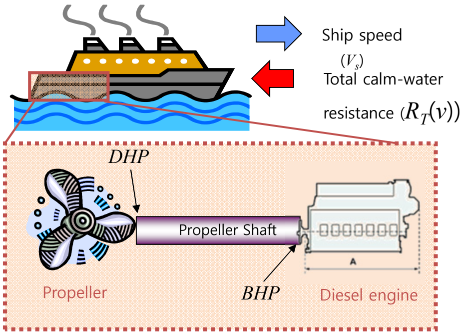
Economical Constraints : Required DFOC (Daily Fuel Oil Consumption)
➡ Hull Form Design and Hydrodynamic Performance Equation

☑ Goal: Meet the Required DFOC.

At first, we have to estimate <u>total calm-water resistance of a ship</u>

$$EHP = \boxed{R_T(v)} \cdot V_s$$

Then, the <u>required brake horse power</u> (BHP) can be predicted by estimating propeller efficiency, hull efficiency, relative rotative efficiency, shaft transmission efficiency, sea margin, and engine margin.

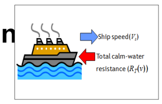


Economical Constraints : Required DFOC (Daily Fuel Oil Consumption)
➡ Propeller and Engine Selection

① EHP (Effective Horse Power)

$$EHP = \boxed{R_T(v)} \cdot V_s \quad \text{(in calm water)}$$

Resistance Estimation



② DHP (Delivered Horse Power)

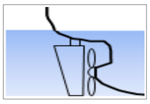
$$DHP = \frac{EHP}{\boxed{\eta_D}}$$

(η_D : Propulsive efficiency)

$\eta_D = \eta_O \cdot \eta_H \cdot \eta_R$
η_O : Open water efficiency
η_H : Hull efficiency
η_R : Relative rotative efficiency

Propeller Efficiency

Thrust deduction and wake
(due to additional resistance by propeller)
Hull-propeller interaction



③ BHP (Brake Horse Power)

$$BHP = \frac{DHP}{\eta_T}$$

(η_T : Transmission efficiency)

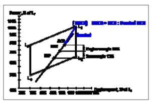
④ NCR (Normal Continuous Rating)

$$NCR = BHP(1 + \frac{\text{Sea Margine}}{100})$$

⑤ DMCR (Derated Maximum Continuous Rating)

$$\boxed{DMCR = \frac{NCR}{\text{Engine Margin}}}$$

Engine Selection



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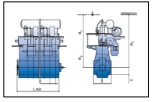
Engine Data



⑥ NMCR (Nominal Maximum Continuous Rating)

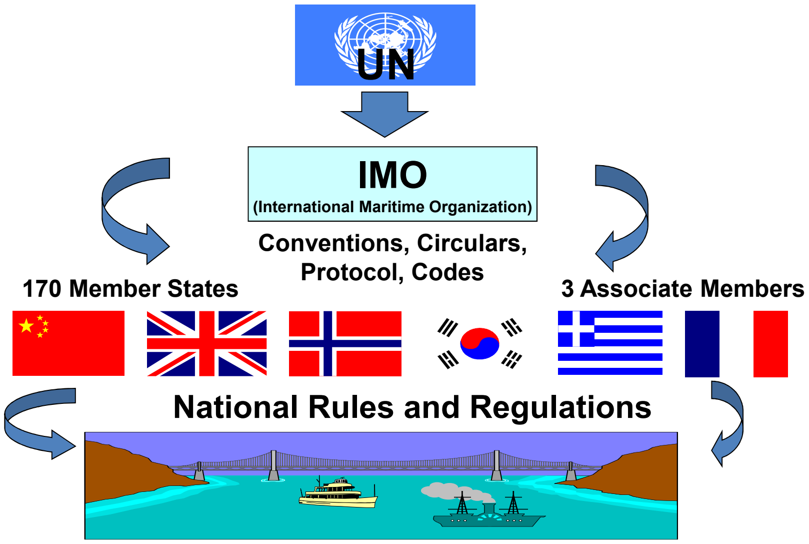
$$NMCR = \frac{DMCR}{\text{Derating rate}}$$

(7) Regulatory Constraints

Regulatory Constraints
- Rules by Organizations

- International Maritime Organizations (IMO)
- International Labor Organizations (ILO)
- Regional Organizations (EU, ...)
- Administrations (Flag, Port)
- Classification Societies
- International Standard Organizations (ISO)

IMO (International Maritime Organization)



UN

IMO

(International Maritime Organization)

Conventions, Circulars, Protocol, Codes

170 Member States

3 Associate Members

National Rules and Regulations

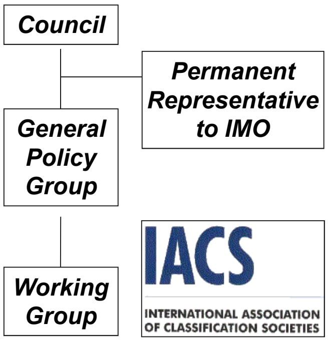
IMO Instruments

- ☑ Conventions
  - ■ SOLAS / MARPOL / ICLL / COLREG / ITC / AFS / BWM ……
- ☑ Protocols
  - ■ MARPOL Protocol 1997 / ICLL Protocol 1988
- ☑ Codes
  - ■ ISM / LSA / IBC / IMDG / IGC / BCH / BC / GC ……
- ☑ Resolutions
  - ■ Assembly / MSC / MEPC
- ☑ Circulars
  - ■ MSC / MEPC / Sub-committees ……

Regulatory Constraints
- Rules by Classification Societies

☑ 10 Members
- ABS (American Bureau of Shipping)
- DNV (Det Norske Veritas)
- LR (Lloyd's Register)
- BV (Bureau Veritas)
- GL (Germanischer Lloyd)
- KR (Korean Register of Shipping)
- RINA (Registro Italiano Navale)
- NK (Nippon Kaiji Kyokai)
- RRS (Russian Maritime Register of Shipping)
- CCS (China Classification Society)

☑ 2 Associate Members
- CRS (Croatian Register of Shipping)
- IRS (Indian Register of Shipping)



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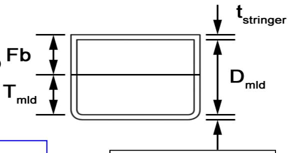
(8) Required Freeboard

Required Freeboard of ICLL 1966

- **Regulatory constraints**
  - **International Convention on Load Lines (ICLL)1966**



$$D_{Fb} = D_{mld} + t_{stringer}$$

$$D_{Fb} - T \ \geq \ Fb_{ICLL}(L, B, D_{mld}, C_B)$$

: Freeboard Equation

✓ **Check : Actual freeboard ($D_{Fb} - T$) of a ship should not be less than the freeboard required by the ICLL 1966 regulation (Fb_{ICLL}).**

Freeboard (Fb) means the distance between the water surface and the top of the deck at the side (at the deck line). It includes the thickness of freeboard deck plating.

- The freeboard is closely related to the draught.
  A 'freeboard calculation' in accordance with the regulation determines whether the desired depth is permissible.

Mathematical Formulation and Its Solution

Mathematical Model for Determination of Optimal Principal Dimensions of a Ship
- Summary ("Conceptual Ship Design Equation")

Find (Design variables) $L,\ B,\ D,\ C_B$ — length, breadth, depth, block coefficient

Given (Owner's requirements) $DWT,\ CC_{req},\ T_{max}(=T),\ V$ — deadweight, Required cargo hold capacity, maximum draft, ship speed

Physical constraint

→ Displacement - Weight equilibrium (Weight equation) – Equality constraint

$$L \cdot B \cdot T \cdot C_B \cdot \rho_{sw} \cdot C_\alpha = DWT_{given} + LWT(L, B, D, C_B)$$
$$= DWT_{given} + C_s \cdot L^{1.6}(B+D) + C_o \cdot L \cdot B$$
$$+ C_{power} \cdot (L \cdot B \cdot T \cdot C_B)^{2/3} \cdot V^3 \quad \cdots (2.3)$$

Economical constraints (Owner's requirements)

→ Required cargo hold capacity (Volume equation) - Equality constraint

$$CC_{req} = C_{CH} \cdot L \cdot B \cdot D \cdots (3.1)$$

- DFOC (Daily Fuel Oil Consumption)
  : It is related with the resistance and propulsion.
- Delivery date
  : It is related with the shipbuilding process.

Regulatory constraint

→ Freeboard regulation (ICLL 1966) - Inequality constraint

$$D \ge T + C_{FB} \cdot D \cdots (4)$$

$$Min. Roll\ Period : e.g.,$$
$$T_R \ge 12 \text{ sec} ....(6)$$

Stability regulation (MARPOL, SOLAS, ICLL)

$$GM \ge GM_{Required} \cdots (5)$$
$$GZ \ge GZ_{Required}$$

Objective function (Criteria to determine the proper principal dimensions)

$$Building\ Cost = C_{PS} \cdot C_s \cdot L^{1.6}(B+D) + C_{PO} \cdot C_o \cdot L \cdot B + C_{PM} \cdot C_{power} \cdot (L \cdot B \cdot T \cdot C_B)^{2/3} \cdot V^3$$

4 variables (L, B, D, C_B), 2 equality constraints ((2.3), (3.1)), 3 inequality constraints ((4), (5), (6))
➡ Optimization problem

Determination of the Optimal Principal Dimensions of a Ship by Using the Lagrange Multiplier (1/5)

- *Given*: $DWT, CC_{req}, D, T_s, T_d$
- *Find*: L, B, C_B
  - Hydrostatic equilibrium (Weight equation)

$$L \cdot B \cdot T_s \cdot C_B \cdot \rho_{sw} \cdot C_\alpha = DWT_{given} + LWT(L, B, D, C_B)$$
$$= DWT_{given} + \boxed{C_s \cdot L^{1.6} \cdot (B+D)} + C_o \cdot L \cdot B + \boxed{C_{power} \cdot (L \cdot B \cdot T_d \cdot C_B)^{2/3} \cdot V^3} \quad ...(a)$$

Simplify ①
$$\rightarrow C_s{}' \cdot L^{2.0} \cdot (B+D)$$

Simplify ②
$$\rightarrow C_{power}{}' \cdot (2 \cdot B \cdot T_d + 2 \cdot L \cdot T_d + L \cdot B) \cdot V^3$$

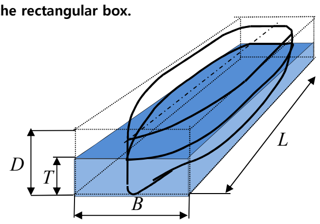
$(L \cdot B \cdot T_d \cdot C_B)^{2/3}$ is (Volume)$^{2/3}$ and means the submerged area of the ship. So, we assume that the submerged area of the ship is equal to the submerged area of the rectangular box.

  - Required cargo hold capacity (Volume equation)

$$CC_{req} = C_{CH} \cdot L \cdot B \cdot D \quad ...(b)$$

  - Recommended range of obesity coefficient considering maneuverability of a ship

$$\frac{C_B}{(L/B)} < 0.15 \quad ...(c)$$



➡ Indeterminate Equation: 3 variables (L, B, C_B), 2 equality constraints ((a), (b))

⇨ It can be formulated as an optimization problem to minimize an objective function.

Determination of the Optimal Principal Dimensions of a Ship by Using the Lagrange Multiplier (2/5)

- ***Given***: $DWT, V_{H.req}, D, T_s, T_d$
- ***Find***: L, B, C_B
- ***Minimize***: **Building Cost**

$$f(L,B,C_B) = C_{PS} \cdot C_s' \cdot L^{2.0} \cdot (B+D) + C_{PO} \cdot C_o \cdot L \cdot B + C_{PM} \cdot C_{power}' \cdot (2 \cdot B \cdot T_d + 2 \cdot L \cdot T_d + L \cdot B) \cdot V^3$$

- ***Subject to*** $\quad ...(d)$
  - **Hydrostatic equilibrium (Simplified weight equation)**

$$L \cdot B \cdot T_s \cdot C_B \cdot \rho_{sw} \cdot C_\alpha = DWT_{given} + LWT(L,B,D,C_B)$$

$$= DWT_{given} + C_s' \cdot L^{2.0} \cdot (B+D) + C_o \cdot L \cdot B + C_{power}' \cdot (2 \cdot B \cdot T_d + 2 \cdot L \cdot T_d + L \cdot B) \cdot V^3 \quad ...(a')$$

$$CC_{req} = C_{CH} \cdot L \cdot B \cdot D \quad ...(b)$$

$$\frac{C_B}{(L/B)} < 0.15 \quad ...(c)$$

Determination of the Optimal Principal Dimensions of a Ship by Using the Lagrange Multiplier (3/5)

- **By introducing the Lagrange multipliers λ_1, λ_2, u, formulate the Lagrange function H.**

$$H(L,B,C_B,\lambda_1,\lambda_2,u,s) = f(L,B,C_B) + \lambda_1 \cdot h_1(L,B,C_B) + \lambda_2 \cdot h_2(L,B,D) + u \cdot g(L,B,C_B,s) \quad ...(e)$$

$$f(L,B,C_B) = C_{PS} \cdot C_s' \cdot L^2 \cdot (B+D) + C_{PO} \cdot C_o \cdot L \cdot B + C_{PM} \cdot C_{power}' \cdot \{2 \cdot (B+L) \cdot T_d + L \cdot B\} \cdot V^3$$

$$h_1(L,B,C_B) = L \cdot B \cdot T_s \cdot C_B \cdot \rho_{sw} \cdot C_\alpha - DWT_{given} - C_s' \cdot L^{2.0} \cdot (B+D) - C_o \cdot L \cdot B - C_{power}' \cdot \{2 \cdot (B+L) \cdot T_d + L \cdot B\} \cdot V^3$$

$$h_2(L,B,D) = C_{CH} \cdot L \cdot B \cdot D - CC_{req}$$

$$g(L,B,C_B,s) = \frac{C_B}{(L/B)} - 0.15 + s^2$$

$$L \rightarrow x_1, B \rightarrow x_2, C_B \rightarrow x_3$$

$$H(x_1,x_2,x_3,\lambda_1,\lambda_2,u,s)$$

$$= C_{PS} \cdot C_s' \cdot x_1^2 (x_2+D) + C_{PO} \cdot C_o \cdot x_1 \cdot x_2 + C_{PM} \cdot C_{power}' \cdot \{2 \cdot (x_2+x_1) \cdot T_d + x_1 \cdot x_2\} \cdot V^3$$

$$+\lambda_1 \cdot [x_1 \cdot x_2 \cdot T_s \cdot x_3 \cdot \rho_{sw} \cdot C_\alpha - DWT_{given} - C_s \cdot x_1^2 \cdot (x_2+D) - C_o \cdot x_1 \cdot x_2 - C_{power}' \cdot \{2 \cdot (x_2+x_1) \cdot T_d + x_1 \cdot x_2\} \cdot V^3]$$

$$+\lambda_2 \cdot (C_{CH} \cdot x_1 \cdot x_2 \cdot D - CC_{req})$$

$$+u \cdot \{x_3/(x_1/x_2) - 0.15 + s^2\} \quad ...(f)$$

Determination of the Optimal Principal Dimensions of a Ship by Using the Lagrange Multiplier (4/5)

$L \rightarrow x_1, B \rightarrow x_2, C_B \rightarrow x_3$

$$H\left(x_1,x_2,x_3,\lambda_1,\lambda_2,u,s\right)=C_{PS}\cdot C_s'\cdot x_1^2(x_2+D)+C_{PO}\cdot C_o\cdot x_1\cdot x_2+C_{PM}\cdot C_{power}'\cdot\{2\cdot\left(x_2+x_1\right)\cdot T_d+x_1\cdot x_2\}\cdot V^3$$
$$+\lambda_1\cdot[x_1\cdot x_2\cdot T_s\cdot x_3\cdot\rho_{sw}\cdot C_\alpha-DWT_{given}-C_s\cdot x_1^2\cdot(x_2+D)-C_o\cdot x_1\cdot x_2-C_{power}'\cdot\{2\cdot\left(x_2+x_1\right)\cdot T_d+x_1\cdot x_2\}\cdot V^3]$$
$$+\lambda_2\cdot\left(C_{CH}\cdot x_1\cdot x_2\cdot D-CC_{req}\right)+u\cdot\left\{x_3/\left(x_1/x_2\right)-0.15+s^2\right\}\quad ...(f)$$

- **To determine the stationary point (** x_1, x_2, x_3 **) of the Lagrange function** H **(equation (** f **)), use the Kuhn-Tucker necessary condition:** $\nabla H\left(x_1,x_2,x_3,\lambda_1,\lambda_2,u,s\right)=0$ **.**

$$\frac{\partial H}{\partial x_1}=2C_{PS}\cdot C_s'\cdot x_1\cdot(x_2+D)+C_{PO}\cdot C_o\cdot x_2+C_{PM}\cdot C_{power}'\cdot\left(2\cdot T_d+x_2\right)\cdot V^3$$
$$+\lambda_1\cdot(x_2\cdot T_s\cdot x_3\cdot\rho_{sw}\cdot C_\alpha-[2\cdot C_s\cdot x_1\cdot(x_2+D)+C_o\cdot x_2+C_{power}'\cdot(2\cdot T_d+x_2)\cdot V^3])$$
$$+\lambda_2\cdot\left(C_{CH}\cdot x_2\cdot D\right)+u\cdot\left(-x_3\cdot x_2/x_1^2\right)=0\quad ...(1)$$

$$\frac{\partial H}{\partial x_2}=C_{PS}\cdot C_s'\cdot x_1^2+C_{PO}\cdot C_o\cdot x_1+C_{PM}\cdot C_{power}'\cdot(2\cdot T_d+x_1)\cdot V^3$$
$$+\lambda_1\cdot[x_1\cdot T_s\cdot x_3\cdot\rho_{sw}\cdot C_\alpha-C_s'\cdot x_1^2-C_o\cdot x_1-C_{power}'(2\cdot T_d+x_1)\cdot V^3]$$
$$+\lambda_2\cdot\left(C_{CH}\cdot x_1\cdot D\right)+u\cdot\left(x_3/x_1\right)=0\quad ...(2)$$

Determination of the Optimal Principal Dimensions of a Ship by Using the Lagrange Multiplier (5/5)

$L \rightarrow x_1, B \rightarrow x_2, C_B \rightarrow x_3$

$$H\left(x_1,x_2,x_3,\lambda_1,\lambda_2,u,s\right)=C_{PS}\cdot C_s'\cdot x_1^2(x_2+D)+C_{PO}\cdot C_o\cdot x_1\cdot x_2+C_{PM}\cdot C_{power}'\cdot\{2\cdot\left(x_2+x_1\right)\cdot T_d+x_1\cdot x_2\}\cdot V^3$$
$$+\lambda_1\cdot[x_1\cdot x_2\cdot T_s\cdot x_3\cdot\rho_{sw}\cdot C_\alpha-DWT_{given}-C_s\cdot x_1^2\cdot(x_2+D)-C_o\cdot x_1\cdot x_2-C_{power}'\cdot\{2\cdot\left(x_2+x_1\right)\cdot T_d+x_1\cdot x_2\}\cdot V^3]$$
$$+\lambda_2\cdot\left(C_{CH}\cdot x_1\cdot x_2\cdot D-CC_{req}\right)+u\cdot\left\{x_3/\left(x_1/x_2\right)-0.15+s^2\right\}\quad ...(f)$$

- **Kuhn-Tucker necessary condition:** $\nabla H\left(x_1,x_2,x_3,\lambda_1,\lambda_2,u,s\right)=0$

$$\frac{\partial H}{\partial x_3}=\lambda_1.x_1\cdot x_2\cdot T_s\cdot\rho_{sw}\cdot C_\alpha+u\cdot\left(x_2/x_1\right)=0\quad ...(3)$$

$$\frac{\partial H}{\partial \lambda_1}=x_1\cdot x_2\cdot T_s\cdot x_3\cdot\rho_{sw}\cdot C_\alpha-DWT_{given}-C_s\cdot x_1^2\cdot(x_2+D)-C_o\cdot x_1\cdot x_2$$
$$-C_{power}'\cdot\{2\cdot\left(x_2+x_1\right)\cdot T_d+x_1\cdot x_2\}\cdot V^3\quad\cdots(4)$$

$$\frac{\partial H}{\partial \lambda_2}=C_{CH}\cdot x_1\cdot x_2\cdot D-CC_{req}=0\quad ...(5)$$

$$\frac{\partial H}{\partial u}=x_3\cdot x_2/x_1-0.15+s^2=0\quad ...(6)$$

$$\frac{\partial H}{\partial s}=2\cdot u\cdot s=0,\quad\left(u\geq 0\right)\quad ...(7)$$

$\nabla H(x_1, x_2, x_3, \lambda_1, \lambda_2, u, s)$**: Nonlinear simultaneous equation having the 7 variables ((1)~(7)) and 7 equations**

➡ It can be solved by using a numerical method!

Example for the Determination of Optimal Principal Dimensions of a Bulk Carrier

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Determination of Optimal Principal Dimensions of a Bulk Carrier - Problem Definition

☑ **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

Determination of Optimal Principal Dimensions of a Bulk Carrier - Problem Formulation

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)

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

Required cargo hold capacity condition (Inequality constraint)

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

Required freeboard condition (Inequality constraint)

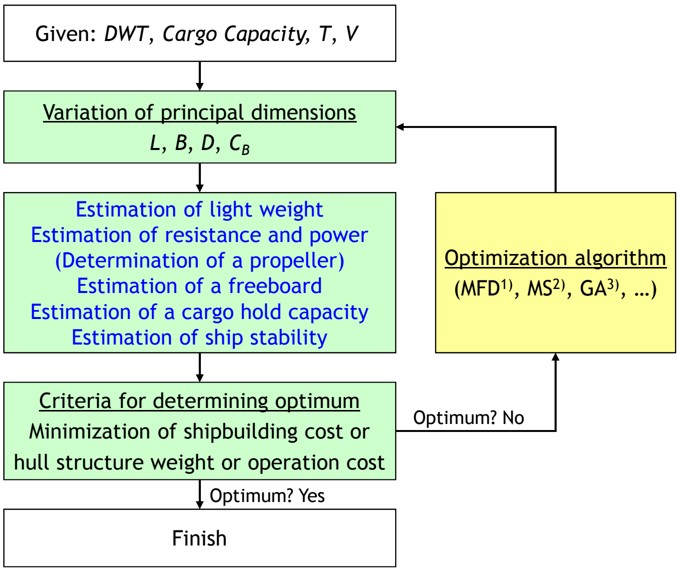
$$D \ge T + C_{FB} \cdot D$$

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



Given: *DWT*, *Cargo Capacity*, *T*, *V*

Variation of principal dimensions
L, *B*, *D*, C_B

Estimation of light weight
Estimation of resistance and power
(Determination of a propeller)
Estimation of a freeboard
Estimation of a cargo hold capacity
Estimation of ship stability

Criteria for determining optimum
Minimization of shipbuilding cost or hull structure weight or operation cost

Optimum? No

Optimization algorithm
(MFD¹⁾, MS²⁾, GA³⁾, …)

Optimum? Yes

Finish

---

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

Determination of Optimal Principal Dimensions of a Bulk Carrier - Given Information

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		
F O C	SFOC	126.0 g/HP.H		Based on NCR
	TON/DAY	41.6		
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

Determination of Optimal Principal Dimensions of a Bulk Carrier - Optimization Result

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

Example for the Determination of Optimal Principal Dimensions of a Naval Ship

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Determination of Optimal Principal Dimensions of a Naval Ship

☑ **Problem for determining optimal principal dimensions of a 9,000ton missile destroyer (DDG)**

- **Objective**
  - **Minimization of a power (BHP) or Fuel Consumption (FC) of a main engine (f_1)**

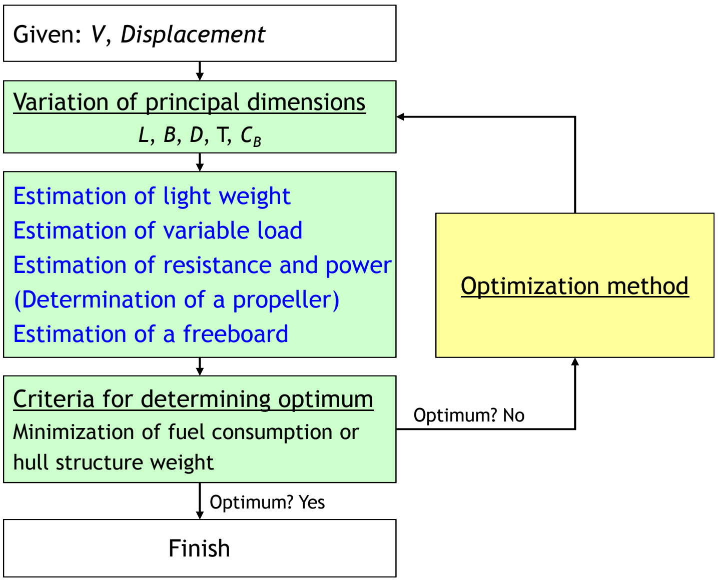
  or

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

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

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

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



Given: *V*, *Displacement*

Variation of principal dimensions
L, *B*, *D*, T, C_B

Estimation of light weight
Estimation of variable load
Estimation of resistance and power
(Determination of a propeller)
Estimation of a freeboard

Criteria for determining optimum
Minimization of fuel consumption or hull structure weight

Optimum? No

Optimization method

Optimum? Yes

Finish

Mathematical Formulation of a Problem for Determining Optimal Principal Dimensions of a Naval Ship

Find L, B, D, T, C_B

Design Variables

Minimize $BHP[HP](\text{or } FC[kg/h])$ 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**

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)

* $w_1 = w_2 = 0.5$

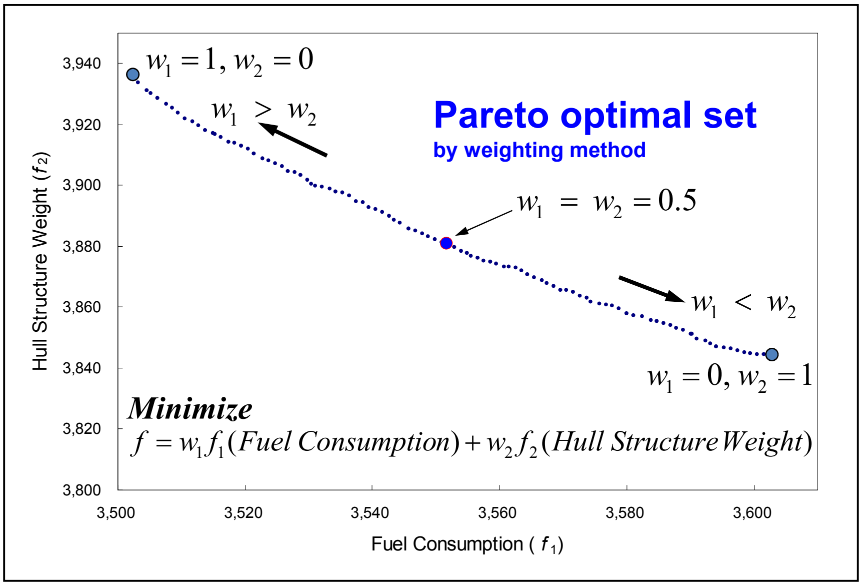
	Unit	DDG-51	MFD	MS	GA	HYBRID w/o Refine	HYBRID with Refine
L	m	142.04	157.37	157.02	156.74	156.54	156.51
B	m	17.98	19.99	19.98	19.82	19.85	19.82
D	m	12.80	12.70	12.69	12.73	12.82	12.84
T	m	6.40	5.61	5.62	5.67	5.77	5.80
C_B	-	0.508	0.510	0.506	0.506	0.508	0.508
P_i	m	8.90	9.02	9.51	9.33	9.50	9.05
A_E/A_O	-	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
$w_1 f_1 + w_2 f_2$	-	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	CASE 2	CASE 3
			Minimize f_1 (fuel consumption)	Minimize f_2 (hull structure weight)	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



$w_1 = 1, w_2 = 0$

$w_1 > w_2$

Pareto optimal set

by weighting method

$w_1 = w_2 = 0.5$

$w_1 < w_2$

$w_1 = 0, w_2 = 1$

Minimize

$$f = w_1 f_1(Fuel\ Consumption) + w_2 f_2(Hull\ Structure\ Weight)$$

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

---

8.4 Determination of Optimal Principal Dimensions of Hatch Cover

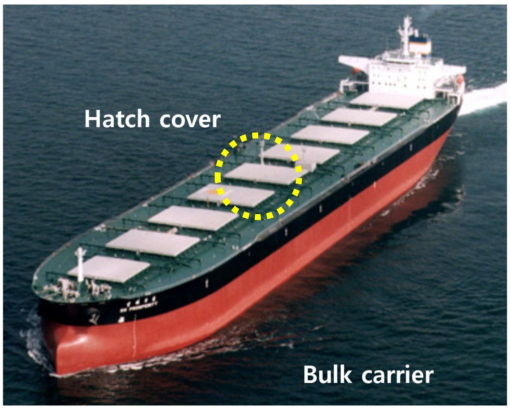
Generals
Mathematical Formulation and Its Solution
Example

Generals

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.

Mathematical Formulation and Its Solution

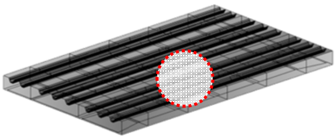
Idealization of Hatch Cover of a Bulk Carrier

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

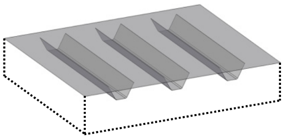
☑ The hatch cover can be idealized for the effective optimization.

☑ 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

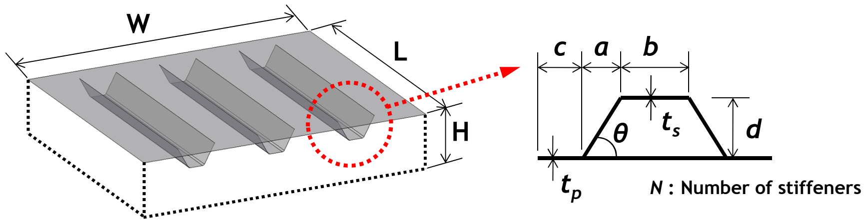
☑ Criteria for determining optimal principal dimensions (Objective function)
- Minimization of the weight of hatch cover

☑ 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

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

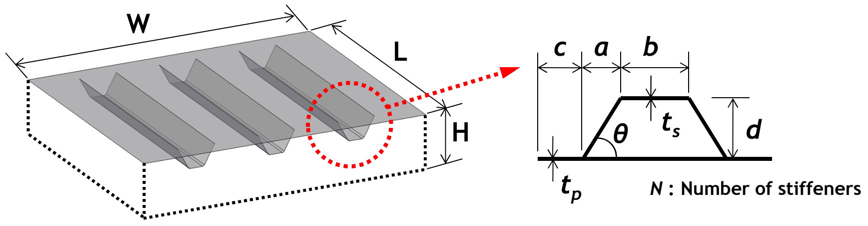
➡ Optimization problem having 6 design variables (unknowns) and 8 inequality constraints

---

Mathematical Formulation of an Optimization Problem - Design Variables

☑ The shape of the hatch cover, that is, principal dimensions can be represented with six parameters.

- Plate thickness (t_p), stiffener thickness (t_s), stiffener size (*b*, *a*, *d*), and number of stiffeners (*N*)
- These are design variables of the optimization problem.
- Cf. Dependent variables: *c*, *θ*



Idealized model

Stiffener section

Mathematical Formulation of an Optimization Problem - Constraints (1/6)

☑ **Maximum Permissible Stress of the Hatch Cover**

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

where,

$\sigma_v = \sqrt{\sigma^2 + 3\tau^2} \; [N/mm^2]$ or $\sigma_v = \sqrt{\sigma_x^2 - \sigma_x \cdot \sigma_y + \sigma_y^2 + 3\tau^2} \; [N/mm^2]$

(σ_v: equivalent stress, τ: shear stress, σ_x and σ_y: normal stress in x- and y- direction)

$\sigma = \sigma_b + \sigma_n$

(σ_b: bending stress, σ_n: normal stress)

R_{eH}: yield strength, given as: 235 [N/mm^2] for mild steel,
315 [N/mm^2] for AH32, 355 [N/mm^2] for AH36

Mathematical Formulation of an Optimization Problem - Constraints (2/6)

☑ **Maximum Permissible Deflection of the Hatch Cover**

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

where,

f: deflection [m] of the hatch cover

l_g: The largest span [m] of girders in the hatch cover

Mathematical Formulation of an Optimization Problem - Constraints (3/6)

☑ **Minimum Thickness of a Top Plate of the Hatch Cover**

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

where,

$$t_{\min} = \max(t_1, t_2, t_3) \qquad t_1 = 16.2 \cdot c_p \cdot c \cdot \sqrt{\frac{p}{R_{eH}}} + t_k \ [mm]$$

$$t_2 = 10 \cdot c + t_k \ [mm] \qquad t_3 = 6.0 + t_k \ [mm]$$

t_k: corrosion additions (2.0 mm for hatch covers in general, See Table 17.1 in [1])
c_p: coefficient, defined as

$$c_p = 1.5 + 2.5 \cdot \left(\frac{|\sigma|}{R_{eH}} - 0.64 \right) \ge 1.5 \ \text{ for } p = p_H$$

c: spacing [m] of stiffeners
p: design load [kN/m^2]
p_H: load on the hatch cover [kN/m^2] (See Table 17.2 in [1])

---

[1] Germanischer Lloyd, 2014. Rules for classification and construction, Rules I. Ship Technology, Part 1. Seagoing Ships, Chapter 1. Hull Structures, Section 17. Cargo Hatchways, Germanischer Lloyd

Mathematical Formulation of an Optimization Problem - Constraints (4/6)

☑ **Minimum Section Modulus of Stiffeners of the Hatch Cover**

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

where,

M_{net}: net section modulus [cm^3]

$M_{\min}$: minimum section modulus, defined as

$$M_{net} = \frac{104}{R_{eH}} \cdot c \cdot l^2 \cdot p \ [cm^3]$$

Mathematical Formulation of an Optimization Problem - Constraints (5/6)

☑ **Minimum Shear Area of Stiffeners of the Hatch Cover**

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

where,

A_{net}: net shear area [cm^2]

$A_{\min}$: minimum shear area, defined as

$$A_{\min} = \frac{10 \cdot c \cdot l \cdot p}{R_{eH}} \ [cm^2]$$

l: unsupported span [m] of stiffener

Mathematical Formulation of an Optimization Problem - Constraints (6/6)

☑ **Geometric Limitations Related to the Shape of the Hatch Cover**

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

where,

W: width [m] of the hatch cover

D: depth [m] of the hatch cover

θ: angle between the plate and stiffener

➡ **This optimization problem has total 8 inequality constraints.**

Mathematical Formulation of an Optimization Problem - Objective Function

☑ **An optimal hatch cover means a hatch cover having minimum weight.**

☑ **Thus, the weight of the hatch cover was selected as the objective function of the optimization problem.**

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

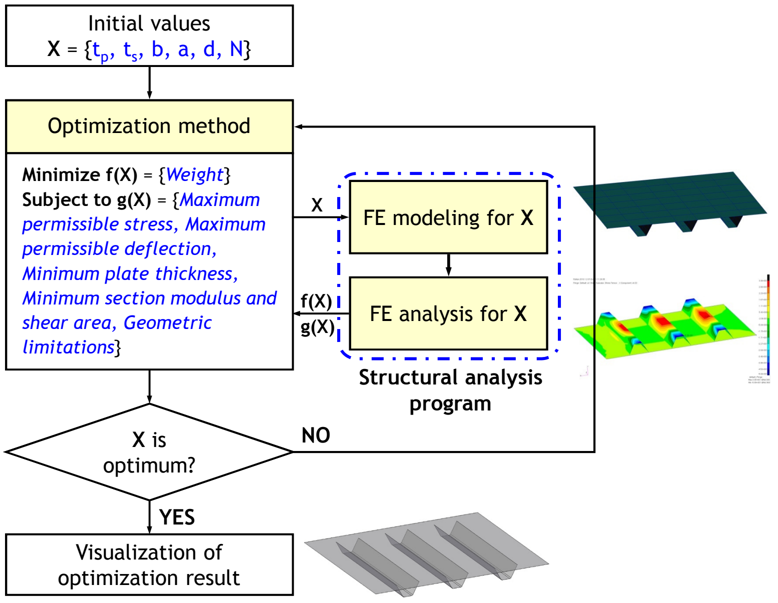
where,

ρ_p and ρ_s: specific gravity [ton/m^3] of plate and stiffener, respectively

L: length [m] of the hatch cover

$A_{\min}$: stiffener thickness [mm]

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



Initial values
X = {t_p, t_s, b, a, d, N}

Optimization method

Minimize f(X) = {*Weight*}
Subject to g(X) = {*Maximum permissible stress, Maximum permissible deflection, Minimum plate thickness, Minimum section modulus and shear area, Geometric limitations*}

X

FE modeling for X

FE analysis for X

f(X)
g(X)

Structural analysis program

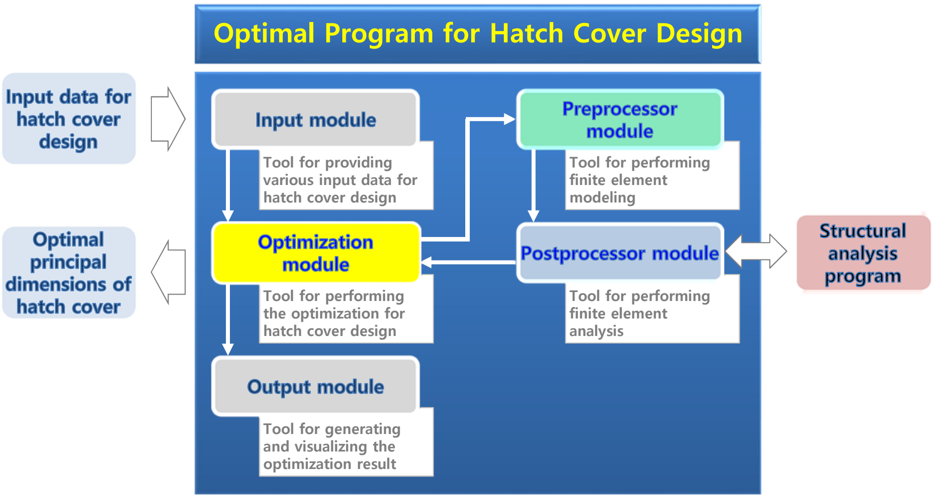
X is optimum?

NO

YES

Visualization of optimization result

Optimization Program for the Hatch Cover Design - Configuration



Optimal Program for Hatch Cover Design

Input data for hatch cover design

Optimal principal dimensions of hatch cover

Input module
Tool for providing various input data for hatch cover design

Optimization module
Tool for performing the optimization for hatch cover design

Output module
Tool for generating and visualizing the optimization result

Preprocessor module
Tool for performing finite element modeling

Postprocessor module
Tool for performing finite element analysis

Structural analysis program

Optimization Program for the Hatch Cover Design - Components (1/5)

☑ Input Module

- The input module inputs some data for optimization of the hatch cover from a designer.
- The data includes the size (length, width, and depth) of the hatch cover, materials of plate and stiffeners, and so on.
- In addition, the input module generates initial values for design variables and transfers them to the optimization module.

Optimization Program for the Hatch Cover Design - Components (2/5)

☑ Optimization Module

- The optimization module includes the multi-start optimization algorithm.
- The module calculates the values of an objective function and constraints are calculated.
- By using the values, the module improves the current values of the design variables.
- At this time, the finite element modeling and analysis for the current values of the design variables should be performed in order to calculate some structural responses such as the stress and deflection of the hatch cover for the values of the design variables.
- Thus, this module is linked with the preprocessor and postprocessor modules, and calls them when needed.

Optimization Program for the Hatch Cover Design - Components (3/5)

☑ Preprocessor Module

- To calculate the structural responses by using a structural analysis program, a finite element model is required.
- The preprocessor module is used to generate the finite element model for the current values of the design variables.
- That is, the role of the module is the finite element modeling.
- In this module, an input file for the execution of the structural analysis program is generated with the current values of the design variables.
- The input file is transferred to the postprocessor module.

Optimization Program for the Hatch Cover Design - Components (4/5)

☑ Postprocessor Module

- In the post processor module, the structural analysis program is executed with the input file from the preprocessor module.
- That is, the role of the module is to perform the finite element analysis.
- In this study, the ANSYS which is one of commercial structural analysis programs was used for the structural analysis.
- After performing the finite element analysis with the structural analysis program, the structural responses such as the stress and deflection of the hatch cover can be acquired.
- The values of the structural responses are written in the output file by the structural analysis program.
- The postprocessor module parses the output file by the structural analysis program, and transfers the values of the structural responses to the optimization module.

Optimization Program for the Hatch Cover Design - Components (5/5)

☑ Output Module

- The output module outputs an optimization result from the optimization module.
- The result includes optimal dimensions (optimal values of the design variables), weight, maximum stress, maximum deflection of the hatch cover, and so on.

Example

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

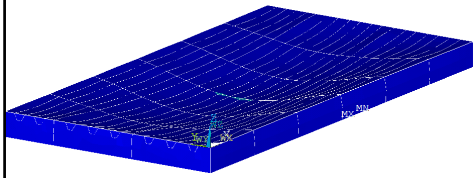
$0^\circ < \theta \le 90^\circ$: geometric limitation

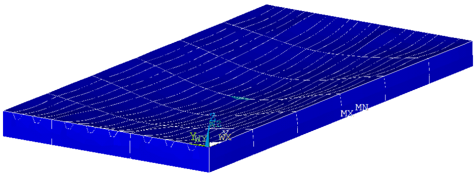
➡ **Optimization problem having 6 design variables and 8 inequality constraints**

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

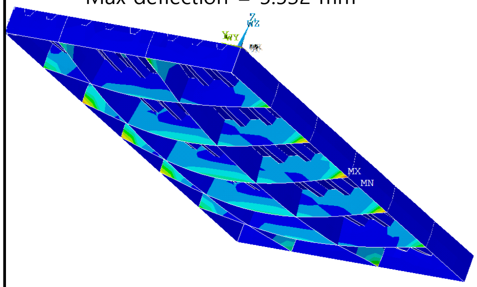
Hatch Cover Design of a Deadweight 180,000 ton Bulk Carrier
- Optimization Result (2/2)

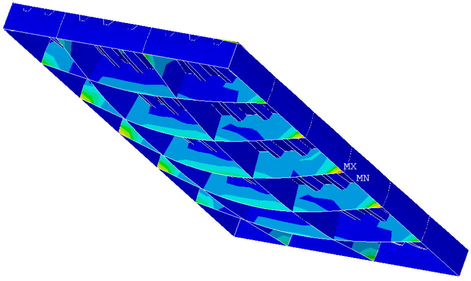




Max equivalent stress = 218 Mpa
Max deflection = 5.532 mm

Max equivalent stress = 252 Mpa
Max deflection = 6.388 mm





Before optimization
(manual design)

After optimization
(this study)

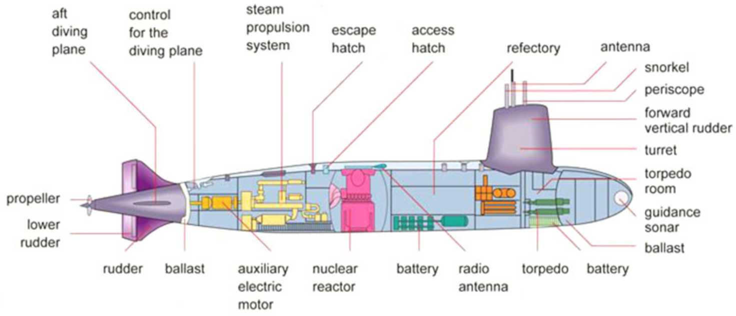
8.5 Determination of Optimal Principal Dimensions of Submarine

Generals
Mathematical Formulation and Its Solution
Example

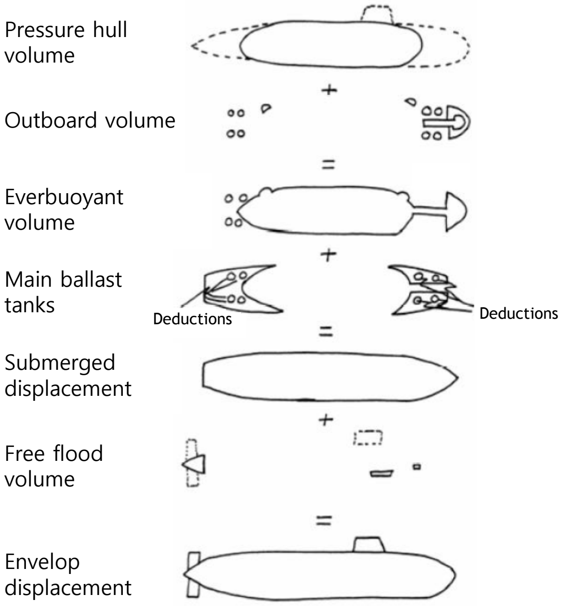
Generals

Composition of Submarine

- ☑ **Hull Structure**
- ☑ **Propulsion Systems**
- ☑ **Electric Systems**
- ☑ **Command and Control Systems**
- ☑ **Auxiliary Systems**
- ☑ **Outfit and Furnishing**
- ☑ **Armament**



Volume and Displacement of Submarine (1/3)



Pressure hull volume

+

Outboard volume

=

Everbuoyant volume

+

Main ballast tanks

Deductions

Deductions

=

Submerged displacement

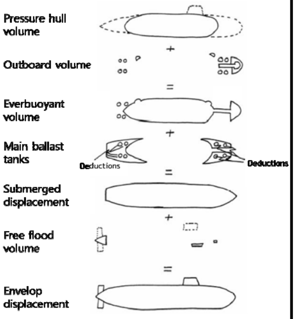
+

Free flood volume

=

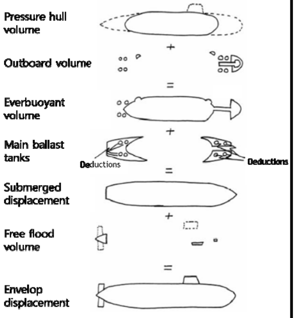
Envelop displacement

Volume and Displacement of Submarine (2/3)



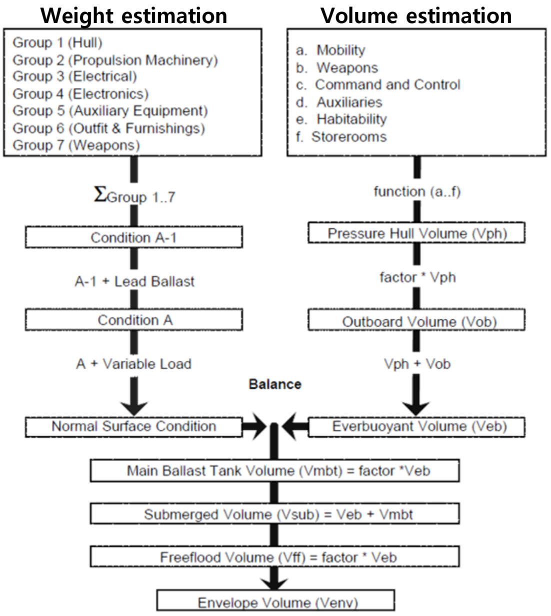
- ☑ **Pressure Hull Volume**
  - ■ Watertight volume having important parts of submarine
- ☑ **Outboard Volume**
  - ■ Volume of weapons and propulsion systems which are installed outside of pressure hull
- ☑ **Everbuoyant Volume**
  - ■ Total volume related to buoyancy among volumes of submarine
  - ■ Basis for calculating Normal Surface Condition Weight (NSCW)
  - ■ NSCW = Ever buoyant volume / density of sea water

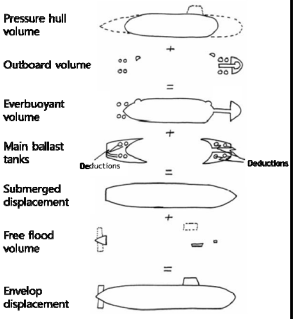
Volume and Displacement of Submarine (3/3)



- ☑ **Main Ballast Tanks**
  - ■ Volume of ballast tanks required for controlling trim (attitude) of submarine
- ☑ **Submerged Displacement**
  - ■ Ever buoyant volume + Main ballast tanks
- ☑ **Free Flood Volume**
  - ■ Volume of the region that sea water can move freely
- ☑ **Envelop Displacement**
  - ■ Submerged displacement + Free flood volume

Balance Control of Submarine





Weight Estimation of Submarine

☑ **Composition of Weight (Displacement)**

- **Lightweight (LWT) + Variable Load (VL, cargo weight)**
- **Most of displacement becomes the lightweight.**

☑ **Weight Estimation Method (SWBS* Group of US Navy)**

Group	Item
100	Hull Structure
200	Propulsion
300	Electric Systems
400	Communication and Control
500	Auxiliary System
600	Outfitting and Furnishing
700	Armament

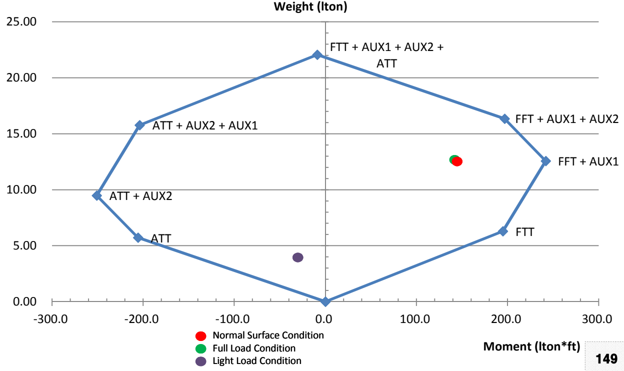
* Straubinger, E.K., Curran, V.L., "Fundamentals of Naval Surface Ship Weight Estimating, Naval Engineers Journal, pp.127-143, 1983.
* SWBS : Ships Work Breakdown Structure

Meaning of Equilibrium Polygon (1/2)

☑ The equilibrium polygon is a graphical tool that is used to ensure that the submarine will be able to remain neutrally buoyant and trimmed level while submerged in any operating (loading) condition.

☑ In all operating conditions the ship must be able to compensate which is accomplished through the variable ballast tanks.

☑ The polygon is a diagram of weight vs. moment.

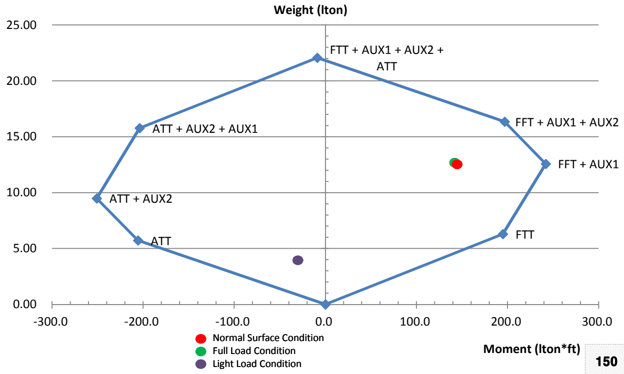


Meaning of Equilibrium Polygon (2/2)

☑ The boundaries of the graphic are calculated from the variable tanks.

☑ Weights and moments are then calculated based on their compensation for all extreme loading conditions.

☑ The ship is adequately able to compensate for each loading conditions if each point lies within the polygon.



Mathematical Formulation and Its Solution

Mathematical Formulation of a Problem for Determining Optimal Principal Dimensions of a Submarine

Find $\mathbf{X} = \{L_{bow}, L_{mid}, L_{aft}, B, D, C_{man}, ASW, C4I, ISR, MCM, SPW, PSYS, BAT_{typ}, N_g\}$

Maximize $F_1 = Performance(\mathbf{X})$ ***and***

: Overall measure of performance

Minimize $F_2 = Cost(\mathbf{X})$ ***and*** $F_3 = Risk(\mathbf{X})$

: Cost

: Overall measure of risk

Subject to

$g_1 = atr - ata(\mathbf{X}) \le 0$: Constraint about the allowable area

$g_2 = vff_{\min} - vff(\mathbf{X}) \le 0$: Constraint about the minimum free flood volume

$g_3 = vff(\mathbf{X}) - vff_{\max} \le 0$: Constraint about the maximum free flood volume

$g_4 = wlead_{\min} - W_8(\mathbf{X}) \le 0$: Constraint about the minimum lead ballast

$g_5 = W_8(\mathbf{X}) - wlead_{\max} \le 0$: Constraint about the maximum lead ballast

$g_6 = Vs_{\min} - Vs(\mathbf{X}) \le 0$: Constraint about the minimum sustained speed

$g_7 = KWg_{req} - KWg(\mathbf{X}) \le 0$: Constraint about the required electrical power

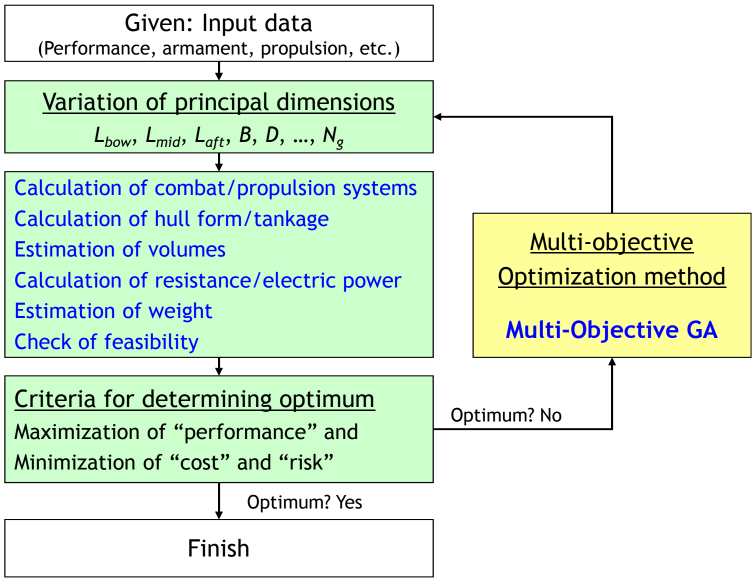
$g_8 = GM_{\min} - GM(\mathbf{X}) \le 0$ $g_9 = GB_{\min} - GB(\mathbf{X}) \le 0$: Constraints about the minimum GM and GB

$g_{10} = E_{\min} - E(\mathbf{X}) \le 0$: Constraint about the minimum endurance range

$g_{11} = Es_{\min} - Es(\mathbf{X}) \le 0$: Constraint about the minimum sprint range

➡ **Optimization problem having 14 design variables, 11 inequality constraints, and 3 objective functions**

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



Given: Input data
(Performance, armament, propulsion, etc.)

Variation of principal dimensions
L_{bow}, L_{mid}, L_{aft}, B, D, …, N_g

Calculation of combat/propulsion systems
Calculation of hull form/tankage
Estimation of volumes
Calculation of resistance/electric power
Estimation of weight
Check of feasibility

Criteria for determining optimum
Maximization of "performance" and
Minimization of "cost" and "risk"

Optimum? No

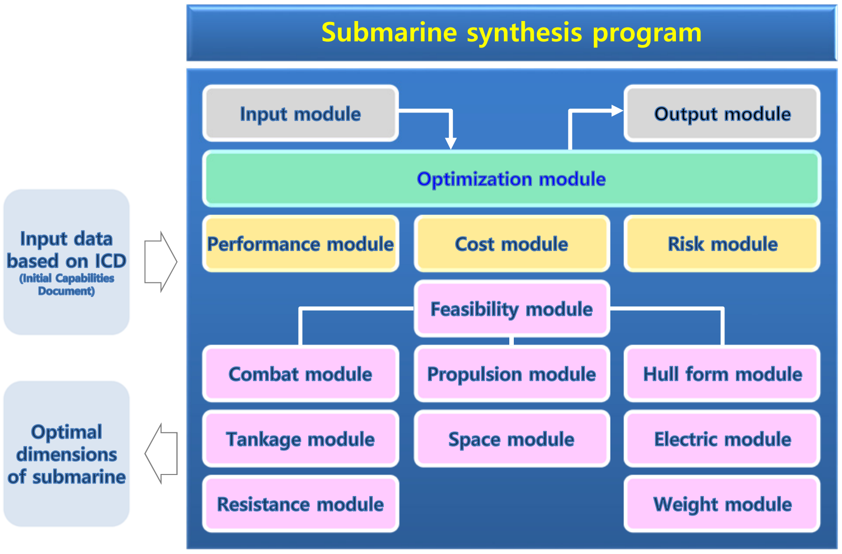
Multi-objective Optimization method

Multi-Objective GA

Optimum? Yes

Finish

Optimization Program for Conceptual Design of Submarine - Configuration



Submarine synthesis program

Input module
Output module
Optimization module
Performance module
Cost module
Risk module
Feasibility module
Combat module
Propulsion module
Hull form module
Tankage module
Space module
Electric module
Resistance module
Weight module

Input data based on ICD
(Initial Capabilities Document)

Optimal dimensions of submarine

8.6 Generation of Weight Estimation Model Using the Optimization Method

Generals

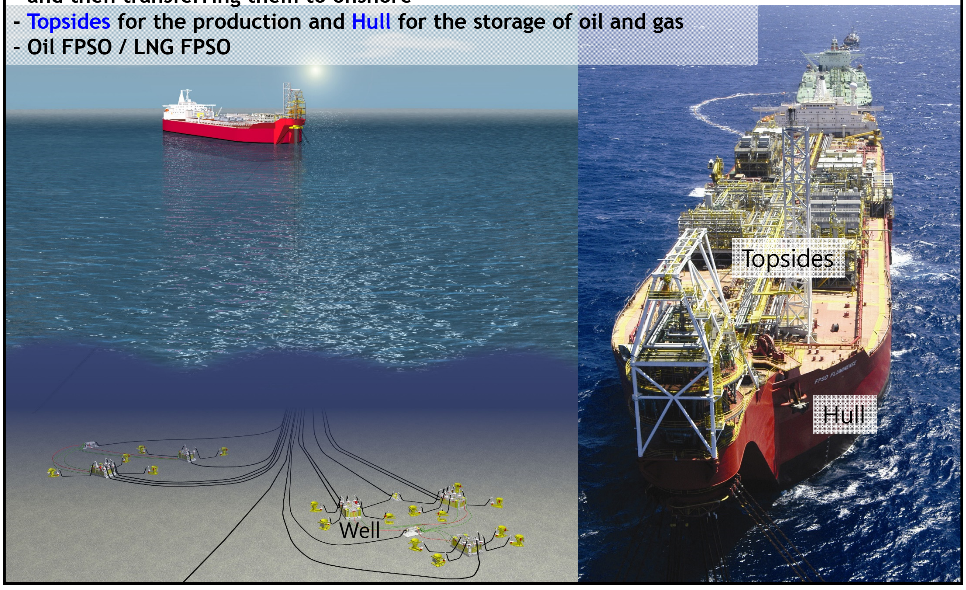
Generation of Weight Estimation Model by Using Genetic Programming

Example

Generals

Example of an Offshore Plant for Deep Sea Development

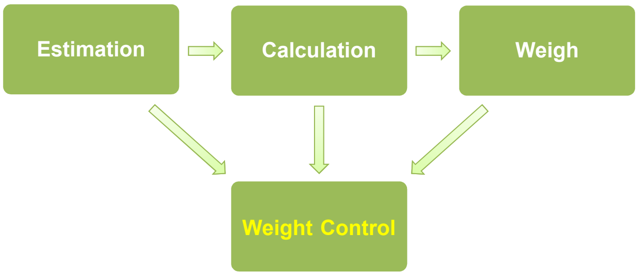
- Production plant for separating the well stream into oil, gas, and water and then transferring them to onshore
- Topsides for the production and Hull for the storage of oil and gas
- Oil FPSO / LNG FPSO



Necessity of the Weight Estimation of Offshore Topsides

☑ The weight estimation of offshore topsides is necessary,
  - To provide the information required for hull structural design
  - To estimate the equipment to be built and the amount of material to be procured
  - To estimate total cost and construction period of the project

☑ If the topsides weight can be accurately estimate at FEED state, it is possible to control efficiently the weight and to produce stably material cost.


Estimation
Calculation
Weigh
Weight Control

Weight engineering process of high level

Classification of Weight Estimation Methods (1/3)

☑ Volumetric Density Method
- A method of estimating the detailed weight group by the multiplication of space volume and bulk factor (density)
- e.g., detailed weight = space volume * bulk factor

☑ Parametrics
- A method of representing the weight with several parameters, and an essential prerequisite of the following ratiocination
- e.g., hull structural weight = $L^{1.6}(B + D)$

☑ Ratiocination
- A method of estimating the weight with a ratio from past records and a parametric equation
- e.g., hull structural weight = $C_S \cdot L^{1.6}(B + D))$

☑ Baseline Method
- A method of estimating the weight by using the result of the first one for a series of ships and offshore plants

---

Classification of Weight Estimation Methods (2/3)

☑ Midship Extrapolation Method
- A method of estimating the weight by the multiplication of the length and the midship weight per unit length
- e.g., fore body weight = midship weight per unit * fore body length * coeff.

☑ Deck Area Fraction Method
- A method of estimating the weight by the multiplication of the deck area and the deck weight per unit area
- e.g., detailed weight = deck weight per area * deck area * coeff.

☑ Synthesis Method
- A method of estimating by using a delicate synthesis program which was made from the integration all engineering fields (e.g., performance) based on requirements
- Most ideal method but it needs much time and efforts.

Classification of Weight Estimation Methods (3/3)

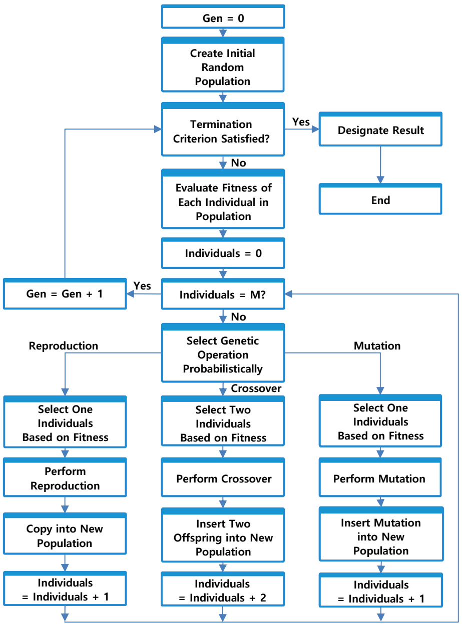
☑ Statistical Method
  - A method of developing a weight equation from statistical analysis of various past records, and of estimating the weight by using the equation

☑ Optimization Method ➡ To be presented here
  - A method of developing a weight equation by optimization method such as genetic programming

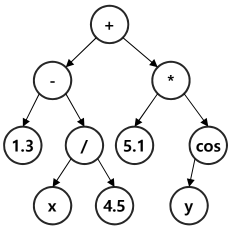
---

Generation of Weight Estimation Model by Using Genetic Programming

Cycle of Genetic Programming



Chromosome Representation of Tree Structure in Genetic Programming



Decoding

Encoding

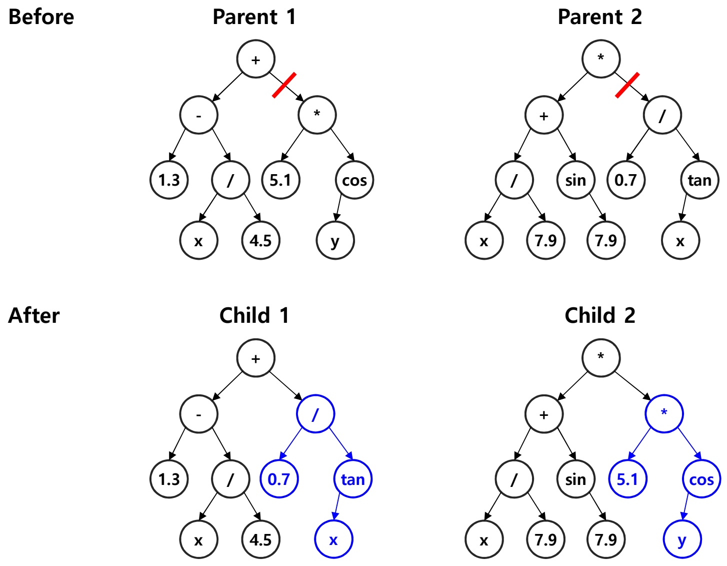
$$(1.3-(x/4.5))+(5.1\times\cos y)$$

Chromosome in tree structure

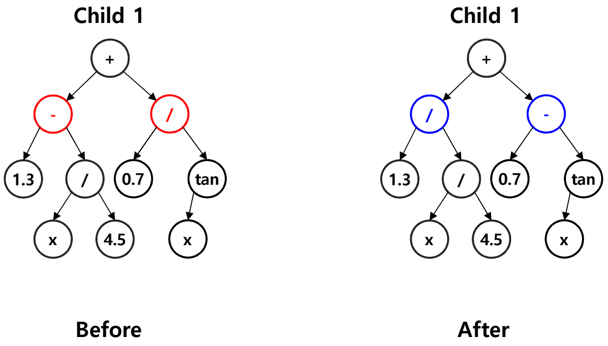
Expression

Terminal Set = {x, y}
Function Set = {+, -, *, /, cos}

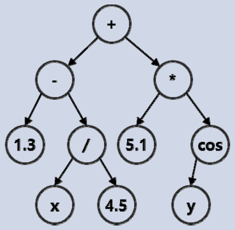
Genetic Operator in Genetic Programming - Crossover



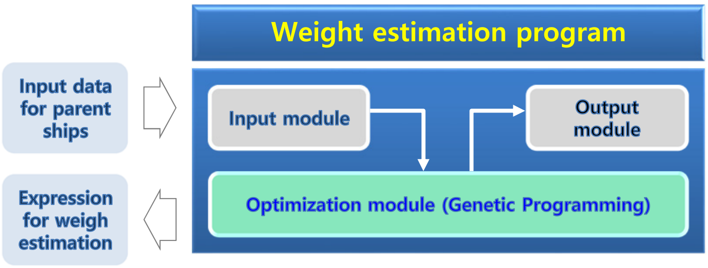
Genetic Operator in Genetic Programming - Mutation



Difference between Genetic Algorithms and Genetic Programming

	Genetic algorithms (e.g., Binary-string coding)	Generic Programming
Expression	Binary string of 0 and 1	**Function**
	String	**Tree**
	Fixed length	**Length variable**
Main operator	Crossover	**Crossover**
Structure	1010110010101011	

Weight Estimation Program of Topsides of Offshore Plant - Configuration



Weight estimation program

Input data for parent ships

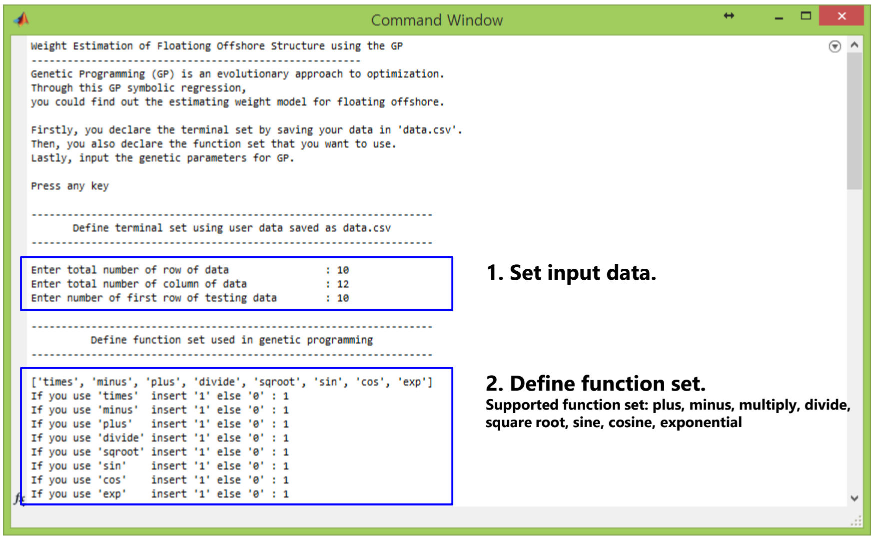
Expression for weigh estimation

Input module

Output module

Optimization module (Genetic Programming)

Weight Estimation Program of Topsides of Offshore Plant - Procedures (1/3)



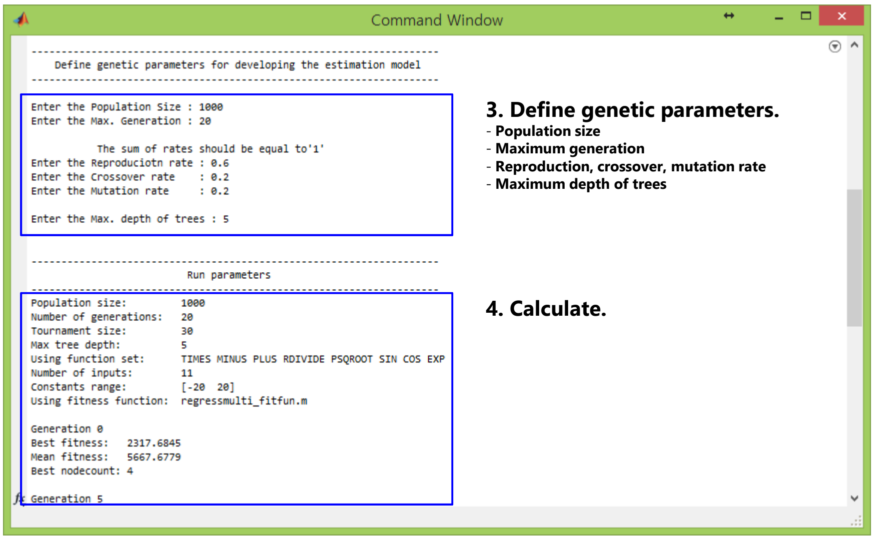
```
Weight Estimation of Floationg Offshore Structure using the GP
-------------------------------------------------------
Genetic Programming (GP) is an evolutionary approach to optimization.
Through this GP symbolic regression,
you could find out the estimating weight model for floating offshore.

Firstly, you declare the terminal set by saving your data in 'data.csv'.
Then, you also declare the function set that you want to use.
Lastly, input the genetic parameters for GP.

Press any key

-------------------------------------------------------------------
       Define terminal set using user data saved as data.csv
-------------------------------------------------------------------

Enter total number of row of data                : 10
Enter total number of column of data             : 12
Enter number of first row of testing data        : 10

-------------------------------------------------------------------
          Define function set used in genetic programming
-------------------------------------------------------------------

['times', 'minus', 'plus', 'divide', 'sqroot', 'sin', 'cos', 'exp']
If you use 'times'  insert '1' else '0' : 1
If you use 'minus'  insert '1' else '0' : 1
If you use 'plus'   insert '1' else '0' : 1
If you use 'divide' insert '1' else '0' : 1
If you use 'sqroot' insert '1' else '0' : 1
If you use 'sin'    insert '1' else '0' : 1
If you use 'cos'    insert '1' else '0' : 1
If you use 'exp'    insert '1' else '0' : 1
```

1. Set input data.

2. Define function set.
Supported function set: plus, minus, multiply, divide, square root, sine, cosine, exponential

---

Weight Estimation Program of Topsides of Offshore Plant - Procedures (2/3)

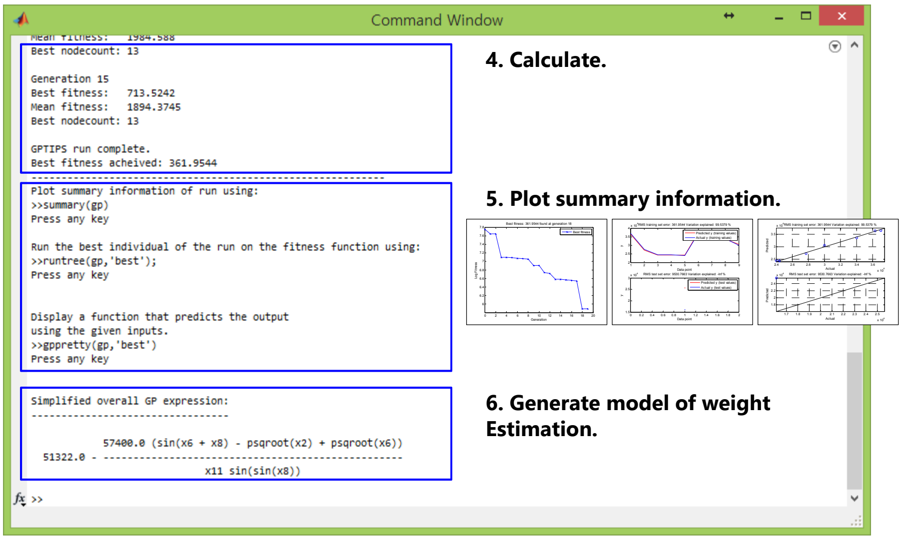


```
--------------------------------------------------------------------
    Define genetic parameters for developing the estimation model
--------------------------------------------------------------------

Enter the Population Size : 1000
Enter the Max. Generation : 20

           The sum of rates should be equal to'1'
Enter the Reproduciotn rate : 0.6
Enter the Crossover rate    : 0.2
Enter the Mutation rate     : 0.2

Enter the Max. depth of trees : 5

--------------------------------------------------------------------
                          Run parameters
--------------------------------------------------------------------
Population size:          1000
Number of generations:    20
Tournament size:          30
Max tree depth:           5
Using function set:       TIMES MINUS PLUS RDIVIDE PSQROOT SIN COS EXP
Number of inputs:         11
Constants range:          [-20  20]
Using fitness function:   regressmulti_fitfun.m

Generation 0
Best fitness:    2317.6845
Mean fitness:    5667.6779
Best nodecount: 4

Generation 5
```

3. Define genetic parameters.
- **Population size**
- **Maximum generation**
- **Reproduction, crossover, mutation rate**
- **Maximum depth of trees**

4. Calculate.

Weight Estimation Program of Topsides of Offshore Plant - Procedures (3/3)



```
Mean fitness:   1984.588
Best nodecount: 13

Generation 15
Best fitness:   713.5242
Mean fitness:   1894.3745
Best nodecount: 13

GPTIPS run complete.
Best fitness acheived: 361.9544
------------------------------------------------------------
Plot summary information of run using:
>>summary(gp)
Press any key

Run the best individual of the run on the fitness function using:
>>runtree(gp,'best');
Press any key


Display a function that predicts the output
using the given inputs.
>>gppretty(gp,'best')
Press any key

Simplified overall GP expression:
---------------------------------


            57400.0 (sin(x6 + x8) - psqroot(x2) + psqroot(x6))
  51322.0 - --------------------------------------------------
                            x11 sin(sin(x8))

>>
```

4. Calculate.

5. Plot summary information.

6. Generate model of weight Estimation.

Example

Generation of Weight Estimation Model for FPSO Topsides - Input (1/2)

☑ Past records for FPSOs from the literature survey

	L [m]	B [m]	D [m]	T [m]	Hull weight [ton]	DWT [ton]	Storage capacity [MMbbl]	Oil production [MMbopd]	Gas production [MMscf/d]	Water processing [MMbwpd]	Crew	Topsides weight [ton]
Akpo	310	61	31	23	70,500	303,669	2.00	0.185	530.00	0.420	220	**37,000**
USAN	310	61	32	24	75,750	353,200	2.00	0.160	500.00	0.420	180	**27,700**
Kizomba A	285	63	32.3	24	56,300	340,660	2.20	0.250	400.00	0.420	100	**24,400**
Kizomba B	285	63	32.3	25	56,300	340,660	2.20	0.250	400.00	0.420	100	**24,400**
Greater Plutonio	310	58	32	23	56,000	360,000	1.77	0.220	380.00	0.400	120	**24,000**
Pazflor	325	61	32	25	82,000	346,089	1.90	0.200	150.00	0.380	240	**37,000**
CLOV	305	61	32	24	63,490	350,000	1.80	0.160	650.00	0.380	240	**36,300**
Agbami	320	58.4	32	24	68,410	337,859	2.15	0.250	450.00	0.450	130	**34,000**
Dalia	300	60	32	23	52,500	416,000	2.00	0.240	440.00	0.405	160	**30,000**
Skarv-Idun	269	50.6	29	19	45,000	312,500	0.88	0.085	670.00	0.020	100	**22,000**

* Clarkson, 2012, The Mobile Offshore Production Units Register 2012, 10th Edition, Clarkson

* Kerneur, J., 2010, 2010 Worldwide Survey of FPSO Units, Offshore Magazine

---

Generation of Weight Estimation Model for FPSO Topsides - Input (2/2)

☑ Selection of initial independent variables

	L [m]	B [m]	D [m]	T [m]	Hull weight [ton]	DWT [ton]	Storage capacity [MMbbl]	Oil production [MMbopd]	Gas production [MMscf/d]	Water processing [MMbwpd]	Crew	Topsides weight [ton]
Akpo	310	61	31	23	70,500	303,669	2.00	0.185	530.00	0.420	220	**37,000**
USAN	310	61	32	24	75,750	353,200	2.00	0.160	500.00	0.420	180	**27,700**
~~**Kizomba A**~~	~~285~~	~~63~~	~~32.3~~	~~24~~	~~56,300~~	~~340,660~~	~~2.20~~	~~0.250~~	~~400.00~~	~~0.420~~	~~100~~	~~**24,400**~~
Kizomba B	285	63	32.3	25	56,300	340,660	2.20	0.250	400.00	0.420	100	**24,400**
Greater Plutonio	310	58	32	23	56,000	360,000	1.77	0.220	380.00	0.400	120	**24,000**
Pazflor	325	61	32	25	82,000	346,089	1.90	0.200	150.00	0.380	240	**37,000**
CLOV	305	61	32	24	63,490	350,000	1.80	0.160	650.00	0.380	240	**36,300**
Agbami	320	58.4	32	24	68,410	337,859	2.15	0.250	450.00	0.450	130	**34,000**
Dalia	300	60	32	23	52,500	416,000	2.00	0.240	440.00	0.405	160	**30,000**
Skarv-Idun	269	50.6	29	19	45,000	312,500	0.88	0.085	670.00	0.020	100	**22,000**

Items	Independent Variables	Dependent Variable
Principal dimensions	**L, B, D, T, H_LWT, DWT**	T_LWT (to be estimated)
Capacity	**S_C, O_P, G_P, W_P**	
Miscellaneous	**CREW**	

* H_LWT: Hull light weight [ton], DWT: Deadweight [ton], S_C: Storage capacity [MMbbl], O_P: Oil production [MMbopd], GP: Gas production [MMscf/d]
WP: Water processing [MMbwpd], T_LWT: Topsides weight [ton], CREW: Crew number

Generation of Weight Estimation Model for FPSO Topsides - Output

☑ Simplified model for the weight estimation

- The model can be represented as the nonlinear relationship between 11 independent variables and the corresponding coefficients.

$$\begin{aligned}&T_{LWT} = 67.38 \cdot CREW + 67.38 \cdot B + 67.38 \cdot S\_C -\\&3059 \cdot \cos(L \cdot W\_P \cdot (H\_LWT - 3.838)) +\\&12533 \cdot \cos(\exp(\sin(S\_C))) + 0.5007 \cdot B \cdot T +\\&67.38 \cdot O\_P \cdot G\_P +\\&0.5007 \cdot D \cdot \sin(H\_LWT) \cdot L^2 - 30033\end{aligned}$$

* H_LWT: Hull light weight [ton], DWT: Deadweight [ton], S_C: Storage capacity [MMbbl], O_P: Oil production [MMbopd], GP: Gas production [MMscf/d]
WP: Water processing [MMbwpd], T_LWT: Topsides weight [ton], CREW: Crew number

---

Generation of Weight Estimation Model for FPSO Topsides - Verification of the Weight Estimation Model

$$\begin{aligned}&T_{LWT} = 67.38 \cdot CREW + 67.38 \cdot B + 67.38 \cdot S\_C - 3059 \cdot \cos(L \cdot W\_P \cdot (H\_LWT - 3.838)) +\\&12533 \cdot \cos(\exp(\sin(S\_C))) + 0.5007 \cdot B \cdot T + 67.38 \cdot O\_P \cdot G\_P +\\&0.5007 \cdot D \cdot \sin(H\_LWT) \cdot L^2 - 30033\end{aligned}$$

FPSOs	Actual weight [A]	Estimated weight [B]	Ratio [A/B]
Akpo	37,000	36,951	0.9987
USAN	27,700	27,672	0.9990
Kizomba A	24,400	24,352	0.9980
Kizomba B	24,400	24,383	0.9993
Greater Plutonio	24,000	24,063	1.0226
Pazflor	37,000	36,918	0.9978
CLOV	36,300	36,318	1.0005
Agbami	34,000	33,906	0.9972
Dalia	30,000	30,059	1.0020
Skarv-Idun	16,100	16,093	0.9996
Test	25,000	24,928	0.9971
Mean			1.0011