Computer Aided Ship Design

Part I. Optimization Method

Ch. 8 Determination of Optimal Principal Dimensions of a Ship

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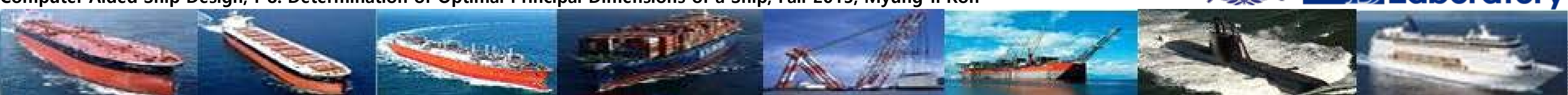
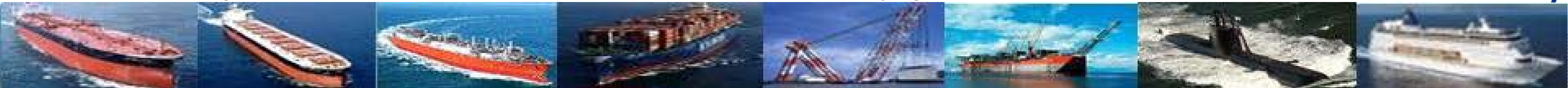


Ch. 8 Determination of Optimal Principal Dimensions of a Ship

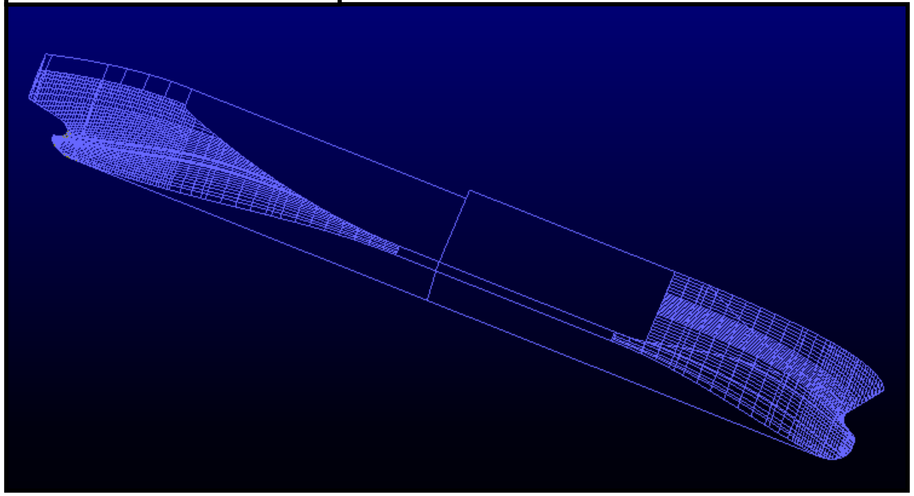


What is a "Hull form"?

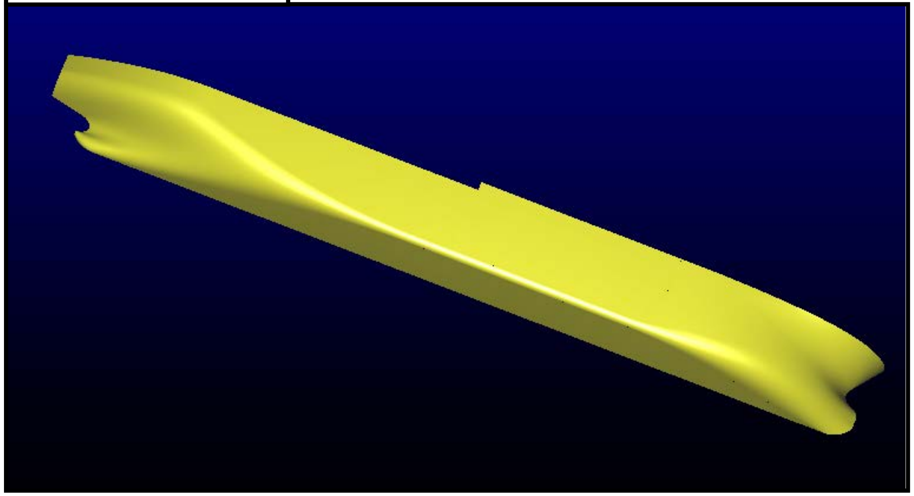
- Hull form
  - Outer shape of the hull that is streamlined in order to satisfy requirements of a ship owner such as a deadweight, ship speed, and so on
  - Like a skin of human
- Hull form design
  - Design task that designs the hull form

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

Wireframe model

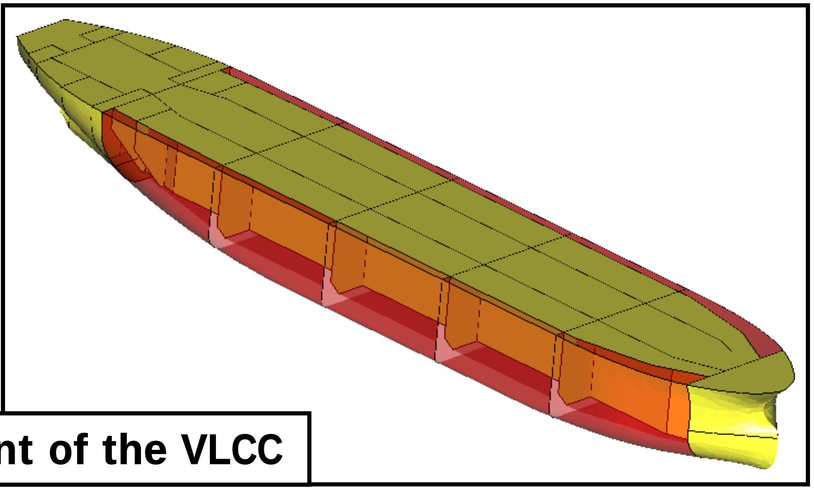


Surface model



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

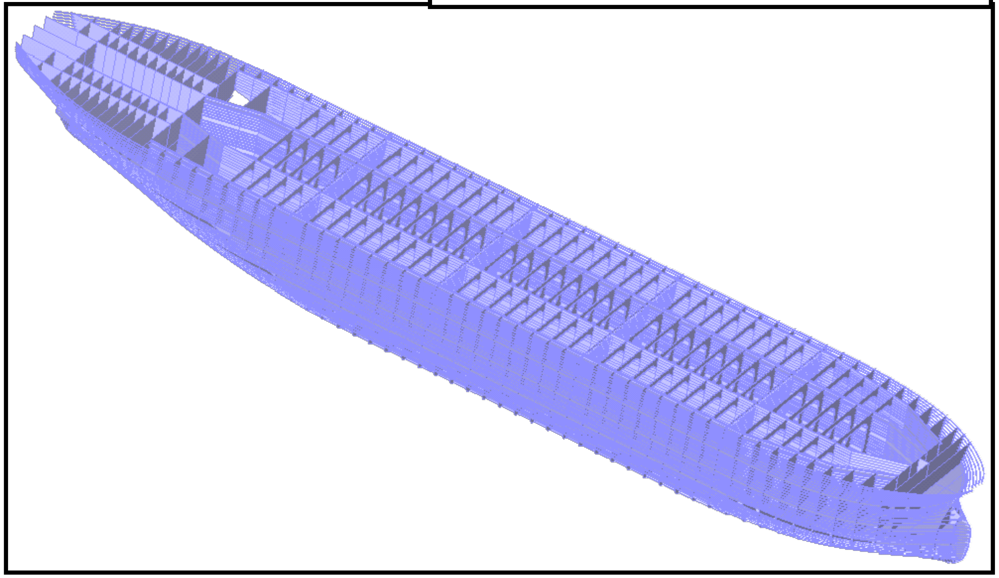


Compartment of the VLCC

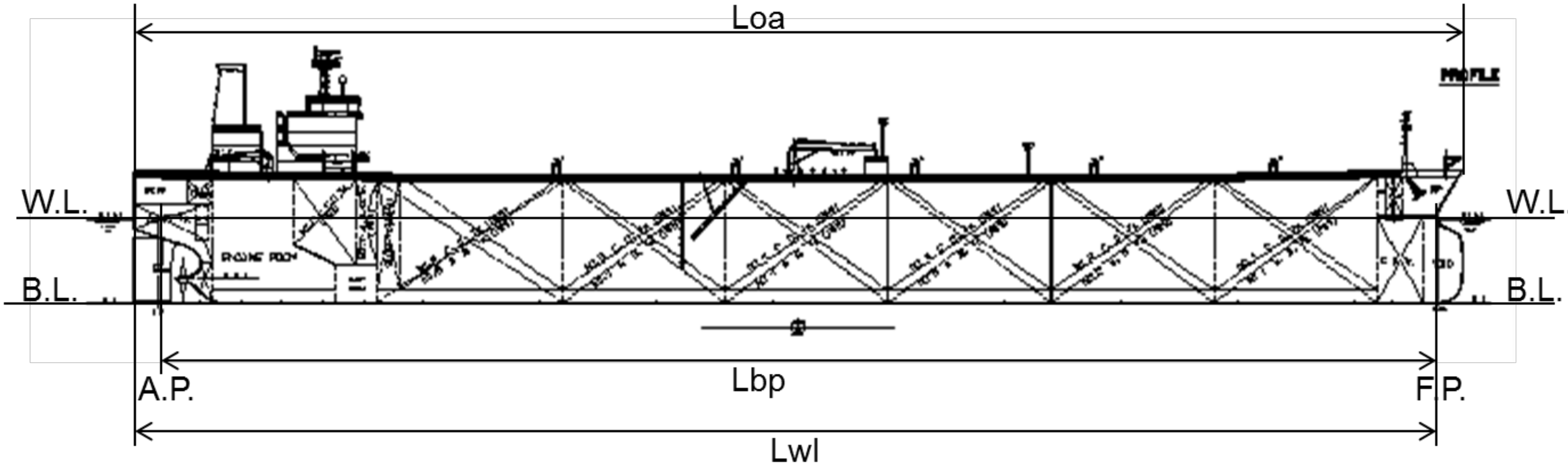
What is a "Hull structure"?

- **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

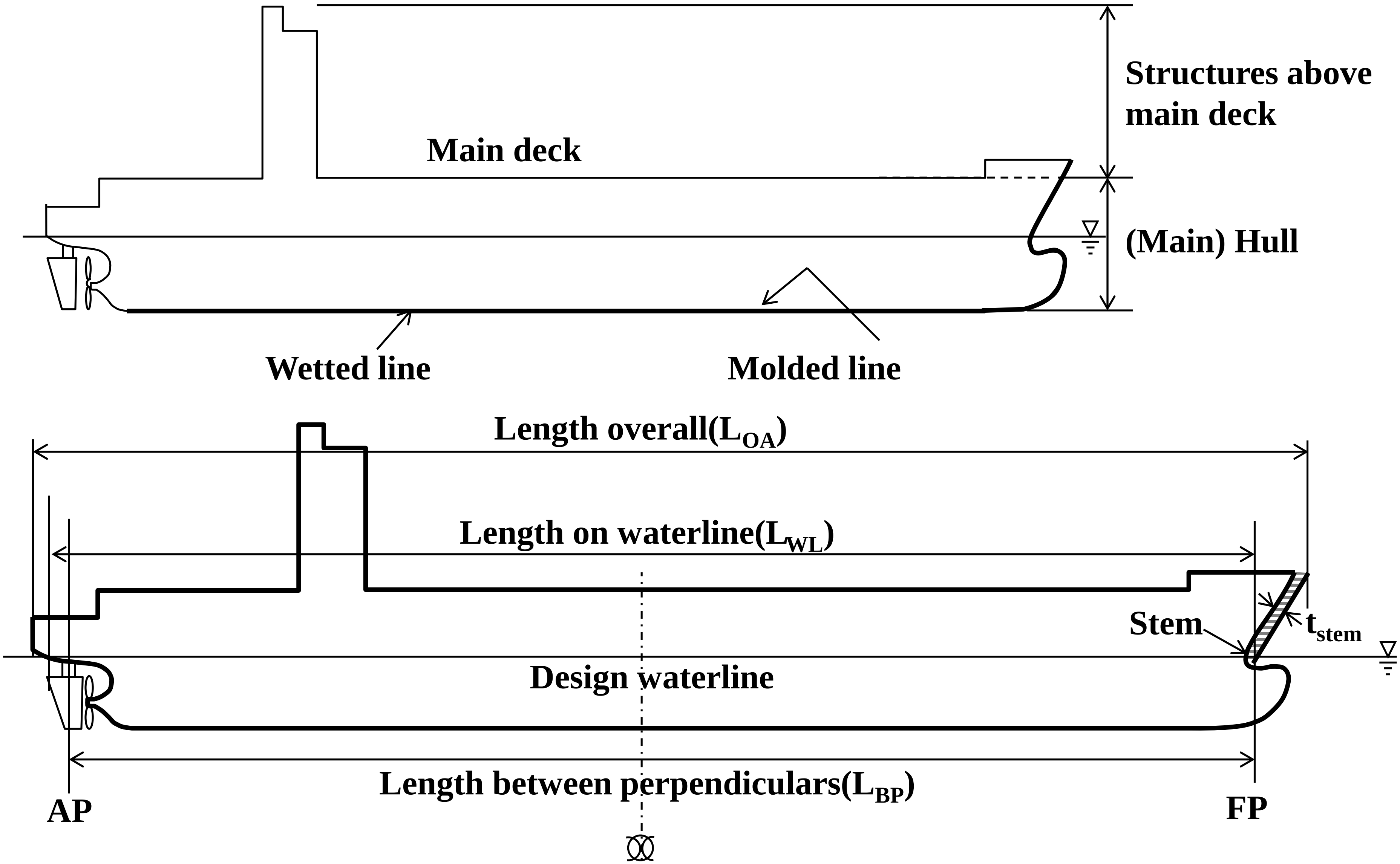


Principal Characteristics (1/2)

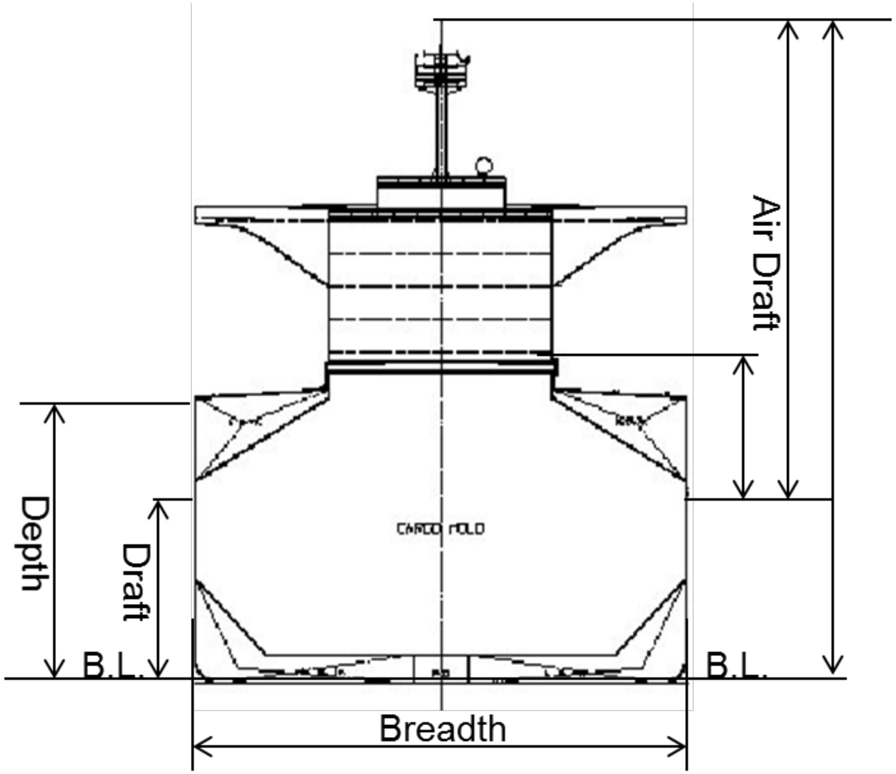


- ☑ LOA (Length Over All) [m] : Maximum Length of Ship
- ☑ LBP (Length Between Perpendiculars (A.P. ~ F.P.)) [m]
  - A.P. : After perpendicular (normally, center line of the rudder stock)
  - F.P. : Inter-section line between designed draft and fore side of the stem, which is perpendicular to the baseline
- ☑ 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)

Definitions for the Length of a Ship



Principal Characteristics (2/2)

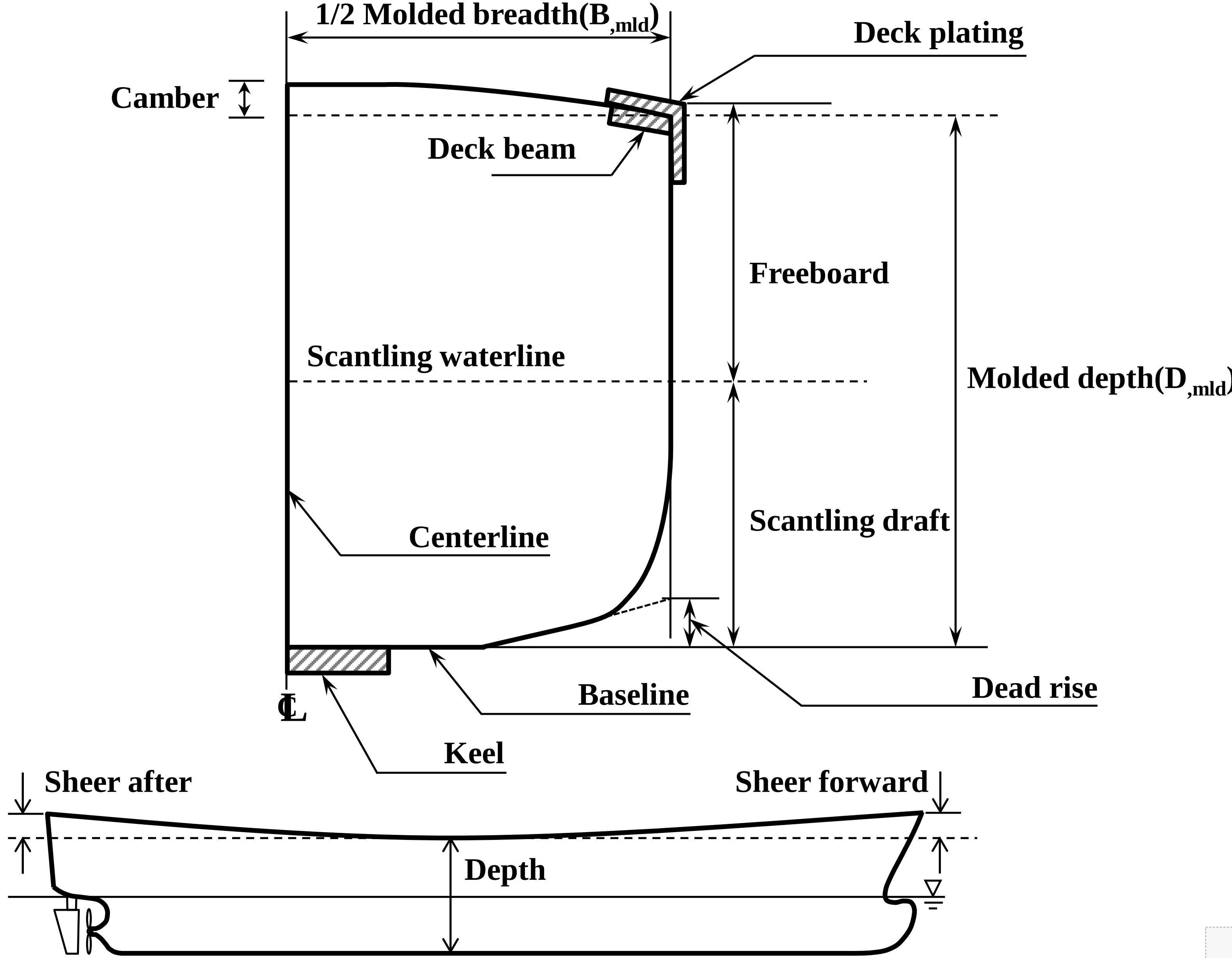


- B (Breadth) [m] : Maximum breadth of the ship, measured amidships
  - B,molded : excluding shell plate thickness
  - B,extreme : including shell plate thickness
- D (Depth) [m] : Distance from the baseline to the deck side line
  - D,molded : excluding keel plate thickness
  - D,extreme : including 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

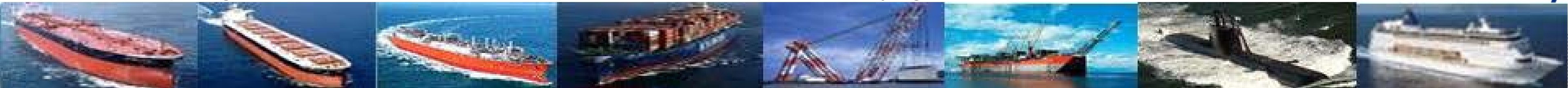
- Air Draft

  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
  - ...

Definitions for the Breadth and Depth of a Ship



8.1 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 Draft with Sea Margin, Engine Power & RPM

- Dimensional Limitations: Panama canal, Suez canal, Strait of Malacca, St. Lawrence Seaway, Port limitations

- Maximum Draft(T_{max})

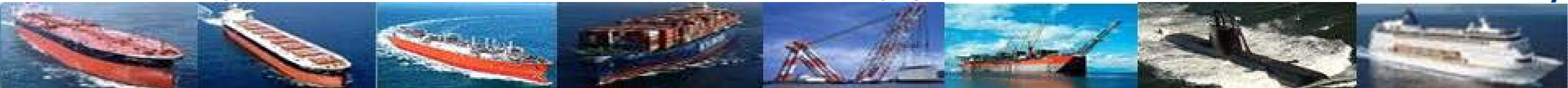
- Daily Fuel Oil Consumption(DFOC): Related with ship's economy

- Special Requirements
  - Ice Class, Air Draft, Bow/Stern Thruster, Special Rudder, Twin Skeg

- Delivery Day
  - Delivery day, with (   )$ delay penalty per day
  - Abt. 21 months from contract

- The Price of a ship
  - Material & Equipment Cost + Construction Cost + Additional Cost + Margin

8.2 Derivation of the Design Equations

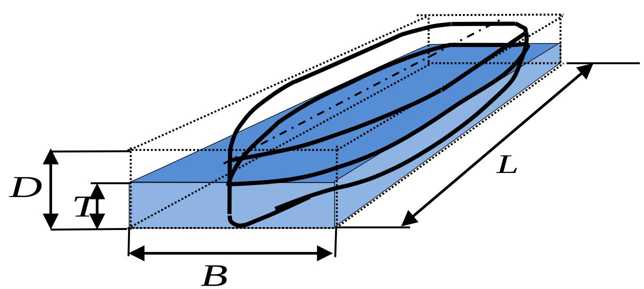


Derivation of the Design Equations (1/2)

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.



Derivation of the Design Equations (2/2)

Example of owner's requirements

- ✓ **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

At early design stage, there are few data available to estimate the principal dimensions, the <u>initial estimates of the principal dimensions</u> and hull form coefficients can be derived from the basis ship*.

Speed and power estimation will be discussed later.

*Basis ship: It is a ship whose principal dimensional ratios and hull form coefficients are similar with the ship being designed.

Example) VLCC(Very Large Crude Carrier)

308,000DWT

318,000DWT

Example of a Basis Ship of 279,500 ton of Deadweight VLCC and Owner's Requirements of 297,000 ton Deadweight VLCC

– 297,000 ton Deadweight VLCC(Very Large Crude Carrier)

		Basis Ship	Owner's Requirements	
Pricipal Dimensions	Loa	abt. 330.30 m		
	Lbp	314.00 m		
	B,mld	58.00 m		
	Depth,mld	31.00 m		
	Td(design)	20.90 m	21.50 m	
	Ts(scant.)	22.20 m	22.84 m	
Deadweight(scant)		301,000 ton	320,000 ton	
Deadweight(design)		279,500 ton	297,000 ton	
Speed (at design draft 90% MCR(with 15% Sea Margin))		15.0 Knots	16.0 Knots	
M/E	TYPE	B&W 7S80MC		
	MCR	32,000 PS x 74.0 RPM		
	NCR	28,800 PS x 71.4 RPM		
FOC	SFOC	122.1 Gr/BHP.h		Based on NCR
	TON/DAY	84.4 (HFO)		
Cruising range		26,000 N/M	26,500 N/M	
Shape of Midship Section		Double side / Double bottom	Double side / Double bottom	
Capacity	Cargo Hold	abt. 345,500 m³	abt. 360,000 m³	
	H.F.O.	abt. 7,350 m³		
	D.O.	abt. 490 m³		
	Fresh Water	abt. 460 m³		
	Ballast	abt. 103,000 m³		Including Peak Tanks

Basis Ship

- **Dimensional Ratios**

$$L/B = 5.41,\quad B/T_d = 2.77,\quad B/D = 1.87,\quad L/D = 10.12$$

- **Hull form coefficient**

$$C_{B\_d} = 0.82$$

- **Lightweight(=41,000ton)**
  - **Structural weight ≈ 36,400 ton (88%)**
  - **Outfit weight ≈ 2,700 ton (6.6%)**
  - **Machinery weight ≈ 1,900 ton (4.5%)**

$$\text{Cargo density} = \frac{\text{Deadweight}_{scant}}{\text{Cargo hold capacity}} = \frac{301,000}{345,500} = 0.87\,[ton/m^3] > 0.77$$

⇩

Deadweight Carrier

Example of a Basis Ship of 138,000 m³ LNG Carrier and Owner's Requirements of 160,000 m³ LNG Carrier

– 160,000 m³ LNG Carrier

		Basis Ship	Owner's Requirements	
Principal Dimensions (m)	L_{OA}	277.0		
	L_{BP}	266.0		
	B_{mld}	43.4		
	D_{mld}	26.0		
	T_d (design)	11.4	11.4	
	T_s (scantling)	12.1	12.1	
Cargo Hold Capacity(m^3)		138,000	160,000	
Service speed (knots)		19.5	19.5	
Main Engine	Type	Steam Turbine	2 Stroke Diesel Engine (×2)	
	DMCR	36000 PS, 88 RPM		With engine margin 10%
	NCR	32400 PS, 85 RPM		With sea margin 21%
SFOC (Ton/day)		180.64		
Deadweight (ton)		69,000	80,000	
DFOC (ton/day)		154.75		
Cruising Range (N.M)		13,000	11,400	

Basis Ship

- **Dimensional Ratios**

$$L/B = 6.31,$$
$$B/T_d = 3.81,$$
$$B/D = 1.67,$$
$$L/D = 10.23$$

- **Hull form coefficient**

$$※ C_{B\_d} = 0.742$$

- **Lightweight(=31,000ton)**
  - **Structural weight ≈ 21,600 ton (≈70%)**
  - **Outfit weight ≈ 6,200 ton (≈ 20%)**
  - **Machinery weight ≈ 3,200 ton (≈ 10%)**

$$\text{Cargo density} = \frac{\text{Deadweight}}{\text{Cargo hold capacity}} = \frac{69,000}{138,000} = 0.5\ [ton/m^3] < 0.77$$

Volume Carrier

Example of a Basis Ship of 3,700 TEU Container Carrier and Owner's Requirements of 4,100 TEU Container Carrier

*TEU : twenty-foot equivalent units

– 4,100 TEU Container Carrier

	Basis Ship	Owner's Requirements
Principal Dimensions LOA LBP Bmld Dmld Td / Ts (design / scantling)	 257.4 m 245.24 m 32.2 m 19.3 m 10.1 / 12.5 m	 Less than 260.0 m Less than 32.25 m Abt. 11.0 / 12.6 m
Deadweight (design / scantling)	 34,400 / 50,200 MT(metric ton)	 40,050/49,000 ~ 51,000 MT
Capacity Container on deck / in hold Ballast water Heavy fuel oil	 2,174 TEU / 1,565 TEU 13,800 m3 6,200 m3	 Abt. 4,100TEU Abt. 11,500 m3
Main Engine & Speed M / E type MCR (BHP x rpm) NCR (BHP x rpm) Service speed at NCR (Td, 15% SM) DFOC at NCR Cruising range	 Sulzer 7RTA84C 38,570 x 102 34,710 x 98.5 22.5 knots (at 11.5m) at 30,185 BHP 103.2 MT 20,000 N.M	 24.5 knots (at 11.0m) Abt. 20,000 N.M
Others Complement	30 P.	30 P.

Basis Ship

- **Dimensional Ratios**

$L/B = 7.62$

$B/T_d = 3.19$

$B/D = 1.67$

$L/D = 12.71$

- **Hull form coefficient**

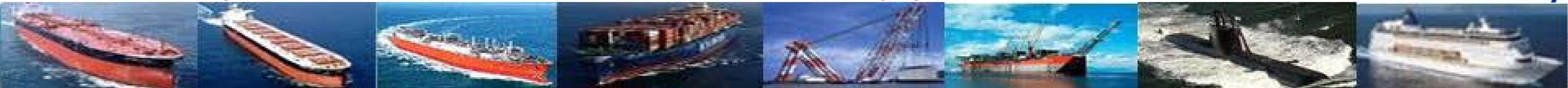
※ $C_{B\_d} = 0.62$

- **Lightweight(=16,000ton)**
  - **Structural weight** $\approx$ **11,000 ton ($\approx$68%)**
  - **Outfit weight** $\approx$ **3,200 ton ($\approx$ 20%)**
  - **Machinery weight** $\approx$ **1,800 ton ($\approx$ 12%)**

$$\text{Cargo density} = \frac{\text{Deadweight}_{\text{scant}}}{\text{Cargo hold capacity}} = \frac{\text{Deadweight}_{\text{scant}}}{V_{\text{container}} \times N_{\text{container in cargo hold}}} = \frac{50,200}{46.9 \cdot 1,565} = 0.68\ [ton/m^3] < 0.77$$

Volume Carrier

8.3 Constraints of the Design Equations



Constraints of the Design Equations

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

- Physical constraint
  - Floatability: Hydrostatic equilibrium
- Economical constraints
  - Owner's requirements

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

1) n.m = nautical mile
1 n.m = 1.852 km

- Regulatory constraints

  International Maritime Organization[IMO] regulations,
  International Convention for the Safety Of Life At Sea[SOLAS],
  International Convention for the Prevention of Pollution from Ships[MARPOL],
  International Convention on Load Lines[ICLL]
  Rules and Regulations of classification societies

Constraints of the Design Equations
- 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**:

$$F_B \overset{!}{=} W$$

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

: **Weight equation of a ship**

*Lightweight(LWT) reflects the weight of a 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.

Constraints of the Design Equations
- Economical Constraints

- **Economical constraints**

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

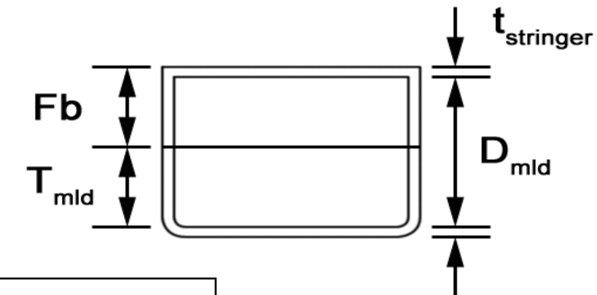
$$\boxed{V_{CH} = f(L, B, D)}$$

: Volume equation of a ship

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

Constraints of the Design Equations
- Regulatory Constraints

- **Regulatory constraints**
  - Freeboard[1)] regulation
  : International Convention on Load Lines(ICLL)1966



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

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

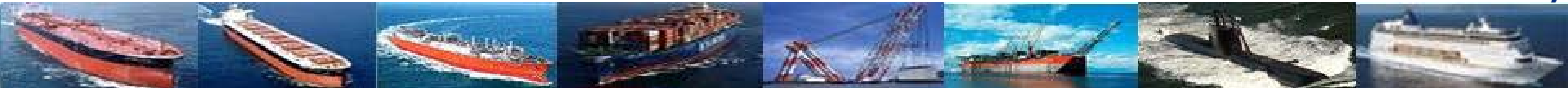
: Freeboard calculation of a ship

✓ **Check**: Freeboard of a ship should be greater than that required by the freeboard regulation.

1) Freeboard(Fb): The distance between the water line and the top of the deck at the side(at the deck line). It includes the thickness of upper deck.

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

8.4 Deadweight Carrier vs. Volume Carrier



Deadweight Carrier vs. Volume Carrier

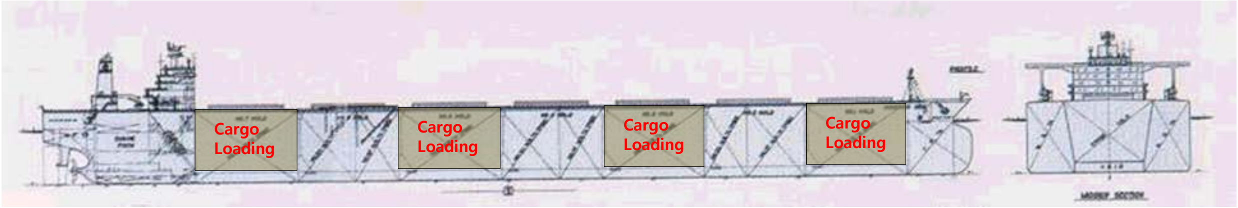
1. Deadweight Carrier

: Deadweight carrier is the ship whose weight is the critical factor when the cargo to be carried is "heavy" in relation to the space provided for it.

The ship will be weight critical when the ship carries a cargo which has a density more than $0.77 ton/m^3$ or inversely less than $1.29\ m^3/ton$.

Ore Carrier

For an example, ore carrier loads the iron ore (density ≈ $2.5\ ton/m^3$) in alternate holds, "alternated loading", therefore this kind of ship uses less than half of the hold volume.



<Alternated loading in ore carrier>

※ Approximate formula of roll periods (T_r)

$$T_r = \frac{2k \cdot B}{\sqrt{GM}}$$

GM: Metacentric height
B: Breadth,
k: 0.32~0.39 for full loading
0.37~.040 for ballast condition

2. Volume Carrier

: Volume carrier is the ship whose volume is the critical factor when the cargo to be carried is "light" in relation to the space provided for it.

Membrane-type LNG Carrier

Examples of the Volume Carrier (1/3)

➢ Container Carrier

Containers are arranged in bays in lengthwise, rows in beam wise, tiers in depth wise. It means that the principal dimensions are determined discontinuously. Therefore, the length, breadth and depth of the container carrier vary stepwise according to the number and size of the containers.

Container Carrier

Moreover, the container carrier loads the containers on deck, and that causes stability to be the ultimate criterion.

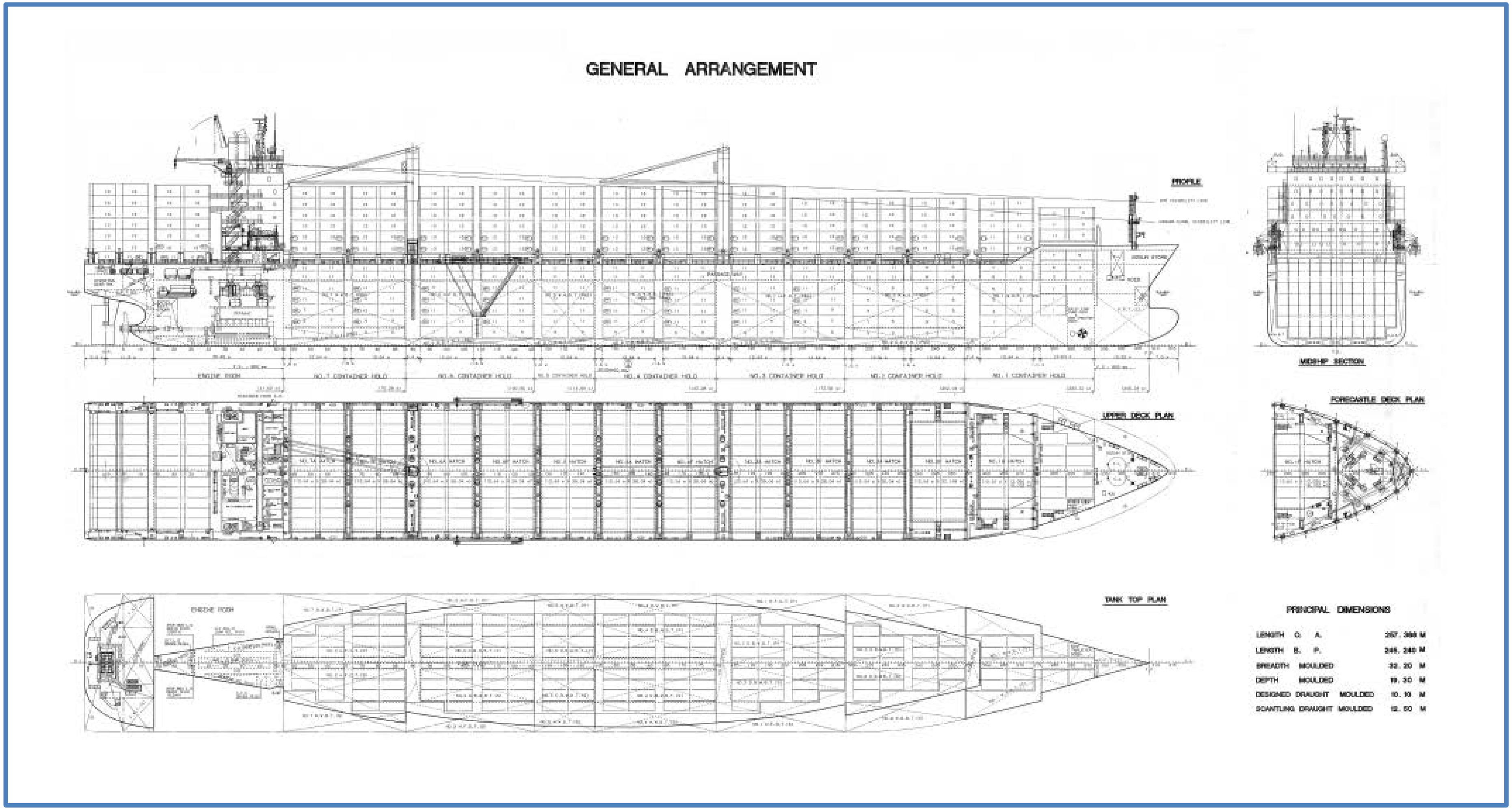
➢ Cruise ship

Cruise ship has many decks, so the *KG* is higher and that becomes the critical criterion on cruise ship.


Cruise ship

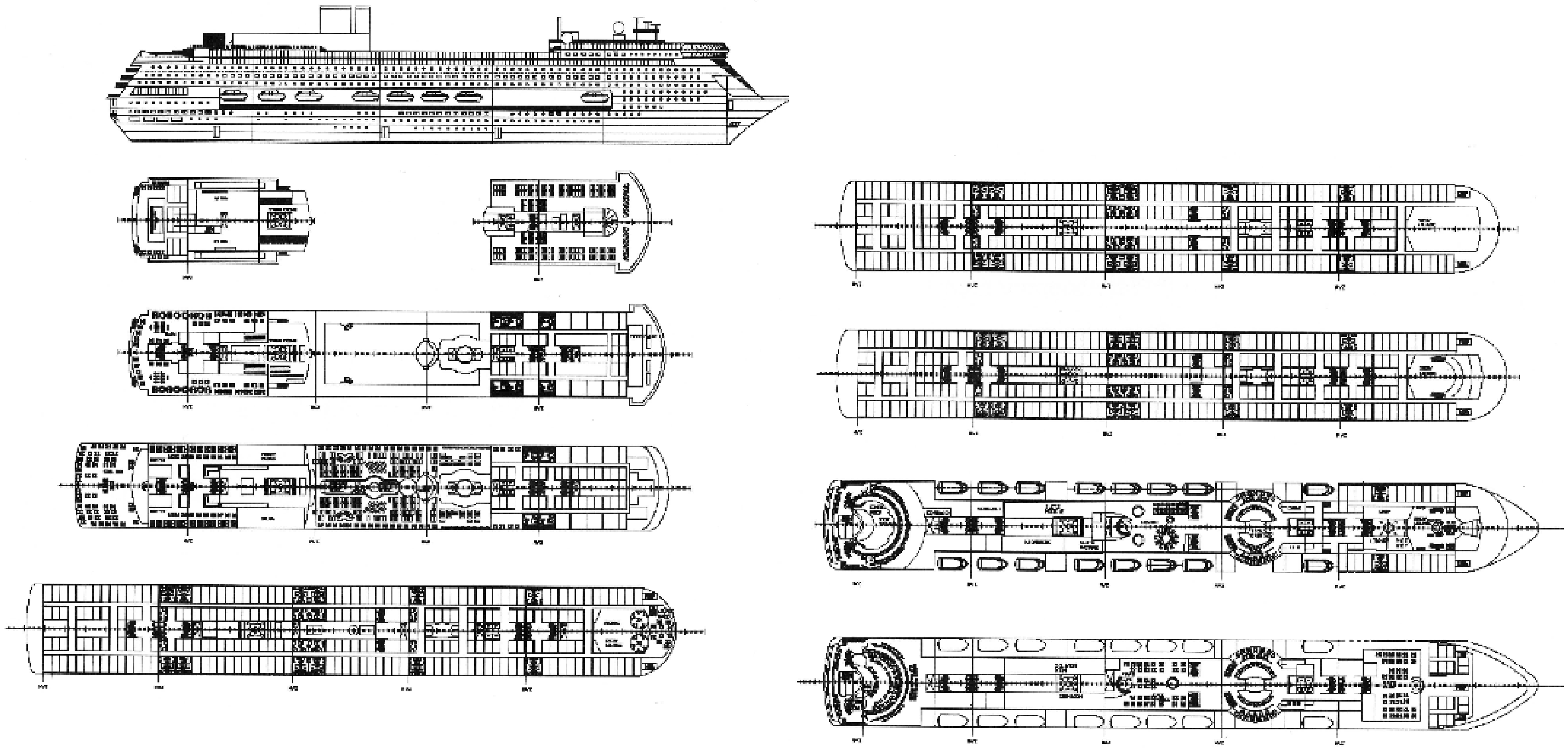
Examples of the Volume Carrier (2/3)

An example of the General Arrangement(GA) of 3,700 TEU container carrier



Examples of the Volume Carrier (3/3)

An example of the General Arrangement(GA) of a cruise ship



Determination of the Optimal Principal Dimensions of a Deadweight Carrier

Deadweight Carrier

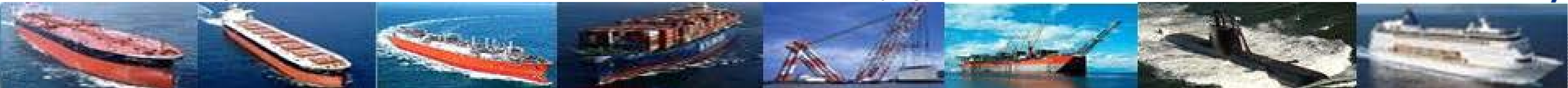
1	•**At first**, the principal dimensions such as *L*, *B*, *T*, C_B are determined according to the **weight equation**.	**Weight Equation**(Physical constraint) $\rho \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha) = DWT + LWT$ ✓ **Given**: DWT (owner's requirements) ✓ **Find**: L, B, T, C_B
2	•**Then**, the depth is determined considering the required cargo hold capacity according to the **volume equation**.	**Volume Equation**(Economical constraints) $V_{CH} = f(L, B, D)$ ✓ **Given**: L, B, V_{CH} (owner's requirements) ✓ **Find**: D
3	•Then, it should be checked **lastly** that whether the depth and draft satisfy the **freeboard regulation**.	**Freeboard calculation**(Regulatory constraints) $D \geq T + Fb(L, B, D, C_B)$ ✓ **Given**: L, B, D, T, C_B ✓ **Check**: Whether the chosen depth is equal or greater than draft plus required freeboard or not.

Determination of the Optimal Principal Dimensions of a Volume Carrier

Volume Carrier

1	•At first, the principal dimensions such as *L, B, D* are determined to provide the required cargo hold capacity according to the volume equation.	**Volume Equation(Economical constraints)** $\boxed{V_{CH} = f(L, B, D)}$ ✓ Given: V_{CH} (owner's requirements) ✓ Find: L, B, D
2	•Next, the principal dimensions such as T, C_B are determined according to weight equation.	**Weight Equation(Physical constraint)** $\boxed{\rho \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha) = DWT + LWT}$ ✓ Given: L, B, DWT (owner's requirements) ✓ Find: T, C_B
3	•Then, it should be checked lastly that whether the depth and draft satisfy the freeboard regulation.	**Freeboard calculation(Regulatory constraints)** $\boxed{D \geq T + Fb(L, B, D, C_B)}$ ✓ Given: L, B, D, T, C_B ✓ Check: Whether the chosen depth is equal or greater than draft plus required freeboard or not.

8.5 Derivation of the Weight Equation



Derivation of the Weight Equation - Physical Constraint (1/2)

*Lightweight(LWT) reflects the weight of vessel which is ready to go to sea without cargo and loads

*Deadweight(DWT) is the weight that a ship can load till the maximum allowable.

- **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:

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

(R.H.S) Total weight of a commercial ships is usually composed of the lightweight(LWT) and deadweight(DWT) which consists of the cargo and other variable loads.

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

Derivation of the Weight Equation - Physical Constraint (2/2)

- Physical constraint : hydrostatic equilibrium

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

(L.H.S) $W = LWT + DWT$

ρ :density of sea water = 1.025 Mg/m³
α : displacement of shell, stern and appendages
C_B : block coefficient
g : gravitational acceleration

V : the immersed volume of the ship.

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

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

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

Buoyant Force is the weight of the displaced fluid.

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

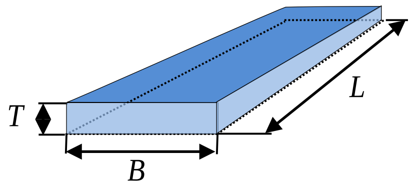
- Displacement volume ∇
- Displacement mass Δ
- Displacement Δ_g

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

Derivation of the Weight Equation
- Block coefficient(C_B) (1/2)

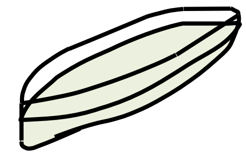
V : immersed volume
V_{box} : volume of box
L : length, B : breadth
T : draft

Do a ship and airplane usually have box shape?



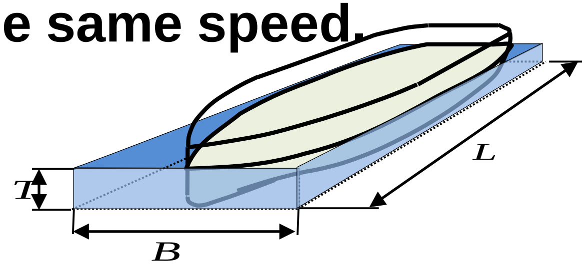
No.

They have a streamlined shape.



Why do a ship and airplane have a streamlined shape?

They have a <u>streamlined shape</u> <u>to minimize the drag force</u> they experience when they travel, then the engine needs a smaller power output to achieve the same speed.



Block Coefficient is introduced to describe the relation between immersed volume and principal dimensions.

<u>Block coefficient(C_B)</u> is <u>the ratio</u> of the <u>immersed volume</u> to <u>box bounded by L, B, T.</u>

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

Derivation of the Weight Equation - Block coefficient(C_B) (2/2)

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

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.
Thus, the 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 submerged hull to the inside of the shell plating, and 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).

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

Derivation of the Weight Equation - Weight vs. Mass (1/2)

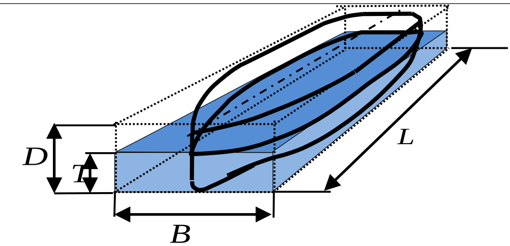
- **Physical constraint : hydrostatic equilibrium**

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

(R.H.S) $W = LWT + DWT$

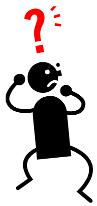
(L.H.S) $F_B = \rho \cdot g \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha)$

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



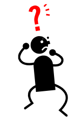
(L.H.S) = (R.H.S)

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



What is the unit of the lightweight and deadweight ?

Derivation of the Weight Equation
- Weight vs. Mass (2/2)

Question: Aren't "weight" and "mass" the same? 

Answer : No!

Mass is a measure of the amount of matter in an object.

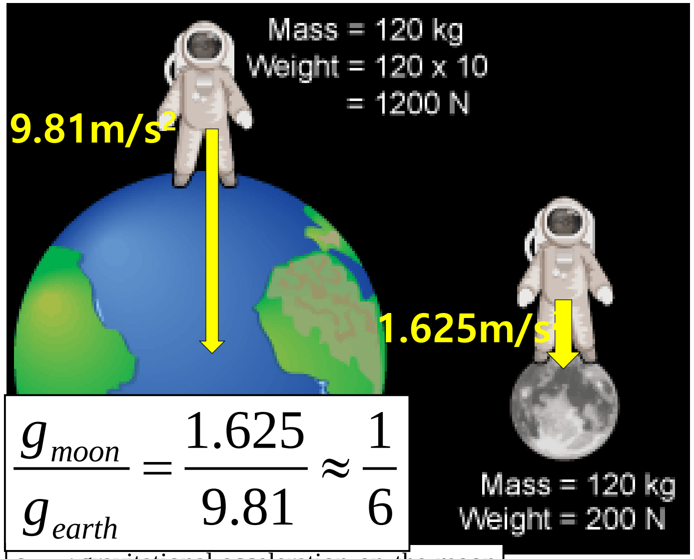
Weight is a measure of the force on the object caused by a gravitational field.

Gravity causes weight.

An object's mass doesn't change (unless you remove some), but its weight can change.

For example, an astronaut's weight on the moon is one-sixth of that on the Earth.

But the astronaut's mass doesn't change.



$$\frac{g_{moon}}{g_{earth}} = \frac{1.625}{9.81} \approx \frac{1}{6}$$

g_{moon} : gravitational acceleration on the moon

g_{earth} : gravitational acceleration on the earth

Derivation of the Weight Equation
- Weight Equation

• **Physical constraint** : hydrostatic equilibrium

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

$$\rho \cdot g \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha) = LWT + DWT \qquad ...(2)$$

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

ATTENTION

In the shipping world, they use "ton" for the unit of the lightweight and deadweight in practice.

But "ton" is "Mg (mega gram)" and is the unit of "Mass".

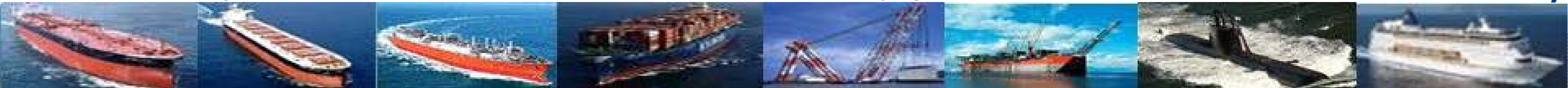
Therefore, from now on, the "weight equation" will be regarded as following :

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

"Weight equation"

where ρ := 1.025 Mg/m^3

8.6 Determination of the Optimal Principal Dimensions of a Ship by the Weight Equation



Determination of the Optimal Principal Dimensions of a Ship by the Weight Equation
- Weight Estimation

- **Weight equation**

The dimensions of a deadweight carrier whose design is weight critical are determined by the following equation.

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

✓ **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

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

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

How can you estimate the LWT?

Determination of the Optimal Principal Dimensions of a Ship by the Weight Equation - Weight Estimation : Method 1 (1/3)

- Weight equation of a ship

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

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

Method ①: $LWT = LWT_{Basis}$

How can you estimate the lightweight(LWT)?

At the early design stage, there are few data available for estimating 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 : Assume that the lightweight is the same as that of basis ship.

$$LWT = LWT_{Basis}$$

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

It will be noted that finding a solution to 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 indeterminate equation.

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

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

So, 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 iterated until the displacement becomes equal to the total weight of the ship.
  (∵ nonlinear equation)
- And we can get many sets of solution by applying the different assumptions.
  (∵ indeterminate equation)
  Thus, we need a certain criteria to select the proper solution.

Determination of the Optimal Principal Dimensions of a Ship by the Weight Equation - Weight Estimation : Method 1 (3/3)

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

For example, this is the first set of solution.

The values of the principal dimensional ratios L/B, B/T, B/D 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.

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

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

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

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

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

What kind of criteria is available to select proper solution?

Objective Functions

- In shipbuilding Society : Shipbuilding Cost
- In Shipping Society :
  - Less Power→ Less Energy Consumption→ Minimum Operational Expenditure (OPEX)
  - Operability→ Required Freight Rate(RFR).
  - Minimum Capital Expenditure(CAPEX)

For example, the shipping company will adopt the objective function as RFR. The design ship will have the least required freight rate(RFR) expressed as:

$$\boxed{RFR = \frac{\text{Capital cost+Annual operating cost}}{\text{Annual delivered LNG quantity}}}$$

*Capital cost=Building cost × Capital recovery factor.

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

- Weight equation of a ship

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

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

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

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 : Assume that the total weight(W) is proportional to the deadweight.

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

Design ship and basis ship are assumed to have the same ratio of deadweight to total weight.

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

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

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

- Weight equation of a ship

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

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 : Assume that the lightweight could vary as the volume of the vessel as represented by $\underline{L \cdot B \cdot D}$.

$$LWT = C_{LWT} \cdot L \cdot B \cdot D$$

Assume that the lightweight is dependent on the principal dimensions such as L, B and D.

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

To estimate the lightweight, we will use the volume variable ($L \cdot B \cdot D$).

$$LWT = f(L \cdot B \cdot D)$$

For example, suppose that LWT is proportional to $\underline{L \cdot B \cdot D}$.

$$LWT = C_{LWT} \cdot L \cdot B \cdot D$$

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 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 the lightweight more accurately?

Since a ship consists of the hull structure, outfit and machinery, if we could estimate the weight of each components, the lightweight would be estimated more accurately.

Method 4 : Estimate the structural weight(W_s), outfit weight(W_o) and machinery weight(W_m) respectively.

$$LWT = W_s + W_o + W_m$$

How can you estimate W_s, W_o, W_m ?

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

- 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: $LWT = W_s + W_o + W_m$

Method 4 $LWT = \boxed{W_s} + W_o + W_m$

Method 4-(1) Assume that the structural weight(Ws) is a function of L, $(B+D)$.

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

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

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

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

So, to estimate the structural weight, we will use the area variables such as L·B, B·D.

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

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

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

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

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

- 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

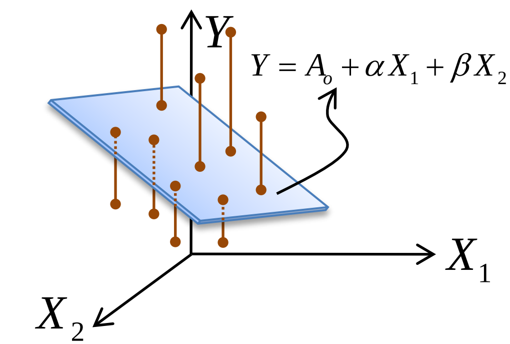
Method ④: $LWT = W_s + W_o + W_m$

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

a) To perform the regression analysis, we transform the above non-linear equation into the linear equation by transforming 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) There are the sets of as-built ship data ($X_{1i}, X_{2i}; Y_i$).

The parameters can be obtained by finding a function that minimize the sum of squared errors, "least square method", which is the difference between the sets of the data and the estimated function.

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

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

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.

- 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: $LWT = W_s + W_o + W_m$

Method 4 $LWT = W_s + \boxed{W_o} + W_m$

Method 4-(2) Assume that the outfit weight(W_o) is proportional to $L \cdot B$.

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

Assume that the outfit weight(W_o) as a function of L, B.

$$W_o = f(L, B)$$

To estimate the outfit weight, we will use the variables such as $L \cdot B$.

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

For example, suppose that the outfit weight is proportional to $L \cdot B$

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

Coefficient C_o is obtained from the basis ship.

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

• 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: $LWT = W_s + W_o + W_m$

Method 4 $LWT = W_s + W_o + \boxed{W_m}$

Method 4-(3) Assume that the machinery weight(W_s) is proportional to $NMCR$

$$W_m = C_m \cdot NMCR$$

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

$$W_m = f(NMCR)$$

For example, suppose that the machinery weight is proportional to $NMCR$.

$$\boxed{W_m = C_m \cdot NMCR}$$

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

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

Determination of the Optimal Principal Dimensions of a Ship by the Weight Equation
- Weight Estimation : Method 4 (3/4) Machinery Weight (2)

- Weight equation of a ship

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

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

Method ④: $LWT = W_s + W_o + \boxed{W_m}$

$$W_m = C_m \cdot \boxed{NMCR}$$

$$\boxed{W_m = C_m \cdot NMCR}$$

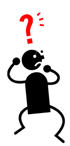
Coefficient C_m can be obtained from the basis ship.

$$W_m = C_m \cdot NMCR$$

Find

From the basis ship

???



Then, how can you estimate the $NMCR$?

Determination of the Optimal Principal Dimensions of a Ship by the Weight Equation
- Estimation of NMCR(Nominal Maximum Continuous Rating) (1/3)

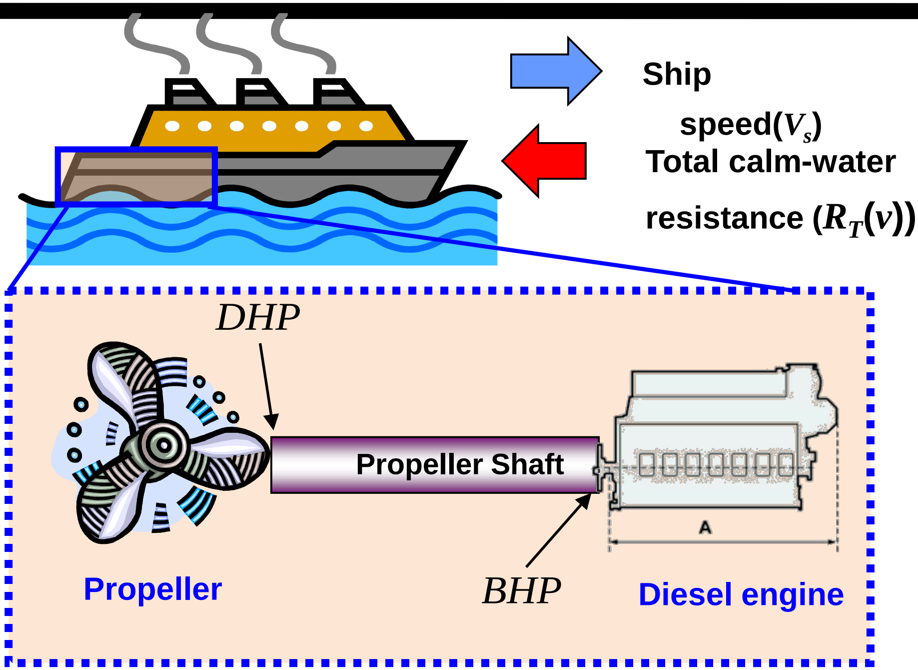
- **Weight equation of a ship**

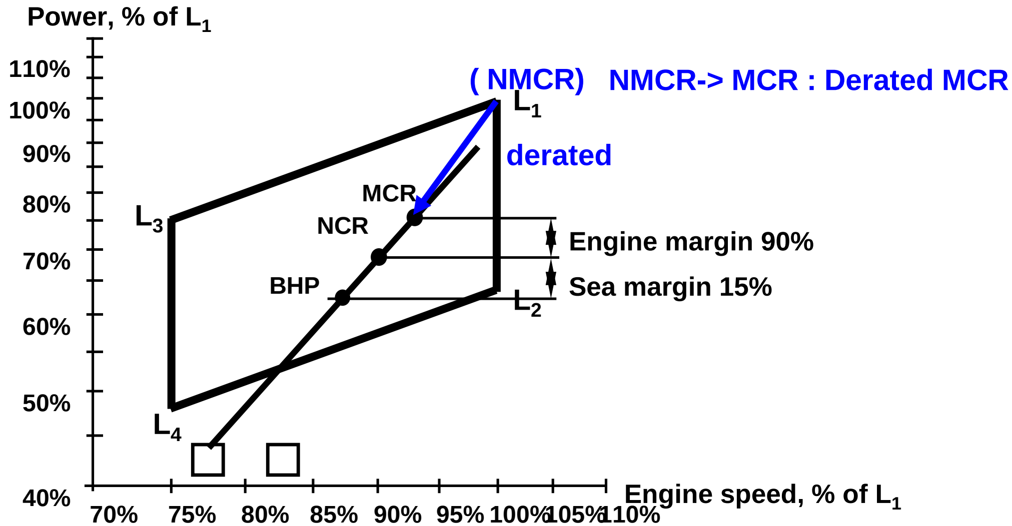
$$\rho \cdot L \cdot B \cdot T \cdot C_B \cdot (1+\alpha) = W$$
$$= DWT + LWT \quad \text{...(3)}$$

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

Method ④: $LWT = W_s + W_o + W_m$

$W_m = C_m \cdot NMCR$





① **EHP (Effective Horse Power)**

$$EHP = R_T(v) \cdot V_s \qquad \text{(In Calm Water)}$$

② **DHP (Delivered Horse Power)**

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

③ **BHP (Brake Horse Power)**

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

④ **NCR (Normal Continuous Rating)**

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

⑤ **DMCR (Derated Maximum Continuous Rating)**

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

⑥ **NMCR (Nominal Maximum Continuous Rating)**

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

- Weight equation of a ship

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

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

Method ④: $LWT = W_s + W_o + W_m$

$W_m = C_m \cdot NMCR$

$$\boxed{W_m = C_m \cdot NMCR}$$

NMCR **can be estimated through the resistance estimation, power prediction and main engine selection. However, there are few data available for estimation of the** ***NMCR*** **at the early design stage, so** ***NMCR*** **can be estimated by 'Admiralty formula'**

Admiralty formula :

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

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

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

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

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

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

- Weight equation of a ship

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

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

Method ④: $LWT = W_s + W_o + W_m$

$W_m = C_m \cdot NMCR$

C_{ad} : Admiralty coefficient
V_s : speed of ship, Δ : displacement

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 is used for a rough estimation. So, after the principal dimensions are determined, DHP needs to be predicted more accurately through resistance estimation and speed-power prediction.

(ref. Innovative Ship Design Lecture note: Resistance estimation, Speed-Power Prediction)

- **Weight equation of a ship**

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

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

Method ④: $LWT = W_s + W_o + W_m$

$W_m = C_m \cdot NMCR$

$$W_m = C_m \cdot NMCR$$

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

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

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

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

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

C_{ad} : Admiralty coefficient
V_s : speed of ship
Δ: displacement
ρ: density of sea water [ton/m^3]

- After principal dimensions are determined, also the $NMCR$ needs to be estimated more accurately through resistance estimation, speed-power prediction.

- If the machinery weight is changed by modified $NMCR$, you have to iterate determination of principal dimension by using changed machinery weight.

Determination of the Optimal Principal Dimensions of a Ship by the Weight Equation - Weight Estimation : Method 4 (4/4)

- Weight equation of a ship

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

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

Method ④: $LWT = W_s + W_o + W_m$

$W_m = C_m \cdot NMCR$

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

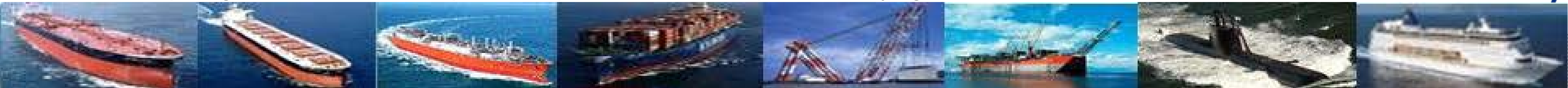
$$LWT = W_S + W_o + W_m$$

$$\begin{cases} W_s = C_s \cdot L^{1.6} \cdot (B+D) \\ W_o = C_o \cdot L \cdot B \\ W_m = C_m \cdot NMCR \\ \quad = C_{power} \cdot (L \cdot B \cdot T \cdot C_B \cdot (1+\alpha))^{2/3} \cdot V_s^{\,3} \end{cases}$$

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/m^3]

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

8.7 Determination of the Optimal Principal Dimensions of a Ship by the Volume Equation



- **Economical constraint**

The dimensions of a volume carrier whose design is volume critical are determined by the following equation.

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

⇨ Volume equation of a ship

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

✓ **Given**: Cargo hold capacity[m^3]

✓ **Find**: L, B, D

How can you estimate the cargo hold capacity?

Determination of the Optimal Principal Dimensions of a Ship 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 cargo hold capacity is proportional to *L·B·D*.

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

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

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.

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

How can you estimate the cargo hold capacity more accurately?

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

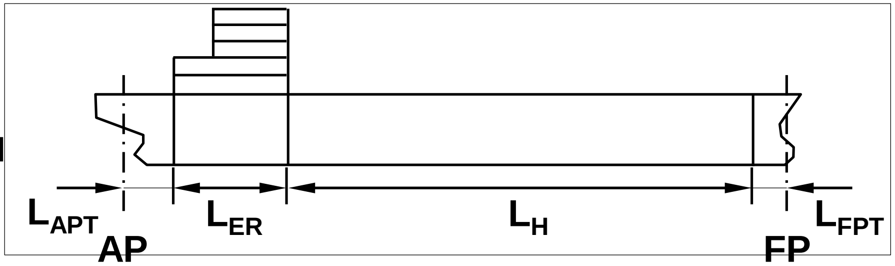
$$V_{CH} = C_{CH} \cdot L_H \cdot B \cdot D$$

Length of the cargo hold(L_H) :

Length of cargo hold(L_H) is defined that 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



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

Determination of the Optimal Principal Dimensions of a Ship by the Volume Equation

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

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

Method 2 :

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

ATTENTION

Since the method 1 and 2 are used for a rough estimation, you have to estimate the cargo hold capacity more accurately after the arrangement of the compartment has been done.

8.8 Freeboard Calculation

Freeboard Calculation (1/3)

- **Regulatory constraint**

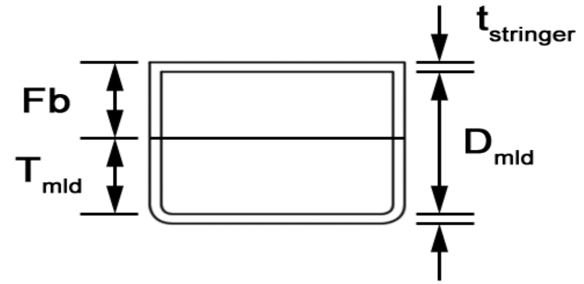
  - **Freeboard[1] regulation**

    -The ship needs an additional safety margin to maintain the buoyancy and stability while operating at sea.

    -This safety margin is provided by the reserve of buoyancy of the hull located above the waterline(freeboard).

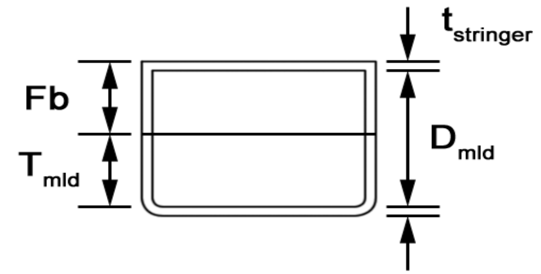
    -Freeboard of a ship should be greater than that in accordance with the freeboard regulation(ICLL 1966).

1) Freeboard(Fb) – The distance between the water line and the top of the deck at the side(at the deck line). It includes the thickness of upper deck.



Freeboard Calculation (2/3)

- **Regulatory constraint**
  - Freeboard calculation

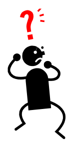


$$\boxed{D_{Fb} \geq T + Fb(L, B, D_{mld}, C_B)}$$

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

✓ **Given**: $L, B, D(=D_{mld}), T, C_B$

✓ **Check**: Freeboard of a ship should be greater than that in accordance with the freeboard regulation.



How can you calculate the required freeboard(Fb) ?

Freeboard Calculation (3/3)

How can you calculate the required freeboard(Fb)?

At the early design stage, there are few data available for estimation of required freeboard. Thus, the required freeboard can be estimated from the basis ship.

Method ① : Assume that the freeboard is proportional to the depth.

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

$$D_{Fb} \geq T + C_{Fb} \cdot D_{mld}$$

Coefficient C_{Fb} can be obtained from the basis ship.

However, the required freeboard have 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 freeboard regulation is not satisfied, the freeboard and depth should be changed.

8.9 Example of an Objective Function

Example of an Objective Function - 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 principal 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

Ex) The value of the coefficients obtained from the 302K VLCC

$$C_{PS} = 2,223.0,\ C_{PO} = 4,834.5,\ C_{PM} = 17,177.0$$

Example of an Objective Function
- Shipbuilding Cost (2/2)

Method to obtain the coefficient related with the cost

The shipbuilding cost is composed as follows.

$$\begin{aligned} Shipbuilding\ Cost = &(\text{Man-hour for the structural + Material cost for the structural}) \\ &+(\text{Man-hour for the outfit +Material cost for the outfit}) \\ &+(\text{Man-hour for the machinery +Material cost for the machinery}) \\ &+\text{Additional cost} \end{aligned}$$

※ **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 structural 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(structural)**

C_{PO} **: Coefficient related with the cost of the outfit**

C_{PM} **: Coefficient related with the cost of the machinery**

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

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

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

■ Comparison of the production cost

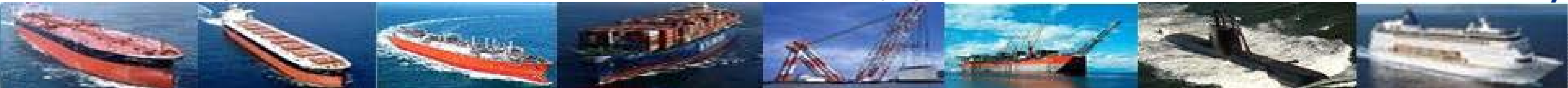
		Korea	Japan	China
Material cost	Steel	17	17	18
	Equipment	42	43	47
	Sum	59	60	65
Wage		27	29	19
Additional Cost		14	13	16
Sum		100	100	100

8.10 Example of a Constrained Nonlinear Optimization Method by Using the Lagrange Multiplier

Determination of the Optimal Principal Dimensions of a Ship

Determination of the Optimal Propeller Principal Dimensions

SYstem Design Laboratory



[Summary] Mathematical Model for Determination of the Optimal Principal Dimensions(L, B, D, T, C_B) - "Conceptual Ship Design Equation"

Find(Design variables) L, B, D, C_B, T_d

length, breadth, depth, block coefficient, design draft

Given(Owner's requirement) DWT, V_{H_req}, $T_s(=T_{max})$, V

deadweight, Required cargo hold capacity, Scantling Draft (maximum), ship speed

Physical constraint

→ **Hydrostatic equilibrium(Weight equation)** – Equality constraint

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

$$= DWT_{given} + C_s \cdot L^{1.6}(B+D) + C_o \cdot L \cdot B$$

$$+ C_{power} \cdot (L \cdot B \cdot T_d \cdot C_B)^{2/3} \cdot V^3 \quad \cdots (2.3)$$

Economical constraints(Owner's requirements)

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

$$V_{H\_req} = C_H \cdot L \cdot B \cdot D \cdots (3.1)$$

- 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(1966 ICLL)** - Inequality constraint

$$D \geq T_s + C_{FB} \cdot D \cdots (4)$$

Objective Function(Criteria to determine the proper principal dimensions)

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

➡ **Optimization problem: 5 variables(L, B, D, C_B, T_d), 2 equality constraints((2.3), (3.1)), 1 inequality constraint((4))**

Determination of the Optimal Principal Dimensions of a Ship (1/6)

Simplified Mathematical Model for Conceptual Ship Design Equation

- ***Given***: $DWT, V_{H.req}, D, T_s, T_d$
- ***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 $\rightarrow C_{power}' \cdot (2 \cdot B \cdot T_d + 2 \cdot L \cdot T_d + L \cdot B) \cdot V^3$

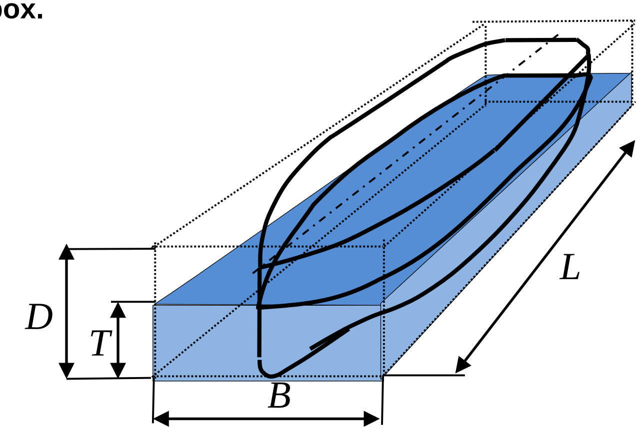
$(L \cdot B \cdot T_d \cdot C_B)^{2/3}$ **is (Volume)$^{2/3}$ and means the submerged area of the ship.**
So, we assume that the submerged area of the ship is equal to the submerged area of the rectangular box.

  - **Required cargo hold capacity(Volume equation)**

$$V_{H.req} = C_H \cdot L \cdot B \cdot D \quad ...(b)$$

  - **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 (2/6)

Simplified Mathematical Model for Conceptual Ship Design Equation

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

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

- ***Subject to***
  - **Hydrostatic equilibrium(Simplified weight equation)**

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

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

$$V_{H.req} = C_H \cdot L \cdot B \cdot D \quad ...(b)$$

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

Determination of the Optimal Principal Dimensions of a Ship (3/6)

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

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

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

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

$$h_2\left(L,B,D\right)=C_H\cdot L\cdot B\cdot D-V_{H.req}$$

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

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

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

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

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

$$+\lambda_2\cdot\left(C_H\cdot x_1\cdot x_2\cdot D-V_{H.req}\right)$$

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

Determination of the Optimal Principal Dimensions of a Ship (4/6)

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

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

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

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

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

Determination of the Optimal Principal Dimensions of a Ship (5/6)

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

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

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

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

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

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

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

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

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

➡ **It can be solved by using a numerical method!**

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

- **Programming by using the Matlab**

```
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.**

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

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

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

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

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

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

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

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

Determination of the Optimal Principal Dimensions of a Propeller (1/4)

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 (2/4)

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

: 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_0 is as follows.

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

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 (3/4)

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

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

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

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

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

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

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

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

Determination of the Optimal Principal Dimensions of a Propeller (4/4)

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

$$\left(\frac{\partial K_Q}{\partial (P_i / D_P)}\right)\left\{J \cdot \left(\frac{\partial K_T}{\partial J}\right) - 4K_T\right\}$$
$$+\left(\frac{\partial K_T}{\partial (P_i / D_P)}\right)\left\{5K_Q - J \cdot \left(\frac{\partial K_Q}{\partial J}\right)\right\} = 0 \quad \cdots\cdots \quad (4)$$

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

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

By definition $J = \dfrac{V(1-w)}{n \cdot D_P}$, 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).

[Reference] Derivation of Eq. (4) from Eqs. (1)~(3) (1/3)

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

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

To eliminate λ, we calculate as follows.

$$\text{Eq. (1)}\times\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)-\text{Eq. (2)}\times\left\{\left(\frac{\partial K_Q}{\partial J}\right)-5\cdot C\cdot J^4\right\}=0$$

$$\text{Eq. (1)}\times\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right):\ \frac{1}{2\pi}\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left(\frac{K_T}{K_Q}\right)+\frac{J}{2\pi}\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\frac{\left\{\left(\frac{\partial K_T}{\partial J}\right)\cdot K_Q-\left(\frac{\partial K_Q}{\partial J}\right)\cdot K_T\right\}}{{K_Q}^2}+\cancel{\lambda\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left\{\left(\frac{\partial K_Q}{\partial J}\right)-5\cdot C\cdot J^4\right\}}=0$$

$$\text{Eq. (2)}\times\left\{\left(\frac{\partial K_Q}{\partial J}\right)-5\cdot C\cdot J^4\right\}:\ \frac{J}{2\pi}\frac{\left\{\left(\frac{\partial K_T}{\partial (P_i/D_P)}\right)\cdot K_Q-\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\cdot K_T\right\}}{{K_Q}^2}\left\{\left(\frac{\partial K_Q}{\partial J}\right)-5\cdot C\cdot J^4\right\}+\cancel{\lambda\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left\{\left(\frac{\partial K_Q}{\partial J}\right)-5\cdot C\cdot J^4\right\}}=0$$

$$\text{Eq. (1)}\times\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)-\text{Eq. (2)}\times\left\{\left(\frac{\partial K_Q}{\partial J}\right)-5\cdot C\cdot J^4\right\}$$

$$=\frac{1}{2\pi}\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left(\frac{K_T}{K_Q}\right)+\frac{J}{2\pi}\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\frac{\left\{\left(\frac{\partial K_T}{\partial J}\right)\cdot K_Q-\left(\frac{\partial K_Q}{\partial J}\right)\cdot K_T\right\}}{{K_Q}^2}-\frac{J}{2\pi}\frac{\left\{\left(\frac{\partial K_T}{\partial (P_i/D_P)}\right)\cdot K_Q-\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\cdot K_T\right\}}{{K_Q}^2}\left\{\left(\frac{\partial K_Q}{\partial J}\right)-5\cdot C\cdot J^4\right\}=0$$

[Reference] Derivation of Eq. (4) from Eqs. (1)~(3) (2/3)

$$\text{Eq. (1)}\times\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)-\text{Eq. (2)}\times\left\{\left(\frac{\partial K_Q}{\partial J}\right)-5\cdot C\cdot J^4\right\}$$

$$=\frac{1}{2\pi}\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\left(\frac{K_T}{K_Q}\right)+\frac{J}{2\pi}\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\frac{\left\{\left(\frac{\partial K_T}{\partial J}\right)\cdot K_Q-\left(\frac{\partial K_Q}{\partial J}\right)\cdot K_T\right\}}{K_Q{}^2}-\frac{J}{2\pi}\frac{\left\{\left(\frac{\partial K_T}{\partial(P_i/D_P)}\right)\cdot K_Q-\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\cdot K_T\right\}}{K_Q{}^2}\left\{\left(\frac{\partial K_Q}{\partial J}\right)-5\cdot C\cdot J^4\right\}=0$$

Multiply 2π and the both side of the equation and rearrange the equation as follows.

$$\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\left(\frac{K_T}{K_Q}\right)+\frac{J}{K_Q{}^2}\underline{\left[\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\left\{\left(\frac{\partial K_T}{\partial J}\right)\cdot K_Q-\left(\frac{\partial K_Q}{\partial J}\right)\cdot K_T\right\}-\left\{\left(\frac{\partial K_T}{\partial(P_i/D_P)}\right)\cdot K_Q-\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\cdot K_T\right\}\left\{\left(\frac{\partial K_Q}{\partial J}\right)-5\cdot C\cdot J^4\right\}\right]}=0$$

The term underlined is rearranged as follows.

$$=\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\left(\frac{\partial K_T}{\partial J}\right)\cdot K_Q\cancel{-\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\left(\frac{\partial K_Q}{\partial J}\right)\cdot K_T}-\left(\frac{\partial K_T}{\partial(P_i/D_P)}\right)\left(\frac{\partial K_Q}{\partial J}\right)\cdot K_Q\cancel{+\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\left(\frac{\partial K_Q}{\partial J}\right)\cdot K_T}+5\cdot\left(\frac{\partial K_T}{\partial(P_i/D_P)}\right)\cdot K_Q\cdot C\cdot J^4-5\cdot\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\cdot K_T\cdot C\cdot J^4$$

$$=\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\left(\frac{\partial K_T}{\partial J}\right)\cdot K_Q-\left(\frac{\partial K_T}{\partial(P_i/D_P)}\right)\left(\frac{\partial K_Q}{\partial J}\right)\cdot K_Q+5\cdot\left(\frac{\partial K_T}{\partial(P_i/D_P)}\right)\cdot K_Q\cdot C\cdot J^4-5\cdot\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\cdot K_T\cdot C\cdot J^4$$

Substituting the rearranged term into the above equation.

$$\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\left(\frac{K_T}{K_Q}\right)+\frac{J}{K_Q{}^2}\left[\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\left(\frac{\partial K_T}{\partial J}\right)\cdot K_Q-\left(\frac{\partial K_T}{\partial(P_i/D_P)}\right)\left(\frac{\partial K_Q}{\partial J}\right)\cdot K_Q+5\cdot\left(\frac{\partial K_T}{\partial(P_i/D_P)}\right)\cdot K_Q\cdot C\cdot J^4-5\cdot\left(\frac{\partial K_Q}{\partial(P_i/D_P)}\right)\cdot K_T\cdot C\cdot J^4\right]=0$$

[Reference] Derivation of Eq. (4) from Eqs. (1)~(3) (3/3)

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

$$\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left(\frac{K_T}{K_Q}\right) + \frac{J}{K_Q^{\,2}}\left[\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left(\frac{\partial K_T}{\partial J}\right)\cdot K_Q - \left(\frac{\partial K_T}{\partial (P_i/D_P)}\right)\left(\frac{\partial K_Q}{\partial J}\right)\cdot K_Q + 5\cdot\left(\frac{\partial K_T}{\partial (P_i/D_P)}\right)\cdot K_Q \cdot C \cdot J^4 - 5\cdot\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\cdot K_T \cdot C \cdot J^4\right] = 0$$

Apply the distributive property.

$$\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left(\frac{K_T}{K_Q}\right) + \left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left(\frac{\partial K_T}{\partial J}\right)\cdot\frac{J}{K_Q} - \left(\frac{\partial K_T}{\partial (P_i/D_P)}\right)\left(\frac{\partial K_Q}{\partial J}\right)\cdot\frac{J}{K_Q} + 5\cdot\left(\frac{\partial K_T}{\partial (P_i/D_P)}\right)\cdot\cancel{\frac{C\cdot J^5}{K_Q}} - 5\cdot\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\cdot\frac{K_T}{K_Q}\cdot\cancel{\frac{C\cdot J^5}{K_Q}} = 0$$

By using Eq. (3) $\dfrac{C\cdot J^5}{K_Q} = 1$

$$\underline{\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left(\frac{K_T}{K_Q}\right)} + \left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left(\frac{\partial K_T}{\partial J}\right)\cdot\frac{J}{K_Q} - \left(\frac{\partial K_T}{\partial (P_i/D_P)}\right)\left(\frac{\partial K_Q}{\partial J}\right)\cdot\frac{J}{K_Q} + 5\cdot\left(\frac{\partial K_T}{\partial (P_i/D_P)}\right) \underline{- 5\cdot\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\cdot\frac{K_T}{K_Q}} = 0$$

The underlined term is calculated as follows.

$$-4\cdot\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left(\frac{K_T}{K_Q}\right) + \left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left(\frac{\partial K_T}{\partial J}\right)\cdot\frac{J}{K_Q} - \left(\frac{\partial K_T}{\partial (P_i/D_P)}\right)\left(\frac{\partial K_Q}{\partial J}\right)\cdot\frac{J}{K_Q} + 5\cdot\left(\frac{\partial K_T}{\partial (P_i/D_P)}\right) = 0$$

Multiply K_Q and the both side of the equation.

$$-4\cdot\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)K_T + \left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left(\frac{\partial K_T}{\partial J}\right)J - \left(\frac{\partial K_T}{\partial (P_i/D_P)}\right)\left(\frac{\partial K_Q}{\partial J}\right)\cdot J + 5\cdot K_Q\left(\frac{\partial K_T}{\partial (P_i/D_P)}\right) = 0$$

Apply the distributive property. $\left(\dfrac{\partial K_Q}{\partial (P_i/D_P)}\right), \left(\dfrac{\partial K_T}{\partial (P_i/D_P)}\right)$

$$\left(\frac{\partial K_Q}{\partial (P_i/D_P)}\right)\left\{J\cdot\left(\frac{\partial K_T}{\partial J}\right) - 4K_T\right\} + \left(\frac{\partial K_T}{\partial (P_i/D_P)}\right)\left\{5K_Q - J\cdot\left(\frac{\partial K_Q}{\partial J}\right)\right\} = 0 \quad \cdots\cdots \quad (4)$$

Reference Slides

[Example] 297,000 ton Deadweight VLCC (Very Large Crude Oil Carrier) Design based on 279,500 ton Deadweight VLCC

[Example] 297,000 ton Deadweight VLCC (Very Large Crude Oil Carrier) Design based on 279,500 ton Deadweight VLCC

		Basis Ship	Owner's Requirements	
Principal Dimensions	Loa	abt. 330.30 m		
	Lbp	314.00 m		
	B,mld	58.00 m		
	Depth,mld	31.00 m		
	Td(design)	20.90 m	21.50 m	
	Ts(scant.)	22.20 m	22.84 m	
Deadweight(scant)		301,000 ton	320,000 ton	
Deadweight(design)		279,500 ton	297,000 ton	
Speed (at design draft 90% MCR(with 15% Sea Margin))		15.0 Knots	16.0 Knots	
M/E	TYPE	B&W 7S80MC		
	MCR	32,000 PS x 74.0 RPM		
	NCR	28,800 PS x 71.4 RPM		
FOC	SFOC	122.1 Gr/BHP.h		Based on NCR
	TON/DAY	84.4 (HFO)		
Cruising range		26,000 N/M	26,500 N/M	
Shape of Midship Section		Double side / Double bottom	Double side / Double bottom	
Capacity	Cargo Hold	abt. 345,500 m³	abt. 360,000 m³	
	H.F.O.	abt. 7,350 m³		
	D.O.	abt. 490 m³		
	Fresh Water	abt. 460 m³		
	Ballast	abt. 103,000 m³		Including Peak Tanks

Basis Ship

- **Dimensional Ratios**

$$L/B = 5.41,\quad B/T_d = 2.77,\quad B/D = 1.87,\quad L/D = 10.12$$

- **Hull form coefficient**

$$C_{B\_d} = 0.82$$

- **Lightweight(=41,000ton)**
  - **Structural weight ≈ 36,400 ton (88%)**
  - **Outfit weight ≈ 2,700 ton (6.6%)**
  - **Machinery weight ≈ 1,900 ton (4.5%)**

$$\text{Cargo density} = \frac{\text{Deadweight}_{scant}}{\text{Cargo hold capacity}} = \frac{301{,}000}{345{,}500} = 0.87\,[ton/m^3] > 0.77$$

⇩

Deadweight Carrier

Step 1) The principal dimensions such as L, B, T_d, $C_{B,d}$ are determined according to the weight equation.

$$\boxed{\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT}$$

ρ: density of sea water = 1.025 ton/m^3
α: a fraction of the shell appendage allowance = 0.0023

$$\left(1+\alpha = \frac{Displacement}{Moulded\ \ Displaced\ Volume}\bigg|_{basis} = \frac{313,007}{312,269} = 1.0023 \right)$$

✓ **Given**: $DWT_d = 297,000\ [ton]$, $T_d = 21.5[m]$, $V_s = 16[knots]$

✓ **Find**: L, B, $C_{B,d}$

*Subscript d: at design draft

Determination of the Principal Dimensions of the 297,000 ton Deadweight VLCC - Step 1: Weight Equation (Method 1) (1/3)

Step 1) Weight Equation → Step 2) Volume Equation → Step 3) Freeboard Calculation

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d = 297,000 [ton], T_d = 21.5[m]
Find: L, B, $C_{B,d}$

Method 1 : Assume that the lightweight is the same as that of basis ship.

$$LWT = LWT_{Basis}$$

$$L \cdot B \cdot T_d \cdot C_{B,d} \cdot \rho \cdot (1+\alpha) = DWT_d + LWT_{Basis}$$

$$LWT_{Basis} = 41,000[ton]$$

$$L \cdot B \cdot T_d \cdot C_{B,d} \cdot \rho \cdot (1+\alpha) = DWT_d + LWT_{Basis}$$

$$L \cdot B \cdot 21.5 \cdot C_{B,d} \cdot 1.025 \cdot (1+0.002) = 297,000 + 41,000$$

$$\boxed{L \cdot B \cdot C_{B,d} \cdot 22.08 = 338,000 \cdots (5.1)}$$

There are 3 unknown variables (L, B, $C_{B,d}$) with one equation.

→ Nonlinear indeterminate equation!

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d = 297,000 [*ton*], T_d = 21.5[*m*]

Find: *L*, *B*, $C_{B,d}$

Method ①: $LWT = LWT_{Basis}$

$$L \cdot B \cdot C_{B,d} \cdot 22.08 = 338,000 \cdots (5.1)$$

Therefore, we have to assume two variables to solve this indeterminate equation.
The values of the principal dimensional ratio L/B and $C_{B,d}$ can be obtained from the basis ship.

$$L / B = L_{Basis} / B_{Basis} = 314/58 = 5.413$$

$$C_{B,d} = C_{B,d,Basis} = 0.8213$$

Substituting the ratio obtained from basis ship into the equation (5.1), the equation can be converted to a square equation in L.

$$L \cdot \left(L/(L/B)\right) \cdot C_{B,d} \cdot 22.08 = 338,000$$

$$L^2 / (L/B) \cdot C_{B,d} \cdot 22.08 = 338,000$$

$$L^2 / 5.413 \times 0.8213 \times 22.08 = 338,000$$

$$L^2 = 100,899 \qquad \therefore L = 315.65[m]$$

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d = 297,000 [ton], T_d = 21.5[m]

Find: L, B, $C_{B,d}$

Method ①: $LWT = LWT_{Basis}$

$$L = 315.65\ [m]$$

We can obtain *B* from the ratio *L/B* of the basis ship.

$$B = L/(L/B)$$
$$= 315.65/5.413$$
$$= 58.30\ [m]$$

$$\therefore L = 315.65[m],\ B = 58.30[m],\ C_{B,d} = 0.8213$$

Step 1) Weight Equation	→	**Step 2) Volume Equation**	→	Step 3) Freeboard Calculation

Step 2) Then, depth is determined considering the required cargo hold capacity according to the volume equation.

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

✓ **Given:** $L=315.65[m]$, $B=58.30[m]$, $V_{CH} = 360{,}000[m^3]$

✓ **Find:** D

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

Given: L=315.65[m], B=58.30[m], V_{CH} = 360,000[m^3]

Find: D

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

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

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

Coefficient C_{CH} can be obtained from the basis ship.

$$C_{CH} = \left. \frac{V_{CH}}{L \cdot B \cdot D} \right|_{Basis} = \frac{345,500}{314 \cdot 58 \cdot 31} = 0.612$$

We can calculate the depth from the volume equation.

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

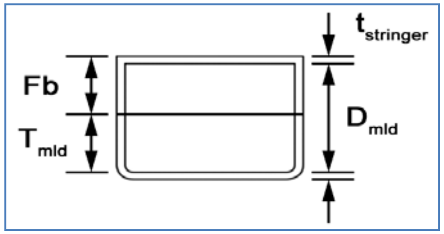
$$360,000 = 0.612 \times 315.65 \times 58.30 \times D$$

$$\therefore D = 31.96[m]$$

Step 1) Weight Equation → Step 2) Volume Equation → **Step 3) Freeboard Calculation**

Step 3) Then, it should be checked lastly that whether the depth and draft satisfy the freeboard regulation.

$$D_{Fb} \geq T_s + Fb(L, B, D_{mld}, C_{B,d})$$



$$\left(D_{Fb} = D_{mld} + t_{stringer}\right)$$

- ✓ **Given**: L=315.65[m], B=58.30[m], D (=D_{mld})= 31.96 [m], T_s=22.84[m], $C_{B,d}$ =0.8213, $t_{stringer}$ = 0.02[m]
- ✓ **Check**: The freeboard of the ship should be larger than the required freeboard which is estimated.

$$D_{Fb} \geq T_s + Fb(L, B, D_{mld}, C_{B,d})$$

Given: L=315.65[m], B=58.30[m], D (=D_{mld})= 31.96[m], T_s = 22.84[m], $C_{B,d}$=0.8213, $t_{stringer}$ = 0.02[m]

Check: Freeboard of the ship should be larger than that in accordance with the freeboard regulation.

At the early design stage, there are few data available for estimation of required freeboard. So, the required freeboard can be estimated from the basis ship.

Assume that the freeboard is proportional to the depth.

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

$$D_{Fb} \geq T_s + C_{Fb} \cdot D_{mld}$$

Coefficient C_{Fb} can be obtained from the basis ship.

$$C_{Fb} = \left.\frac{Fb}{D_{mld}}\right|_{Basis} = \frac{7.84}{31} = 0.253$$

Check: Freeboard of the design ship

$$D_{Fb} \geq T_s + C_{Fb} \cdot D_{mld}$$

$$D_{mld} + t_{stringer} \geq T_s + C_{Fb} \cdot D_{mld}$$

$$31.96 + 0.02 \geq 22.84 + 0.253 \cdot 31.96$$

$$31.98 \geq 30.92$$ **: Satisfied**

It is satisfied. However, this method is used for a rough estimation. So, after the principal dimensions are determined more accurately, freeboard needs to be calculated more accurately through the freeboard regulation.

Determination of the Principal Dimensions of the 297,000 ton Deadweight VLCC - Step 1: Weight Equation (Method 2) (1/4)

Step 1) Weight Equation → Step 2) Volume Equation → Step 3) Freeboard Calculation

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d = 297,000 [ton], T_d = 21.5[m]
Find: $L, B, C_{B,d}$

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

$$W = \frac{W_{Basis}}{DWT_{d,Basis}} \cdot DWT_d$$

$$L \cdot B \cdot T_d \cdot C_{B,d} \cdot \rho \cdot (1+\alpha) = W$$

Design ship and **basis ship** are **assumed** to have the **same ratio** of deadweight to total weight.

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

$$\frac{DWT_{d,Basis}}{W_{Basis}} = \frac{DWT_d}{W} \Rightarrow W = \frac{W_{Basis}}{DWT_{d,Basis}} \cdot DWT_d$$

$$= \frac{320,500}{279,500} \cdot 297,000$$

$$= 340,567\ [ton]$$

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d = 297,000 [ton], T_d = 21.5[m]

Find: L, B, $C_{B,d}$

Method 2: $W = \frac{W_{Basis}}{DWT_{d,Basis}} \cdot DWT_d$

$$L \cdot B \cdot T_d \cdot C_{B,d} \cdot \rho \cdot (1+\alpha) = W$$

$$L \cdot B \cdot 21.5 \cdot C_{B,d} \cdot 1.025 \cdot (1+0.002) = 340,567$$

$$\boxed{L \cdot B \cdot C_{B,d} \cdot 22.08 = 340,567 \cdots (5.2)}$$

There are 3 unknown variables (L, B, $C_{B,d}$) with one equation.

→ Nonlinear indeterminate equation!

Therefore, we have to assume two variables to solve this indeterminate equation.

The values of the principal dimensional ratio L/B and $C_{B,d}$ can be obtained from the basis ship.

$$L/B = L_{Basis} / B_{Basis} = 314/58 = 5.413$$

$$C_{B,d} = C_{B,d,Basis} = 0.8213$$

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: $DWT_d = 297{,}000\,[ton]$, $T_d = 21.5[m]$

Find: L, B, $C_{B,d}$

Method 2: $W = \dfrac{W_{Basis}}{DWT_{d,Basis}} \cdot DWT_d$

$$L \cdot B \cdot C_{B,d} \cdot 22.08 = 340{,}567 \cdots (5.2)$$

$$L/B = 5.413,\ C_{B,d} = 0.8213$$

Substituting the ratio obtained from basis ship into the equation (5.2), the equation can be converted to a square equation in L.

$$L \cdot \left(L / \left(L/B\right)\right) \cdot C_{B,d} \cdot 22.08 = 340{,}567$$

$$L(L/5.143) \cdot 0.8213 \cdot 22.08 = 340{,}567$$

$$L^2 \cdot 3.349 = 340{,}567$$

$$\therefore L = 318.85[m]$$

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + \boxed{LWT}$$

Given: DWT_d = 297,000 [ton], T_d = 21.5[m]
Find: L, B, $C_{B,d}$

Method 2: $W = \frac{W_{Basis}}{DWT_{d,Basis}} \cdot DWT_d$

$$L = 318.85[m]$$

We can obtain B from the ratio L/B of the basis ship.

$$B = L/(L/B)$$
$$= 318.85/5.413$$
$$= 58.90\ [m]$$

$$\therefore L = 318.85[m],\quad B = 58.90[m],\ C_{B,d} = 0.8213$$

Then, depth is determined considering the required cargo hold capacity according to the volume equation.
And it should be checked lastly that whether the depth and draft satisfy the freeboard regulation.

Step 1) Weight Equation → Step 2) Volume Equation → Step 3) Freeboard Calculation

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d = 297,000 [ton], T_d = 21.5[m]
Find: L, B, $C_{B,d}$

Method 3 : Assume that the lightweight could vary as the volume of the vessel as represented by $L \cdot B \cdot D$.

$$LWT = C_{LWT} L \cdot B \cdot D$$

$$L \cdot B \cdot T_d \cdot C_{B,d} \cdot \rho \cdot (1+\alpha) = DWT_d + C_{LWT} \cdot L \cdot B \cdot D$$

Coefficient C_{LWT} can be obtained from the basis ship.

$$C_{LWT} = \left.\frac{LWT}{L \cdot B \cdot D}\right|_{Basis} = \frac{41,000}{314 \cdot 58 \cdot 31} = 0.072$$

$$L \cdot B \cdot T_d \cdot C_{B,d} \cdot \rho \cdot (1+\alpha) = DWT_d + C_{LWT} \cdot L \cdot B \cdot D$$

$$L \cdot B \cdot 21.5 \cdot C_{B,d} \cdot 1.025 \cdot (1+0.002) = 297,000 + 0.072 \cdot L \cdot B \cdot D$$

$$L \cdot B \cdot C_{B,d} \cdot 22.08 = 297,000 + 0.072 \cdot L \cdot B \cdot D \cdots (5.3)$$

There are 4 unknown variables (L, B, D, $C_{B,d}$) with one equation.

→ Nonlinear indeterminate equation!

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d = 297,000 [ton], T_d = 21.5[m]
Find: L, B, $C_{B,d}$

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

$$L \cdot B \cdot C_{B,d} \cdot 22.08 = 297{,}000 + 0.072 \cdot L \cdot B \cdot D \cdots (5.3)$$

Therefore, we have to assume three variables to solve this indeterminate equation.

The values of the principal dimensional ratios L/B, B/D and $C_{B,d}$ can be obtained from the basis ship.

$$L/B = L_{Basis} / B_{Basis} = 314/58 = 5.413$$

$$B/D = B_{Basis} / D_{Basis} = 58/31 = 1.871$$

$$C_{B,d} = C_{B,d,Basis} = 0.8213$$

Substituting the ratios obtained from basis ship into the equation (5.3), the equation can be converted to a cubic equation in L.

$$L \cdot \left(L/(L/B)\right) \cdot C_{B,d} \cdot 22.08 = 297{,}000 + 0.072 \cdot L \cdot \left(L/(L/B)\right) \cdot \left(L/(L/B)/(B/D)\right)$$

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d = 297,000 [*ton*], T_d = 21.5[*m*]
Find: $L, B, C_{B,d}$

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

$$L \cdot \left(L / \left(L / B\right)\right) \cdot C_{B,d} \cdot 22.08 = 297{,}000 + 0.072 \cdot L \cdot \left(L / \left(L / B\right)\right) \cdot \left(L / \left(L / B\right) / \left(B / D\right)\right)$$

$$L(L / 5.143) \cdot 0.8213 \cdot 22.08 = 297{,}000 + 0.072 \cdot L \cdot \left(L / 5.413\right) \cdot \left(\left(L / 5.413\right) / 1.871\right)$$

$$L^2 \cdot 3.349 = 297{,}000 + L^3 \cdot 0.0013$$

$$\therefore L = 318.48\ [m]$$

We can obtain *B* from the ratio *L/B* of the basis ship.

$$B = L / (L / B)$$
$$= 318.48 / 5.413$$
$$= 58.82\ [m]$$

$$\therefore L = 318.48[m], \quad B = 58.82[m], \quad C_{B,d} = 0.8213$$

Then, depth is determined considering the required cargo hold capacity according to the volume equation.
And it should be checked lastly that whether the depth and draft satisfy the freeboard regulation.

Determination of the Principal Dimensions of the 297,000 ton Deadweight VLCC - Step 1: Weight Equation (Method 4) (1/7)

Step 1) Weight Equation → Step 2) Volume Equation → Step 3) Freeboard Calculation

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d= 297,000 [*ton*], T_d = 21.5[*m*], V_S = 16 [knots]
Find: L, B, $C_{B,d}$

A ship consists of hull structure, outfit and machinery. If we estimate the weight of each components, the lightweight estimation would be more accurate.

Method 4 : Estimate the structural weight(W_s), outfit weight(W_o) and machinery weight(W_m) respectively.

$$LWT = W_s + W_o + W_m$$

$$L \cdot B \cdot T_d \cdot C_{B,d} \cdot \rho \cdot (1+\alpha) = DWT_d + W_s + W_o + W_m$$

Structural weight(W_s) is estimated as follows:

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

Coefficient C_s can be obtained from the basis ship.

$$C_s = \left. \frac{W_s}{L^{1.6} \cdot (B+D)} \right|_{Basis} = \frac{36,400}{314^{1.6} \cdot (58+31)} = 0.0414$$

Determination of the Principal Dimensions of the 297,000 ton Deadweight VLCC - Step 1: Weight Equation (Method 4) (2/7)

Step 1) Weight Equation → Step 2) Volume Equation → Step 3) Freeboard Calculation

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d= 297,000 [*ton*], T_d = 21.5[*m*], V_S = 16 [knots]

Find: $L, B, C_{B,d}$

Method 4: $LWT = W_s + W_o + W_m$

Outfit weight(W_o) is estimated as follows:

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

Coefficient C_o can be obtained from the basis ship.

$$C_o = \left.\frac{W_o}{L \cdot B}\right|_{Basis} = \frac{2,700}{314 \cdot 58} = 0.1483$$

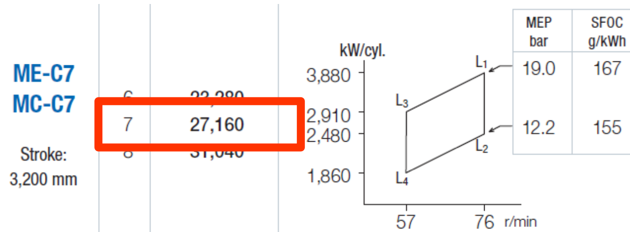
Machinery weight(W_o) is estimated as follows:

$$W_m = C_m \cdot NMCR$$

Coefficient C_m can be obtained from the basis ship.

$$C_m = \left.\frac{W_m}{NMCR}\right|_{Basis} = \frac{1,900}{36,952} = 0.0514$$

Main engine of basis ship : 7S80MC-C



$$NMCR = 27,160[kW]$$
$$= 36,952[PS]$$

NMCR can be estimated through resistance estimation, power prediction and main engine selection. However, there are few data available for estimation of the *NMCR* at the early design stage, so *NMCR* <u>can be estimated by 'Admiralty formula'</u>

Determination of the Principal Dimensions of the 297,000 ton Deadweight VLCC - Step 1: Weight Equation (Method 4) (3/7)

Step 1) Weight Equation → Step 2) Volume Equation → Step 3) Freeboard Calculation

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d= 297,000 [*ton*], T_d = 21.5[*m*], V_S = 16 [knots]
Find: $L, B, C_{B,d}$

Method 4: $LWT = W_s + W_o + W_m$

$$W_m = C_m \cdot NMCR$$

$$NMCR = \frac{1}{\text{Engine Margin}} \cdot \frac{1}{\text{Derating ratio}} \cdot NCR$$

$(\text{Engine Margin} = 0.9,\ \text{Derating ratio} = 0.9)$

$$NMCR = 1.265 \cdot NCR$$

Because there are few data available for estimation of the *DHP* at the early design stage, the *DHP* can be estimated by 'Admiralty formula'. By applying *NCR* to this formula, the *NCR* also can be estimated.

$$NCR = \frac{\Delta^{2/3} \cdot V_s^{\ 3}}{C_{ad}}$$

Coefficient C_{ad} can be obtained from the basis ship.

$$C_{ad} = \left.\frac{\Delta^{2/3} \cdot V_s^{\ 3}}{NCR}\right|_{Basis} = \frac{320,500^{2/3} \cdot 15^3}{28,800} = 548.82 \qquad \left(V_{s,\ at\ design\ draft} = 15[knots]\right)$$

$$NCR = \frac{\Delta^{2/3} \cdot V_s^{\ 3}}{548.82}$$

$$NMCR = 1.265 \cdot \frac{\Delta^{2/3} \cdot V_s^{\ 3}}{548.82}$$

$$= 0.0022 \cdot \Delta^{2/3} \cdot V_s^{\ 3}$$

Determination of the Principal Dimensions of the 297,000 ton Deadweight VLCC - Step 1: Weight Equation (Method 4) (4/7)

Step 1) Weight Equation → Step 2) Volume Equation → Step 3) Freeboard Calculation

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d= 297,000 [*ton*], T_d = 21.5[*m*], V_S = 16 [knots]
Find: $L, B, C_{B,d}$

Method 4: $LWT = W_s + W_o + W_m$

$W_s = C_s \cdot L^{1.6} \cdot (B+D)$	$C_s = 0.0414$
$W_o = C_o \cdot L \cdot B$	$C_o = 0.1483$
$W_m = C_m \cdot NMCR$	$C_m = 0.0514$
	$NMCR = 0.0022 \cdot \Delta^{2/3} \cdot V_s^{\,3}$

$$L \cdot B \cdot T_d \cdot C_{B,d} \cdot \rho \cdot (1+\alpha) = DWT_d + W_s + W_o + W_m$$

$$L \cdot B \cdot T_d \cdot C_{B,d} \cdot \rho \cdot (1+\alpha) = DWT_d + C_s \cdot L^{1.6} \cdot (B+D) + C_o \cdot L \cdot B + C_m \cdot NMCR$$

$$L \cdot B \cdot T_d \cdot C_{B,d} \cdot \rho \cdot (1+\alpha) = DWT_d + C_s \cdot L^{1.6} \cdot (B+D) + C_o \cdot L \cdot B + C_m \cdot (0.0022 \cdot \Delta^{2/3} \cdot V_s^{\,3})$$

$$L \cdot B \cdot T_d \cdot C_{B,d} \cdot \rho \cdot (1+\alpha) = DWT_d + C_s \cdot L^{1.6} \cdot (B+D) + C_o \cdot L \cdot B + C_m \cdot \left(0.0022 \cdot \left(L \cdot B \cdot T_d \cdot C_{B,d} \cdot \rho \cdot (1+\alpha)\right)^{2/3} \cdot V_s^{\,3}\right)$$

$$L \cdot B \cdot 21.5 \cdot C_{B,d} \cdot 1.025 \cdot (1+0.002) = 297{,}000 + 0.0414 \cdot L^{1.6} \cdot (B+D) + 0.1483 \cdot L \cdot B + 0.0514 \cdot \left(0.0022 \cdot \left(L \cdot B \cdot 21.5 \cdot C_{B,d} \cdot 1.025 \cdot (1+0.002)\right)^{2/3} \cdot 16^3\right)$$

Step 1) Weight Equation → Step 2) Volume Equation → Step 3) Freeboard Calculation

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d = 297,000 [*ton*], T_d = 21.5[*m*], V_S = 16 [knots]

Find: $L, B, C_{B,d}$

Method 4: $LWT = W_s + W_o + W_m$

$$L \cdot B \cdot 21.5 \cdot C_{B,d} \cdot 1.025 \cdot (1+0.002) = 297,000 + 0.0414 \cdot L^{1.6} \cdot (B+D) + 0.1483 \cdot L \cdot B$$
$$+0.0514 \cdot (0.0022 \cdot \left(L \cdot B \cdot 21.5 \cdot C_{B,d} \cdot 1.025 \cdot (1+0.002)\right)^{2/3} \cdot 16^3)$$

$$\boxed{L \cdot B \cdot C_{B,d} \cdot 22.08 = 297,000 + 0.0414 \cdot L^{1.6} \cdot (B+D) + 0.1483 \cdot L \cdot B + 0.00012 \cdot (L \cdot B \cdot C_{B,d} \cdot 22.08)^{2/3} \cdot 16^3 \cdots (5.4)}$$

There are 4 unknown variables ($L, B, D, C_{B,d}$) with one equation.

→ Nonlinear indeterminate equation!

Therefore, we have to assume three variables to solve this indeterminate equation.

The values of the principal dimensional ratios L/B, B/D and $C_{B,d}$ can be obtained from the basis ship.

$$L/B = L_{Basis}/B_{Basis} = 314/58 = 5.413$$

$$B/D = B_{Basis}/D_{Basis} = 58/31 = 1.871$$

$$C_{B,d} = C_{B,d,Basis} = 0.8213$$

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d= 297,000 [*ton*], T_d = 21.5[*m*], V_S = 16 [knots]
Find: L, B, $C_{B,d}$

Method 4: $LWT = W_s + W_o + W_m$

$$L \cdot B \cdot C_{B,d} \cdot 22.08 = 297{,}000 + 0.0414 \cdot L^{1.6} \cdot (B+D) + 0.1494 \cdot L \cdot B$$
$$+0.00012 \cdot (L \cdot B \cdot C_{B,d} \cdot 22.08)^{2/3} \cdot 16^3 \cdots (5.4)$$

$$L/B = 5.413,\ B/D = 1.871, C_{B,d} = 0.8213$$

Substituting the ratios obtained from basis ship into the equation (5.4), the equation can be converted to a cubic equation in *L*.

$$L \cdot (L/(L/B)) \cdot C_{B,d} \cdot 22.08 = 297{,}000 + 0.0414 \cdot L^{1.6} \cdot ((L/(L/B)) + (L/(L/B)/(B/D))$$
$$+0.1483 \cdot L \cdot (L/(L/B))$$
$$+0.00012 \cdot (L \cdot (L/(L/B)) \cdot C_{B,d} \cdot 22.08)^{2/3} \cdot 16^3$$

$$L \cdot (L/5.413) \cdot 0.8213 \cdot 22.08 = 297{,}000 + 0.0414 \cdot L^{1.6} \cdot ((L/5.413) + (L/5.413/1.871))$$
$$+0.1483 \cdot L \cdot (L/5.413)$$
$$+0.00012 \cdot (L \cdot (L/5.413) \cdot 0.8213 \cdot 22.08)^{2/3} \cdot 16^3$$

$$L^2 \cdot 3.349 = 297{,}000 + 0.0414 \cdot L^{1.6} \left(0.185 \cdot L + 0.099 \cdot L\right)$$
$$+0.0274 \cdot L^2 + 0.00012 \cdot (L^2 \cdot 3.349)^{2/3} \cdot 16^3$$

$$\therefore L = 318.57\ \ [m]$$

$$\rho \cdot L \cdot B \cdot T_d \cdot C_{B,d} \cdot (1+\alpha) = DWT_d + LWT$$

Given: DWT_d= 297,000 [*ton*], T_d = 21.5[*m*], V_S = 16 [knots]
Find: L, B, $C_{B,d}$

Method 4: $LWT = W_s + W_o + W_m$

$$L = 318.57 \ [m]$$

We can obtain B from the ratio L/B of the basis ship.

$$B = L/(L/B)$$
$$= 318.57/5.413$$
$$= 58.84 \ [m]$$

$$\therefore L = 318.57[m], \ B = 58.84[m], \ C_{B,d} = 0.8213$$

Then, depth is determined considering the required cargo hold capacity according to the volume equation.
And it should be checked lastly that whether the depth and draft satisfy the freeboard regulation.