Innovative Ship and Offshore Plant Design

Part I. Ship Design

Ch. 3 Design Model

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Contents

Ch. 3 Design Model

Problem Statement for Ship Design

☑ **Given**

- Deadweight (DWT),
- Cargo hold capacity (V_{CH}),
- Service speed (V_s),
- Daily Fuel Oil Consumption ($DFOC$), Endurance, etc.

☑ **Find**

- L, B, D, T, C_B

1. Determination of the Principal Dimensions by the Weight Equation

Determination of the Principal Dimensions by the Weight Equation

- **Weight equation**

  Dimensions of a   whose design is
  are determined by the following equation.

$$\rho \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha) = DWT + LWT \quad ...(3)$$

✓ **Given:** DWT (owner's requirement)

✓ **Find:** L, B, T, C_B

ρ: density of sea water = 1.025 Mg/m^3 = 1.025 ton/m^3
α: **a fraction of the shell appendage allowance**, displacement of shell plating and appendages as a fraction of the moulded displacement

$$DWT + LWT = W_{Total}$$

Deadweight is given by owner's requirement, whereas total weight is not a given value.
Thus, lightweight (LWT) should be estimated by appropriate assumption.

How can you estimate the LWT?

Weight Estimation: Method 1
Assume that the lightweight is the same as that of the basis ship. (1/3)

At the early design stage, there are few data available for the estimation of the lightweight.
The simplest possible way of estimating the lightweight is to assume that the lightweight does not change in the variation of the principal dimensions.

Method 1:

$$LWT = LWT_{Basis}$$

$$L \cdot B \cdot T \cdot C_B \cdot \rho \cdot (1+\alpha) = DWT + LWT_{Basis} \quad ...(4.1)$$

It will be noted that finding a solution for this equation is a complex matter, because there are 4 unknown variables (L, B, T, C_B) with one equation, that means this equation is a kind of

.

Moreover, the unknown variables are multiplied by each other, that means this equation is a kind of .

Weight Estimation: Method 1
Assume that the lightweight is the same as that of the basis ship. (2/3)

$$L \cdot B \cdot T \cdot C_B \cdot \rho \cdot (1+\alpha) = W$$
$$= DWT + LWT_{Basis} \quad ...(4.1)$$

The equation (4.1) is called nonlinear indeterminate equation which has infinitely many solutions.

- Therefore, we have to assume three unknown variables to solve this indeterminate equation.
- The principal dimensions must be obtained by successive iteration until the displacement becomes equal to the total weight of ship. (∵ nonlinear equation)
- We can have many sets of solution by assuming different initial values. (∵ indeterminate equation)

Thus, we need a certain criteria to select proper solution.

Weight Estimation: Method 1
Assume that the lightweight is the same as that of the basis ship. (3/3)

For example, this is the first set of solution.

The ratios of the principal dimensions L/B, B/T, and C_B can be obtained from the basis ship.

Substituting the ratios obtained from the basis ship into the equation (4.1), the equation can be converted to a cubic equation in L.

$$L \cdot B \cdot T \cdot C_B \cdot \rho \cdot (1+\alpha) = W$$

$$L \cdot \left(L \cdot \frac{B}{L} \right) \cdot \left(B \cdot \frac{T}{B} \right) \cdot C_B \cdot \rho \cdot (1+\alpha) = W$$

$$L^2 \cdot \left(\frac{B}{L} \right) \cdot \left(L . \frac{B}{L} \right) \cdot \left(\frac{T}{B} \right) \cdot C_B \cdot \rho \cdot (1+\alpha) = W$$

$$L^3 \cdot \left(\frac{B}{L} \right)^2 \cdot \left(\frac{T}{B} \right) \cdot C_B \cdot \rho \cdot (1+\alpha) = W$$

$$\Rightarrow L = \left(\frac{W \cdot (L/B)_{Basis}{}^2 \cdot (B/T)_{Basis}}{\rho \cdot C_{B\_Basis} \cdot (1+\alpha)} \right)^{1/3}$$

Weight Estimation: Method 2
Assume that the total weight (W) is proportional to the deadweight.

- **Weight equation of a ship**

$$\rho \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha) = W = DWT + LWT \quad ...(3)$$

Given : DWT, **Find :** L, B, T, C_B

Method ②: $W = \frac{W_{Basis}}{DWT_{Basis}} \cdot DWT$

Since the lightweight is assumed to be invariant in the 'Method 1', even though the principal dimensions are changed, the method might give too rough estimation.

How can you estimate the lightweight more accurately than the 'Method 1'?

Method 2:

$$\frac{DWT_{Basis}}{W_{Basis}} = \frac{DWT}{W}$$

Therefore, the total weight of design ship can be estimated by the ratio of deadweight to total weight of the basis ship.

$$W = \frac{W_{Basis}}{DWT_{Basis}} \cdot DWT$$

$$L \cdot B \cdot T \cdot C_B \cdot \rho \cdot (1+\alpha) = W \quad ...(4.2)$$

Weight Estimation: Method 3

Assume that the lightweight could vary as the volume of the ship.

• Weight equation of a ship

$$\rho \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha) = W$$
$$= DWT + LWT \quad ...(3)$$

Given : DWT, Find : L, B, T, C_B

Method ③: $LWT = C_{LWT} L \cdot B \cdot D$

The lightweight estimated in the 'Method 2' still has nothing to do with the variation of the principal dimensions.

How can you estimate the lightweight more accurately than the 'Method 2'?

Method 3:

$$LWT = f(L, B, D)$$

To estimate the lightweight, we will introduce the volume variable ***L·B·D*** and assume that LWT is proportional to ***L·B·D***.

where, the coefficient C_{LWT} can be obtained from the basis ship.

$$L \cdot B \cdot T \cdot C_B \cdot \rho \cdot (1+\alpha) = DWT + C_{LWT} \cdot L \cdot B \cdot D \quad ...(4.3)$$

Weight Estimation: Method 4

Estimate the structural weight(W_s), outfit weight (W_o), and machinery weight(W_m) in components.

• Weight equation of a ship

$$\rho \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha) = W$$
$$= DWT + LWT \quad ...(3)$$

Given : DWT, Find : L, B, T, C_B

Method ④: $LWT = W_s + W_o + W_m$

How can you estimate lightweight more accurately?

We assume that a ship is composed of hull structure, outfit, and machinery. Based on this assumption, the lightweight estimation would be more accurate, if we could estimate the weight of each components.

Method 4:

How can you estimate W_s, W_o, and W_m ?

Assume that W_s, W_o, W_m are dependent on the principal dimensions.

Structural Weight Estimation: Method 4-1

$$LWT = W_s + W_o + W_m$$

Assume that the structural weight (W_s) is a function of L, B, and D as follows:

$$W_s = f(L, B, D)$$

Since the structural weight of a ship is actually composed of stiffened plate surfaces, some type of 'area variables' would be expected to provide a better correlation.

To estimate the structural weight, we will introduce an '**area variables'** such as $L{\cdot}B$ or $B{\cdot}D$.

$$W_s = f(L \cdot B, B \cdot D)$$

For example, assume that structural weight is proportional to L^{α} and $(B+D)^{\beta}$.

Method 4-1:

Unknown parameters (C_s, α, β) can be obtained from as-built ship data by regression analysis*.

* Regression analysis is a numerical method which can be used to develop equations or models from data when there is no or limited physical or theoretical basis for a specific model. It is very useful in developing parametric models for use at the early design stage.

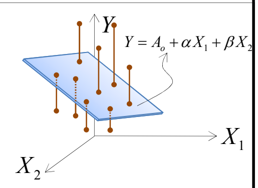
Regression Analysis to obtain a Formula for the Structural Weight Estimation

$$W_s = C_s L^{\alpha} (B+D)^{\beta}$$

a) In order to perform the regression analysis, we transform the above nonlinear equation into the linear equation by applying logarithmic operation on both sides, then we have a logarithmic form

$$\underbrace{\ln W_s}_{Y} = \underbrace{\ln C_S}_{A_0} + \alpha \underbrace{\ln L}_{X_1} + \beta \underbrace{\ln(B+D)}_{X_2}$$: Logarithmic Form

$$\rightarrow Y = A_o + \alpha X_1 + \beta X_2$$: Linear Equation



Regression analysis plane for data on the variables Y, X_1 and X_2

b) If sets of as-built ship data ($X_{1i}, X_{2i}; Y_i$) are available, then, the parameters can be obtained by finding a function that minimize the sum of the squared errors, "least square method", which is the difference between the sets of the data and the estimated function values.

$$\rightarrow C_S, \alpha = 1.6, \ \beta = 1$$

e.g., 302K VLCC: $C_s = 0.0414$

Above equation reflects that length (L) will exponentially affect on the steel weight much more than other variables, B and D.

Outfit Weight Estimation: Method 4-2

$$LWT = W_s + W_o + W_m$$

Assume that the outfit weight (W_o) is a function of L, B : $W_o = f(L, B)$

To estimate the outfit weight, we will use the area variable $L \cdot B$.

$$W_o = f(L \cdot B)$$

For example, assume that outfit weight (W_o) is proportional to $L \cdot B$.

Method 4-2:

where, the coefficient C_o can be obtained from the basis ship.

W_s : structural weight
W_o : outfit weight
W_m : machinery weight

Machinery Weight Estimation: Method 4-3

$$LWT = W_s + W_o + W_m$$

To estimate the machinery weight, assume that the machinery weight (W_s) is a function of $NMCR$:

$$W_m = f(NMCR)$$

For example, assume that machinery weight is proportional to $NMCR$:

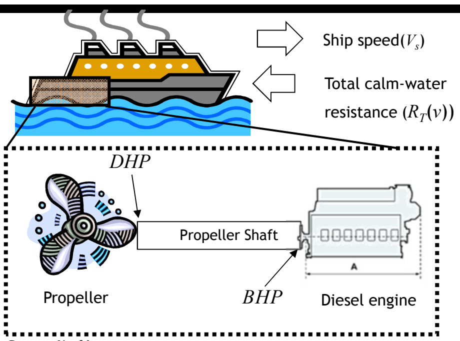
Method 4-3:

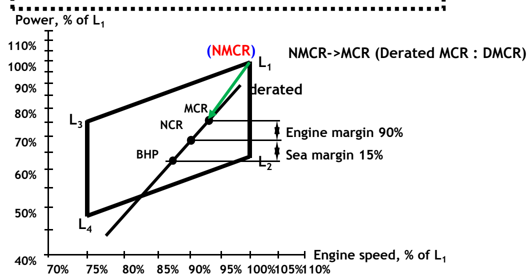
where, the coefficient C_m can be obtained from the basis ship.

* NMCR (Nominal maximum continuous rating) is the maximum power/speed combination available for the engine and is a criteria for the dimensions, weight, capacity, and cost of the engine.

Then, how can you estimate the $NMCR$?

Estimation of the NMCR (Nominal Maximum Continuous Rating)





① EHP (Effective Horse Power)

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

② DHP (Delivered Horse Power)

$$DHP = \frac{EHP}{\eta_D} \quad (\eta_D\text{: Propulsive efficiency})$$

③ BHP (Brake Horse Power in calm water)

$$BHP = \frac{DHP}{\eta_T} \quad (\eta_T\text{: Transmission efficiency})$$

④ NCR (Normal Continuous Rating)

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

⑤ DMCR (Derated Maximum Continuous Rating)

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

⑥ NMCR (Nominal Maximum Continuous Rating)

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

Estimation of the NMCR by Admiralty Formula

$$W_m = C_m \cdot NMCR$$

NMCR **can be estimated based on the prediction of resistance and propulsion power. However, there are few data available for the estimation of the *NMCR* at the early design stage, *NMCR* can be approximately estimated by empirical formula such as 'Admiralty formula'.**

Admiralty formula:

$$DHP_{Calm\,water} = f(\Delta, V_s)$$

C_{ad}: Admiralty coefficient
V_s: speed of ship [knots]
Δ: displacement [ton]

⇩

$$DHP_{Calm\,water} = C_{DHP} \cdot \Delta^{2/3} \cdot V_s^3$$

⇩

Define $C_{ad} \equiv \frac{1}{C_{DHP}}$

C_{ad} **is called "Admiralty coefficient".**

$$DHP_{Calm\,water} = \frac{\Delta^{2/3} \cdot V_s^3}{C_{ad}}$$

Admiralty Coefficient: A Kind of Propulsive Efficiency (η_D)

Admiralty formula:

$$DHP_{Calm\,water} = \frac{\Delta^{2/3} \cdot V^3}{C_{ad}}$$

C_{ad} **: Admiralty coefficient**

$$C_{ad} = \frac{\Delta^{2/3} \cdot V^3}{DHP_{Calm\,water}}$$

Since $\Delta^{2/3} \cdot V_s^3$ is proportional to ***EHP***, the Admiralty coefficient can be regarded as a kind of the propulsive efficiency (η_D).

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

However, this should be used only for a rough estimation. After the principal dimensions are determined, ***DHP*** needs to be estimated more accurately based on the resistance and power prediction.

(Ref.: Resistance Estimation, Speed-Power Prediction)

Machinery Weight in Terms of Principal Dimensions

$$W_m = C_m \cdot NMCR$$

$$NMCR = \frac{1}{\eta_T} \cdot (1 + \frac{\text{Sea Margine}}{100}) \cdot \frac{1}{\text{Engine Margin}} \cdot \frac{1}{\text{Derating ratio}} \cdot DHP_{Calm\,water}$$

$$= C_1 \cdot DHP_{Calm\,water}$$

$$DHP_{Calm\,water} = \frac{\Delta^{2/3} \cdot V_s^3}{C_{ad}}$$, (Admiralty formula)

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

$$W_m = C_m \cdot \frac{C_1}{C_{ad}} \cdot (\rho \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha))^{2/3} \cdot V_s^3$$

Define

$$C_{power} \equiv C_m \cdot \frac{C_1}{C_{ad}}$$

$$W_m = C_{power} \cdot (\rho \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha))^{2/3} \cdot V_s^3$$

If the machinery weight is changed due to the changed $NMCR$, the principal dimension must be adjusted to the changed machinery weight.

Determination of the Principal Dimensions by the Weight Equation

- **Weight equation of a ship**

$$\rho \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha) = W = DWT + LWT \quad ...(3)$$

Given : DWT, Find : L, B, T, C_B

Method ④: $LWT = W_s + W_o + W_m$, $W_m = C_m \cdot NMCR$

$$L \cdot B \cdot T \cdot C_B \cdot \rho \cdot (1+\alpha) = DWT + LWT \cdots (3)$$

$$LWT = W_S + W_o + W_m$$

$$W_s = C_s \cdot L^{1.6} \cdot (B + D)$$

$$W_o = C_o \cdot L \cdot B$$

$$W_m = C_m \cdot NMCR = C_{power} \cdot (L \cdot B \cdot T \cdot C_B \cdot (1+\alpha))^{2/3} \cdot V_s^3$$

W_s : structural weight
W_o : outfit weight
W_m : machinery weight
V_s : speed of ship
Δ : displacement
ρ : density of sea water [ton/m³]

$$L \cdot B \cdot T \cdot C_B \cdot \rho \cdot (1+\alpha) = DWT + C_s \cdot L^{1.6} \cdot (B+D) + C_o \cdot L \cdot B + C_{power} \cdot (\rho \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha))^{2/3} \cdot V_s^3 \quad ...(4.4)$$

It will be noted that finding a solution for this equation is a complex matter, because there are 5 unknown variables (L, B, D, T, C_B) with one equation, that means this equation is a kind of indeterminate equation.
Moreover, the unknown variables are multiplied by each other, that means this equation is a kind of nonlinear equation. Therefore, we have to assume four unknown variables to solve this indeterminate equation.
The principal dimensions must be obtained by successive iteration until the displacement becomes equal to the total weight of ship (∵ nonlinear equation). We can have many sets of solution by assuming different initial values (∵ indeterminate equation). Thus, we need a certain criteria to select proper solution.

Criteria to Select Proper Solution - Objective Function

What kind of Criteria is available to select proper solution?

Possible Criteria (Objective Function)
- For Shipbuilding Company: Shipbuilding Cost
- For Shipping Company:
  - Less Power ➡ Less Energy Consumption ➡ Minimum OPerational EXpenditure (OPEX)
  - Operability ➡ Required Freight Rate (RFR)
  - Minimum CAPital EXpenditure (CAPEX)
  - Minimum Main Engine Power/DWT

For example, shipping company will adopt objective function as RFR, then the design ship should have the least RFR expressed as:

$$RFR = \frac{\text{Capital cost+Annual operating cost}}{\text{Annual transported cargo quantity}}$$

*Capital cost=Building cost × Capital recovery factor.

$$\text{*CRF(Capital Recovery Factor)} = \frac{i(1+i)^n}{(1+i)^n - 1}$$

2. Determination of the Principal Dimensions by the Volume Equation

Determination of the Principal Dimensions by the Volume Equation

- **Economical constraint: Required cargo hold capacity [m^3]**
  - Principal dimensions have to satisfy the required cargo hold capacity.

  The dimensions of a whose design is can be determined by the following equation.

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

✓ Given: Cargo hold capacity (V_{CH}) [m^3]

✓ Find: L, B, D

How can you represent the cargo hold capacity in terms of the principal dimensions?

Determination of the Principal Dimensions by the Volume Equation - Method 1

• Volume equation of a ship

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

Given: *Cargo hold capacity*, Find: *L, B, D*

Method ①: $f(L,B,D) = C_{CH} \cdot L \cdot B \cdot D$

How can you **estimate** the cargo hold capacity?

Method 1: Assume that the

where, the coefficient C_{CH} can be obtained from the basis ship.

It will be noted that finding a solution to this equation is a complex matter, because there are 3 unknown variables L, B, D with one equation, that means this equation is also a kind of indeterminate equation.
Moreover, the unknown variables are multiplied by each other, that means this equation is a kind of nonlinear equation.

This kind of equation is called a nonlinear indeterminate equation, which has infinitely many solutions.

Determination of the Principal Dimensions by the Volume Equation - Method 2

• Volume equation of a ship

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

Given : *Cargo hold capacity*, Find : *L, B, D*

Method ②: $f(L,B,D) = C_{CH} \cdot L_H \cdot B \cdot D \cdot C_{MD}$

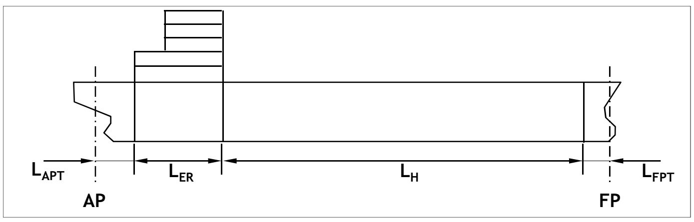
Hold capacity can be estimated more accurately by using the length of cargo hold (L_H) instead of the ship's length (L)

Method 2: Assume that the

L_H : Length of the cargo hold

The Length of cargo hold (L_H) is defined as being L_{BP} subtracted by L_{APT}, L_{ER}, and L_{FPT}:

$$L_H = L_{BP} - L_{APT} - L_{ER} - L_{FPT}$$



L_{BP}: Length between perpendicular
L_{APT}: Length between aft perpendicular to aft bulkhead
L_{FPT}: Length between forward perpendicular to collision bulkhead
L_{ER}: Length of engine room

where, the coefficient (C_{CH}) and partial lengths, L_{APT}, L_{ER}, and L_{FPT} can be obtained from the basis ship.

[Summary] Determination of the Principal Dimensions by the Volume Equation

Method 1: Assume that the cargo hold capacity is proportional to $L \cdot B \cdot D$.

$$V_{CH} = C_{CH} \cdot L \cdot B \cdot D$$

Method 2: Assume that the cargo hold capacity is proportional to $L_H \cdot B \cdot D$.

$$V_{CH} = C_{CH} \cdot L_H \cdot B \cdot D$$

Since the method 1 and 2 are used for a rough estimation,
the cargo hold capacity should be estimated more accurately after the arrangement of compartment has been made.

3. Recommendation on Block Coefficient

Recommended Value for Block Coefficient

- **Recommended value for obesity coefficient considering maneuverability:**

- **Recommended value for C_B proposed by Watson & Gilfillan:**

  This formula seems to confirm its continuing validity and many naval architects are using this equation up to now.

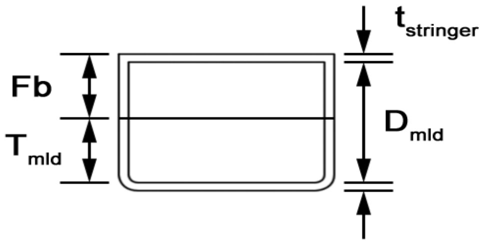
4. Estimation of Freeboard

What is Freeboard*?

- ICLL (International Convention on Load Lines) 1966

  - Ships need safety margin to maintain buoyancy and stability while operating at sea.

  - This safety margin is provided by   of the hull located above the water surface.

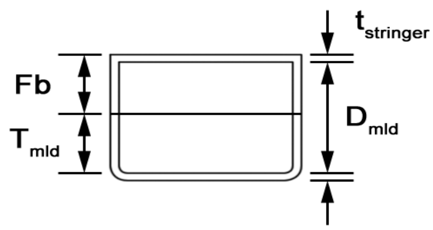


$$D_{Fb} = D_{mld} + t_{stringer}$$

* 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.

Regulatory Constraint by ICLL 1966

✓ Actual freeboard ($D_{Fb} - T$) of a ship should   than the required freeboard (Fb) determined in accordance with the freeboard regulation.



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

How can you determine the required freeboard (Fb) ?

Estimation of Freeboard

• Volume equation of a ship

$$D_{Fb} \geq T + Fb(L, B, D_{mld}, C_B)$$

Given : $L, B, D\ (=D_{mld}), T, C_B$, Check: Satisfaction of the freeboard regulation

$$Fb(L, B, D, C_B) = C_{FB} \cdot D$$

How can you determine the required freeboard (Fb) ?

At the early design stage, there are few data available to calculate required freeboard. Thus, the required freeboard can be roughly estimated from the basis ship.

Assume that the freeboard is proportional to .

$$Fb(L, B, D_{mld}, C_B) = C_{Fb} \cdot D_{mld}$$

where, the coefficient C_{Fb} can be obtained from the basis ship.

In progress of the design, however, the required freeboard has to be calculated in accordance with ICLL 1966.

$$Fb(L, B, D_{mld}, C_B) = f(L_f, D_{mld}, C_B, \text{Superstructure}_{\text{Length}}, \text{Superstructure}_{\text{Height}}, \text{Sheer})$$

If ICLL 1966 regulation is not satisfied, the depth should be changed.

5. Estimation of Shipbuilding Cost

Estimation of Shipbuilding Cost (1/2)

Objective Function (Criteria to select the proper principal dimensions)

Assume that the shipbuilding cost is proportional to the weight of the ship.

$$Building\ Cost = C_{PS} \cdot W_S + C_{PO} \cdot W_O + C_{PM} \cdot W_M$$

If the weight of the ship is represented by the main dimensions of the ship, the shipbuilding cost can be represented by them as follows:

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

C_{PS} : Coefficient related with the cost of the steel(structural)
C_{PO} : Coefficient related with the cost of the outfit
C_{PM} : Coefficient related with the cost of the machinery

← **Coefficients can be obtained from the as-built ship data.**

e.g. The value of the coefficients obtained from the 302K VLCC.

$$C_{PS} = 2,223,\ C_{PO} = 4,834,\ C_{PM} = 17,177$$

Estimation of Shipbuilding Cost (2/2)

Method to obtain the coefficient related with the cost

The shipbuilding cost is composed as follows:

Shipbuilding Cost=(Man-hour for the steel structure + Material cost for the steel structure)
+(Man-hour for the outfit +Material cost for the outfit)
+(Man-hour for the machinery +Material cost for the machinery)
+Additional cost

※ The shipbuilding cost of the VLCC is about $130,000,000.

If we assume that the shipbuilding cost is proportional to the weight of the ship and the weight of the ship is composed of the steel structure weight, outfit weight and machinery weight, the shipbuilding cost can be represented as follows.

$$Building\ Cost = C_{PS} \cdot W_S + C_{PO} \cdot W_O + C_{PM} \cdot W_M$$

C_{PS} : Coefficient related with the cost of the steel structure
C_{PO} : Coefficient related with the cost of the outfit
C_{PM} : Coefficient related with the cost of the machinery

$$C_{PS} = \frac{\text{(Man-hour for the steel structure + Material cost for the steel structure)}}{W_S}$$

$$C_{PO} = \frac{\text{(Man-hour for the outfit +Material cost for the outfit)}}{W_O}$$

$$C_{PM} = \frac{\text{(Man-hour for the machinery +Material cost for the machinery)}}{W_M}$$

[Reference] International Completive Power of the Domestic Shipbuilding and Ocean Industry Wage Level / Production Cost

☑ Comparison of the Shipbuilding Cost [Unit: %]

		Korea	Japan	China
Material Cost	Steel	**17**	17	18
	Equipment	**42**	43	47
	Sub sum	**59**	60	65
Labor Cost		**27**	29	19
General Cost		**14**	13	16
Total sum		**100**	100	100

6. Determination of the Optimal Principal Dimensions

Design Model for the Determination of the Optimal Principal Dimensions (L, B, D, T, C_B)

Find (Design variables) L, B, D, C_B, T_d — length, breadth, depth, block coefficient, design draft

Given (Owner's requirement) DWT, V_{CH}, $T_s(=T_{max})$, V — deadweight, Required cargo hold capacity, Scantling Draft (maximum), ship speed

Physical constraint

➡ Hydrostatic equilibrium (Weight equation) – Equality constraint

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

Economical constraints (Owner's requirements)

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

$$V_{CH} = C_H \cdot L \cdot B \cdot D$$

- **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 (1966 ICLL) - Inequality constraint

$$D \geq T_s + C_{FB} \cdot D$$

Objective Function (Criteria to determine the proper principal dimensions)

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