Mechanical Engineering

Lecture Notes on Basic Naval Architecture

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Aalto University

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Abstract

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Abstract
Shipping is responsible for 90% of world trade. The design, equipment and function of ships are subject to constant evolution that intensified recently because of emerging sustainability and safety requirements, the changing patterns of world trade and technological evolution. It is becoming increasingly evident that the Naval Architects and Marine Engineers of the future will be less tied to conventional ship types, will work in less deterministic ways and will have to adapt to market demands. Yet good understanding of the basics shall remain essential. With the above in mind, this set of lecture notes outlines some of the Principles of Naval Architecture and Marine Engineering for use in concept ship design. The material presented can be used by undergraduate students or early stage postgraduate students of Marine Technology.

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Merenkulku vastaa 90% maailmankaupasta. Laivojen suunnittelu, varustus ja toiminta muuttuvat jatkuvasti, ja ne ovat kiihtyneet viime aikoina nousevien kestävyys- ja turvallisuusvaatimusten, maailmankaupan muuttuvien mallien ja teknologisen kehityksen vuoksi. Tulee yhä ilmeisemmäksi, että tulevaisuuden merivoimien arkkitehdit ja merimoottorit ovat vähemmän sidoksissa perinteisiin laivatyyppeihin, työskentelevät vähemmän deterministisillä tavoilla ja joutuvat sopeutumaan markkinoiden vaatimuksiin. Silti perusasioiden hyvä ymmärtäminen on edelleen välttämätöntä. Edellä oleva mielessä tämä luentosarja sisältää joitakin merivoimien arkkitehtuurin ja meritekniikan periaatteita, joita voidaan käyttää konseptialusten suunnittelussa. Esitettyä materiaalia voivat käyttää perustutkinto -opiskelijat tai meritekniikan jatko -opiskelijat.

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Eur.Ing Dr. Spyros Hirdaris CEng FRINA

Professor (Assoc.), Marine Technology

Aalto University, Finland

September, 2021

Preface

Shipping is responsible for 90% of world trade. The design, equipment and function of ships are subject to constant evolution that intensified recently because of emerging sustainability and safety requirements, the changing patterns of world trade and technological evolution. It is becoming increasingly evident that the Naval Architects and Marine Engineers of the future will be less tied to conventional ship types, will work in less deterministic ways and will have to adapt to market demands. Yet good understanding of the basics shall remain essential.

With the above in mind, this set of lecture notes outlines some of the Principles of Naval Architecture and some Marine Engineering concepts for use in concept ship design. The material presented can be used by undergraduate students or early stage postgraduate students of Marine Technology. I am grateful to my Teaching Assistants Zeiad Abdelghafor, Hassan Yosri and Sarah Blackwell for helping me to conceptualize the material presented.

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Espoo, September 2021

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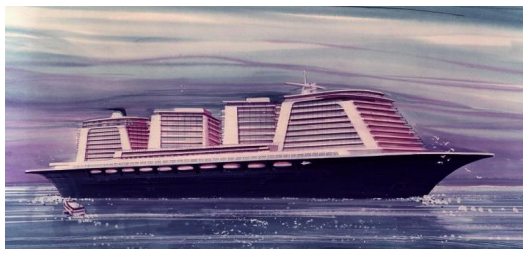
Lecture 1
Introduction to Naval Architecture

Transportation by sea is one of the oldest and most economical ways to transport materials and people around the world. This is because of reduced costs in comparison to air or road transport alternatives. Shipping is a very complex industry because there are so many types of ships depending on distance, travel routes, speed, and efficiency expectations etc. It was one of the first industries to be globalized and will never cease to exist unless some revolutionary technology is put into practice. The industry and the profession are at large conservative in nature and heavily regulated by governing bodies like the United Nations Maritime Organization (IMO), Flag Administrations and Classification Societies[1] who provide the license for ships to operate.

Naval architecture is a fascinating and demanding discipline. It is fascinating because of the variety of floating structures and the many compromises necessary to achieve the most effective product. It is demanding because a ship is a very large capital investment and because of the need to protect the people on board and the marine environment. At inception, the design of ships has been more of a craft than science. Nowadays ship design requires the application of scientific, empirical, and artistic methods. Therefore, naval architecture brings together these principles by studying ship's resistance / powering and maneuvering, structural integrity, and stability in waves. The socioeconomic and artistic principles involved mostly pertain to aspects of human behavior, ergonomics, and aesthetics.

The role of the naval architect is to design floating assets that are safe, environmentally friendly, and efficient. This is because design failures may be costly and endanger human lives, but it is also driven by the international trends to operate shipping assets that are environmentally sustainable. In conclusion, naval architects are a highly specialized group of engineers with sound knowledge on the principles of marine engineering, hydrodynamics, directional control, materials and structural engineering, product development and design and architecture. Since these assorted factors bring together a considerable level of uncertainty the role of naval architects is to ensure that risks and uncertainties in the engineering solutions proposed are minimal.

(a) © Hellenic Naval Academy



(b) © Knud E. Hansen

Figure 1-1 Ship Design Evolution (a) Replica of ancient Greek Trireme Olympias; (b) The Phoenix – World City Cruise ship

[1] Safer and Cleaner Shipping - IACS

1. The ship design spiral

In Naval Architecture the design spiral (Figure 1-2) serves the iterative design logic of designing a ship. The spiral comprises of 4 phases of design namely, concept design, preliminary design, contract design, and detailed design. The different stages are defined as follows (Thomas, 2003):

- **Concept design stage** is just the translation of the mission requirements to the ship. In this phase a basic outline is created by taking into consideration all the steps of the design process.
- **Preliminary design stage** comprises of iterations that help refine concept design. Some properties defined during concept design do not change (e.g. ship dimensions, weight, and power).
- **Contract design stage** involves an iteration or two where the major characteristics of the ship are unchanged. The plan and specifications are prepared in this stage and are a part of the contract for the shipowner. In the detailed design phase, the production plans are made. This phase is the most time consuming.

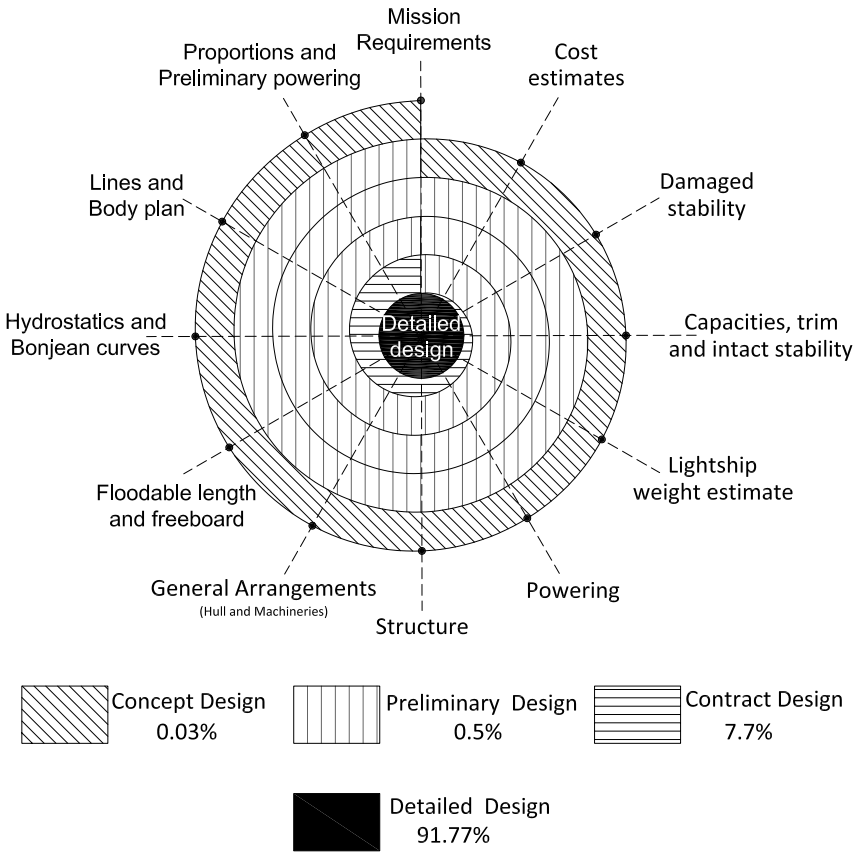


Figure 1-2 Typical design Spiral of a large merchant ship

2. Ship types and mission requirements

At concept design stage, mission requirements should be defined objectively. The ship mission should rely on the **owner's requirements**; i.e. the requirements specified by the shipowner who is commissioning the design. Typical owner's requirements may include ship type, speed, deadweight, cargo capacity (volume), size limitations based on port (see physical requirements), fuel oil consumption, and price. The purpose is to ensure economic ship operations that do not overarch safety objectives of the mission. The emphasis on different type of requirements depends very much on the ship type. Examples are explained below. For **naval ships,** the concept exploration must prioritize the capabilities and design parameters that have significant impact on ship balance, military effectiveness, and less on cost and risk. The process does not begin by jumping into specific requirements or design characteristics. On the other hand, for **commercial ships**, involved with either transportation or services, the owner whilst deciding on a vessel or a fleet and their mission requirements, usually considers the following scenarios:

- Expansion or modification of existing services/routes;
- Development of new service (including new cargo type)/route;
- Replacement or conversion of old or obsolete vessels;
- Development of a new vessel to undertake existing or new services/routes.

A wrong set of mission requirements, even when satisfied, will not produce a successful design. Thus, in any of the above-mentioned scenarios concept design decisions must consider the size and type and speed of vessel. It is not always the case that the largest the ship (subject to route/port constraints of beam and draught) the most economical she will be. Besides, whilst trying to optimize ship transportation/service economics, one must consider factors such as cargo handling facilities, journey itineraries, alternative or multiple cargo-carrying etc. The extent to which fleet simulation studies are carried out may be important as their results define the mission requirements.

For a **cargo ship**, in general, one of the main missions is to transport a specified kind of cargo from point A to point B in a defined time considering changes in the ship course and the operational area during the ship's lifetime. Additionally, achieving this mission should include maximizing the profit by maximizing the payload, reducing the time of loading/unloading and route optimization. Cargo ships require large deadweight capacity (see Figure 1-3,

Figure *1-5*). For example, **container ships** use an uninterrupted almost prismatic volume, to allow for easy storage and loading/unloading of containers. Nevertheless, the naval architect must compromise between a long and full hull form and high-speed requirements which in turn leads to a fine underwater forward part for this type of vessel. The superstructure may be positioned nearer to one-third of the hull's length from the stern. This is done to satisfy ship strength requirements, i.e., to provide stiffness to an open box, as well as operational requirements (e.g., to ensure visibility for containerships with stacks of containers on the top of the deck). Operational visibility may also be ensured by locating the superstructure at the

forward end of the ship whilst the accommodation is at the aft end. The structure is cellular / double skin (in way of both ship bottom and sides) and there are, in general, no transverse bulkheads between the holds.

Tankers have low freeboard, a short deckhouse situated aft, single screw, no stabilizers and a full form for maximum deadweight capacity (see Figure 1-4). **LNG carriers**, comprise of double-walled structures on which an appropriate containment system is supported (see

Figure *1-5*). The draught is relatively shallow, the hull form is relatively full-but not as full as a tanker. High speed is required, to ensure as little as possible cargo boil off. This results in high power requirements. Choice of material is important due to the transportation of extremely low-temperature liquids. In any case the choice of the containment system, i.e., spherical, rectangular tanks etc., is an important part of the design process.

Dry cargo bulk carriers (i.e., ore, coal, grain carriers etc.) are like tankers as they require no special containment of the cargo except the hold constraints but with large deck openings, i.e. hatches, to allow for cargo loading and unloading (see

Figure 1-6). The structure is single skin with double bottom and transverse bulkheads between each hold. **Oil bulk ore (OBO) carriers**, on the other hand, possess longitudinal bulkheads or other structural configuration to allow for separate containment of the different cargoes they carry (see Figure 1-7).

Passenger ships require swift and comfortable travel (see Figure 1-8). Thus, they have higher freeboard, long superstructure and multiple decks for extensive passenger entertainment, fine forms for high speed, multiple propellers for high power with reduced vibration risk and some type of roll stabilization, such as bilge keel, active or passive fins and tanks. In addition, they are prone to highly demanding damage stability and survivability requirements. In a Roll on Roll Off (Ro-Ro) vessel, there are large uninterrupted deck spaces with no transverse bulkheads to allow for easy loading on and off. For passenger ships, design objectives are multiple and tangled so that they are challenging to specify. This is because some non-technical aspects such as the customer experience are difficult to define in technical terms. Passengers might not be concerned with the ship's operational efficiency as much as they are interested in aesthetics and various facilities onboard.

The **offshore sector** describes offshore oil rigs and the supporting vessels transport goods, people, and hotel services for oil rig workers. Recently, there have been developments in renewable energy offshore. These include offshore wind turbines and wave energy facilities. It is expected that the growth of the r**enewable energy** sector will be significant in the years to come[2].

[2] The Growth of Renewable Energy: What Does the Future Hold? | Earth.Org - Past | Present | Future

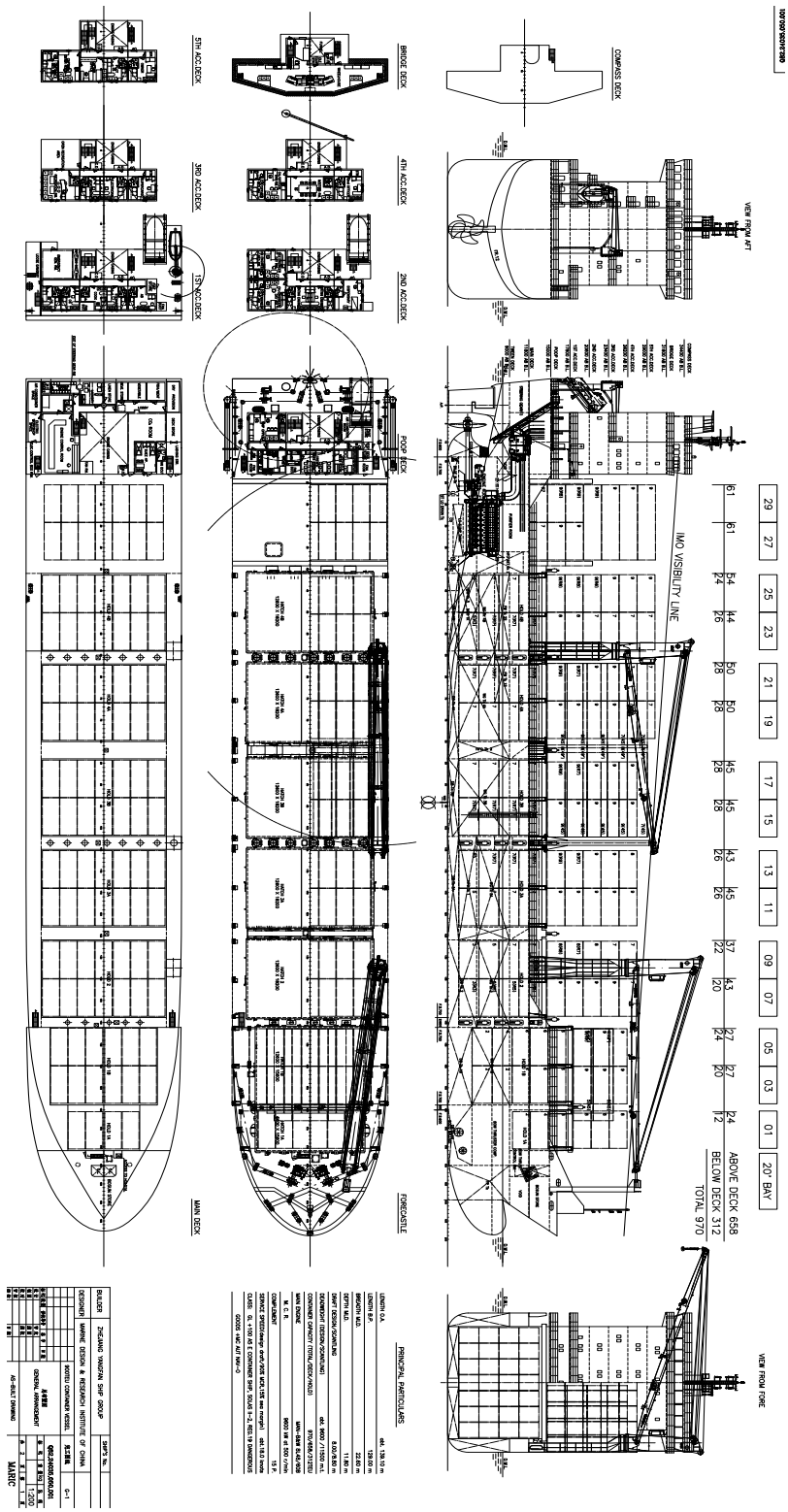


Figure 1-3 General Arrangement of a Container Ship (©Marine Design and Research Institute of China)

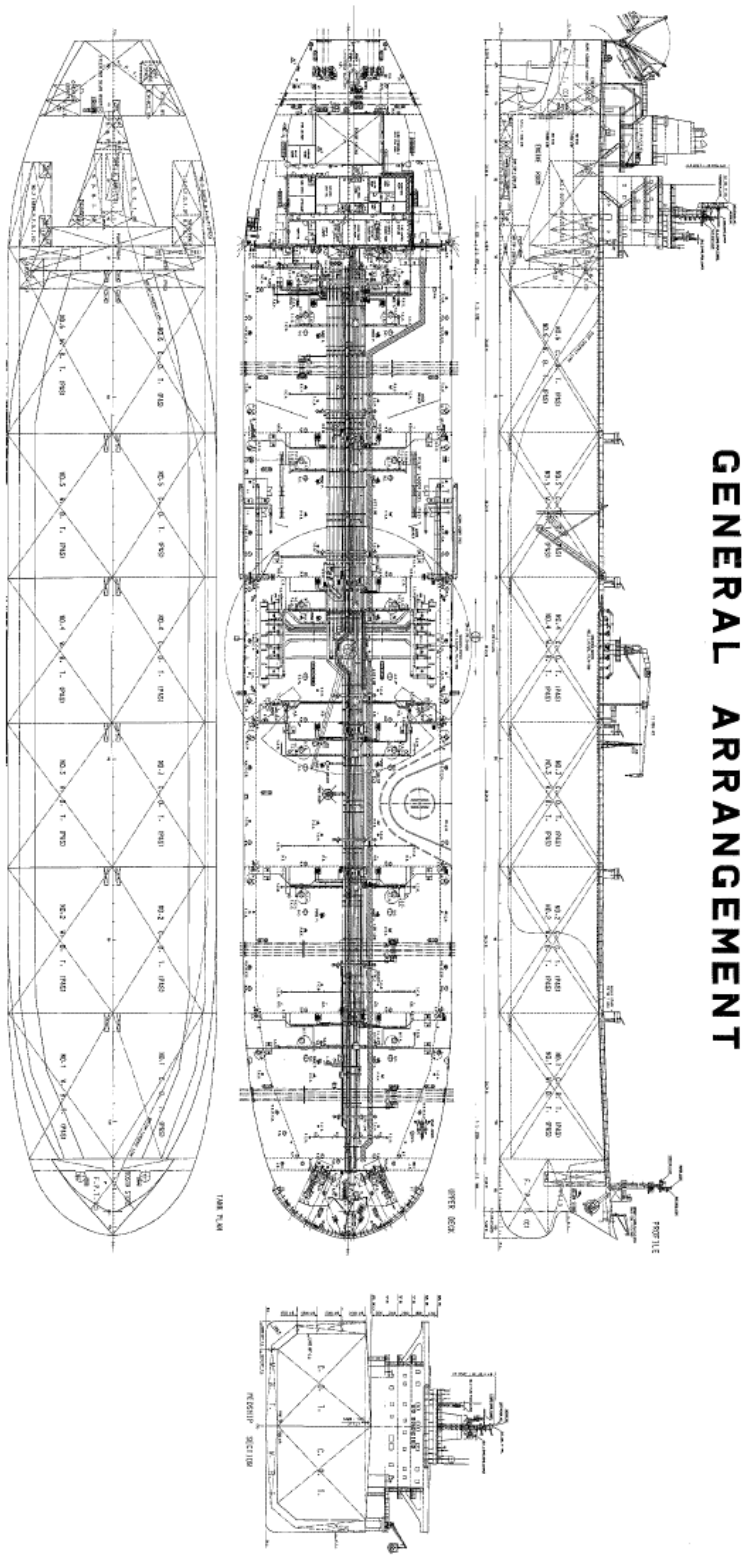
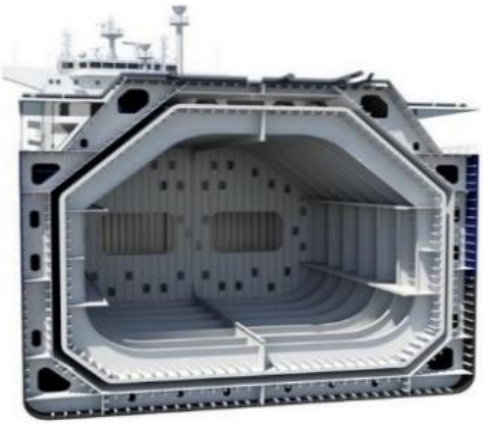


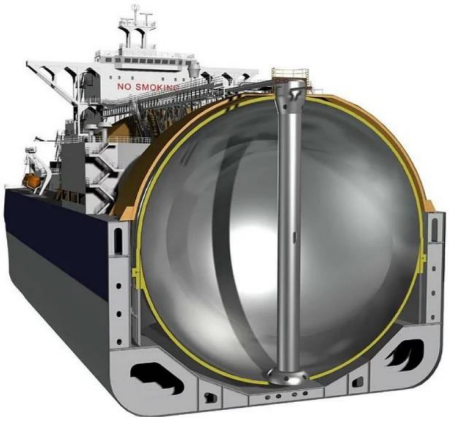
Figure 1-4 General Arrangement of a modern Tanker Ship ((Papanikolaou, 2014))

(a) Membrane type LNG ship *© shipinsight.*

(b) Moss type LNG CARRIER *© modelshipmaster*



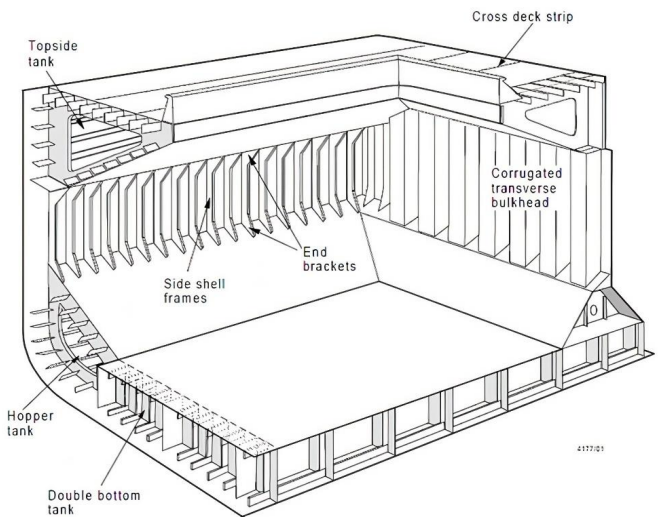
(c) Typical Mark III type LNG containment system ©Glasgow Marine Academy



(d) Moss Rosenberg type LNG cargo containment system ©Glasgow Marine Academy

Figure 1-5 Modern LNG carriers and their containment systems

(a) Modern Handy-size Bulk carrier ©Bluetech Finland Ltd.



(b) Typical mid-ship section of a bulk carrier © theshipyardblog

Figure 1-6 Bulk Carrier concepts

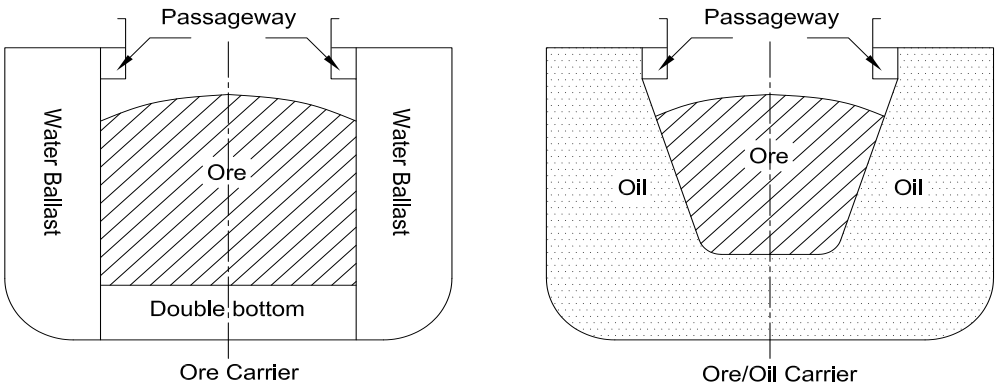


Figure 1-7 Mid ship section of an Ore and Oil-Bulk-Ore (OBO) Carrier

Figure 1-8 Aerial view of Happag Lloyd Europa 2 cruise ship (© Happag Lloyd)

3. Ship design parameters

After assessing owner's requirements and ship mission, the design variables should be determined. Ship design variables can be the dimensions, hull ship characteristics, weights, volumes, propulsion power, electoral loads etc. Their changes may affect the shape, size, properties of the ship. They may be computed from first principles or estimated using parametric models derived from experience. The aim of defining design variables is to produce a fully balanced and feasible ship design for use in conceptual design or preliminary design phases for optimization. A full model for a feasible design should include the required objectives, well-defined design variables and constraints related to ship stability, operational practicality, regulatory requirements, and accepted design practice. In this section we focus only on conceptualizing the importance of key environmental, operational, and economic parameters and their interdependences.

3.1 Environmental parameters

A ship operates in a hostile environment. The most important environmental effects on a ship's function come from wind-generated waves. The major effects of wind on ships are:

- Increase in hull resistance resulting in speed loss.
- Ship motions resulting in possible structural/cargo damage and discomfort to crew and passengers and operational difficulties.
- Difficulties in course keeping and maneuvering and control.

To predict the forces exerted on ships by the seaway, the water surface should be modelled first. This is rather difficult as waves are random. Wave statistics generated from many samples of geographically dispersed buoy measurements or satellite data are today used to provide the necessary information. For submarine and offshore structures, and to an extent

for ships depending on mission/operation, currents are also important. Tides are also significant for ships depending on their operations. Worldwide information is available on currents and tides. The variation of salinity in different water depths, is important for submarines as in reality they operate in stratified rather than a homogenous fluid domain. Independent to different ship types, salinity itself leads to corrosion of the hull structure, thus requiring treatment (painting) to avoid reduced structural strength and increase resistance. Fouling due to marine growth on the wetted surface of the hull also leads to increased resistance if not treated. The effects of the wind itself on the above water surface of the hull can be significant for some ships in terms of increasing resistance and inducing motions (e.g., heeling moment). In addition to wind and sea waves, ships that operate in ice conditions must be stiffened enough to withstand ice loads. The major effects of the ice on ships are:

- High local structural loads especially on the side shell and the bottom;
- Additional resistance due to ice bending and crushing;
- High maneuvering capabilities need as well as high power requirements.

3.2 Economic parameters

In ship design it is critical to get an overview of the relationship between ship form and size and main cost resources (amortised in the case of basic building costs), namely hull, outfitting equipment, machinery, and fuel. The total cost of ships is not constant, i.e., a long and narrow ship costs less than a short and full ship. Also note that an increase in beam and/or fullness increases cost. The shorter the ship the higher the share of fuel costs and the lower the share of the outfit and, up to a point, hull costs. Machinery costs do not vary significantly for ships of similar type and mission requirements. On the other hand, the type of ship and her operations will also affect the overall operational economic model. For example, for a naval ship a lifetime cost model is more appropriate. For a commercial vessel, such as a Ro-Ro, an amortised annual cost model is more suitable. For a commercial ship, before an economic model/criterion can be defined and assessed, we must have a model to estimate the annual cash flow shows whether enough cash is generated for the operations to be funded. There is only one source of inward cash flow namely, ship revenues and five major sources of costs namely:

- Operational costs (including repair and maintenance)
- Voyage costs (mainly fuel costs and port related costs)
- Cargo handling costs
- Amortised capital costs (consisting of capital and interest)
- Taxes and dividends

Freight rates, fuel prices, interest rates can fluctuate in accordance with market pressure and, thus, cause ambiguities when incorporated into the ship design model. Such costs are very difficult to predict particularly in a model applicable to the life of the ship. The ship owner/operator has to set a freight rate which is determined by market forces. An economic criterion has to be set to help control risks associated with cost fluctuations. Furthermore,

this criterion must enable comparisons between investments in various marine transportation operations and services and investment opportunities in other sectors.

4. Shipping regulations

There can be various physical constraints while designing a ship as the path, the ports, and the seas she encounters vary and matter. While the ship is constructed, the shipyard should consider those. Technical constraints relate to the limitations of ship equipment and systems (e.g., propulsion, power generation and delivery, etc.), material choice and degradation, etc. These limitations link to budget and regulatory restrictions and should be considered at early design stages. Shipping laws, rules, and regulations are available to ensure that ship design activities are carried out without endangering the safety of the crew and passengers, the integrity of hull and cargo, and the marine environment. This section outlines some of the key background to maritime regulation with the view to increase the reader's understanding on the importance of regulations for naval architecture design and shipping practice. Further knowledge is available under the following web sites:

- International Maritime Organization (www.imo.org)
- International Labor Organization (www.ilo.org)
- International Association of Classification Societies (www.iacs.org)
- The European Maritime Safety Agency (www.emsa.org)
- The Paris MOU port state control authorities (https://www.parismou.org/)
- The Oil Companies International Maritime Forum (https://www.ocimf.org/)
- The Cruise Lines International Association (https://cruising.org/)
- The Baltic Environmental Protection Commission (https://helcom.fi/)
- The Baltic exchange (https://www.balticexchange.com/)
- RightShip (https://www.rightship.com/);
- The Green Award Foundation (https://www.greenaward.org/)

Because ships can sail around the world between different states, it is appropriate to have worldwide regulations to avoid a situation where each coastal state has its own rules on issues like ship structure, manning etc. Thus, maritime safety regulation starts from the international level (the **United Nations** - UN), but it is also monitored at supra-national (the European Union - EU), national (e.g. Finland), and regional (e.g. the **Gulf of Finland**) levels (Figure 1-9).

The modern format of the international regulatory framework is based on the **UN C**onvention on the **L**aw **O**f the **S**ea (**UNCLOS**) introduced in 1994 (Churchill & Lowe, (1999)). The convention establishes the most fundamental rules governing all uses of the oceans and their resources, including the movements of ships. Under this convention, states are obliged to prevent and control marine pollution and are liable for damage caused by the violation of their international obligations to combat such pollution. UN delegates maritime issues to two UN agencies namely: (a) the **International Maritime Organization (IMO)** and (b) the **International Labour Organization (ILO)**.

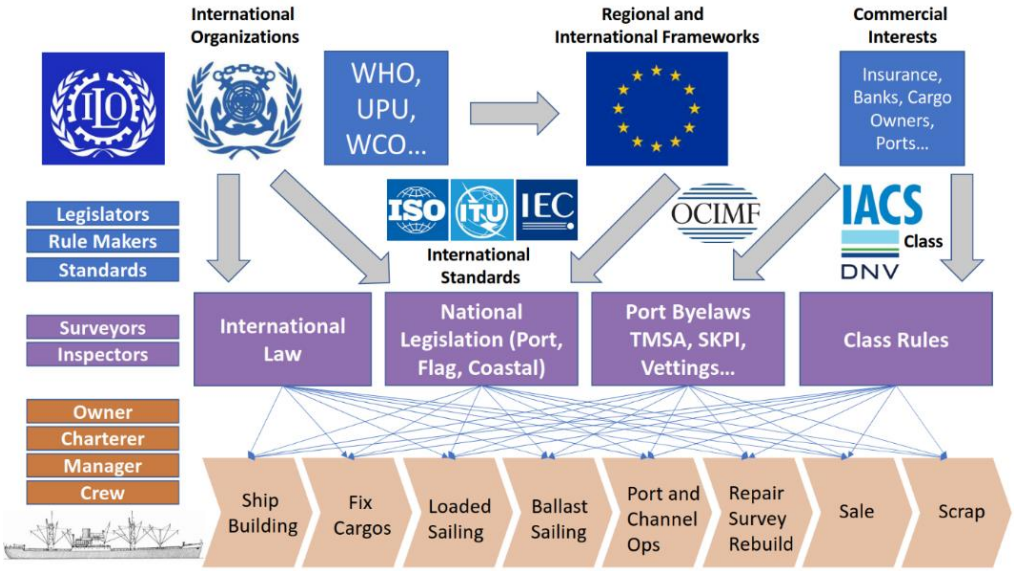


Figure 1-9 The interplay of maritime regulations (©www.marinelink.com)

IMO is the agency responsible for ship safety, pollution and security. ILO is responsible for the laws governing maritime personnel. The main instrument of both agencies is conventions, that become laws when they are enacted by each UN member state. IMO and ILO also give codes, guidelines or recommended practices on important matters not considered suitable for regulation by formal treaty instruments. Key regulatory instruments that influence ship design are the codes for Safety of Life at Sea (SOLAS) and the international code for Maritime Pollution Prevention (MARPOL)[3].

Flag State Control is one of the basic premises of the IMO conventions. It means that the state where a ship is registered is responsible for supervising that the ship fulfils the requirements of those IMO Conventions that the state has ratified. The UNCLOS Convention gives the right for any state to register ships, in so far as there is a link between the ship and the state. In practice, the state can define the nature of this link, and so it can register any vessel it chooses. Port state control is a complementary instrument to flag state control, and it has been born due to the fact that flag states have different standards in flag state control, and some allow the operation of sub-standard ships. IMO adopted a resolution on port state control inspections to identify deficiencies in a ship, her equipment or crew. These procedures are mostly shipping operations focused, not mandatory, but many countries have followed them, e.g., Paris MOU states. Ships with serious deficiencies are detained, and a ship can also be banned. The ships inspected are often selected using statistical methods to identify high-risk vessels, e.g., on the basis of ship age, flag and ship type.

[3] For the complete list of IMO conventions refer to http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/Default.aspx

Figure 1-10 Headquarters of the International Maritime Organisation (IMO), London, UK (GMaps)

The shift in policy legitimacy from the international level to the **EU** was promoted by structural changes in both the supply and demand sides of the shipping market, e.g., the flagging-out of ships, the struggle of traditional maritime nations to maintain their market share through the relaxation of taxation and crew nationality requirements, the establishment of multi-national companies, and the increase of low-cost labour from developing countries. To monitor such issues the European Union established the **E**uropean **M**aritime **S**afety **A**gency (**EMSA**) in 2000. These changes contributed to the depersonalization and reorganization of ship-owning, as well as the increase of asset players who speculate in the market. This led to the inflation of the safety problems and increased the opportunities for ship-owners to avoid specific regulatory frameworks. All of these factors contributed to the possibility for the EU institutions to put forward common policy responses. The EU policy making also benefited from the public attention on maritime incidents and their consequences on people and the environment. The national policy level focuses on the implementation of the policies agreed at international and/or supra-national levels Maritime safety issues in Finland belong to the sphere of authority of the Ministry of Transportation and Communications, which is responsible for maritime policy in Finland, drafting maritime legislation and contributing to any legislative drafting at the EU level. The **Baltic Sea** is a special area by definition of the **IMO** MARPOL. This means that emitting of oil and oil-bearing mixtures into the sea is prohibited. The **Helsinki Commission's (HELCOM)** aim is to protect the marine environment in the Baltic Sea, and it also deals with pollution from maritime traffic. The work of HELCOM is founded on the Helsinki Convention of 1992, of which the coastal states of the Baltic Sea are the members. HELCOM's work is guided by declarations and strategies approved in ministerial meetings. HELCOM gives recommendations for member states to implement, although they are not legally obliged to do so. In practice, member states usually follow the recommendations. The ice-going features of a ship are outside the international regulations but central from the point of view of the Gulf of Finland. Finland has given national regulations

on ice classes, which are based on the ice class rules. Ice class rules are made in cooperation with the Swedish maritime authorities. Also, international classification societies have participated in the drafting of ice class rules and have included them in their own rules.

Classification Societies represent the shipping industry's own system for regulating the technical and operational standards of ships (in other words, they guarantee that a vessel is properly constructed and in good condition). Historically they started to justify that vessels insured are seaworthy. Today they work as surveyors, on occasion consultants, technical advisers and assist in making and implementing maritime regulators. They also develop Rules and grant the SAFCON (Safety in Construction) classification certificate required by insurance underwriters. Most major maritime nations have a classification society and, altogether, there are more than 50 classification societies operating worldwide. The 10 largest societies (e.g., Lloyds Register **LR**, Det Norske Veritas **DNV**, Nippon Kaiji Kyokai, American Bureau of Shipping **ABS**, Germanischer Lloyd **GL**, and Russian Register) cover over 90% of the cargo and passenger fleet in the world and are members of the International Association of Classification Societies (**IACS**).

Among some charterers, there have been doubts about the performance of either flag or port state control or classification societies, and they have chosen to rely on their own surveyors to assess the quality of ships, especially in the oil industry. The mistrust began to appear in 1980's after some major accidents. Rightship is a ship vetting service that ranks vessels from 1 to 5 stars. It combines information received through vetting inspections, port state control, casualties, ship particular and ship-owner information to rank vessels. Rio Tinto Shipping and BHB-Billiton Freight Trading and Logistics founded Rightship in 2001. Rightship's aim is to make sure that vessels meet the given standards. The Rightship system is mainly for dry bulk carriers but also for tankers. Physical inspections are performed when it seems that the vessel is in a higher risk class. Inspections can take up to 48 hours. Green award inspections originate from the non-profit Green Award Foundation. Inspections are performed on oil tankers and bulk carriers and paid by ship-owners. The inspections cover all aspects of shipboard operations. If the vessel fulfils the requirements, it will get a certificate entitling the ship-owner to have discounts on port dues from ports participating in the program. Inspections have to be performed from time to time to keep the vessel certified.

5. The role of technology in green ship design

Although shipping as compared to road and rail transport is widely known for its overall environmentally friendly performance, it is responsible for emissions coming under increasing attention and scrutiny as a result of growing awareness on climate change. In 2014, the Third GHG study by the International Maritime Organization (IMO) estimated that international shipping accounts for around 2.2% of global annual CO_2 emissions and that emissions from international shipping could grow between 50% and 250% by 2050 mainly due to the growth of the world trade. Moreover, IMO predictions for 2050 foresee that 15% of total CO_2

emissions will be attributable to maritime transport. Further estimates of 2019 foresee a 39% demand growth for seaborne trade by 2050. Particularly, the deep-sea segment is estimated to account for more than 80% of world fleet CO_2 emissions, thus making clear that it is particularly important to find technically feasible and cost-effective emission reduction solutions for this segment. Shipping emits various pollutants. Carbon dioxide (CO_2) is the most significant greenhouse gas (GHG) released by ships.

Other examples are: Sulfur Oxides (SO_x) and Nitrogen Oxides (NO_x) that contribute to the formation of acid rain and are highly undesirable due to their effects on human health; Carbon monoxide (CO), volatile organic compounds (VOC) and particulate matter (PM) including black carbon (CO). It is essential to realize that in the years to come naval architecture and ship design will be influenced by the development of a number of green technologies like those summarized in Table 1-1.

6. Questions

1. Explain the different design phases within the context of the ship design spiral.
2. Discuss the environmental, economic, and operational aspects in ship design and provide examples to show how they are interconnected.
3. Discuss the main constraints in ship design. Provide examples in your discussion
4. Outline the importance of key environmental and operational parameters in ship design
5. Discuss the framework and impact of shipping regulation and classification on ship design
6. What is the role of Classification Societies and what is their difference in comparison to Flag Administrations?
7. What is the role of EMSA in terms of developing and enforcing maritime regulations
8. How are marine rules and regulations developed, applied and how do they influence ship design?
9. Discuss the importance shipping sustainability and the importance of green technologies on ship design.
10. List the main ship types and explain for each how their missions relate to their design parameters.

Table 1-1 Outlook of environmental technologies for shipping (Hirdaris & Cheng, 2012)

Research Area	Technology	2010-2014	2014-2020	2020-2030
Resistance and Powering	Ship Resistance in Waves	P	P	
	Optimization	P	P	
	Novel Hull Forms		P	P
Auxiliary Propulsion	Novel Propulsors	P	P	P
	Propeller Design Methods	P	P	
	Propulsor/appendage Interactions	P	P	
	Retrofit Technology Support	P	P	
	Wind Propulsion	P	P	
	Propulsor Efficiency Indexing		P	
Operational Aspects	Operational Optimization	P	P	
	Hull Air Lubrication	P	P	P
	Ice and Cold Operations	P		P
	Ballast Free Operations			P
Environmental Aspects	Noise & Vibration	P	P	P
	Performance Assessment	P		
	Acoustic Emissions Monitoring		P	P
Fuels	LNG and CNG as Fuel	P	P	P
	Biofuels, Methanol, & Ethanol		P	P
Engineering Systems	New Diesel Engines	P	P	
	Heat Recovery Systems	P	P	
	Selective Catalytic Reduction	P		
	Fuel Water Emulsions	P		
	Exhaust Gas Recirculation	P		
	Advanced Battery Technology	P	P	
	Fuel Cells		P	P
	Scrubbers	P	P	
	Nuclear Propulsion			P
	Tidal Stream Ships		P	P
	Wave Power Propulsion		P	P
Corrosions and Coatings	Protective Coatings	P		
	Cathodic Protection Systems	P	P	
	Autonomous Intelligent Systems	P		
	Antifouling Systems	P	P	
	Coatings for Ice Class Ships	P	P	
	Corrosion Monitoring Systems	P		
	Tank Corrosion Maintenance	P	P	
	Coatings Condition Monitoring	P	P	
	Effect on High Strength Steels		P	
Marine Structures	Ship Motions and Loads	P	P	P
	Climatology	P	P	
	Damaged Ship Structures	P	P	
	Crack Monitoring	P	P	
	Stress Monitoring	P	P	
	Crack Tolerant Approaches	P	P	P

Lecture 2
General definitions and terminology

This section presents definitions for the main characteristics of a ship, the terms and the basic design coefficients used in Naval Architecture. The aim is to familiarize students with terms that may help define a ship's general particulars (i.e., main dimensions, displacement), her shape and form.

1. Basic Terminology

Ship Length is defined as the most commonly used ship length definitions (see Figure 2-1) are:

- **Length between perpendiculars (L_{BP} or L_{PP}).** This is the distance measured along the summer load waterline from the aft to the fore perpendicular of the hull. The aft perpendicular is commonly taken as the line passing through the rudder stock. The fore perpendicular is the vertical line through the intersection of the forward side of the stem with the summer load waterline.

- **Length overall (L_{OA}).** This is the distance between the extreme points forward and aft measured parallel to the summer (or design) waterline. Forward the point may be on the raked stem or on a bulbous bow. Simply, the extreme length of the ship.

- **Design waterline length (L_{WL}).** This is the length on the summer load waterline, at which the ship happens to be floating between the intersections of the bow and aft end with the waterline.

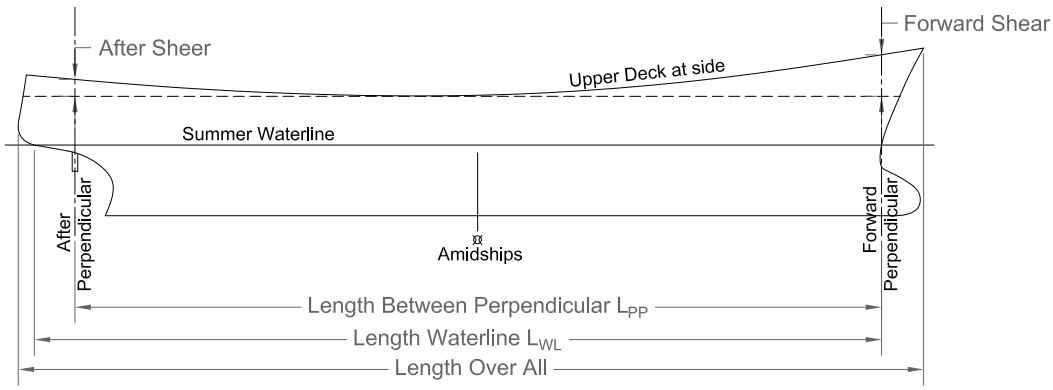


Figure 2-1 Ship Principal Dimensions

In literature there are various empirical dimensions for the estimation of **ship length** (e.g., see (Papanikolaou, 2014) and (Tupper, 2013). Some formulas from statistical analyses of data of existing ships are explained below:

Ayre's formula

$$L_{pp}/\nabla^{1/3} = 3.33 + 1.67\, V/\sqrt{L_{pp}} \tag{2-1}$$

where, V is the ship speed in **Knots,** ∇ is the displacement in m^3 and L is the length in **meter**.

Posdunine and V. Lammeren formula

$$L_{pp} = C(V/(V+2)^2)\nabla^{1/3} \tag{2-2}$$

where, V is the ship speed in knots, L is the length in m, ∇ is the displacement in m^3 and C is an empirical coefficient that depends on the ship type as follows :

$$\begin{aligned} C &= 7.62 \text{ all types} \\ &= 7.16 \text{ cargo ships} \\ &= 7.32 \text{ fast twin-screw ships} \\ &= 7.92 \text{ fast passenger ships} \end{aligned} \tag{2-3}$$

Völker's formula

$$L/\nabla^{1/3} = \mathrm{C}_1 + 4.5\, V/\sqrt{g \cdot \nabla^{1/3}} \tag{2-4}$$

where g is the gravitational acceleration in m/s^2; V design/service speed in m/s, ∇ is the displacement in m^3 and $C_1$is an empirical coefficient that depends on the ship type and is defined as:

$$\begin{aligned} C_1 &= 3.5 && \text{dry bulk cargo ships and containerships} \\ C_1 &= 3 && \text{reefer ships} \\ C_1 &= 2 && \text{fishing and short sea cargo ships.} \end{aligned} \tag{2-5}$$

Schneekluth Formula (used to estimate the "length of minimum building cost")

$$L_{pp} = C \cdot \Delta^{0.3} \cdot V^{0.3} \tag{2-6}$$

where L is the length between perpendicular in m, V service speed in knots, ∇ is the displacement in ton and $C$is an empirical coefficient that depends on the ship's block coefficient as follows:

$$\begin{aligned} C &= 3.2 \quad \text{for} \quad C_\mathrm{B} = 0.145/F_n \\ C &= 3.2\,\frac{C_\mathrm{B}+0.5}{(0.145/F_n)+0.5} \quad \text{for} \quad C_\mathrm{B} \neq 0.145/F_n \end{aligned} \tag{2-7}$$

Alternatively, C can be calculated based on the empirical formulae by Friis :

$$\begin{aligned} C &= 3.4 - (\Delta - 10^3)/10^6 \quad \text{for} \quad 1{,}000\mathrm{t} \leq \Delta \leq 201{,}000\mathrm{t} \\ &= 3.2 \quad \text{for } \Delta > 201{,}000\mathrm{t} \end{aligned} \tag{2-8}$$

Commonly used definitions for **Ship Breadth (or beam, *B*)** of the ship (Figure 2-2) are:

- **Moulded Beam** which is the greatest distance between the inside of plating on the two sides of the ship at the greatest width at the section chosen (Figure 2-2).
- **Breadth extreme** which is measured to the outside of plating but also takes under account over-hangs or flare (Figure 2-2).

Variations in breadth for a particular design may give rise to:

(1) **ship resistance** changes so there has to be an optimum B/T and L/B;
(2) potential increase in **production costs** for increased B;
(3) changes in **stability** criteria, roll amplitude and acceleration;
(4) **draught** changes - e.g. smaller T if $B \times T = constant$ while B is increased.

Ship Depth (or **moulded depth, $\boldsymbol{D}$)** varies along the length but is usually quoted for amidships. It is measured from the underside of the deck plating at the ship's side to the top of the inner flat keel plate (Figure 2-2). Unless otherwise specified, the depth is to the uppermost continuous deck. $\boldsymbol{D}$ is used to determine the ship's volume and the freeboard. It also influences the longitudinal strength.

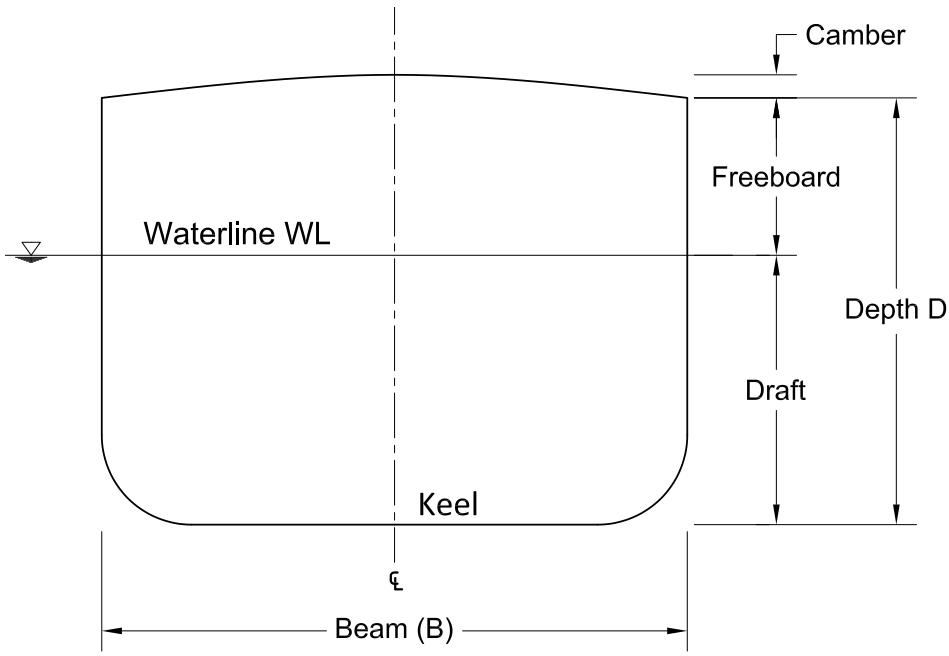


Figure 2-2 Hull characteristics (transverse view)

Ship Draught **(**or **moulded draught/draft, $\boldsymbol{T}$)** is the distance from the keel to the surface of the water (the waterline). **Mean draft ($\boldsymbol{T_m}$)** is the average of the bow (T_{fwd}) and stern drafts (T_{aft}) at the perpendiculars. Mean draft is typically the draft at amidships defined as :

$$T_m = \frac{T_{fwd} - T_{aft}}{2} \tag{2-9}$$

Given that the draught must relate to the displacement equation, a large draught will benefit a low resistance and give greater freedom to the propeller design and the selection of large propeller clearances.

Camber is defined as the rise of the deck in going from the side to the center (Figure 2-3). Decks are cambered to enable water to run off them more easily. For ease of construction, and reduce cost, camber is applied usually only to weather decks, and straight-line camber often replaces the older parabolic curve. **Rise of floor/Deadrise** is the bottom of a ship, in the midships region. It is usually flat but not necessarily horizontal. If the line of bottom is extended out to intersect the moulded breadth line, the height of this intersection above the keel is called the rise of floor or deadrise (Figure 2-3 right). Most ships have a flat keel and the extent to which this extends athwartships is termed the **flat of keel or flat of bottom** (Figure 2-3 right). The forward sections of most ships have a bow characteristic called **flare**. On a flared bow, the half-breadths increase as distance above the keel increases. Flare improves a ship's wave piercing performance, resistance to roll, and increases the available deck space. **Tumblehome** is the opposite of flare and the beam at the waterline. In some ships, the sides are not vertical at amidships. If the upper deck beam is less than that at the waterline, it is said to have tumble home (Figure 2-3).

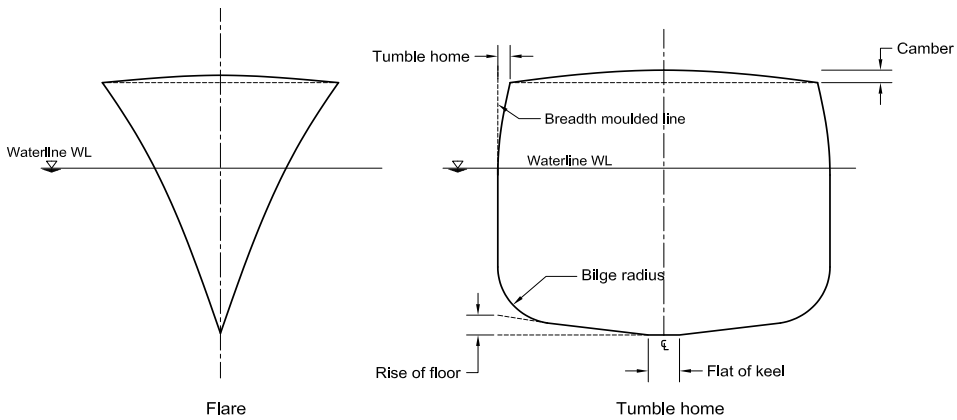


Figure 2-3 Ship section idealizations

Freeboard is the difference between the depth at side and the draught. In other words, it is the height of the deck at side above the waterline. It influences the shape of the righting arm and hence it is important in determining intact stability at large angles. It may be also useful in damage stability situations where reserve buoyancy is essential. **Sheer** (see Figure 2-1) permits a distribution of freeboard along the length of the ship thus giving increased

freeboard forward and aft. In this way it assists avoidance of deck wetness in poor weather conditions. The basic freeboard of the ship is calculated based on the **International Load Line Convention (ILLC)**[4] contained in IMO SOLAS and its value depends on whether the ship carries liquid cargoes or bulk cargoes.

The summer freeboard represents the distance measured down from a line denoting the top of the freeboard deck at side and a second line is painted on the side with its top edge passing through the center of a circle. This marking is known as the **Plimsoll mark**. To allow for different water densities and for severe conditions in different seasons a series of lines are painted on the ship's side to represent the maximum allowed draught in each condition. These paintings are known as **load line marks** (Figure 2-4).

In general, the evaluation of freeboard is very complex and depends on the ship type. Nevertheless, it is worthwhile mentioning that the evaluation of freeboard for ships longer than $100\,m$ is a function of C_B, D, shear, superstructure, bow height and - in general - comprises of the following steps:

- Determine a preliminary freeboard estimate from the tables contained in IMO ILLC based on a standard ship with a $C_B = 0.68$; $L/D = 15$ assuming no superstructure, a parabolic shear and minimum bow height.
- Correct the tabular freeboard for the C_B of the ship you design to obtain the ship's basic freeboard.
- Apply D, deck shear, superstructure corrections based on the ship designed.
- Check the minimum bow height and the reserve buoyancy
- When all of the corrections have been applied to the basic freeboard this results in the minimum summer freeboard for the ship.

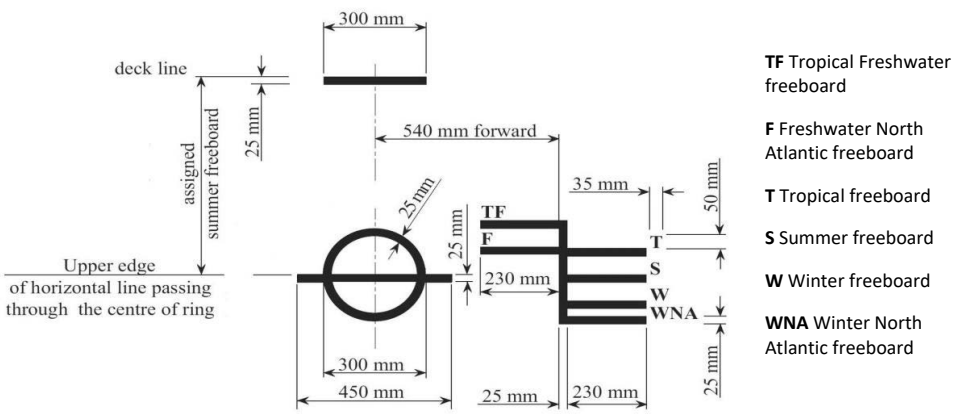


Figure 2-4 Plimsoll Marks/Load line marks (ILLC, 1966)

[4] For further information on IMO ILLC please refer to :
http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-on-Load-Lines.aspx

2. Displacement and tonnage

Displacement represents the mass of the ship in tonnes or her weight in KN. A ship's displacement varies mainly with the draft (T). There are different displacements for different loading conditions. Usually, the fully loaded ship condition is assumed to study the performance. Key nomenclature is:

Δ: mass displacement (tonnes)

∇: volume of the displaced water (m^3)

ρ density of water (usually taken for seawater $1.025\ t/m^3$, for fresh water $1.0\ t/m^3$ and for the Finnish coast $1.05\ t/m^3$)

$\Delta = \rho \cdot \nabla\ (tonnes)$ or $\Delta = \rho \cdot \nabla \cdot g\ (KN)$

The ship **deadweight** is defined as her profitable cargo carrying capacity. Thus, as a quantity it also defines the earning power of the ship. In deterministic terms, deadweight is the difference between the displacement of the ship and her lightship weight. **Lightship weight** is mainly the weight of the hull, machinery, and outfitting. **Cargo deadweight** refers only to the weight of cargo the ship can carry. Displacement then is the sum of deadweight and lightweight. **Tonnage** is a volume measure. Formerly, the standard tone was about 100 cubic feet ($2.83\ m^3$). Nowadays, two terms represent tonnage are commonly used and are known as: (a) **Gross Tonnage (GT)** based on the volume of all enclosed spaces and representing the overall size of a vessel; (b) **Net Tonnage (NT)** based on the volume of cargo spaces plus the volume of passenger spaces multiplied by a coefficient so representing its carrying capacity. The empirical equation used is:

$$NT = k \times GT \tag{2-10}$$

where $k = 0.3 - 0.5$ for Container Ships and 0.5 for other ships.

3. Fineness coefficients

In naval architecture, comparison of different hull forms is achieved with the aid of coefficients. Fineness coefficients express the fullness of the hull form (e.g. some hulls have a very full rounded ends and some have very sharp knife-like ends). The fineness coefficients of a vessel are dependent on the speed she is designed for and the seakeeping conditions that are considered for the vessel. This means that the faster the ship is the finer her hull form. The typical fineness coefficients for different types of ships summarized in Table 2-1 are defined as follows:

Block coefficient (C_B) is the ratio of the volume of displacement to the product of the length, breadth, and draught of the ship as shown below in Figure 2-5. The variation of C_B to ship speed (Froude No.) is illustrated in Figure 2-6.

$$C_B = \frac{\text{Displacement Volume}}{Length \times Breadth \times Draught} = \frac{\nabla}{L \times B \times T} \tag{2-11}$$

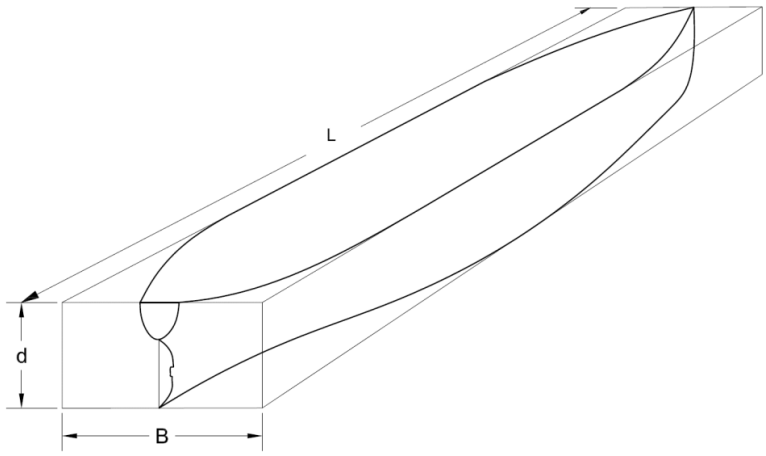


Figure 2-5 Ship Block Coefficient

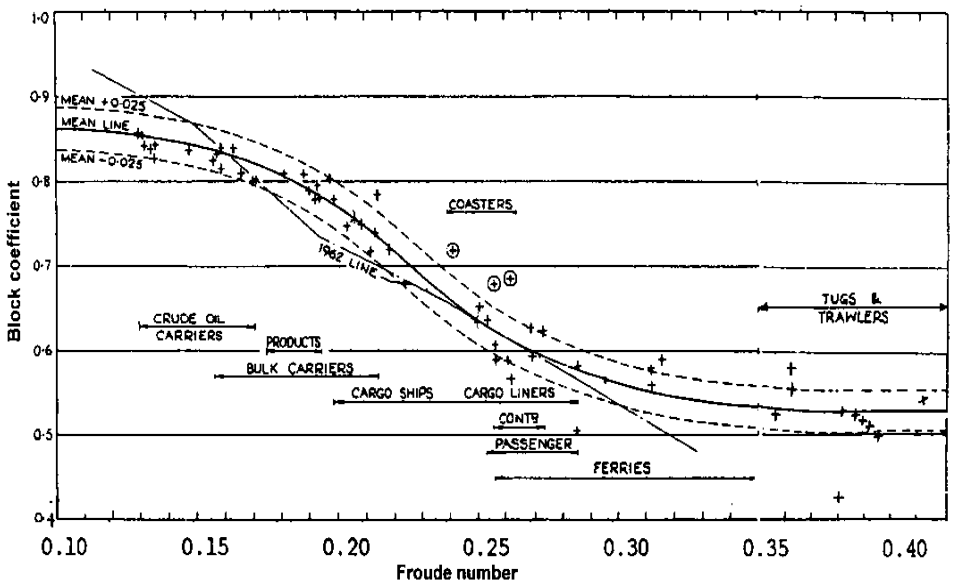


Figure 2-6 Demonstration of the variation of C_B to ship speed (Froude No.) (Tupper, 2013)

Midship Coefficient ($\mathbf{C_M}$) is the ratio of the area of the immersed portion of the midship section to the product of the breadth and the draught of the ship (see Figure 2-7) defined as:

$$\mathrm{C_M} = \frac{\text{Midship sectional area}}{Beam \times Draught} = \frac{A_m}{B \times T} \tag{2-12}$$

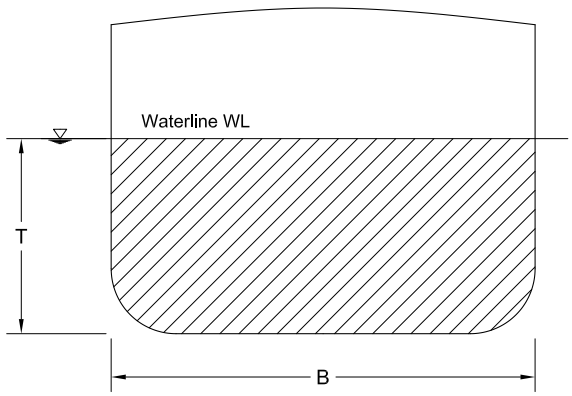


Figure 2-7 Explanation of Midship area coefficient

Prismatic Coefficient ($\mathbf{C_P}$) is the ratio of the volume of displacement to the product of the length and the immersed portion of the midship section (see Figure 2-8) defined as :

$$\mathrm{C_P} = \frac{\text{Displacement Volume}}{Length \times \text{Midship sectional area}} = \frac{\nabla}{L \times A_m} \tag{2-13}$$

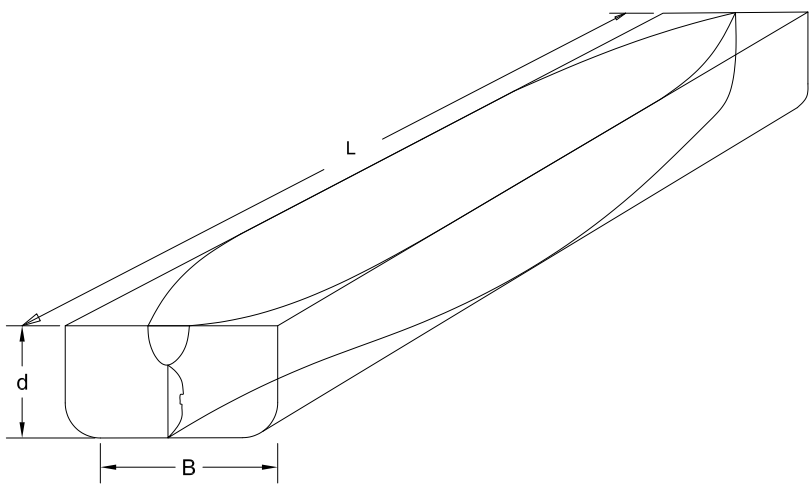


Figure 2-8 Explanation of Prismatic coefficient.

Waterplane Area Coefficient (C_W) defined as the ratio of the area of the waterplane to the product of the length and breadth of the ship (Figure 2-9).

$$C_W = \frac{\text{Waterplane area}}{Length \times Beam} = \frac{A_W}{L \times B} \tag{2-14}$$

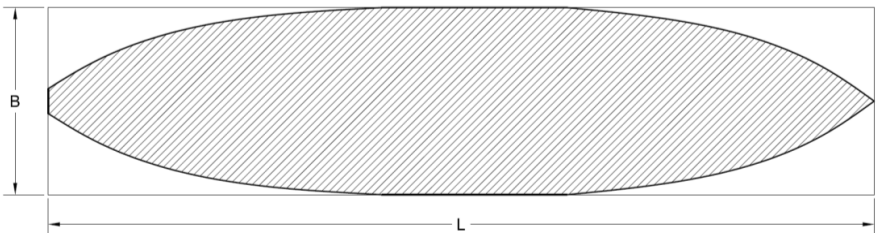


Figure 2-9 Explanation of waterplane area coefficient.

Table 2-1 *Typical fineness coefficients for different ship types*

Ship type	C_P	C_m	C_B	C_W
Trawler	0,648	0,880	0,570	0,720
Car Ferry	0,551	0,920	0,507	0,640
Fast Cargo Liner	0,664	0,980	0,650	0,749
Cargo Tramp.	0,735	0,980	0,720	0,803
Tanker	0,842	0,985	0,830	0,887
Sailing Yacht ex fin keel	0,550	0,680	0,374	0,700

Deadweight coefficient (C_D) is defined as the ratio of the ship's deadweight to displacement:

$$C_D = \frac{payload}{\text{the total weight}} = \frac{\text{Cargo } Deadweight}{Dispalcement} \tag{2-15}$$

In the above equation, cargo deadweight is the weight of a loaded ship without the lightweight i.e., weight of the items that are not a part of the hull or fittings. Typical values of C_D of certain types of vessels are summarized in Table 2-2.

Table 2-2 Typical values of the Deadweight Coefficient

Ship Type	C_D
Super tanker	0,78
Container Ship	0,65
Hydrofoil Ferry	0,30

Speed Parameters. A ship's speed is dependent on ship size. The most common speed parameter is Froude Number (F_n). It is a dimensionless parameter representing the speed to length ratio of a ship. Froude number is commonly used in resistance and propulsion analysis.

$$F_n = \frac{V}{\sqrt{gL}} \tag{2-16}$$

4. Slenderness coefficients

Slenderness coefficients express the relation between displacement and hull length.

$$\textbf{Taylor Displacement to Length Ratio} = \frac{Displaced\ Mass\ (tons)}{[Length(ft)/100]^3} = \frac{\Delta}{(\frac{L}{100})^3} \tag{2-17}$$

$$\textbf{Volumetric Coefficient}\ (C_V) = \frac{Displacment\ Volume}{Length^3} = \frac{\nabla}{L^3} \tag{2-18}$$

$$\textbf{Froude Displacement Coefficient}\ (M) = \frac{Length}{Displaced\ Volume^{1/3}} = \frac{L}{\nabla^{1/3}} \tag{2-19}$$

In the above equations C_V and M are non-dimensional and therefore useful in general design (see Table 2-3).

Table 2-3 Typical Values of Slenderness Coefficients

Ship Type	M	C_V	Taylor Displacement /Length Ratio
Racing VIII	17,00	0,2	6
Frigate/Destroyer	7,5	2,5	70
Light Displacement Racing Yacht	7,0	3,0	80
Container Ship	6,5	3,5	105
Large Tanker	5,0	8,0	230
Cruising Yacht	4,75	9,5	270
Salvage Tug	4,25	13,0	370

5. Ship type characteristics

There are various ways to categorize ships namely : mission, applied technologies, operational area, design limiting factors, cargo handling system, number of hulls etc. (see Figure 2-10 and Table 2-4). **The mission and service** category assumes that a ship can operate for commercial services (e.g., to carry cargo for trade) or for defense (naval ship) or for leisure and tourism (passenger ship) or for special purpose (e.g., ice breakers, pleasure yachts and leisure boats). On the other hand, the **applied technologies** category comprises of the following sub-categories:

- *Hydrodynamic capability and material type*. An example segment under this sub – category is innovative High-Speed Crafts (HSC). Such vehicles are sensitive to

hydrodynamic-lift / loads and the use of lightweight hull materials (aluminum, composites, carbon-fiber).

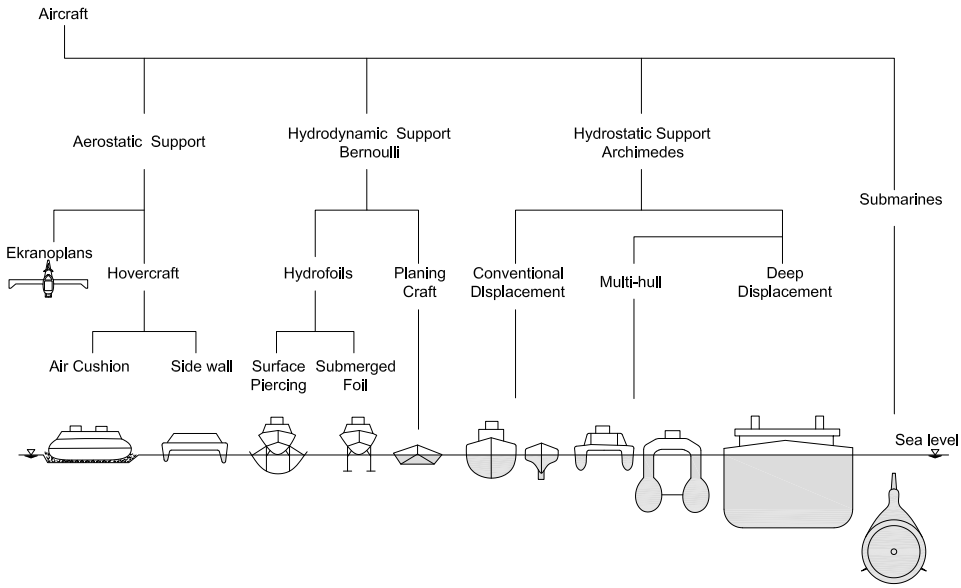


Figure 2-10 Overview of ship categories

On the other hand, the **applied technologies** category comprises of the following sub-categories:

- *Hydrodynamic capability and material type*. An example segment under this sub – category is innovative High-Speed Crafts (HSC). Such vehicles are sensitive to hydrodynamic-lift / loads and the use of lightweight hull materials (aluminum, composites, carbon-fiber).

- *Cargo handling and storage* sub - category has broad application on a variety of vessels. For example, LNG/LPG and Tanker ships use piping systems for the transfer of liquid cargo during loading. Container ships and bulk carriers use vertical lifting equipment (pallets and cranes); On Roll on Roll off (Ro-Ro) ships cargo is rolled onto and rolled off the ship.

- *Propulsion capability* applies on LNG and passenger ships with single or twin-screw propeller. In HSC the use of high-performance waterjets is broadly spread. Use of sails or Fletner rotors that could be used for energy efficient ocean-going ships or for small boats are other examples.

- *Power generation methods* (e.g., batteries, hydrogen fuel cells etc.) are expected to grow over the years to come mainly because of shipping sustainability requirements.

Table 2-4 Some ship type characteristics

Ship Type	Advantages	Limitations
Monohulls	✚ Many empirical design data available ✚ Low building cost per unit displacement ✚ Small relative wetted area	Speed in heavy weather is limited by roll and pitch motions, slamming, green seas and longitudinal bending moments
Catamarans	✚ Low building cost per unit displacement ✚ High altitude cruising in waves and thus low wave resistance ✚ Low probability of slamming	✚ Wide overall beam ✚ High metal weight per unit displacement ✚ Speed limited by pitch motion, wet deck slamming and longitudinal bending moments
Trimarans	✚ Wide cargo deck well above water line ✚ Satisfactory initial transverse stability ✚ Lower wave resistance than mono-hulls ✚ Low probability of bottom slamming ✚ Transverse bending moments less than catamarans	✚ Large wetted deck area ✚ High longitudinal bending moment especially in high seas ✚ Maneuvering / directional control problems

Ships can also be categorized based on their **area of operations.** For example, ships designed to operate worldwide or ships that operate in restricted areas (e.g., Canadian Great Lakes, Baltic or South China seas, the ice infested regions of the Arctic and the Southern Ocean, coastal areas or inland waterways). **Ship categorization based on limiting design factors** accounts for weight/space/size limited ships. Weight limited ships are those carrying heavy cargo (e.g., bulk carriers, timber cargo ships). Space limited ships are those which are transporting people (e.g., cruise ships, RoPax ships) and light cargo ships (e.g., high speed craft). Size limited ships are ship designs affected by infrastructure in specific areas of the world (e.g., draft and beam constraints for operation in Panama or Suez canals or draft limits in ports). The final main category clasifis ships according to their **hull numbers**. Two main ship types are considered here namely the mono-hull vessels (e.g., classic designs of bulk carriers, tankers, cruise liners, etc.) and innovative multi-hull vessels (see Table 2-5). Examples of multi-hull vessels are Small Water Plane Area Twin Hull - SWATH ships designed for relatively high speed and a stable platform in moderately rough weather, Table 2-5, Wave Piercing Catamarans – WPC design for short sea high speed coastal service and trimaran war ships (Table 2-4) or even pentamaran container ship designs for transatlantic service (Figure 2-11).

Table 2-5 Advantages and limitations of Small Waterplane Area Twin Hull ships (SWATH)

Advantages	Limitations
Wide and well elevated deck area with excellent initial stability, roll and pitch motions.	Wide overall beam.
Low longitudinal bending moment which drops at higher speed in head seas.	Transverse bending moment is greater than for a catamaran.
Low wave resistance.	Greater relative wetted area
Low slamming probability	Narrow struts and gondolas make it difficult to place and access the main engines.
Low additional resistance in waves	

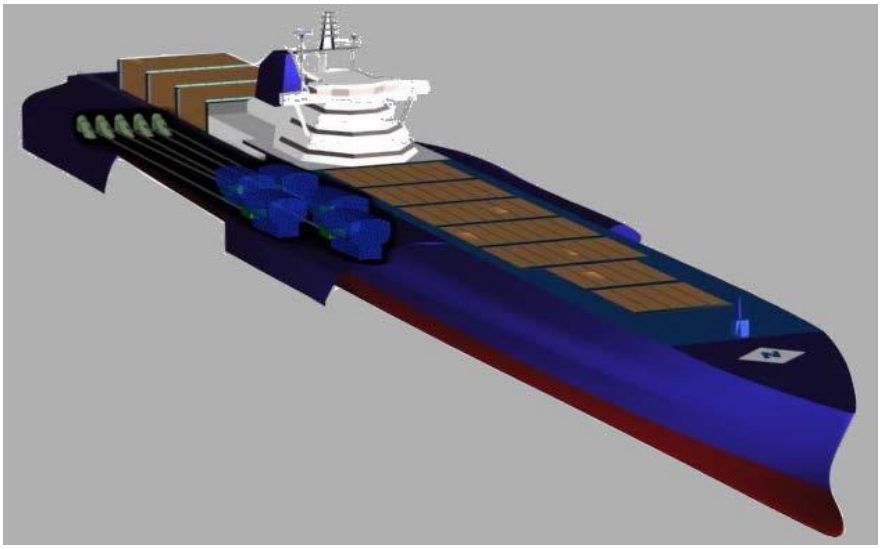


Figure 2-11 Artist impression of a pentmaran container ship © BMT, UK

6. Questions

1. A box barge 65m long and 12m wide floats at a draught of 5.5m in sea water. Calculate the displacement in sea water and in fresh water.
2. A ship has a constant triangular cross-section float in sea water. The ship is 85m long, 12m wide, at the deck and has a depth from keel to deck of 9m. Draw a curve of displacement as a function of draught using 1.5m intervals of draught up to 7.5m waterline. Use the curve to obtain the displacement at 5.5m draught.
3. A cylinder 15 m long and 4 m outside diameter floats in sea water with its axis in the waterline. Calculate the mass of the cylinder.
4. A two-man sailing dinghy displaces volume of 0.27m^3. Its load waterline length is 4.25m and the waterline beam at amidships is 1.1m. Assuming C_P = 0.58 and a midship section area coefficient C_M =0.63 calculate the values of M, C_B and draught.
5. A luxury motor yacht is to have a displacement volume of 350m^3 and a beam to draught ratio of 3.5. Assuming Froude number F_n =0.40 use the design, trend lines to estimate suitable length (L_{BP}), beam (B_{mld}) and draught (T_{mld}) for this vessel. Also calculate the vessel speed corresponding to the proposed Froude number.
6. Sketch and explain the ship's main dimensions and their different definitions.
7. Define: Sheer, Camber, Rise of floor, flat of keel, tumble home, and freeboard.
8. Explain and write the equations of the fineness coefficients.
9. Explain briefly the ship's different classifications.
10. Explain the difference between displacement, deadweight, and lightship weight.

Lecture 3
Ship Main Dimensions

1. Introduction

In early design stage there are two main methods for the estimation of the main dimensions namely (a) the empirical and (b) the parametric. **In the empirical method**, the basis of assessment depends on the utilization of statistical data of similarly built ships. Data may come from an open-source or a commercial/internal database and are usually represented on graphs. The method is based on two assumptions: (a) data are reliable; (b) ships included in the database are economically and efficiently designed. **In the parametric method**, a study from scratch is conducted seeking for a suitable combination of dimensions and form coefficients that satisfy some selected objectives and design constraints. For instance, a ship's main dimensions can be estimated based on an optimization model for selected economic objectives such as minimum operating or building cost. The parametric method is used when there is a lack of data on the same type and size of the new design.

2. Selection factors

Although the main objective in selecting the main dimensions is to fulfil the owner's requirements in terms of payload and speed, IMO regulations and the Classification requirements may affect design (see Lecture 1, Sections 4 and 5). Accordingly, assorted factors should be considered during the selection of ship main dimensions and form coefficients. These factors may help design for (a) hydrodynamic performance (resistance & propulsion, seakeeping, and maneuverability); (b) transverse and longitudinal stability; (c) structural strength; (d) sufficient volume for cargo and also ensure sustainable construction costs. The basic design factors are categorized as follows:

Factors affecting ship length (L). Length is a function of displacement and speed. It has a significant influence on the weight of steel structure and accommodation/outfitting, hence on the construction cost. Also, it strongly affects both the ship's calm water resistance and seakeeping performance (motions, accelerations, dynamic loads, added resistance, and speed loss in seaways).

Factors affecting the Breadth (B), Draught (T), and Depth (D). These dimensions are coupled in fine form coefficients (see Lecture 2, Section 2 and 3). The volume of a hold depends on the type of cargo, the stowage factor and affects mainly the depth required; **B** has a significant influence on transverse stability and cargo-carrying capacity. Maneuvering and propulsion efficiency are affected by **T**. In rough seas, both breadth and draught affect the wave added resistance while draught affects slamming. The required freeboard affects the selection of both draught and depth of the ship. Consequently, breadth, draught, and depth are key in

damage stability pertaining to safety against flooding and capsize. The coupling of the length with the draught has a compelling impact on the longitudinal strength.

Factors affected by physical constraints (e.g. ship route) **operational limitations** (e.g. port drafts and confinement, shipyard dry dock principal particulars, crossing channel width and depth limitations, bridge crossings etc.; e.g. see Table 3-1) that may override an initially set mission and performance objectives.

Table 3-1 Canal constraints on ship design[5]

Canal	Constraints
Kiel	$LOA < 315m$ $B < 40m$ $T < 9.5m$
Panama (old)	$LOA < 290m$ $B \leq 32.24m$ $T < 13m$
New Panama Canal	$L_{OA} = 427m$ $B < 55m$ $T < 18.3m$
St Lawrence	$L_{OA} < 222m$ $B < 23m$ $T < 7.6m.$
Suez	$T < 14.63m.$ (≈ 1984 increased to 18.29 m.)

There are three practical approaches that may be used to decide the main dimensions of a ship. Those are known as Normand's number, statistical and direct calculations approaches and are explained in the following sections.

3. Normand's number

Normand's number (N) approach is defined as a factor by which the change in one or various weight components is multiplied to give the change in the total displacement of a ship.

$$N = \frac{d\Delta}{dW} = \frac{\Delta}{\Delta - (W_H + W_O) - \frac{2}{3}(W_M + W_F)} \tag{3-1}$$

where dW is the difference between the deadweight of the new design and the reference ship, $d\Delta$ is the difference in displacement between the new design and the reference ship, W_H is the hull weight of the reference ship, W_O is the outfitting weight of the reference ship, W_M is the machinery weight of the reference ship, and W_F is the fuel weight of the reference ship.

A challenge in Normand's number approach is the lack of available data. Empirical charts are summarized in Figure 3-1. The main ship dimensions are calculated by setting one or two of the reference ship's characteristics as constant (e.g., C_B).

[5] see : www.pancanal.com/eng/general ; http://www.suezcanal.gov.eg; http://www.greatlakes-seaway.com

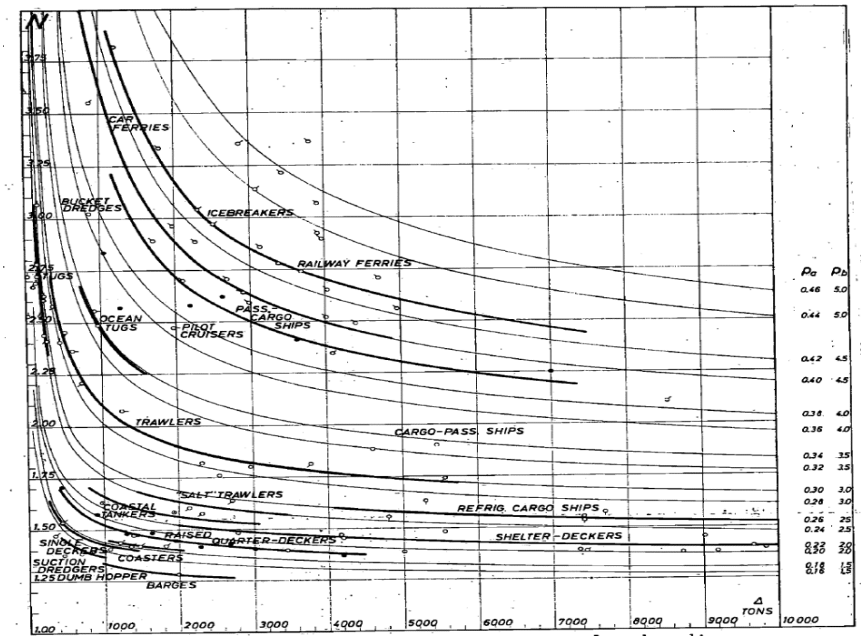


Figure 3-1 Normand's number for merchant ships less than 10,000 tons. Image credits: (Harvald, 1964)

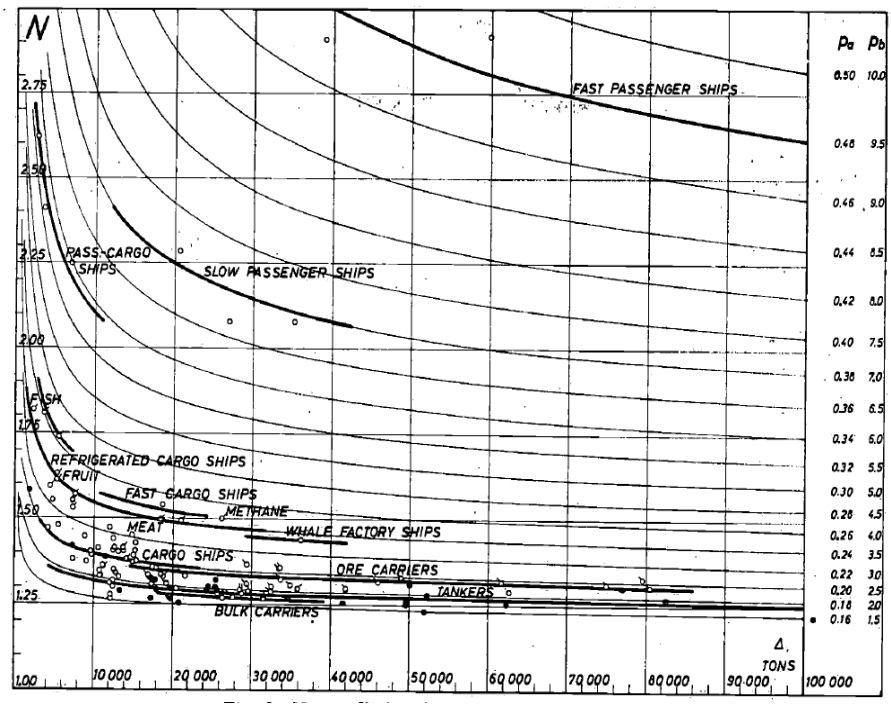


Figure 3-2 Normand's number for merchant ships up to 100,000 tons. Image credits: (Harvald, 1964)

4. Statistical approach

In the statistical approach, the empirical method is used to select the main dimensions. There are various procedures, curves, and regression-based equations that may be used to decide on selecting a ship's main characteristics. An example of the procedure to be followed is given as follows:

- The displacement of the new design is calculated based on tabular values of deadweight displacement ratios. Deadweight should be known as an owner requirement.
- The length of the ship is calculated using regression-based equations.
- The block coefficient is calculated using regression-based equations.
- The length to breadth ratio is estimated based empirical formulae or tabular values. Hence, breadth is calculated.
- The draught is calculated based on displacement, breadth, length, and the block coefficient. Any limitations on the draught, D/T or B/T ratios should be considered.
- The length to depth ratio is calculated based on tabular values from statistical data.
- The depth is obtained.

As an example, statistical tables for Ship Design are given by (Papanikolaou, 2014)). These can be used to compare the new ship to existing ships to check that the parameters are within a normal range.

5. Direct calculations

Direct calculations may be used when there is a lack of data from similar type or size of ships or when the new design is uncommon in shape and/or size, it is crucial to start the design from scratch based on objectives, requirements, and constraints. In such cases the purpose of the designer is to seek the best combination of dimensions and form characteristics that will satisfy the given objectives. However, at preliminary design stages definition of accurate relationships between the different ship parameters and design economic objectives may be challenging. Thus, solutions are implemented at detailed design stage through the use of a mathematical optimization model embedded in a commercial software (e.g., NAPA, Rhinoceros, MAXSURF, etc.).

6. Practical examples

Let us assume that you are required to design a container ship for a shipping line company operating a fleet of cargo vessels. The ship is similar to the last built ship in the fleet; however, for economic reasons her deadweight needs to be increased by $5{,}000\ tonnes$. Based on the sister ship's operational profile, the draught limit is 9m. Additionally, for minimizing the fuel consumption, the length to breadth ratio should be increased ($L/B = 7.5$). Calculate the displacement and the main characteristics of the new design using Normand's number and

the statistical approaches. In your calculations you may assume that the block coefficient is constant. The data of the reference ship are given below:

Table 3-2 Reference ship data for a cargo vessel

Item	Reference Ship data
Length, L (m)	300
Beam, B (m)	42
Draft, T (m)	18
Block Coefficient, C_B	0.72
Hull weight W_H (tonne)	8000
Machinery Weight W_M (tonne)	3000
Outfitting weight W_O (tonne)	2000
Fuel weight W_F (tonne)	3000
Deadweight (tonne)	24824
Length to Beam ratio, L/B	7.14
Speed	12 knots

6-1 Solution using Normand's number approach

- Calculate the displacement of the reference ship based on the main dimensions and C_B by the formulae :

$$\Delta = \rho . L . B . T . C_B . \lambda = 168382.67\ tonne \tag{3-2}$$

where λ is the shell and appendage allowance =1.006 and ρ is the density of seawater $1.025\ {}^{t}/_{m^3}$

- Calculate Normand's number based on equation (3-1) and the given reference ship data according to the formulae:

$$N = \frac{168382.67}{168382.67 - (8000 + 2000) - \frac{2}{3}(3000 + 3000)} = 1.091 \tag{3-3}$$

- Based on the deadweight change required and Normand's number, the displacement of the new design can be calculated as:

$$\Delta_{new} = \Delta + NdW = 168382{,}67 + (1{,}091 \times 5000) = 173836{,}09 \text{ tonnes} \tag{3-4}$$

- To determine the main dimensions $L/B, C_B$, and T are assumed to be unchanged.
- Since C_B and T do not change; $L \times B = \frac{\Delta}{C_B . T}$ and $L/B\ for\ the\ new\ design = 7.5$, therefore, L, B of the new design can be deduced; $L = 313.3\ m$ and $B\ = 41.8\ m$.
- The main particulars of the new design are shown in the Table 3-3.

Table 3-3 Main particulars of the new design based on Normand's number approach

Item	New Ship data
$L\ (m)$	313.28
$B\ (m)$	41.77
$T\ (m)$	18
C_B	0.72
$\Delta\ (tonne)$	173836.09
$Cargo\ Deadweight\ (tonne)$	160382.67
L/B	7.50

6-2 Solution using the statistical approach

- To estimate the ship displacement for the required deadweight, the deadweight to displacement ratio should be used. Table 3-4 summarizes this for different types of ships.

Table 3-4 Upper and lower bound DWT to displacement ratios for different designs (Papanikolaou, 2014)

Ship type	Limits		$\mathbf{DWT/\Delta}$ (%)	$\mathbf{W_{ST}/W_L}$ (%)	$\mathbf{W_{OT}/W_L}$ (%)	$\mathbf{W_M/W_L}$ (%)
	Lower	Upper				
General cargo ships (t DWT)	5,000	15,000	$65-80$	$55-64$	$19-33$	$11-22$
Coasters, cargo ships (GRT)	499	999	$70-75$	$57-62$	$30-33$	$9-12$
Bulk carriers (t DWT)	20,000	50,000	$74-85$	$68-79$	$10-17$	$12-16$
	50,000	200,000	$80-87$	$78-85$	$6-13$	$8-14$
Tankers (**t** DWT)	25,000	120,000	$78-86$	$73-83$	$5-12$	$11-16$
	200,000	500,000	$83-88$	$75-88$	$9-13$	$9-16$
Containerships (t DWT)	10,000	15,000	$65-74$	$58-71$	$15-20$	$9-22$
	15,000	$165,000$	$65-76$	$62-72$	$14-20$	$15-18$
Ro-Ro (cargo) (t DWT)	$L \cong 80$ m	16,000 t	$50-60$	$68-78$	$12-19$	$10-20$
Reefers $(\mathbf{ft^3})$ of net ref. vol.	300,000	500,000	$45-55$	$51-62$	$21-28$	$15-26$
Passenger Ro-Ro/ferries	$L \cong 85$ m	L ≅120 m	$16-33$	$56-66$	$23-28$	$11-18$
Large passenger ships (cruise ships)	L ≅200m	L ≅ 360 m	$23-34$	$52-56$	$30-34$	$15-20$
Small passenger ships	$L \cong 50$ m	L ≅120 m	$15-25$	$50-52$	$28-31$	$20-29$
Stern Trawlers	$L \approx 44$ m	L ≅ 82 m	$30-58$	$42-46$	$36-40$	$15-20$
Tugboats	$P_B \cong 500$	3,000KW	$20-40$	$42-56$	$17-21$	$38-43$
River ships (towed)	$L \cong 32$ m	$L \cong 35$ m	$22-27$	$58-63$	$19-23$	$16-21$
River ships (self-propelled)	$L \cong 80$ m	$L \cong 110$ m	$78-79$	$69-75$	$11-13$	$13-19$

$\mathbf{W_L}$ Light ship weight; $\mathbf{W_{ST}}$ weigth of steel structure; $\mathbf{W_{OT}}$ weight of outfitting and $\mathbf{W_M}$ weight of machinery installation

- The L_{PP} of the ship is to be calculated based on Schneekluth's 1998 formula (2-6), $L_{PP} = \Delta^{0.3}V^{0.3}C$, where V is the vessel speed in knots = 12 knots, and C can be obtained from equation (2-8), $C = 3.4 - (\Delta - 10\text{^}3)/(10\text{^}6\ )$.

- L/B is already given in the example = 7.5, however, in general there are many empirical equations can be used to estimate the L/B ratio based on the ship type and length, see (Papanikolaou, 2014). The breadth then can be calculated, $B\ =\ L_{PP}/7.5$.

- Froude's number (Fn) can be calculated using Eq.(2-16), i.e. $Fn = (V(m/s))/\sqrt{(gL(m))}$

- Draft then can be obtained based on the ship's breadth using the following formula:

$$T = \frac{\nabla}{L \times B \times C_B} \tag{3-5}$$

In case C_B is not given, it can be obtained using one of the following empirical formulae:

$$C_B = 0{,}7 + 0{,}125\, tan^{-1}[(23 - 100Fn)/4] \text{ [Watson \& Gilfillan]} \tag{3-6}$$

$$C_B = -4.22 + 27.8\sqrt{Fn} - 39.1Fn + 46.6Fn^3 \text{ for } 0.15 \leq \text{Fn} \leq 0.32 \tag{3-7}$$

- Recommendations on the L/D ratio which is important for longitudinal strength and through which you can calculate the depth of the ship are provided by (Papanikolaou, 2014) as follows:

Table 3-5 Upper and lower bound L_{PP} to depth ratios for different designs (Papanikolaou, 2014).

Ship types	Ratio of main dimensions (L_{pp}/D)
Fast seagoing ships	9.9-13.5
Slow seagoing cargo ships	10.0 – 12.0
Small short sea passenger ships	10.4 – 11.6
Ferries	8.6 – 10.3
Fishing vessels	8.2 – 9.0
Tugboats	7.7 – 10.0
Bulk carriers	10.5 – 12.8
Tankers with Froude no. 0.15	12.0 – 14.0
Tankers with Froude no. 0.16 – 0.18	10.5-12.8
Fast going reefers	11.0

7. Questions

1. A shipowner has a fleet of old tankers. He requested from your firm to support them with a new tanker which has a 2% increase in the deadweight in comparison to the last tanker. As the fleet is very old, some weight data estimates are missing. The length of the dock at which the ship will be built limits the length to 200 meters. The maximum breadth to draught ratio (B/T) required is estimated based on the formula $(B/T)_{max} = 9.625 - 7.5 \times C_B$. The main characteristics of the reference tanker are given in the table. If the block coefficient is constant, calculate the displacement and the main characteristics of the new design using both Normand's number approach and the statistical design method.

Item	Reference ship data
L (m)	200
B (m)	33.3
T (m)	12
C_B	0.84
Deadweight (tonne)	55,737

2. You are working in a design office, and your task is to select the main dimensions of a new container ship based on concise owner requirements. According to a feasibility study, the ship owner expects that a deadweight of 25,000 tonnes, and a design speed of 12 Knots will achieve the required return on investment. Calculate the ship's main characteristics using a statistical method.
3. Describe the factors associated with the use of statistics in the definition of ship main dimensions?
4. What can be done with clustering of data when you use of statistics in the definition of ship main dimensions? What kind of restrictions you can explain by clustering process?
5. Which issues should be considered when you use statistics in the definition of ship main dimensions?
6. Explain the idea of Normand's number. How can you apply that in selection of main dimensions?
7. A shipping company needs to build a new container ship that is intended to go through Suez Canal. The company has a good reference container ship with the following main particulars:

Length	400 m
Breadth	61 m
Draft	14 m
C_b	0.63
Normand's number	1.3
DWT	150000 tonne

Assume that the maximum allowed draft in Suez Canal for ships with B > 47.55 m is 10.67 m. Define the deadweight after modifying the draft, consider constant block coefficient.

8. A client suggests the following main dimensions of a cruise vessel. Compare these dimensions against the statistical data provided in the database excel sheet and then judge if these dimensions are reliable.

Length	220 m
Breadth	30 m
Draught	7 m
Depth	15 m
DWT	6000 tonne
C_b	0.75
Velocity	20 knot
Passengers	1500

9. Suggests suitable midship coefficient, water plane coefficient and prismatic coefficient of the vessel in question 8, note you can use the empirical formula in the tutorial.
10. A passenger ship of 30 m breadth, volumetric displacement $\nabla = 31500\ m^3$ and speed 20 knot. Use Ayre's formula to estimate the ship length and then calculate the block coefficient using Schneekluth formula.

Lecture 4
The basics of ship hull form design

A ship's hull is a very complicated 3D shape. Since it is difficult to express a ship's shape by a single equation Naval Architects place great emphasis on the graphical description of hull forms by line drawings. In the past this work was done by hand. Today high-speed digital computers and Computer Aided Design (CAD) packages can assist with hull form design (both line drawings and hull surface construction). However, neither are substitutes for imagination and sound judgment.

1. Ship lines plan

Hull line drawings consist of the intersection of the hull with a series of planes. The planes are equally spaced in each of the three dimensions. Sets of planes are mutually perpendicular or orthogonal, i.e. planes in one dimension are perpendicular to planes in the other two dimensions. The points of intersection of these orthogonal planes with the hull result in a series of lines that are projected onto a single plane located on the bow, deck, or side shell of the ship. This results in three separate projections, or views, called the ''*Body plan''*, the ''*Half-Breadth plan*'', and the ''*Sheer plan*'' (or *Profile*), respectively. Figure 4-1 and Figure 4-2 and Figure 4-3 display the creation of these views in 3D and 2D respectively. Drawings display idealizations of a classic mono-hull design (i.e., a design that is symmetric about the longitudinal plane).

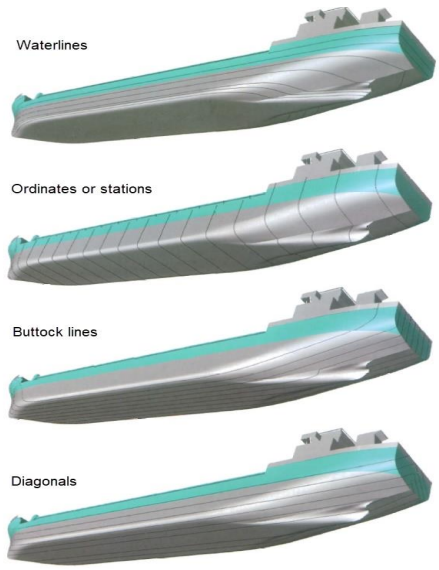


Figure 4-1 3D representations of waterlines, buttock lines, stations, and diagonals (Dokkum K. V., 2016)

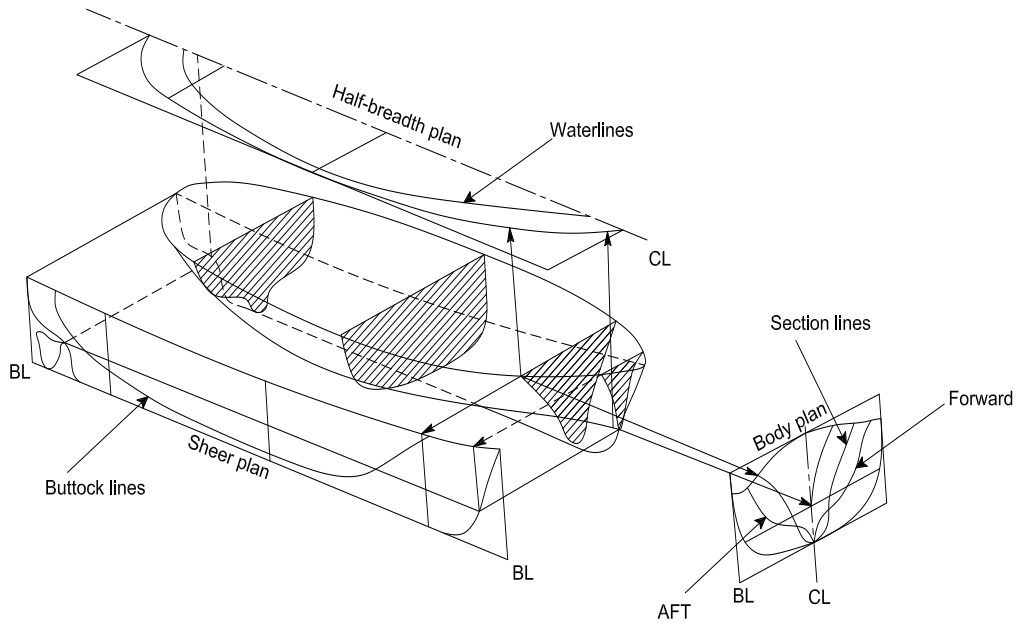


Figure 4-2 3D projection of lines onto three orthogonal planes

The intersection of the horizontal planes with the hull shape results in lines called **waterlines** and their view in the hull lines drawing is known as the **half-breadth plan** as only half of the ship is drawn. Each waterline shows the true shape of the hull from the top view for some elevation above the base plane (or keel) which allows this line to serve as a pattern for the construction of the ship's framing. The lines formed by the intersection of the planes parallel to the middle line longitudinal plane are called **buttocks** and the line of intersection with the middle line plane is called **profile**.

Each buttock line shows the true shape of the hull from the side view for some distance from the centerline of the ship. This allows them to serve as a pattern for the construction of the ship's longitudinal framing. The overall side view of the ship is known as the **sheer profile**. Finally, the lines of the intersection with transverse planes are called stations and are represented on the **body plan** view. Stations are odd in number and therefore evenly/equally spaced (i.e. 11, 21, 31, or 41). The plane that runs from bow to stern directly through the center of the ship and parallel to the sides of the imaginary box is called the **centerline plane**.

Each sectional line shows the true shape of the hull from the front view for some longitudinal position on the ship which allows this line to serve as a pattern for the construction of the ship's transverse framing A series of planes parallel to one side of the centerline plane are imagined at regular intervals from the centerline.

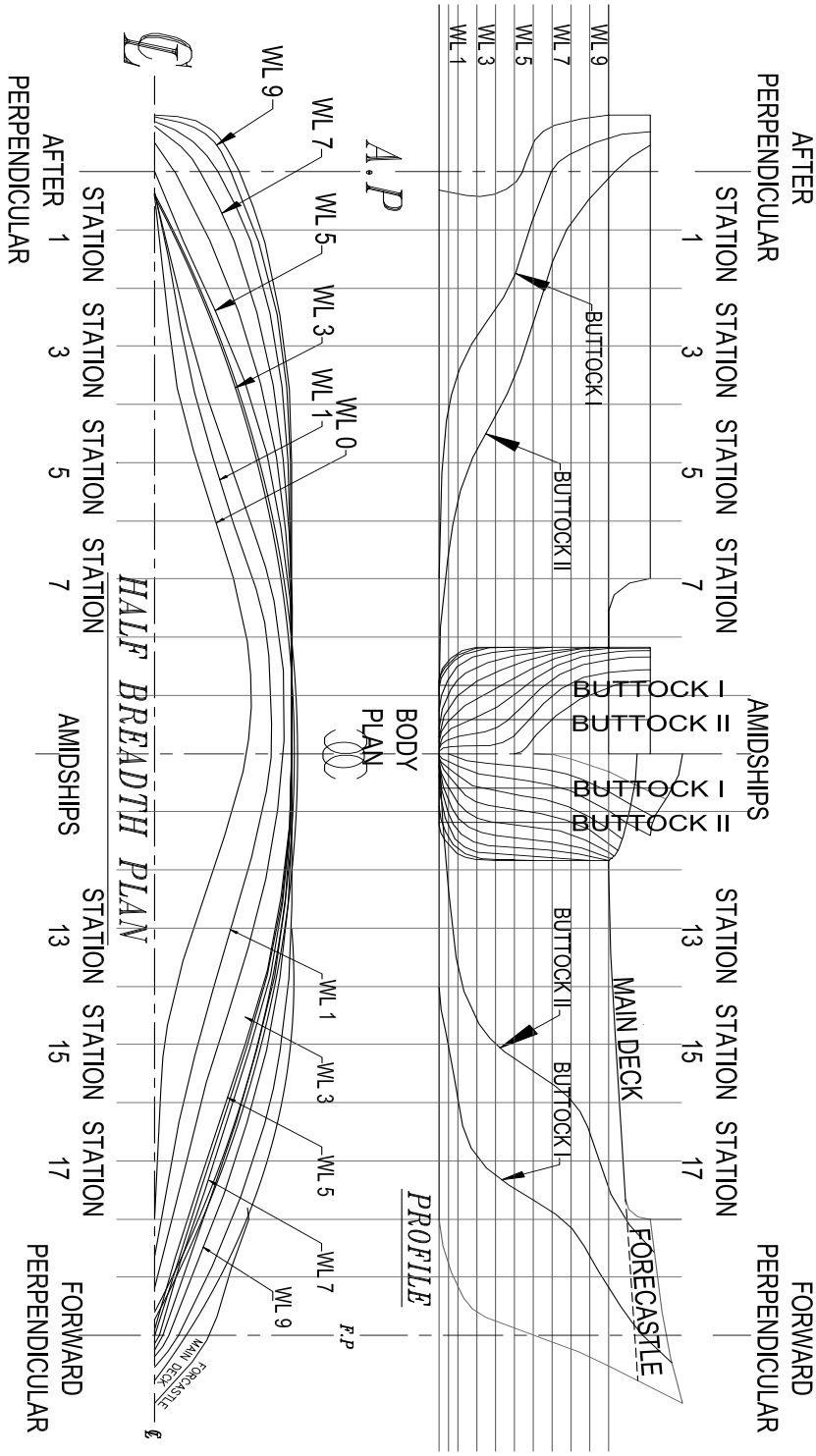


Figure 4-3 2D projection of the lines plan of a mono-hull

2. Determination of the hull shape

In Lectures 2 and 3 we introduced the basics of ship hull form coefficients and different methods for determining a ship's main dimensions. Figure 4-4 outlines a practical process of determining the hull form:

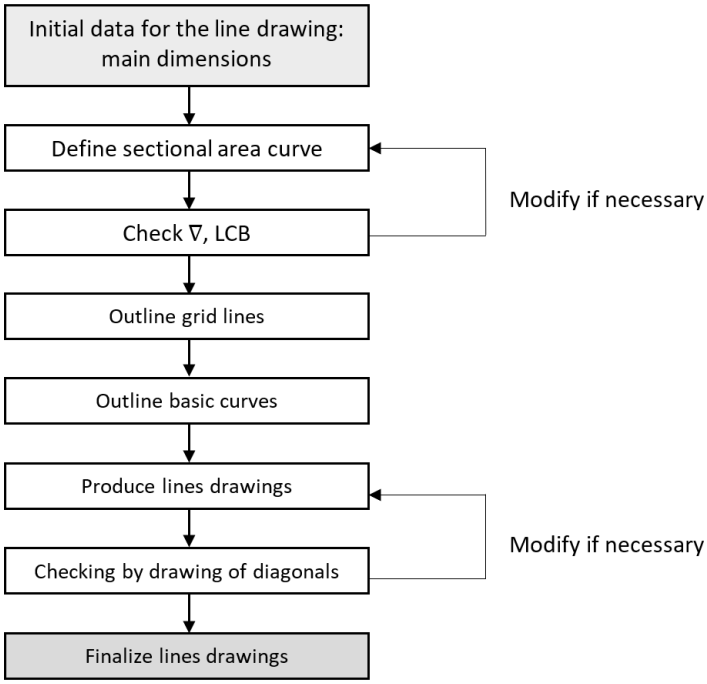


Figure 4-4 Practical method for hull form design

Hull form design influences ship performance. It therefore affects various design decisions related to: (a) ship resistance and propulsion; (b) intact and damage stability; (c) seakeeping performance in waves; (d) maneuvering capabilities; (e) volume of holds and cargo; (g) simplicity, ease and thus cost of construction. Detailed outlined of concepts reflecting the later go beyond the purpose of this course. However, the following sub - sections outline items that if considered appropriately can help with the practical hull lines generation outlined in Figure 4-3.

3. Section Area curve

Sectional Area Curve. When the ship main dimensions (L, B, T), and the displacement are known, the displacement's longitudinal distribution can be determined by using the sectional area curve (Figure 4-5). Longitudinal positions on this curve represent sectional area values. The integrated area under the sectional area curve gives the displaced volume and the center of this area gives the center of volume of the ship (the longitudinal center of buoyancy LCB). The curve is extended over the ship's length which is divided into three lengths namely: (a)

the entrance length, (b) the length of run, and (c) the length of the parallel middle body. The Parallel body length $L_P$corresponds to the part of ship's length for which we have constant sectional area. The length of entrance L_E and the length of run L_R correspond to the fore and the aft of the vessel's sectional area curve.

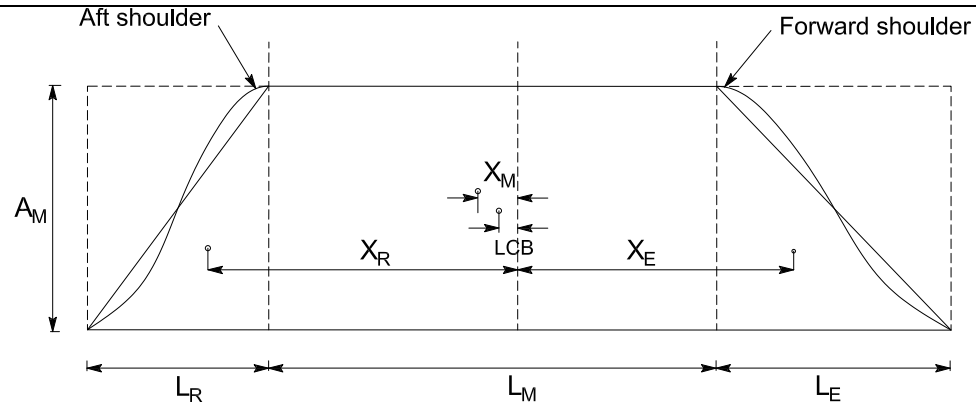


Figure 4-5 Geometric generation of the sectional area curve

X_M , X_E and X_R are the longitudinal centroids, from the amidships, of parallel middle body portion ∇_M, entrance portion ∇_E and run portion ∇_R of the SAC, respectively. The following definitions apply :

$$A_M = C_M \times B \times T, \quad \nabla_E = {}^1/_2\, A_M \times L_E \;, \quad \nabla_M = A_M \times L_M, \quad \nabla_R = {}^1/_2\, A_M \times L_R$$

$$\nabla = \nabla_E + \nabla_M + \nabla_R$$

$$LCB = [\nabla_E \times X_E + \nabla_M \times X_M + \nabla_R \times X_R]/\nabla$$

Longitudinal Center of Buoyancy (LCB). To decide on the longitudinal center of buoyancy in early stages of design, there are some recommended optimal values derived from systematic experiments and numerical investigations. A graph for the optimum LCB as a function of the block coefficient and the sectional form type by Danckwardt is shown in (Figure 4-6). Generally, the LCB position is around the midship and tends toward the fore part or the stern depending on Froude number (Fn), and hence the block coefficient (C_B).

Length of Parallel Middle-body. As the length of the parallel middle-body may increase the mid-ship region outlined by the sectional area it may in turn lead to increase in the value of the prismatic coefficient and hence the ship's wave resistance. For low-speed ships, the wave resistance part is not significant and consequently the effect of increasing the size of the parallel mid - ship body length is not momentous. From a construction perspective, the parallel mid - ship body is simple to construct because of the identical frames and structural elements used. Some recommended values for the length of parallel middle body are shown in (Table 4-1) and (Figure 4-7).

Length of entrance and length of run determine the forward and the abaft ship shoulder. The length of entrance(L_E) selection attempts to minimize the generated bow waves. Hence,

wave resistance. The length of run (L_R) is selected should be selected in a way that we can minimize resistance. The aim is to avoid a very sharp aft shoulder which causes flow separation and increases in resistance. Figure 4-8 shows some recommended values of L_E, L_P and their relative position with respect to amidships versus the ship's prismatic coefficient (C_P).

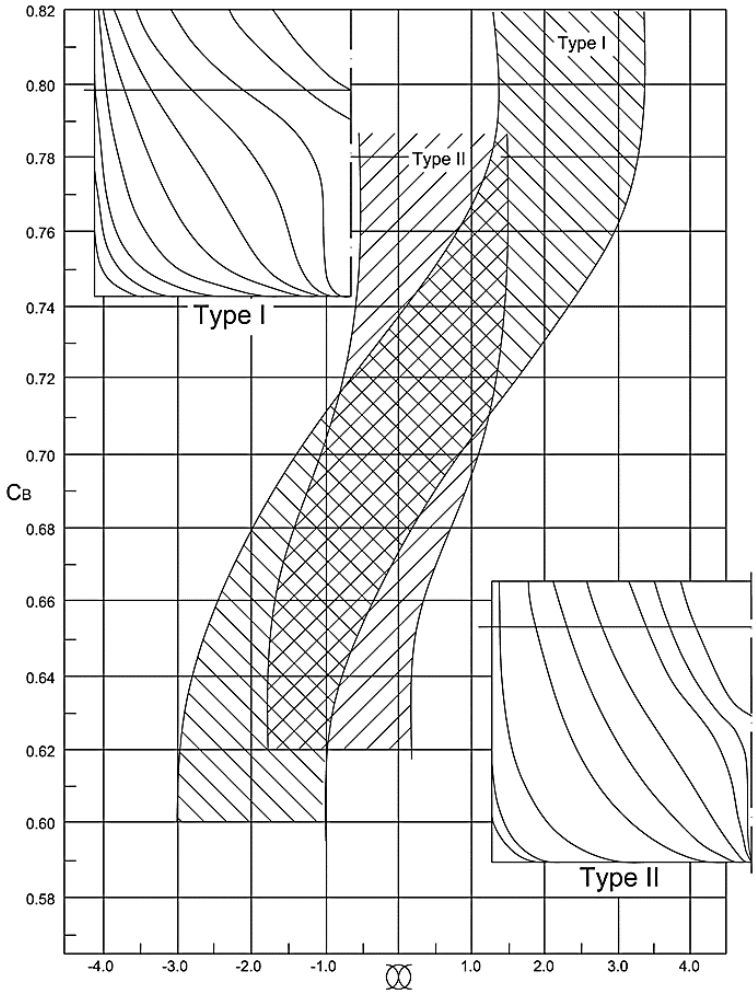


Figure 4-6 LCB as a function of C_B and hull form type (Papanikolaou, 2014)

Table 4-1 Statistical data for recommended parallel middle-body (Papanikolaou, 2014)

Ship type	L_{pp}
Slow cargo ships	0.0 – 0.1 L
Tankers and Bulk Carriers	0.3 – 0.4 L
Coasters	0.1 – 0.15 L
Other ships	N/A

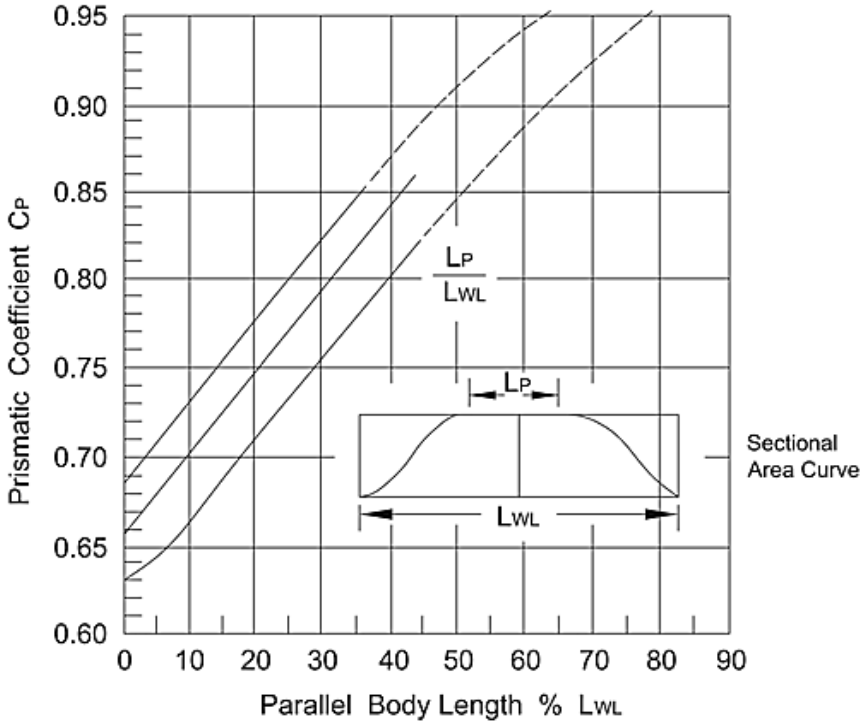


Figure 4-7 Parallel body length vs. prismatic coefficient (Papanikolaou, 2014)

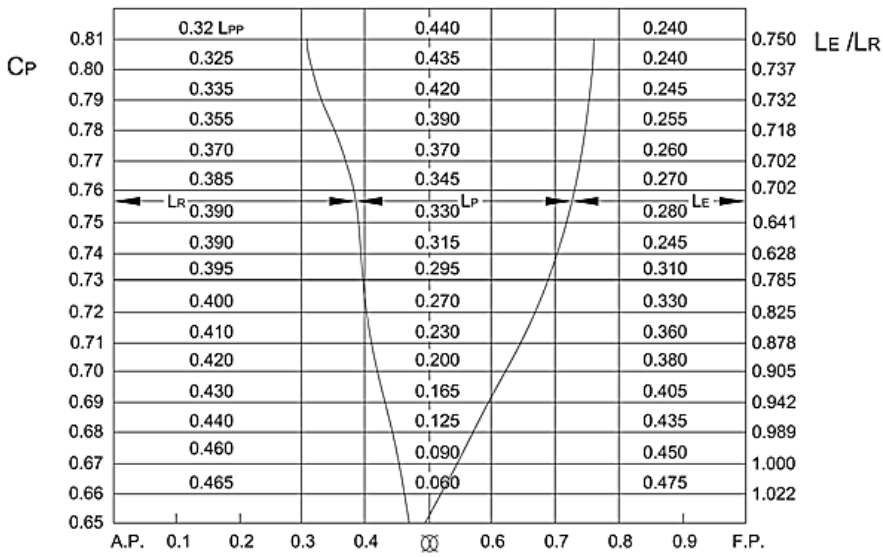


Figure 4-8 Length of entrance (L_E), length of run (L_R) and parallel middle body length versus prismatic coefficient (C_P) (Papanikolaou, 2014)

4. Ship sections

Common types of sections used in the field of Naval Architecture (see Figure 4-9) are: (a) U-type; (b) V-type; (c) rectangular with round bilge (commonly for midship sections); (d) circular type (nearly constant radius for sailing yachts); (e) hard chine (single or double chines); (f) Bulbous type (commonly for bow and stern regions).

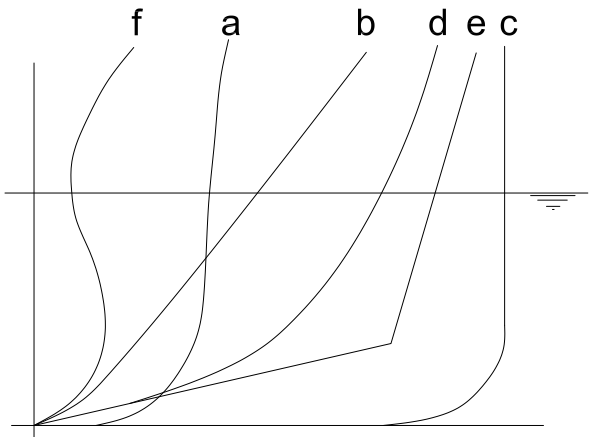


Figure 4-9 Different types of sections (Papanikolaou, 2014)

The **midship section** is the most relevant section for preliminary ship design and depends on the ship type. A rectangular mid - ship section is commonly used for cargo ships and a larger bilge can be used for fast ships. On the other hand, hard chine cross sections are usually used for High-Speed Crafts (HSC). The midship area A_m , B, T and C_M are defined before the definition of a mid-ship section. So, the only variables of configuration are the bilge radius and the bottom deadrise.

The relationship of **bow and stern sections** with the midship section; bow and stern shape requirements and the type of ship depends on the types of sections used. For example, if the midship section is full, then U or V type sections may represent the connection between the midship region and the stern or bow regions. Conversely, if the midship section is of a V-type (e.g., for a catamaran ship or another HSC), the connection should be only a V type in the bow and the stern. A ship that has a bulbous bow and/or a transom stern affects the selection of the fore and aft most neighboring sections. A transom stern requires relatively wide sections in way of the stern while the bulbous bow is based on relatively streamlined sections (see Figure 4-9). Operational requirements associated with a specific ship type may also affect the bow and stern forms. For example, ferries need a large deck area, so a V-type section is preferable. In bulk carriers and tankers, as the demand of having a large deck area is not important, the U section is preferable to allow the best use of enclosed spaces for cargo. It is noted that the selection of hull section type may also influence intact / damage stability and

seakeeping performance and strength. However, these items are more deterministic and shall be discussed later on in the course and throughout the academic year.

As described earlier, the midship section has an impact on the selection of the stern and bow sections and in consequence on the shape of the stern and bow respectively. In addition, there are many other factors affect the selection of the stern and bow shapes as the hydrodynamic efficiency, construction simplicity, flow patterns and aesthetics. For instance, the stern shape has many configurations, see Figure 4-10; the more common forms are the elliptical, cruiser and transom stern, however, there are other special forms like raked, counter, square, etc. Similarly for bow shapes illustrated in Figure 4-11, where the selection is more sensitive to the ship speed and the interaction of the with the ship at entry at the fore end.

Several modern shapes of bow and stern are illustrated in Figure 4-12. The Queen Mary 2, has a unique and special stern shape, see Figure 4-12 (a). It is designed using a hybrid stern, called Constanzi Stern, by melding a rounded into the square shape in response to the rough seas that the ship would experience in a North Atlantic winter. A constanzi stern provides the transom required for azimuthal pod propulsions, and provides better sea holding characteristics in a following swell than a standard transom stern.

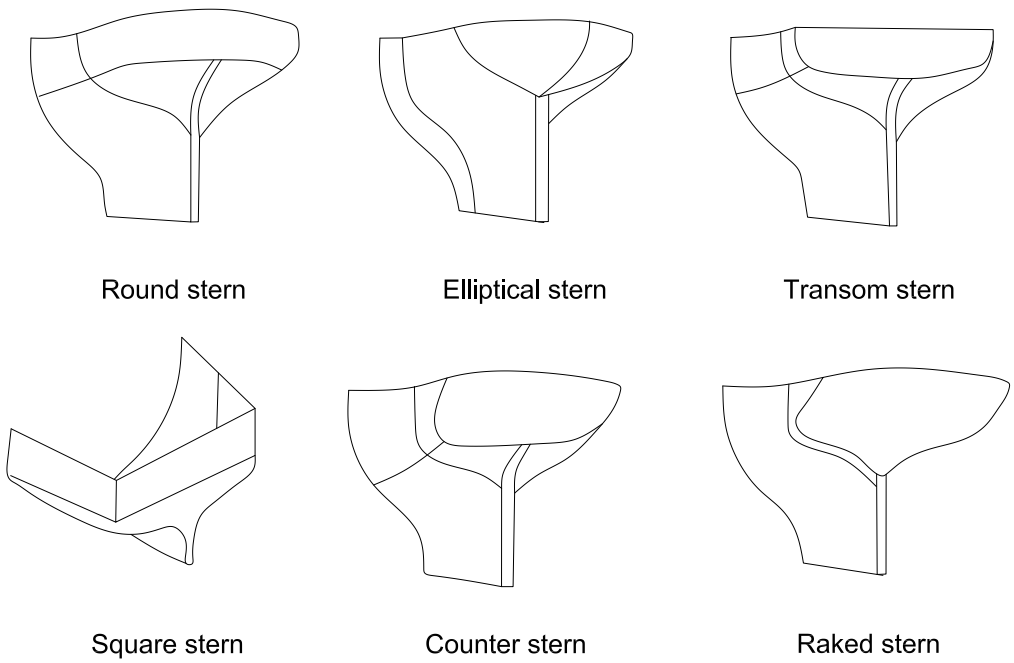


Figure 4-10 Different types of ship stern

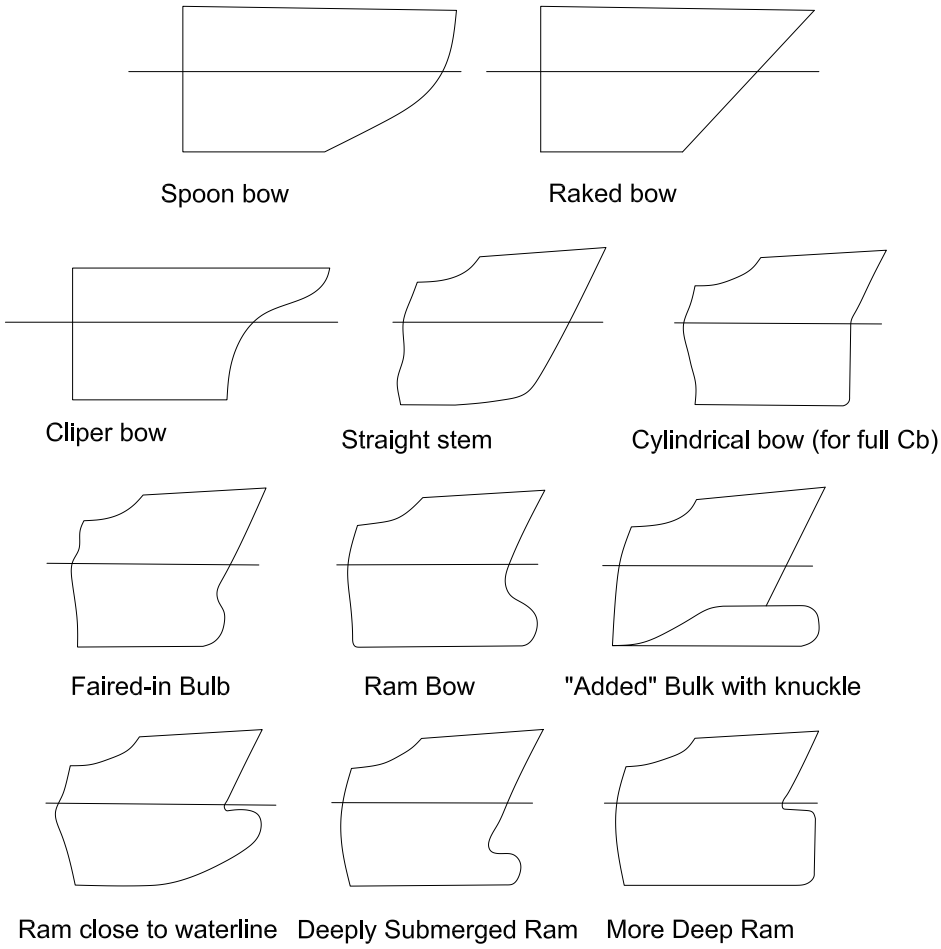
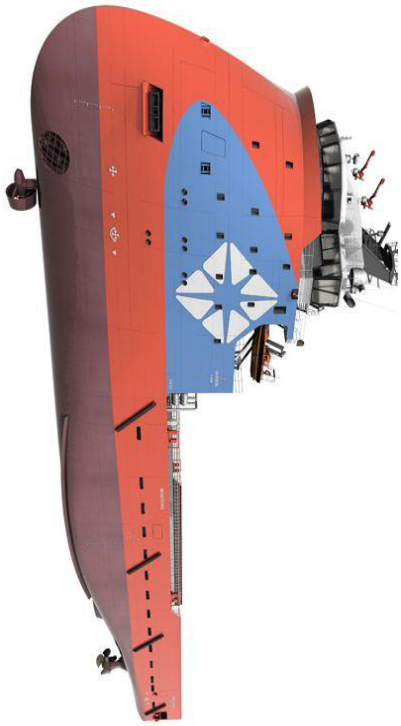


Figure 4-11 Different types of ship bow



(a) CAD model of a hull form with fine stern ©Ulstein

(b) plump bow ©SetzerYacht

(c) Queen Mary II Constanzi stern ©Wikibedia

(d) X bow ©Ulstein

Figure 4-12 CAD models and modern ship bow and stern designs

5. Questions

1. Choose the suitable midship section type for: container ship, sailing yacht, passenger ferry.
2. Draw a sketch for the sectional area curve of a bulk carrier C_P=0.8 and L_{PP}=150m. Calculate L_P, L_R and L_E .
3. Discuss the factors affected by the choice of the length of the parallel middle body, the length of run, and the length of entrance.
4. Discuss and provide examples on the relationship of ship's sections in different regions along its length.
5. What are the main variables when selecting a midship section of your ship?
6. The hull shape is traditionally described with a lines drawing. List and sketch the various items in a lines drawing and explain, what is the influence of the hydrodynamic factors on the optimal volume distribution of the hull.
7. Present a reflection on the process which you have used to define the hull form of your concept. Which factors affecting the hull form have you taken into account or you should have taken into and how? Justify your answers. Include the ship type of your concept in the answer.
8. Discuss the factors affecting the selection of bow and stern shape. How does the bow/stern shape relate to ship type and operational requirements?
9. Define "fairness" of hull lines and describe the process of fairing your hull.
10. Using the following lines drawing, explain (visually or in words) how the points between different views must match. Explain how the intersection points are used in a Table of Offsets and how this relates the 3D modeling.

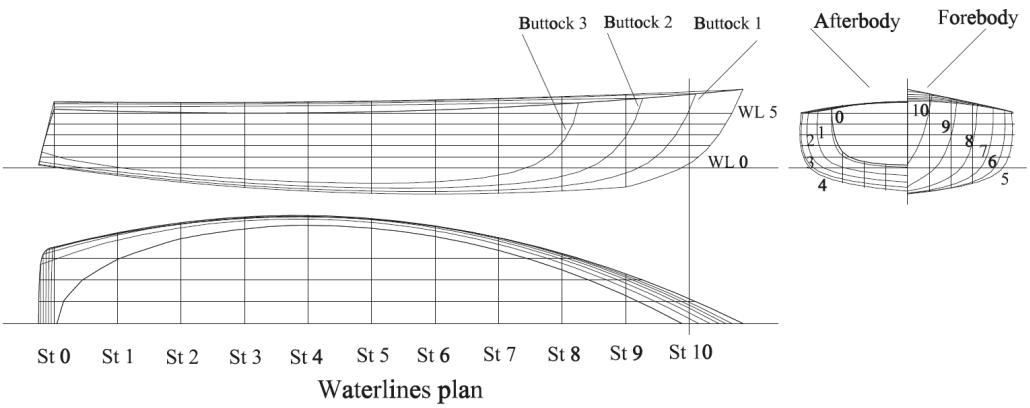


Figure 4-13 lines drawing of a boat ©sciencedirect

Lecture 5
Basic ship hydrostatics and stability

After defining the ship's main dimensions, form coefficients, hull form the next logical step of preliminary design is to calculate hydrostatics and some parameters beneficial for stability assessment. The concept of hydrostatics and stability can be deemed as one of the most important areas of focus in ship design and operation. With this in mind this lecture outlines basic concepts for use in basic ship design.

1. Ship flotation and stability – the basics

Hydrostatics is a branch of mechanics assuming that fluids lie at rest (i.e., fluid velocity effects are neglected) and the pressure in a fluid or the pressure exerted by a fluid on a floating or immersed body is investigated within the context of static equilibrium. This is fundamental in terms of understanding the concept of flotation namely: *''If a solid body is immersed in a liquid, there is an apparent loss in weight. This loss in weight is the up - thrust (known as* ***buoyancy****) exerted by the liquid on the body and is equal to the weight of the volume of liquid which the body displaces''*. So, if a solid body is suspended in fresh water, completely immersed, this up - thrust represents the weight of the fresh water having the same volume as the body. ***This principle is the base of hydrostatics and stability and is known as*** **Archimedes' Principle[6].**

The centroid of the operating waterplane is the point about which the ship will list and trim. This point is called the **center of flotation ($\boldsymbol{F}$)** and it acts as a fulcrum or pivot point for a floating ship. The distance of the center of flotation from the centerline of the ship is called the **transverse center of flotation (TCF)**. When the ship is upright, the center of flotation is located on the centerline so that the $TCF = 0$. The distance of the center of flotation from amidships (or the forward or after perpendicular) is called the **longitudinal center of flotation ($\boldsymbol{LCF}$)**. LCF is referenced from amidships or from one of the perpendiculars. If the reference is amidships, one must also indicate if the distance is toward the forward or aft end of the ship. By convention, a negative sign is used to indicate distances aft of midships. The center of flotation is always located at the centroid of the current waterplane, meaning its vertical location is always on the plane of the water. When the ship lists to port or starboard, trims down by the bow or stern, or changes draft, the shape of the waterplane will change, thus the location of the centroid will move, leading to a change in the location of the center of flotation.

[6] For a vessel to float freely in water the weight of the vessel must be equal to the weight of the volume of water she displaces (see https://www.britannica.com/biography/Archimedes)

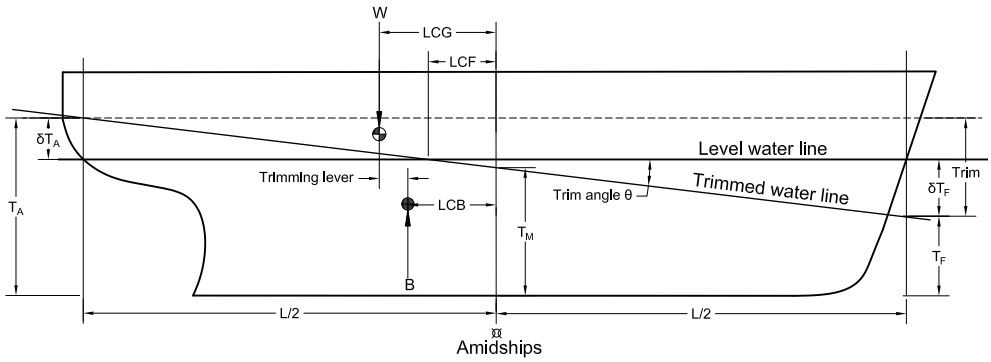


Figure 5-1 Typical ship trim diagram

LCG is the longitudinal center of Gravity of the ship, W is the weight of the ship, B is the buoyancy force, T_F and T_A are the forward and aft draft, and δT_F and δT_A are the changes in forward and aft drafts from the level water line, respectively.

The centroid of the underwater volume of the ship is the location where the resultant buoyant force acts. This point is called the **center of buoyancy (B)** and is extremely important in static stability calculations (see Figure 5-1 and Figure 5-2). The center of buoyancy is always located at the centroid of the submerged volume of the ship. When the ship lists to port or starboard, or trims down by the bow or stern, or changes draft, the shape of the submerged volume will change, thus the location of the centroid will move and alter the center of buoyancy. As opposed to center of flotation, the center of buoyancy is always located below the plane of the water. The distance of the center of buoyancy from the centerline of the ship is called the **transverse center of buoyancy ($\boldsymbol{TCB}$)**. When the ship is upright the center of buoyancy is located on the centerline so that the $TCB = 0$. The vertical location of the center of buoyancy from the keel (or baseplane) is written as $\boldsymbol{KB}$. The distance of the center of buoyancy from amidships (or the forward or aft perpendicular) is called the **longitudinal center of buoyancy ($\boldsymbol{LCB}$)**. Similar to LCF, LCB is referenced from forward or aft perpendiculars and if referenced from amidships, the distance forward or aft of must be annotated (+ve FWD and -ve AFT).

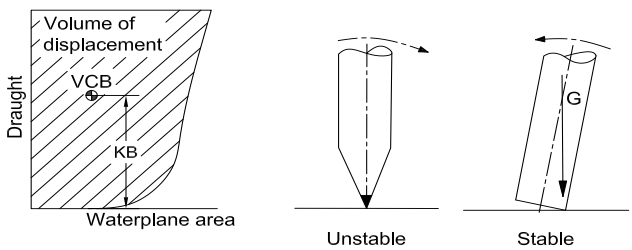


Figure 5-2 Concepts of floatation and stability (left) displacement curve.; (right) The concept of static stability[7] (Stokoe, 2012)

[7] Theoretically, it is possible to balance a pencil on its sharp end if the center of gravity is vertically above this end, but in practice, this is impossible as any disturbance will cause a loss of stability and the pencil will fall. Contrarily, it is possible to balance a pencil on its flat end even if there is a slight disturbance, the center of gravity will still lie within the limits of the flat base and the pencil may return upright again.

A ship displaces her own weight when afloat. This **body weight** (**w**) acts downward through the **center of gravity of the body** (**G**) and is resisted by an **upward buoyant force** (equal to w), which acts through the center of buoyancy (**B**) (see Figure 5-3). B is the geometric center of the submerged volume displaced by the ship. The **metacenter (M)** is the point through which all vertical forces are said to act. According to Archimedes the actual ''all up weight" of a ship and its contents is equal to the weight of water displaced by the hull. This is referred to as **displacement volume**. A vessel's displacement varies over a range of conditions from extreme lightship to a deep, heavy-loaded condition. For example, the displacement alters as cargo or ballast is loaded or discharged or as fuel is consumed.

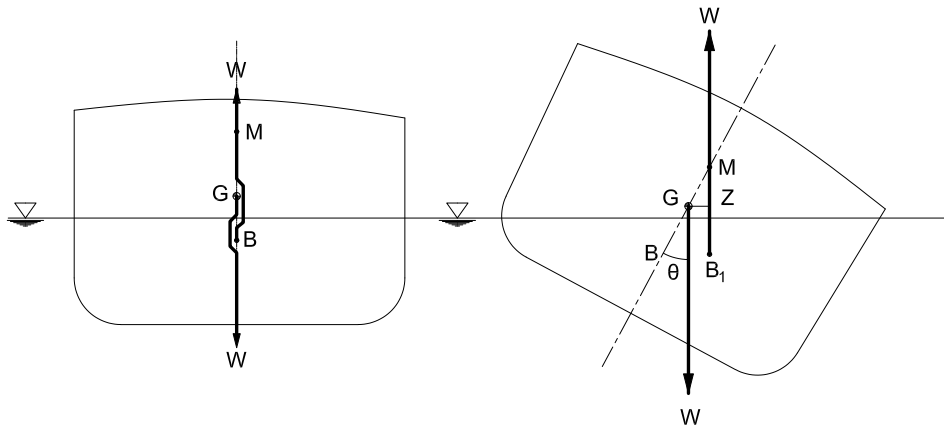


Figure 5-3 Righting lever

If the ship is stable, the centers of buoyancy and gravity strive at all times to remain vertically aligned. When a stable ship is caused to heel by an external force, such as wind, wave, or turning motion (not weight shift), the consequent change in underwater hull shape will result in (B) moving to one side (B_1) while (G) does not move. The horizontal separation of (B_1) and (G) is referred to as the righting lever, GZ (see Figure 5-4), and the resulting righting moment, (w x GZ), will cause the vessel to oscillate from side to side as it attempts to realign (B_1) and (G). The measure of a ship's initial stability, when she is upright or nearly upright, is indicated by the height of the metacenter (M) above (G), which is referred to as the **metacentric height (GM).** The horizontal distance (GZ), more accurately indicates the measure of stability at **angles of heel (*ϑ*)** in excess of 5 degrees from the vertical plane ordinate. **GZ is referred to as the measured of static stability**. Should the ship's center of gravity (G) coincide with (M) and an external force is applied, the ship will assume an ‘‘**angle of loll**’’. In real conditions the ship will maintain the assumed angle until a further force is applied. Should another external force be applied, the ship may assume an angle of loll to the other side or may worsen the existing loll condition if there is no righting lever, GZ, to correct the assumed heel angle. In this condition the ship is said to have zero or no GM (see Figure 5-4).

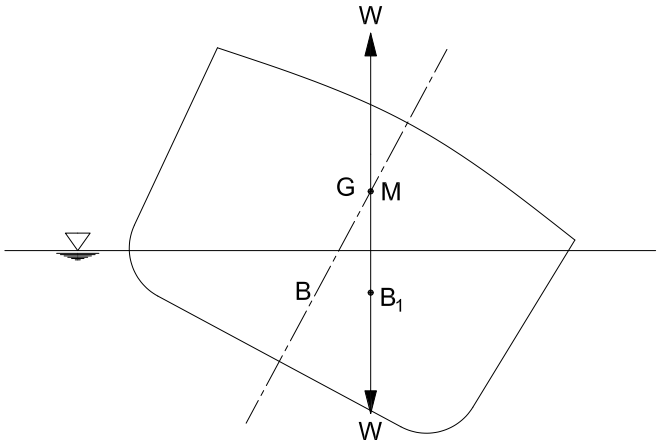


Figure 5-4 Condition of zero GM

As shown in Figure 5-4, when the vessel is upright, the center of buoyancy, (B_1), and the center of gravity of the ship, (G), remain in line and the ship is transversely stable, even with slack; that is, even with the ballast tanks partially full. However, if an external force is applied (because of wind, wave action or the ship turning) and the ship is caused to heel, the center of gravity of the water in the ballast tanks (G_1) and (G_2) will move to positions (G_3) and (G_4); thus, resulting in the center of gravity of the ship moving from (G) to (G_5) (see Figure 5-5).

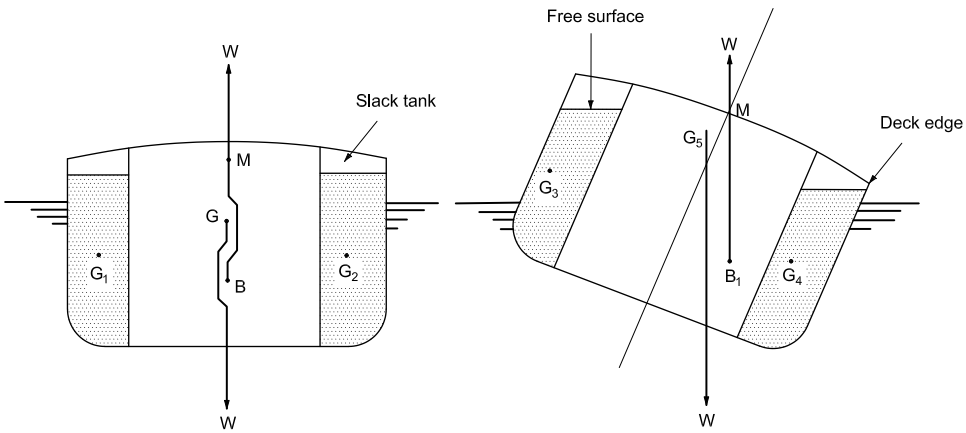


Figure 5-5 Reduced GM with slack tanks (free surface effect)

This movement reduces the original righting lever, GZ, and the resultant height of the ship's GM. The ship therefore becomes less transversely stable. Should the ship, for whatever reason, continue to heel, the position of (G_5) will continue to move due to the movement of the COG of the affected ballast tanks, thereby reducing the vessel's GM and the resulting GZ. If the deck edge becomes immersed, then B will move inboard (B_1), the effect of which

will again reduce GM and the resultant righting moment, GZ. This change will make the vessel become very tender and she will possibly flop from side to side. If more tanks are made slack or there is a cargo shift due to the excessive angle of heel, it is possible for (B_1) and (G_5) to reverse positions. Should this occur, GZ will be converted from a righting lever into a coupled turning force, which could cause the ship to capsize. This condition is known as negative GM (see Figure 5-6).

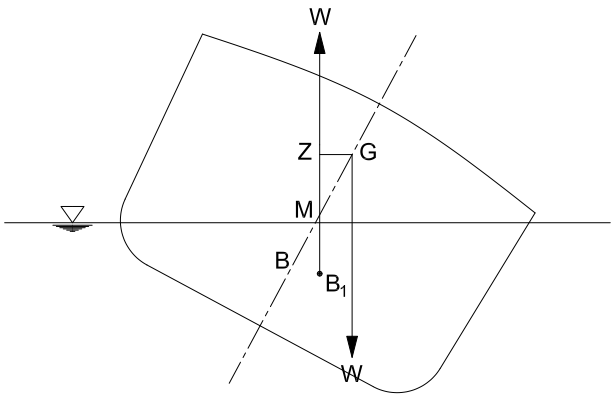


Figure 5-6 Condition of negative GM that may lead to ship capsize

2. Basic hydrostatic calculations

After defining the hull form lines plan ship designers calculate areas, volumes and their centers that are enclosed by the hull lines (see Lecture 4). To get the center of volume of those, we have to calculate the first moment of areas about a chosen reference axis (aft perpendicular - AP, amidships or forward perpendicular - FP). The second moment of area (moment of inertia about a reference axis) is also needed in some of these calculations. Properties could be calculated analytically for uniform shapes. However, it is very difficult to define hull mathematical expressions as the form has three-dimensional curvatures. In practice, numerical integration methods may be used. In these methods non-uniform curves are approximated using a series of uniform curves; a series of straight lines or higher order curves. Areas are usually defined by dividing a space into equal sections using parallel lines of constant interval (h) representing stations, see Figure 5-7. Results are obtained by different numerical integration methods. In the **trapezoidal rule method**, the points of intersection of the parallel lines with the area perimeter are joined by straight lines, A, B and C in Figure 5-7, so that each section could be represented by a trapezoid. The final area is a summation of this set of trapezoids. When hand based or spreadsheet numerical calculations are used Simpson's 1st Rule is the preferred numerical integration technique used to calculate geometric properties. This is because it is less tedious than higher order integration methods (e.g. Simpson's 2nd Rule, Integration over Bonjean curves) and gives good enough accuracy when using a small number of points. Further details are given in the following section.

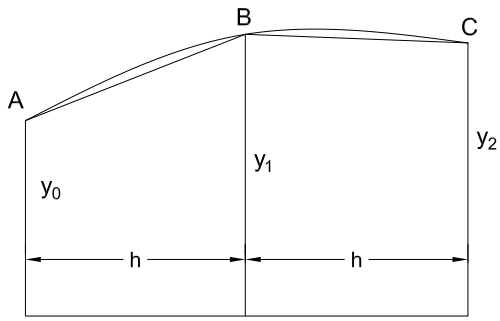


Figure 5-7 Trapezoidal rule.

3. Simpson's 1st Rule

Simpson's rule approximates the ship curves by 3rd order polynomial functions, i.e., $y = a_0 + a_1x + a_2x^2 + a_3x^3$. Vertical divisions are represented by three equally spaced ordinates y_0, y_1 and y_2 (see Figure 5-8). The derivation finally leads to the formula:

$$A = \frac{h}{3}(y_0 + 4y_1 + y_2) \tag{5-1}$$

It may be generalized for any odd number of equally spaced ordinates with distance h as follows:

$$\begin{aligned} A &= \frac{h}{3}(y_0 + 4y_1 + y_2 + y_2 + 4y_3 + y_4 + y_4 + ..) \\ \therefore A &= \frac{h}{3}(y_0 + 4y_1 + 2y_2 + 4y_3 + 2y_4 + 4y_{n-1} + y_n) \end{aligned} \tag{5-2}$$

For classic merchant ship designs, 10 divisions of the ship's hull with 11 ordinates may be considered sufficiently accurate. Calculating areas in a tabular format results to better accuracy. The distance h is termed the common interval and the numbers 1, 4, 2, 4, etc. are termed Simpson's multipliers.

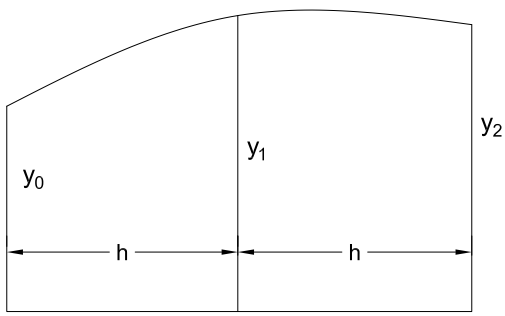


Figure 5-8 Simpson's first rule.

Problem statement 1 – area integration: Let us assume equally spaced half-ordinates of a waterplane section for a symmetric mono - hull vessel that is 27m long. Ship ordinates are positioned at 1.1, 2.7, 4, 5.1, 6.1, 6.9 and 7.7 m respectively. *How can we calculate the waterplane area?*

Solution: The ship is symmetric about her centerline. So, half-ordinates may be used and then the area calculated can be multiplied by 2. The Simpson's integration ordinates, multipliers and area products are given on Table 5-1.

Table 5-1 Simpson's integration table

Station	½ ordinates	Simpson's multiplier	Product for area
0	1.1	1	1.1
1	2.7	4	10.8
2	4	2	8
3	5.1	4	20.4
4	6.1	2	12.2
5	6.9	4	27.6
6	7.7	1	7.7
			$\sum_A = 87.8$

There are seven ordinates with 6 spaces, therefore:

$$h = \frac{27}{6} = 4.5\ m \text{ and } A = \frac{h}{3}\sum_A \times 2 = \frac{4.5}{3} \times 87.8 \times 2 = 263.4\ m^2 \quad (5\text{-}3)$$

As seen in the example, once you have ordinates of any waterplane along the ship's vertical position, you can calculate its area using the same rule. The center of area and the moment of inertia about it are also required to calculate the 1st and 2nd moments of area. As we explained before the centroid of the waterplane area at the waterline is the center of floatation and its longitudinal position is denoted by LCF.

The next step is to calculate the centroid of the waterplane area and the second moment of area about the aft perpendicular and about the centroid. The centroid is near to amidships. So, the reference axis is usually taken at amidships. In this example, for simplicity, let us assume the axis will be in way of the aft perpendicular. The centroid of an area is defined as:

$$C = \frac{\text{First moment of area @ reference axis}}{Area} \quad (5\text{-}4)$$

The first moments of area may be calculated as shown in Table 5.2. The area according to Simpson's rule is given by $A = \frac{h}{3}(\sum_A)$,and the first moment of area is $\frac{h}{3}(\sum MA \times h) =$

$\frac{h^2}{3}\sum MA$ .The center of area is $\frac{\frac{h^2}{3}\sum MA}{\frac{h}{3}\sum_A} = h\frac{\sum MA}{\sum_A}$ and the 2nd moment of area about aft perpendicular is $I_{AP} = \frac{h}{3}\sum i \times h^2 = \frac{h^3}{3}\sum i$. Using parallel axis theorem, the second moment of area about the center of floatation is obtained as follows: $I_F = I_{AP} - Ax^2$ where, x is the distance between the aft perpendicular and the center of floatation. Results are summarized in Table 5-2 and Table 5-3.

Table 5-2 First moment of area

½ ordinates	Simpson's multiplier	Product for area	Lever@ AP	Product for 1st moment	Lever@ AP	Product for 2nd moment
y_0	1	$1y_0$	$0h$	0	$0h$	0
y_1	4	$4y_1$	$1h$	y_1h	$1h$	y_1h^2
y_2	2	$2y_2$	$2h$	$2y_2h$	$2h$	$4y_2h^2$
y_3	4	$4y_3$	$3h$	$3y_3h$	$3h$	$9y_3h^2$
y_4	2	$2y_4$	$4h$	$4y_4h$	$4h$	$16y_4h^2$
y_5	4	$4y_5$	$5h$	$5y_5h$	$5h$	$25y_5h^2$
y_6	1	$1y_6$	$6h$	$6y_6h$	$6h$	$36y_6h^2$
		$\sum_A$		$\sum MA \times h$		$\sum i \times h^2$

Table 5-3 Area centroid and second moment of area calculation

½ ordinates	Simpson's multiplier	Product for area	Lever@ AP	Product for 1st moment	Lever@ AP	Product for 2nd moment
1.1	1	1.1	0	0	0	0
2.7	4	10.8	1	10.8	1	10.8
4	2	8	2	16	2	32
5.1	4	20.4	3	61.2	3	183.6
6.1	2	12.2	4	48.8	4	195.2
6.9	4	27.6	5	138	5	690
7.7	1	7.7	6	46.2	6	277.2
		$\sum_A = 87.8$		$\sum MA = 321$		1388.8

The centroid of area $LCF = 4.5 \times \frac{321}{87.8} = 16.452\ m$ from the AP. The same rule can be applied to midship section or any section along the ship's longitudinal position. The second moment of area of the waterplane is evaluated as:$2 \times (\frac{h^3}{3}\sum i) = 2 \times \frac{(4.5)^3}{3} \times 1388.8 = 84369.6\ m^4$. Thus, the second moment of area about the centroid becomes: $I_F = I_{AP} - Ax^2 = 84369.6 - 263.4(16.452)^2 = 13075.57\ m^4$.

Problem statement 2 – volume intergration: Assume that the immersed cross-sectional areas of a ship that is 180m long, are positioned at equal intervals namely 5, 118, 233, 291, 303, 304, 304, 302, 283, 171, and 0 m^2. Follow similar overall methodology to problem statement 1 to *calculate the displacement and LCB in sea water of 1.025* $tonne/m^3$.

Table 5-4 Displaced volume and LCB calculation table

Station	Cross-sectional areas	SM	Product for volume	Level @AP	Product for 1st moment
AP	5	1	5	0	0
1	118	4	472	1	472
2	233	2	466	2	932
3	291	4	1164	3	3492
4	303	2	606	4	2424
5	304	4	1216	5	6080
6	304	2	608	6	3648
7	302	4	1208	7	8456
8	283	2	566	8	4528
9	171	4	684	9	6156
FP	0	1	0	10	0
			$\sum_V = 6{,}995$		$\sum MV = 36{,}188$

The interval between stations is constant (h) and equals the length between perpendiculars divided by number of intervals:

$$h = \frac{180}{10} = 18\,m \tag{5-5}$$

Volume of displacement, $\nabla = \frac{h}{3}\sum_V = \frac{18}{3} \times 6995 = 41970\,m^3$; this displacement $\Delta = \rho \times \nabla = 1.025 \times 41970 = 43019$ tonnes and the $LCB = h\frac{\sum MV}{\sum_V} = 18 \times \frac{36188}{6995} = 93.12m$ from AP.

4. Simpson's 2nd order Rule

Simpson's 2nd order rule may be used with even number of equally spaced ordinates and the area given as a function of 4 ordinates as follows:

$$A = \frac{3}{8}h(y_0 + 3y_1 + 3y_2 + y_4) \tag{5-6}$$

The above mathematical expression can be extended to cover 7, 10, 13 and so on ordinates, becoming:

$$A = \frac{3}{8}h(y_0 + 3y_1 + 3y_2 + 2y_3 + 3y_4 + \ldots + 3y_{n-1} + y_n) \tag{5-7}$$

The method can be applied in the same fashion to 1st rule as describe in section 5.2.2 and 5.2.4. It is noted that as an alternative Gauss rules may be used when uneven ordinate spacing and multipliers are useful or simply for greater accuracy. The Gauss approach is not often used in manual calculations as it is mathematically complex. In computer programs this is not such a problem and they may be preferred to obtain a greater accuracy.

5. Curves of form

Bonjean curves are used to idealise and estimate underwater volume. They are immersed cross-sectional areas plotted against **T** for each transverse section. They are represented on a ship's profile as shown in Figure 5-9. The immersed areas for such a waterline are obtained by drawing a horizontal line that intersects horizontally (cuts across) all transverse sections. The immersed sectional area value for such e section is the distance from the section position to the intersection point of a Bonjean curve with the waterline. Using Bonjeans displacement and **B** can be calculated for inclined waterlines. This may be useful in trim analysis and ship launching calculations.

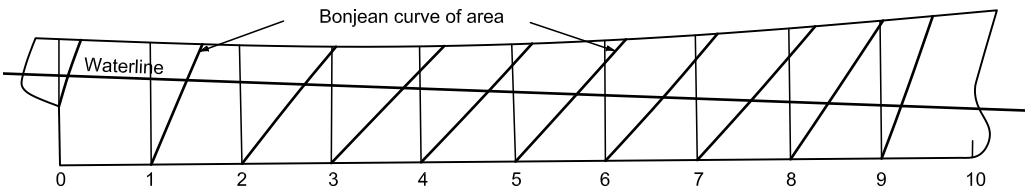


Figure 5-9 Bonjean Curves.

Consider a symmetric ship that heels by a very small angle $\delta\phi$ (Figure 5-10); **B** moved off the ship's centerline to B_1 but w remains unchanged (see Figure 5-10). The distance between the lines of action of weight and buoyancy is the known by the **righting arm (GZ)**. A vertical line that passes through the new position of the center of buoyancy will intersect the centerline of the ship at metacenter **M**. Transverse metacenter (**M_T**) relates to heeling; Longitudinal metacenter (**M_L**) relates to trim. The location of this point will vary with the ship's displacement and trim, but, for any given drafts, it will always be in the same place. Unless there is an abrupt change in the shape of the ship in the vicinity of the waterline, point M will remain practically stationary with respect to the ship. This is because the ship is inclined to small angles (7-10 degrees). The position of M - especially its height - is important indication of ship's stability. In practical ship design it is conventional to obtain the displacement, the position of the center of buoyancy B, the metacenter M and the center of floatation F for a set of waterlines parallel to the design waterline and plot them against the draught on the y-axis. This set of curves is called hydrostatic set curve (Figure 5-11). Each curve has her own scale along horizontal axis.

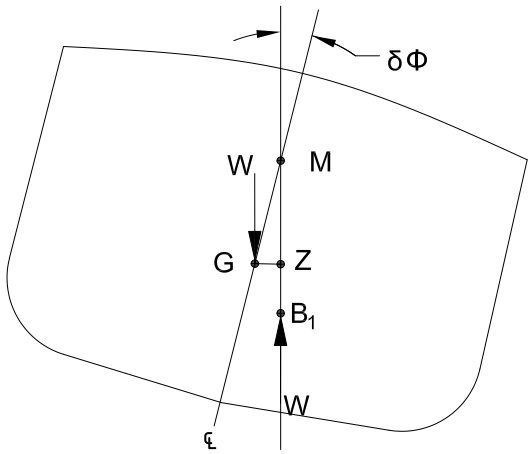


Figure 5-10 Representation of the transverse Metacenter location for small angle of inclination.

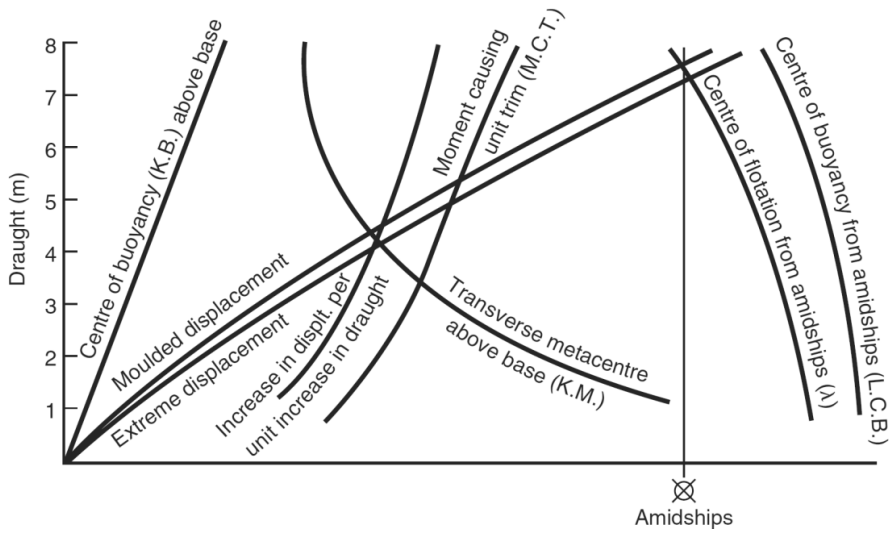


Figure 5-11 Hydrostatic curves (Tupper, 2013)

6. IMO Intact stability requirements

The International Maritime Organisation (IMO) introduced regulations under the Safety of Life at Sea (SOLAS) Convention for ensuring adequate intact stability for merchant ships during operation. The main requirements of properties of the GZ curve are as follows.

- The initial metacentric height G M0 should not be less than 0.15 m.
- The righting lever GZ should be at least 0.20 m at an angle of heel equal to or greater than 30°.
- The maximum righting lever should occur at an angle of heel preferably exceeding 30° but not less than 25°.

- The area under the righting lever curve (GZ curve) should not be less than 0.055 *m·rad* up to ϕ = 30° angle of heel.
- The area under the righting lever curve should not be less than 0.09 m·rad up to φ = 40° or the angle of flooding θi if this angle is less than 40°.
- The area under the righting lever curve between the angles of heel of 30° and 40° or between 30° and φ, if this angle is less than 40°, should not be less than 0.03 m·rad.

The regulations also specify methods of estimation of loss of stability due to free surface in the tanks of the ship, amplitude and period of roll due to wind heeling moment and heel due to ship taking a turn. The regulations also specify satisfaction of stability criteria in all possible loading conditions – fully loaded, partially loaded, ballast and lightship conditions – both in departure and arrival states of the ship. The intact stability requirements of passenger vessels specify that heel due to overcrowding of passengers to one side should not exceed 10°. Similarly, severe wind conditions and turning at speed should ensure roll or heel within specified limits. Grain-carrying ships should ensure limitation of heel due to grain shifting moment. IMO also specifies additional regulations for different ship types other than conventional merchant ships (e.g. container ships. timber cargo vessels, fishing vessels etc.). This is because the classic IMO SOLAS intact stability conditions can be satisfied only up to a certain value of KG (VCG) and if the KG value crosses this limit, this condition would be violated.

7. The inclining experiment

As the position of the center of gravity is so important for initial stability it is necessary to establish it accurately. It is determined initially by calculation by considering all weights making up the ship (e.g. steel, outfit, fittings, machinery and systems) and by assessing their individual centers of gravity. From these data can be calculated the displacement and center of gravity of the light ship.

It is difficult to account for all items accurately in such calculations and it is for this reason that the lightship weight and center of gravity are measured experimentally. The experiment is called the inclining experiment and involves causing the ship to heel to small angles by moving known weights known distances transversely across the deck and observing the angles of inclination (see Figure 5-12). The draughts at which the ship floats are noted together with the water density. Ideally the experiment is conducted before ship launch. To obtain accurate results a number of precautions are taken. First the number of people onboard should be minimum and the experiment should be conducted in calm water with little wind and the ship must be floating freely when records are taken so any mooring lines must be slack and the brow must be lifted clear. All weights must be secure and tanks must be empty or pressed full to avoid free surface effects. If the ship does not return to her original position when the inclining weights are restored this is an indication that a weight has moved in the ship, or that fluid has moved from one tank to another, possibly through a leaking valve.

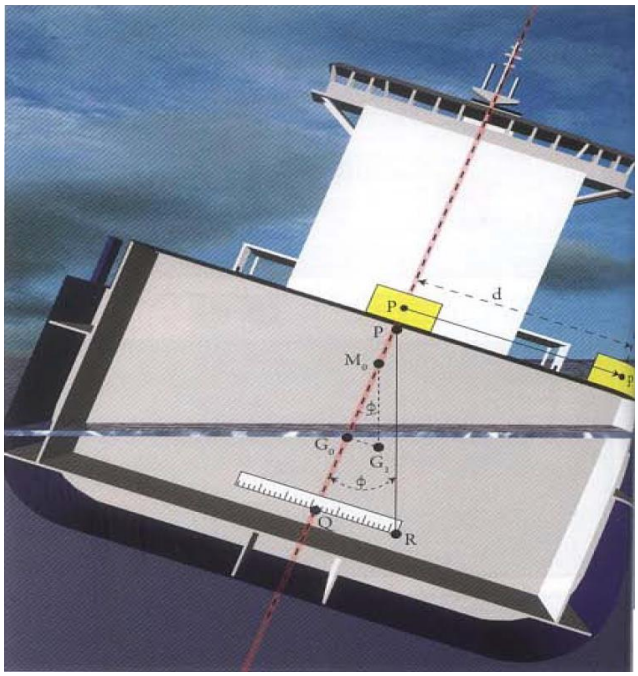
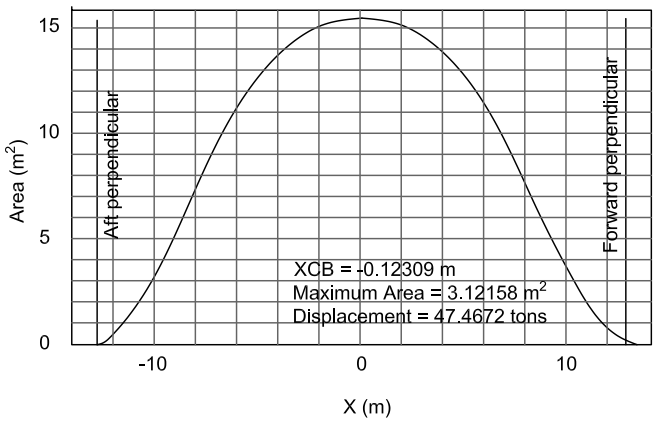


Figure 5-12 Set up of the inclining experiment (Dokkum K. V., 2008)
P is the weight used in the inclining experiment, d is the distance moved, G_0 and G_1 are the center of gravity before and after moving the weight and φ is the inclining angle that can be obtained by measuring the distance a pendulum moves on a tape line (QR).

8. Questions

1. A ship 180 m long has half-widths of waterplane of 1, 7.5, 12, 13.5, 14, 14, 14, 13.5, 12, 7 and 0 m respectively. Calculate: (a) Waterplane area (b) Waterplane area coefficient.
2. The waterplane areas of a ship at 1.5m intervals of draught, commencing at the keel are 865, 1735, 1965, 2040, 2100, 2145, 2215 m^2. Calculate the displacement at 9 m draught.
3. The ½ breadths of the load waterplane of a ship 150 m long, commencing from aft, are 0.3, 3.8, 6, 7.7, 8.3, 9, 8.4, 7.8, 6.9, 4.7 and 0 respectively. Calculate: (a) area of waterplane (b) distance of the centroid from amidships (c) second moment of area about a transverse axis through the centroid.
4. A ship 140 m long and 18 m beam floats at a draught of 9 m. The immersed cross-sectional areas at equal intervals are 5, 60, 116, 145, 152, 153, 153, 151, 142, 85 and 0 m^2 respectively. Calculate: (a) displacement (b) block coefficient (c) midship section area coefficient (d) prismatic coefficient.
5. The immersed cross-sectional areas of a ship 120 m long, commencing from aft, are 2, 40, 79, 100, 103, 104, 104, 103, 97, 58, 0 m^2. Calculate: (a) displacement (b) LCB.

6. Consider a ship of SAC defined below. Calculate her displacement using Simpson 1st rule. What is the longitudinal center of buoyancy (LCB)? Could you tell based on this information if the ship is fast or slow?



7. The half breadths, in meters, of the load water-plane of a ship 240 meters in length, numbered from aft, are as follows:

Stations	0	0.5	1	2	3	4	5	6	7	7.5	8
Half breadths	0	9.2	12.2	15.8	16.0	16.0	15.9	13.9	9.8	6.0	0

Find the position of the center of flotation from amidships, and the value of the TPC in salt water.

8. Find the area and the position of the center of flotation of the following water-plane, 120 m long.
9. The waterplane of a ship is 55 m long and has the following values for the half-ordinates in meters, measured at equal intervals: 0.76, 2.59, 3.81, 4.25, 4.08, 2.93, 0. Find the area of the waterplane using Simpson's first rule.
10. The mean water line length of a ship is 110 m and has the following half ordinates measured at equal intervals: 0, 5.53, 6.36, 6.85, 7.00, 6.80, 5.44, 2.84, and 0 m. If a mass of 160 tonnes is placed on board at the center of flotation by how much will the ship sink forward ?

Lecture 6
Ship General Arrangement (GA)

1. Introduction

A marine vehicle or structure has limited enclosed and exposed space that has to house all equipment required for the functioning of the product at sea and also provide space for accommodating various items including crew and passengers on board. Since the product is at sea, the space distribution becomes an important part of the design and is formally known as general arrangement (GA), and the drawings depicting this arrangement are called GA plans or GA drawings. Layout design includes defining spaces for various requirements, establishing boundaries for such spaces and partitioning such spaces, locating equipment and facilities in each space and providing access to areas within each space and egress during emergencies. The objectives of the GA are to efficiently meet the ship's mission and functional requirements, to provide structural continuity, and to implement SOLAS safety requirements.

The design of a ship's general arrangement is a continuous and iterative process that starts with concept design and is changing through different design phases. This is because GA is affected by the positioning of engineering systems and structural design arrangements. The GA of any ship usually consists of the following drawings:

- Profile View (generally looking from starboard side)
- Midship sections (looking from aft, and looking from forward)
- Main deck plan (also shows the accommodation layout)
- Navigation deck plan.
- Forecastle deck plan
- Tank and tank top plan

Since almost all ships have unique design features there is no specific procedure backed up by Classification Rules and/or Regulations. In fact, the process of developing the GA drawings varies amongst design firms, depending on their procedures and practices. However, the underlying principle always remains the same: ''*GA development is an iterative process, and the final GA is produced, after repeated approvals by the classification society and the owners party.*'' It is not within the purpose of this course to make a conclusive GA for ship design. However, some of the key steps for successful GA development could be summarized as follows:

1. Decide ship type and define the ship's principal particulars followed by a basic ship profile view drawing.
2. Sketch a basic mid ship section and estimate the double bottom height as specified in the rules of the authorized Class Society Rules.

3. Specify the minimum bow height in accordance to IMO ILLC regulations. The ship's forecastle deck area should account for spacing for anchoring and mooring equipment.
4. Decide on frame type (longitudinal or transverse) and spacing according to Classification Society Rules. The frame spacing should be marked on the GA profile drawing and should be followed as the main scale of this drawing[8].
5. Position and size enclosed spaces such as holds, tanks and machinery spaces. As part of this process, the ship should be divided into a certain number of watertight compartments as recommended by the authorized Classification Society subdivision Rules. These Rules can help specify the total number of watertight transverse bulkheads that are necessary to maintain watertight integrity of the ship. The sizes of the spaces here should be in accordance with the specified cargo capacity requirements. For passenger ships, sizes of internal spaces should be in accordance with passenger capacity. Once the number of bulkheads have been decided, the length and number of holds should be planned accordingly. In addition, the required number and length of fire zones should be determined. In ships with large superstructures, such as passenger ships, the fire zones will determine the division of space in the superstructure. Fire zone requirements are found in SOLAS.
6. Accommodation and working areas should be designed to ensure smooth flow of working duties onboard and during emergency or evacuation—pay attention to corridors and stairways in this concern. Aesthetics for the case of cruise ships may be critical. In case of bulk carriers, the slope of the tank top sloping bulkhead is to be taken care of. The tank slope must be more than the angle of repose of the cargo, which is generally around 30 degrees. The slope of the bottom tank is generally maintained at 45 degrees.
7. Include ballast, fresh water, void and other consumables tanks (e.g. fuel tanks) in a way that they well distributed all over the length and breadth of the ship to help her attain stability and trim requirements while empty or loaded. Design of tanks should be done in accordance with the watertight compartment design—lower compartments will be used as tanks.
8. Include cargo handling equipment for efficient cargo loading and unloading.
9. Check for structural continuity in overall hull locations but also in tanks and machinery arrangements. Design choices should enable ease of construction.

[8] In general, ocean going ships that are longer than 120 m are longitudinally strengthened. In practice frame spacing ranges between 500mm to 900mm, while web frame spacing could be on every 3rd or 5th frame depending on a ship's length. Frame spacing is usually constant along the ship's parallel body, but it might vary in the extremities of the hull (bow or stern regions).

2. Additional considerations

Location of machinery spaces. Historically, the engine room of most general cargo ships and passenger ships has been situated at or near amidships. This has been a convenient choice from an engineering perspective as the space required for engines used on such ships can be provided most conveniently in way of amidships. On the other hand, tankers and coasters tend to have their machinery aft. Nowadays, cargo ships have either their machinery aft with all cargo holds forward or may have one small hold abaft the engine room. The former is ideal for slow speed vessels while the latter is better for relatively higher speed vessels with finer form such as container ships and refrigerated cargo ships.

Location of Deckhouse. For cargo ships, the number of decks and location of the deckhouse are critical. This decision should be based on the provision of adequate visibility from the wheelhouse over the forecastle and or over the maximum obstruction caused by containers or other deck cargo the ship is intended to carry. Traditionally the deckhouse is situated aft to ensure sufficient monitoring of the deck area and the ship's course. However, some ships that require a large open deck area such as offshore supply vessels have their deckhouse forward.

Location of Cabins, corridors, and lifeboats on passenger ships. There are mainly two philosophies when deciding the positioning of passenger cabin locations. The first one considers cabins in a specific block where it is easy to meet the criteria for vibration and noise. However, passengers in the same area might cause congestion in passages and corridors. Another philosophy is the smooth distribution of cabins along the superstructure. In this way congestion is no longer an issue. However, it may be difficult to meet noise and vibration criteria in all cabins. Corridor paths mainly depend on the fineness of the ship. Full ships have straight corridors, very similar size cabins located in a straight fashion similarly to a land-based hotel. An exception to this is the bow area. Fine form ships feature some curvature in their corridors and are likely to have cabins with different shapes and sizes. Traditionally, lifeboats and their associated davits are positioned in the upper deck to avoid disturbance in passenger and crew flow. Recently, the trend has been to place lifeboats on the lower deck near to waterline in a large cutout of the superstructure. From a safety perspective, it is easier to launch lifeboats from a lower deck. Also, having lifeboats on a lower deck gives the designer additional flexibility and space for laying out ship facilities such as a swimming pool and various outdoor areas on the sundeck. (Cudahy, 2001).

Galley location. Although the location of the galley is not of great importance in cargo ships, it has a significant influence on the customer experience on passenger ships. This is because on a passenger ship, the position of a galley is attached directly with positions of food entertainment areas and consequently their access is controlled by stairs and lifts. The decision on the position of other public spaces such as shops, offices and public rooms using the same means is also critical. Thus, in order to ensure smooth supply of dry and refrigerated stores, their position should be near to the galley as much as that possible. A designer should keep these matters in mind when deciding on the position of the galley. Main galley should

be situated ideally next to the main restaurant, with lifts connecting to provisions and prep areas as closely as possible.

Bulkheads are partition walls which subdivide the ship interior into watertight compartments. They prevent or at least reduce the extent of seawater flooding in case of damage. They also contribute to ship strength. Types of bulkheads vary upon their usages and locations. For example, aft peak bulkhead is a bulkhead which forms the forward boundary of the aft peak tank; collision bulkhead is the foremost main transverse watertight bulkhead. It extends from the bottom of the hold to the freeboard deck or to the forecastle deck and is designed to keep water away from the forward hold in case of bow collision damage; aft peak bulkhead is the aft most main transverse watertight bulkhead. Similar to the collision bulkhead, it extends from the bottom to the freeboard deck or the poop deck. The engine room bulkhead is a transverse bulkhead directly after or aft the engine room. More specialist types of bulkhead are: (a) portable bulkheads used to divide a long hold into separated sections; (b) corrugated bulkheads formed of corrugated plating used to eliminate the need for welded stiffeners;(c) fire bulkhead used to provide insulation for partitions in accommodation spaces. The Class Society Rules include formulae that can help you specify the minimum/maximum distances of the forepeak bulkhead aft of the forward perpendicular. It is up to the designer, to provide the forepeak collision bulkheads within the above limits, depending on the dimensions of the forepeak ballast tank, anchor equipment, and chain locker dimensions. The position of the engine room's forward bulkhead is fixed according the position and length of the holds. Once this is done, about four frame spaces need to be left out before placing the main engine aft of the engine room forward bulkhead. This helps leave space for maintenance and crew operations. The length of the engine room is decided based on the length of the main engine and the length of the intermediate shaft which is usually coupled with the propeller shaft via a flanged connection. The coupling flange between the intermediate and the propeller shafts should be housed within the engine room. The engine room aft bulkhead is positioned aft the coupling flange. In cases of oil tankers and container ships, decisions on longitudinal bulkheads are to be taken, with respect to prevention of free surface effect, ensure proper cargo distribution and handling characteristics.

Height is discussed in terms of deck height and free height. Deck height is measured from the plating of one deck to the plating of the next deck, while free height excludes the overhead height used for piping and HVAC. Required free height for RORO ships is 4.3 meters for decks that carry lorries, and 4.6 to 6 meters for roll trailers. In passenger vessels and crew areas in cargo vessels, the cabins minimum free height is 2.1 m which corresponding to 2.6 m deck height. While in public spaces like restaurant the deck height should be 2.8 to 3.2 m which depends on the width of the space including spaces going through many decks. Deck curvature especially of the main deck has to be considered in the estimation of the deck height.

Staircases are important to all ships as there are requirements for evacuation in case of emergency. In passenger ships, the staircases are placed so that passengers can access all

passenger areas, and there are additional private staircases for the crew to carry hotel and restaurant goods through the ship. In the hull, the watertight sections require more frequent staircases as connection between watertight compartments is very limited (watertight doors remain shut at sea). The design of staircases relates to the corridor design so that people and provisions have good connections designed in a logical manner.

Bottom and side structures. In the past, ships were constructed with single bottoms. Fuel, oil, and water tanks were separately constructed. Nowadays, only small vessels have a single bottom construction, and all sea-going and ocean-going ships have a double bottom construction which provides safety against grounding as well as spaces for liquid tanks. In 1992 the IMO MARPOL instrument was amended to make it mandatory for tankers of 5,000 dwt and more to be fitted with double hulls; double-side and double bottom.

Cargo handling equipment is a matter of concern associated with the type of cargo being transported. For example, pumping equipment is needed for tankers to transfer liquid cargo in and out of tanks while cranes are provided onboard bulk carriers or container ships to transport cargo in and out of holds. All these items should be accounted for included on the GA.

Container sizes in container ships are measured in twenty-foot equivalent units (TEU). Containers are classified by length (20-foot standard) but have varying heights. The below table shows standard container sizes used to size holds in a container ship GA. As the TEU is a unit in and of itself, the 40-foot unit is defined as 2 TEUs.

Table 6-1 TEU measurements

Length, ft [m]	**Width**, ft [m]	**Height**, ft [m]	**TEU**
20 [6.1]	8 [2.44]	8.5 [2.59]	1
40 [12.2]	8 [2.44]	8.5 [2.59]	2
20 [6.1]	8 [2.44]	9.5 [2.90]	1
20 [6.1]	8 [2.44]	4.25 [1.30]	1

3. Preliminary freeboard estimation

Preliminary freeboard estimation should also be done at this point. The freeboard will determine the height of the main deck and affects the vertical spacing based on the requirement. Freeboard is defined as the height amidships from the summer load waterline to the main deck. Adequate freeboard is needed for safety. Larger freeboard leads to larger reserve buoyancy, which leads to better damage stability. Intact stability is increased as well, as the ship can heel at a larger angle before submerging the deck edge. Minimum values for freeboard are granted by classification societies based on international standards, which are then marked on the ship on the **Plimsoll Mark** (See Figure 2-4). The following freeboard estimation comes from the International Convention on Load Lines (ILLC, 1966).

Freeboard calculations divide ships into 2 types: Type A and Type B. **Type A** ships are tankers. **Type B** ships are any other ship type—if fitted with watertight hatch covers of steel (or equivalent), they may have freeboard reductions. The freeboard calculation includes a basic calculation based on length and ship type, and a series of corrections to this value. First, the basic estimation is found using the table below:

Table 6-2 Minimum Freeboard Estimation Based on Ship Type

Length of Ship (m)	Type A (mm)	Type B (mm)
24	200	200
50	443	443
76	786	816
100	1135	1271
150	1968	2315
200	2612	3264
250	3012	4018
300	3262	4630
350	3406	5160
365	3433	5303

Interpolating for the given ship length and type provides a first value of freeboard. The typical steps followed in the calculation can be as follows [9]:

- *For Type B ships between 24 meters and 100 meters in length having enclosed superstructure with effective length (E) of up to 35% of L.* the freeboard is to be increased by:

$$7.5(100 - L)\left(0.35 - \frac{E}{L}\right) \quad mm \tag{6-1}$$

where L is the **freeboard length**, which is the greater of 96% of total length on waterline situated at 85% of the least molded depth, or the length from fore side of the stem to the axis of the rudder stock on that waterline; *E* is the effective length of the superstructure that can be estimated accurately by following (ILLC, 1966) rules.

- *For ships with a freeboard block coefficient greater than 0.68* the freeboard (modified by Type B corrections as given above, if applicable) should be multiplied by $\frac{C_B+0.68}{1.36}$. In this case the C_B is defined as :

$$C_B = \frac{molded\ volume\ at\ d_1}{LBd_1} \tag{6-2}$$

where d_1 is the moulded draft at 0.85 of the least moulded depth.

[9] For more freeboard corrections see: https://www.iacs.org.uk/media/3753/ui_ll_pdf900.pdf

- An extra correction for length to depth ratio applies if D exceeds L/15. In this case the freeboard should be increased by $R(D - L/15)$, where R measured in mm is defined as:

$R = \frac{L}{0.48}$ *for L<120m*

$R = 250\ mm$ *for L≥120m*

If D is less than $L/15$—a reduction of freeboard is only allowed if there is enclosed superstructure covering at least 0.6L amidships, or a combination of superstructures and trunks (tight structures that do not extend to the sides of vessel). In this case, the reduction is at the same rate as for an excess of D.

4. GA Examples

The 50,200 GT Crystal Symphony **passenger ship** GA is shown in Figure 6-1. The ship operates in the premium segment of RCCL with different itineraries depending on the season of the year. The length of cruise product she offers are between 7 and 19 days. The ship has 480 passenger cabins and 960 lower beds (double occupancy). The maximum passenger capacity including sofa beds is 985 persons. The number of crew is 545 persons. The ship has 9 decks for passenger use. The passenger functions start on Deck 1, where the side doors to the quay are situated. The rest of Deck 1 and the deck below are allocated to the crew and service functions. The diesel-electric machinery, pump rooms and tanks are located on the double bottom. Many public spaces are on Deck 3 with a dining room and an entrance hall below on Deck 2. The show lounge is forward and the secondary lounge is amidships above the dining room. Aft Deck 3 there are several smaller public spaces, such as a special dining room with Japanese cuisine. On Deck 4 an outdoor promenade all around the ship is provided. This is also the embarkation deck for the lifeboats. Most of the passenger cabins are in the narrow super-structure. Between the cabins are the air-conditioning rooms. All cabins are outside cabins. The balcony cabin ratio is 58%.

Examples of GA for **cargo ships** are given in Figure 6-2 and Figure 6-3. For example, Figure 6-2 shows the GA of a Panamax type **container ship**. Such ship is very large in size. Having cargo-handling equipment onboard such ship may be inefficient. The containers themselves are simply reusable boxes made of steel or aluminum. The cargo-carrying section of the ship is divided into several holds with the containers racked in special frameworks and stacked one upon the other within the hold space. Containers may also be stacked on hatch covers and secured by special lashings. Cargo holds are separated by a deep web-framed structure to provide the ship with transverse strength. The structure outboard of the container holds is a box-like arrangement of wing tanks providing longitudinal and torsional strength. The wing tanks may be used for water ballast and can be used to counter the heeling of the ship when discharging containers. A double bottom is fitted which adds to the longitudinal strength and

provides additional ballast space. The accommodation location ensures compliance with IMO visibility criteria. Machinery spaces are located aft leaving the maximum length of full-bodied ship for container stowage. Automatic birthing equipment is located both aft and forth the ship.

The GA of a **bulk carrier** requires a compromise among many conflicting requirements. For dry cargo bulk carriers, volume of cargo space and machinery are basic requirements. In addition, the required volume of fuel, oil, ballast, and freshwater tanks should be considered. Their configuration should satisfy acceptable draft and trim requirements for maximum and minimum cruise range at preliminary design. Cargo space of a dry bulk carrier consists of regular length holds having hatches for handling of cargoes by grab or by blower for grain cargoes. Figure 6-3 shows an example of a 25,000 DWT bulk carrier. This is common dry bulk carrier that has a clear main deck with the machinery room and superstructure. Hatches with unrestricted access to holds are designed on the main deck with steel hatch covers to facilitate easy loading and discharge of cargo. Three deck mounted cranes that have 360 degree access and can load and discharge cargo from the holds immediately forward and aft are available. The fore peak tank in the bulbous bow is used to control and maintain the trim of the vessel and to ensure complete propeller immersion. Ducted keels provide enough space for the passage of pipelines. The ship is longitudinally stiffened, that is the stiffeners on the plates run in a longitudinal direction. This is because the loads may cause longitudinal bending moments. Hence the failure of the hull girder due to longitudinal bending becomes more probable.

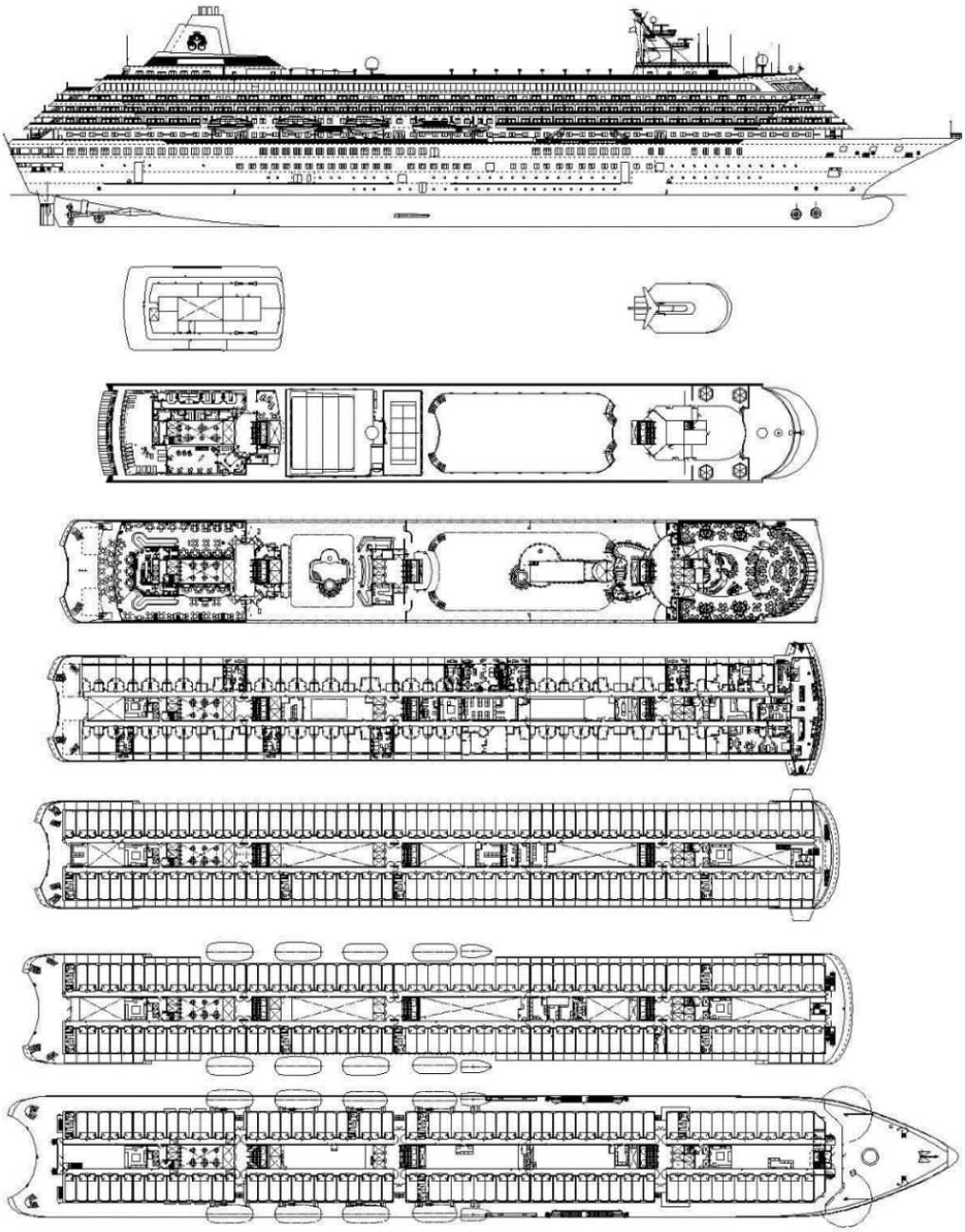


Figure 6-1 Crystal Symphony General Arrangement. Image Credits: (Thomas, 2003)

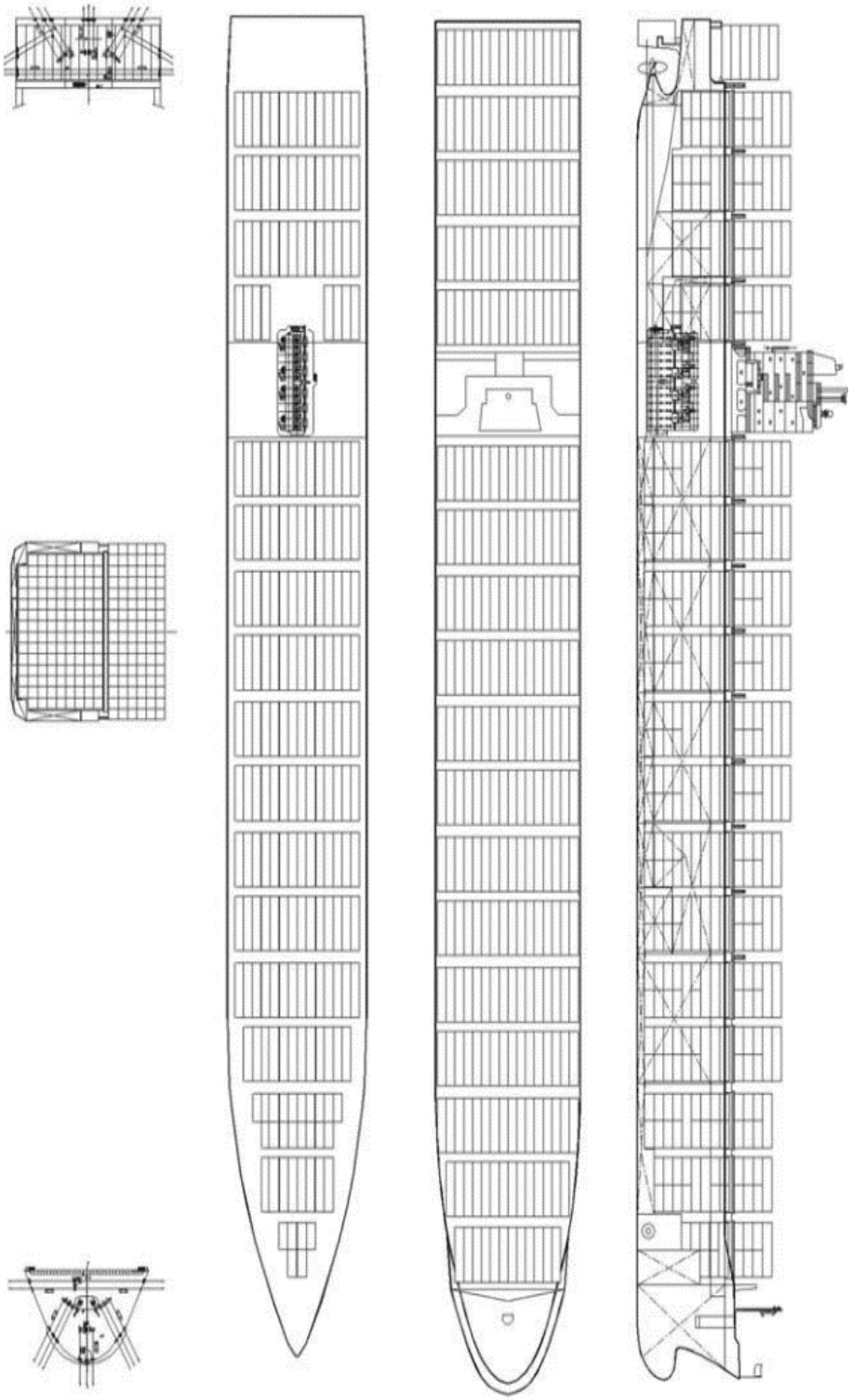


Figure 6-2 Post-panamax container ship. Image Credits: (Thomas, 2003)

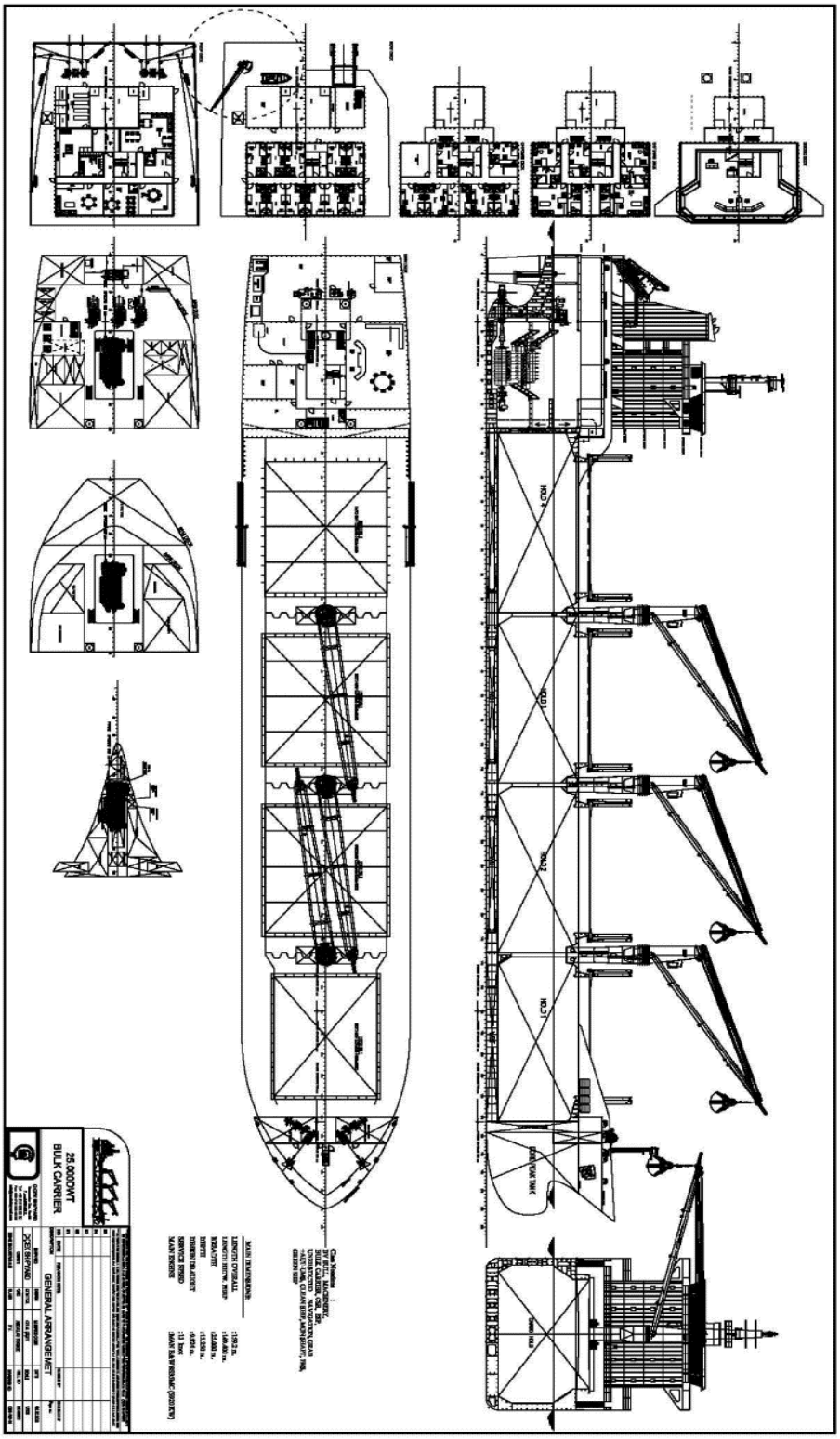
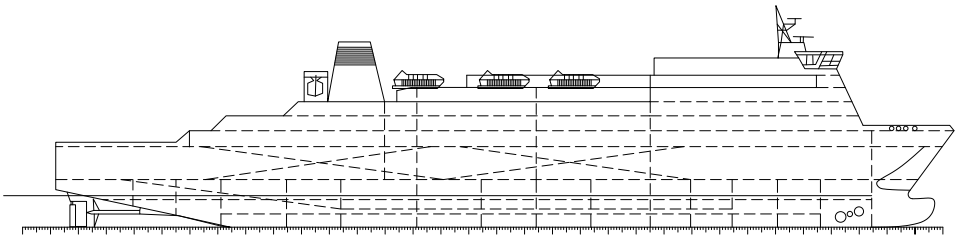


Figure 6-3 Bulk Carrier General Arrangement. Image Credits (Cicek Shipyard)

5. Questions

1. Describe the most important factors affecting the general arrangement of a passenger ship (or your project ship).
2. Describe the various possibilities to locate the cargo space on RoPax vessels and what the benefits and drawbacks for each possibility.
3. Describe the various possibilities to locate the cargo space on container vessels with respect to superstructure and what are the benefits and drawbacks for each possibility.
4. Describe the main issues affecting the positioning of the machinery space in ship general arrangement.
5. Identify and justify 3 strengths and 3 weaknesses in the general arrangement of the ship below. In case you need to implement LNG as the fuel and/or battery technology for auxiliary propulsion, in which place would you position the fuels tanks and batteries? Discuss the factors affecting these choices.



6. You are designing a medium-sized container vessel. Describe the various possibilities to locate the deckhouse. Mention at least four criteria or measures of performance based on which you can compare the merits of the various options.
7. Define at least four general design objectives and criteria for the general arrangement of a ship.
8. Describe the factors that affect the design of the profile view of the general arrangement. What do you consider when designing the profile, and how does it factor into the deck plan of the GA?
9. How do you decide upon a preliminary tank arrangement and/or cargo hold design considering the stability of the ship in preliminary design?
10. How do safety requirements play into the GA design of a passenger ship?

Lecture 7
Ship Structures

Anyone who has been at sea in rough weather will be only too aware that a ship is heavily loaded and strained. Ship design starts with determination of the ship's operational profile, the main dimensions, and the hull form characteristics but until this stage, the ship is just some data stored. However, structural design and analysis is the phase at which the ship changes to actual structural parts to be fabricated in the shipyard. This section is an introduction to structural design for preliminary design.

1. The ship structural design framework

Although structural design is a complex process, the structural designer can benefit from experience of other designers and classification societies. Commonly in the past, design comprises two steps; design of structural arrangement and derivation of scantlings. The ship structural design framework accounts for:

- Loads, defined as the forces acting on the ship structure whether as a beam girder or acting on one of its components. Structural loads result in stresses and deformation in the structure.
- Responses, defined as the load induced deformations and stresses due to an external load.
- Strength defined as the measure of the capacity of the structure to withstand the load without failure or plastic deformation.

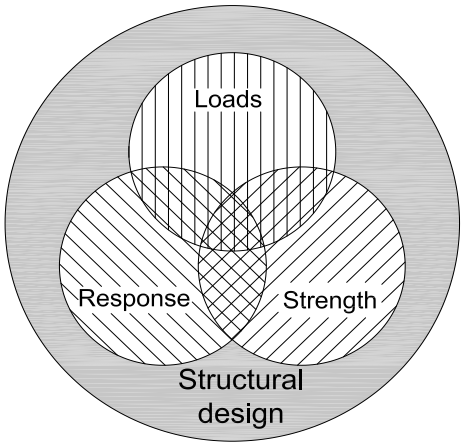


Figure 7-1 Structural design framework

2. Hierarchy levels and initial considerations

Ship structures comprise of units that are dealt upon individually and holistically. The smallest units of a ship's structure are panels bounded by stiffeners. These panels are subject to

normal and in-plane loads that give rise to bending loads, buckling and shear deformations. These small units together form larger flat or curved surface of plating with sets of stiffeners, termed as grillages. Grillages are supported at their edges by bulkheads and deck edges that are relatively stiff. They are also exposed to normal and in-plane loads and experience bending, buckling and shear loads. Finally, bulkheads, grillages and decks together form a hollow box girder which can be dealt with as a beam. Consequently, analysis of ship structures is classified as **(a) primary; (b) secondary and (c) tertiary**.

Structural design starts defining the frame spacing, defining the major structural boundaries (e.g. double bottom height, twin deck height, longitudinal bulkhead location) and by designing the mid ship section (See Figure 7-2 and Figure 7-3). The required inputs are the beam, depth, draft, deadrise and bilge radius. Based on experience, some design choices may change based on the ship type and its operational characteristics (mission and owner requirements). Two systems of framing exist namely **(a) the transverse framing system,** Figure 7-2**, and (b) the longitudinal framing system,** Figure 7-3. The transverse framing system comprises of secondary members that are positioned in the transverse direction of the ship while in the longitudinal system of framing stiffeners are aligned in the longitudinal direction. In addition to the structures themselves, openings should also be added to structures (decks, tanks, solid floors, etc.). The purpose of openings is to provide access for maintenance, piping, and wiring. Openings also reduce overall structural weight, which decreases cost.

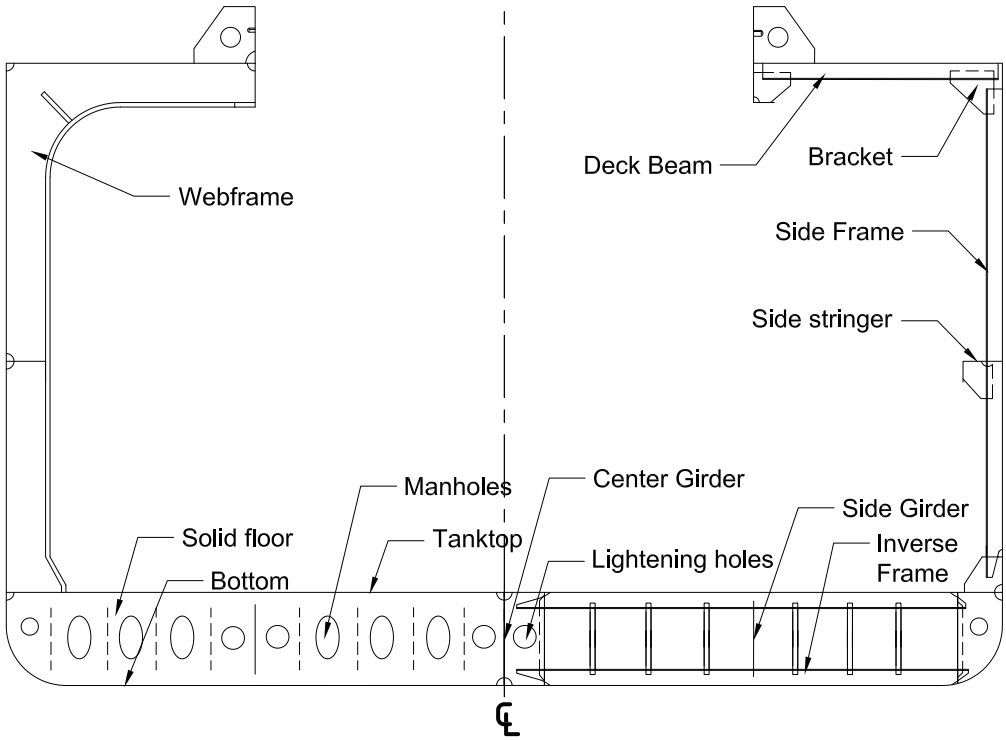


Figure 7-2 Midship section at hatch opening of a transversely stiffened ship (left heavy section, right light section)

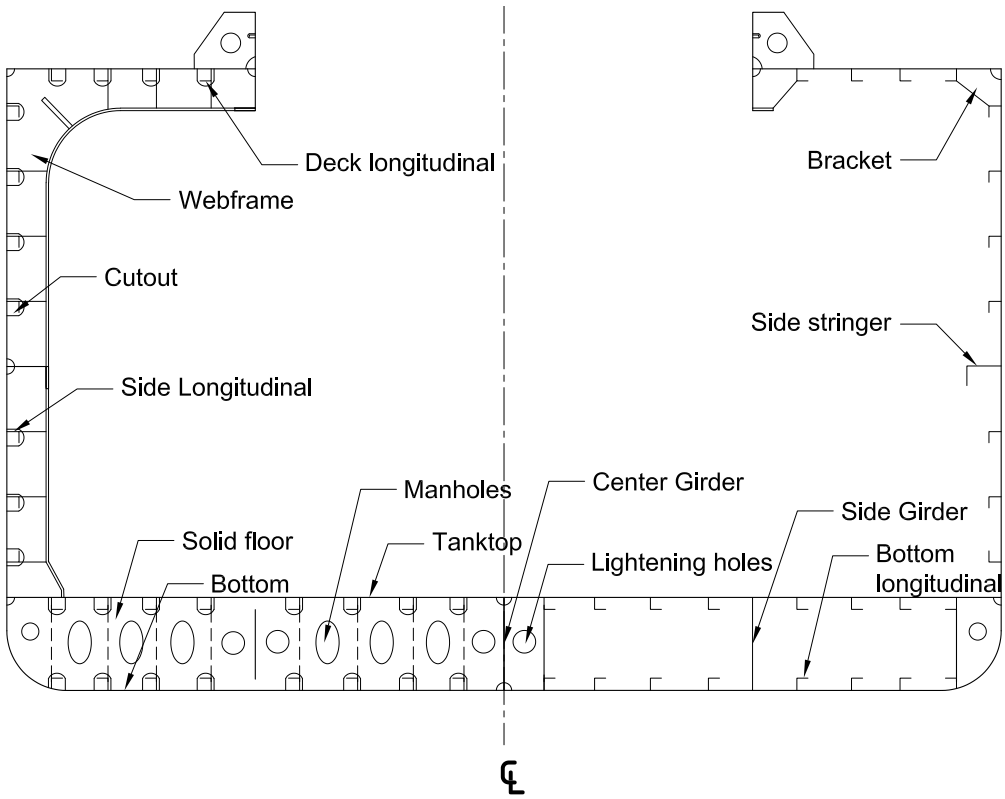


Figure 7-3 Midship section at hatch opening of a longitudinally stiffened ship (left heavy section, right light section)

Understanding the **load-carrying mechanism** is crucial before starting any structural analysis. It indicates how the external and internal loads are transferred to the internal structure details. The external load may refer to waves and still water loads while the internal loads refer to liquids in tanks and cargo, vibration from machinery and other dynamic loads.

The load-carrying mechanism starts first from the elements in direct contact with the loads, which, in most cases, are the plates. These plates are in direct contact with the external pressure from water and possibly internal pressure of liquids in tanks. The plates are supported by longitudinals, hence the load will be transferred to these items as line loads. These light stiffeners or longitudinals are supported by the side web frames at specific intervals, hence the line loads will cause point loads on the web frames at the connection points. The web frames are already supported by the side structures and hence the load carrying mechanism continues. Figure 7-4 shows how the external pressure is carried by the longitudinal frames, how the longitudinal cause point loads on the web frames, and how the web frames are supported by the side structures.

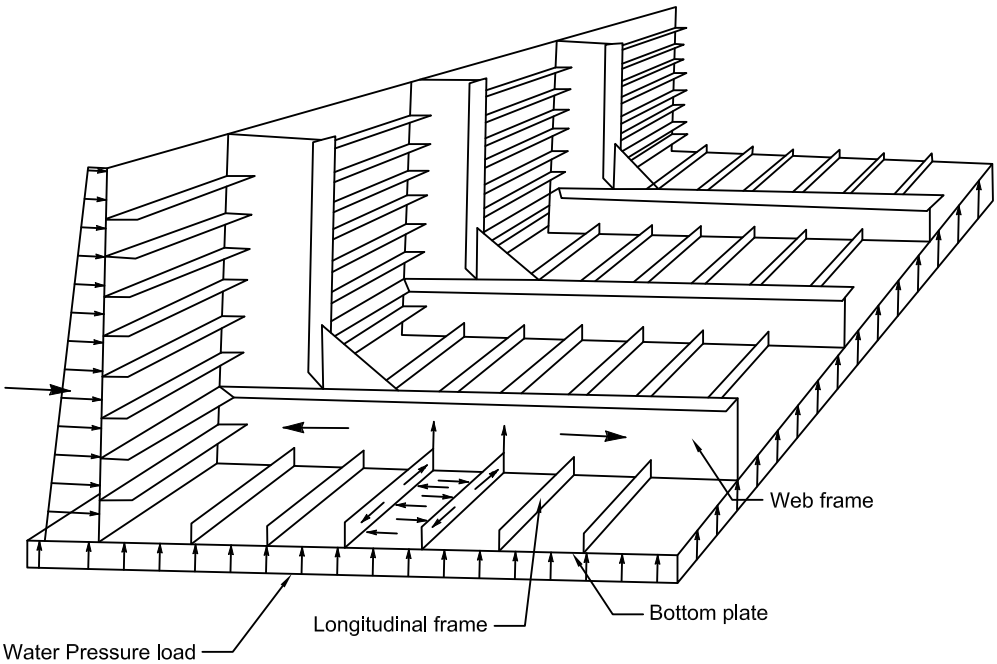


Figure 7-4 Load carrying mechanism

3. Ship loads

An overview to the background of ship loads is given by (Hirdaris, et al., 2014). They can be taxonomized on the basis of frequency and time duration, locality (e.g., global vs local) and limit states (e.g. intact vs damaged). **Static loads** are defined as the loads acting on a ship in either still water and they mostly vary during loading/unloading operations. They act over time that is much longer than the range of sea wave periods. Hence, time is ignored and they are considered as a function of a ship's loading conditions. **Quasi-static loads** have a period corresponding to wave actions (between 3-15 seconds). They are directly induced by waves and resonate with ship motions. **Dynamic Loads** result in responses with frequency components close or equal to resonance modes. When evaluating these responses, the dynamic properties of the ship have to be considered. Dynamic loads may be generated by resonance phenomena associated with wave induced hull vibratory distortions (e.g. springing), or by mechanical excitation of rotating equipment such as the main engine and the propeller. Impulsive loads result in free structural vibrations such as slamming and sloshing in tanks are also important. **High frequency loads** have higher frequency than resonance modes (higher than 10-20 Hz) and they are involved in the study of noise more than structural design. Loads acting on the ship as a girder or a box beam are known as **global loads or primary level loads** and the associated response is termed **primary response**.

Pressure on the hull due wave actions can be either described by **global or local loads**. Examples of local loads are:

- **panting -** an in/out motion of the plating in the bow area due to unequal pressure through waves. It is significant for fine bow ships. Fore peak tanks are used to resist this load;
- **bow slamming**, see Figure 7-5, resulting from sudden bow lift and sudden drops in waves at the forefoot with high acceleration. The phenomenon is linked to heave and pitch ship motions;
- **Whipping**, usually defined as a transient ship structural response due to impulsive loading, usually slamming, or green water.

Examples of global loads are **hydrostatic pressures** caused by water static pressures that are proportional the ship's hull, **racking** caused ship rolling and accelerations on the ship structure, **still water and wave bending moments** caused by the uneven distribution of buoyancy and weight, **shear forces** at each section of the ship and **springing**. **Accidental loads** are low probability events related to collision, grounding or explosions (e.g., see Figure 7-6 and Figure 7-7). They influence the ultimate strength. In recent years several studies have been conducted for investigating the mechanics of collision and grounding in order to find new ways to reduce their consequences (Kim, et al., 2021). Since accidental loads relate with shipping operations traditionally, they are not part of Classification Rules or procedures. Guidelines for the prediction of accidental limit states are still under development. In ship design ship loads are expressed in the form of **bending moments, shear forces and associated stresses**.

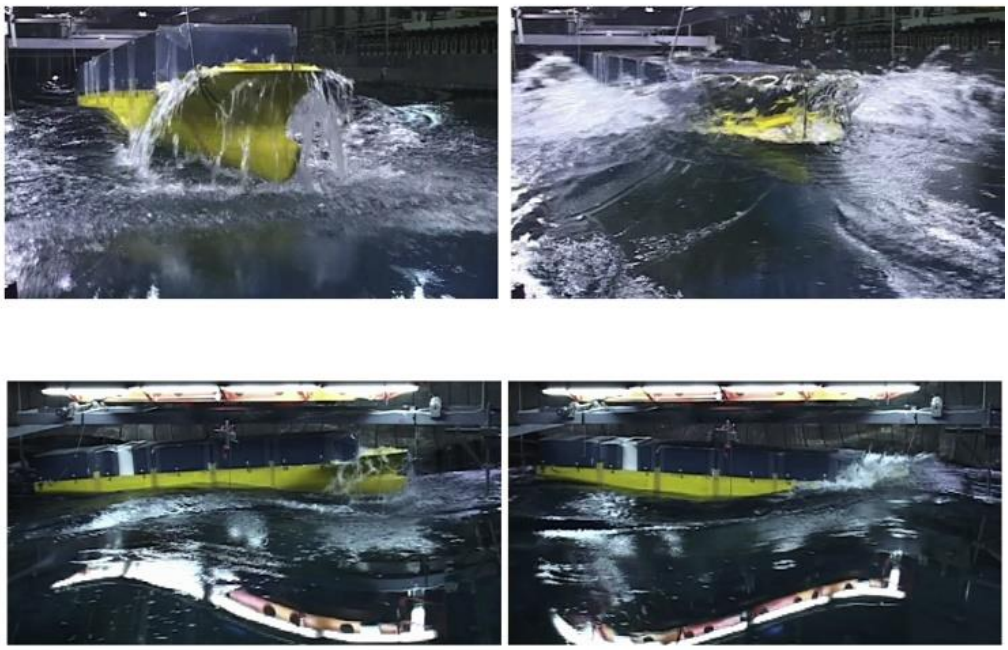


Figure 7-5 experimental investigations on ship bow slamming (Kim, Kim, & Hong, 2019)

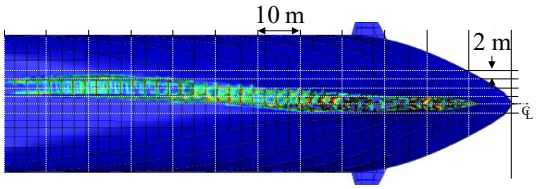


Figure 7-6 Finite Element Analysis simulation of passenger ship subject to hard grounding (Kim, et al., 2021)

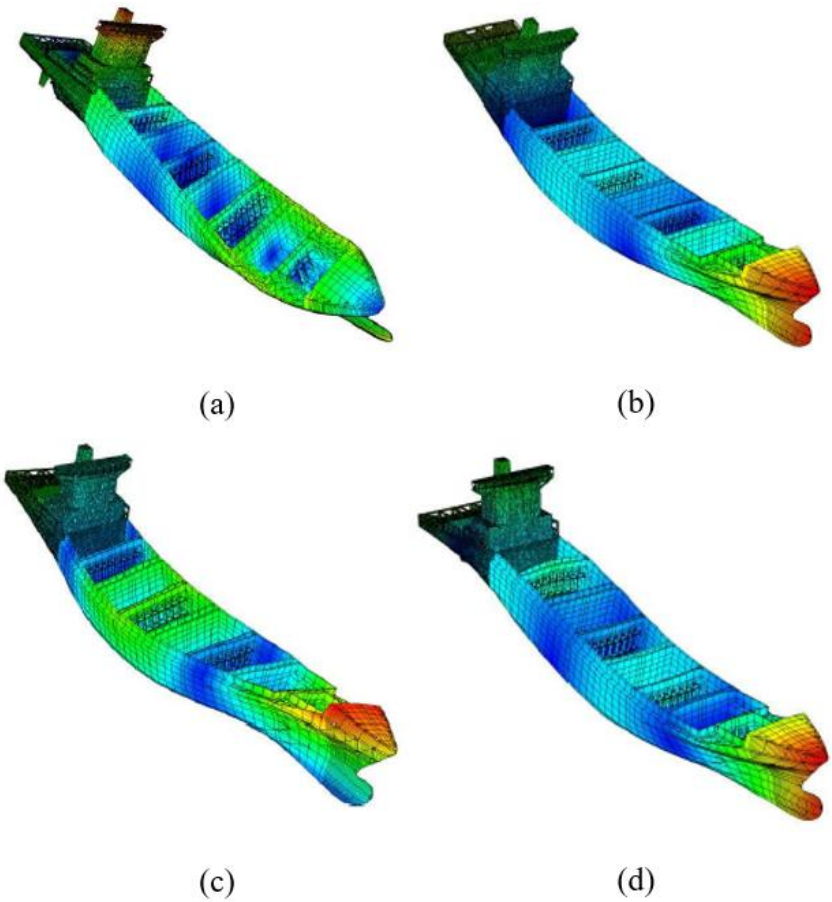


Figure 7-7 Springing modes of a container ship: (a) 1st torsion mode, (b) 1st vertical bending mode, (c) 1st horizontal bending & torsion mode (d) 2nd vertical bending mode

4. Still water loads

In still water conditions, the buoyancy forces acting on a ship must equal in total the sum of the weight of the ship. However, over any given unit length of the hull the forces will not balance out. If the mass per unit length at some point is *m* and the immersed cross-sectional area is *a*, then at that point we can define:

- Buoyancy per unit length = ρga; where ρ is the density of the water where the ship operates, and g is the gravitational acceleration.
- Weight per unit length $= mg$ leading to net force per unit $length = \rho ga - mg$. If this net loading is integrated along the length there will be, for any point, a force tending to shear the structure defined as:

$$\textit{Shear force}, S = \int(\rho ga - mg)dx \tag{7-1}$$

The integration being from one end to the point concerned. Integrating a second time gives:

$$\textit{Longitudinal bending moment}, M = \int Sdx = \iint(\rho ga - mg)dxdx \tag{7-2}$$

For any given loading of the ship the draughts at which it floats can be calculated. Knowing the weight distribution, and finding the buoyancy distribution from the Bonjean curves, gives the net load per unit length. The static forces of weight and buoyancy also act upon a transverse section of the ship as shown in Figure 7-8. The result is a transverse distortion of the structure which the structure must be strong enough to resist these forces. In addition, these forces can produce a local deformation of structure. The hydrostatic loads tend to dish plating between the supporting frames and longitudinals. The deck grillages must support the loads of equipment and cargo. Thus, there are three contributions made by items of structure, namely to the longitudinal, transverse and local strength. Longitudinal strength in a seaway is considered first.

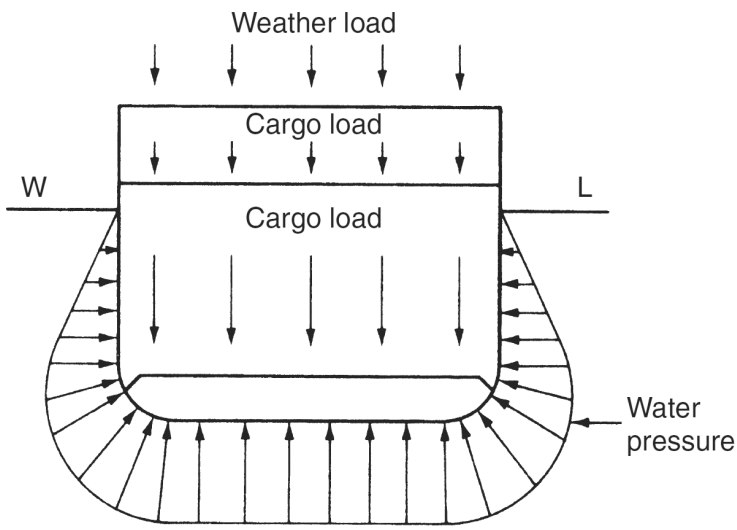


Figure 7-8 Static loads on a transverse ship section (Tupper, 2013)

5. Quasi Static wave loads

In wave conditions the mass distribution is the same as in still water for the same loading condition. The differences in the forces acting are the buoyancy forces and the inertia forces on the masses arising from **ship motions ship motion induced accelerations**. Ship motions are derived by what is known as **seakeeping analysis**. The term relates to **ship seaworthiness** and covers all those features of a vessel that may influence her ability to remain at sea in all conditions and carry out her intended mission. This is involving stability, strength, maneuverability and ship motions. Within the context of wave induced loads seakeeping needs to be considered early in design as most hull form parameters are decided then. In seakeeping the ship is faced as a 6 degree of freedom rigid body system (translation and rotation degrees of freedom for each axis). Ship motions are defined as **surge, sway and heave** for translations along the fore and aft, transverse and vertical axes respectively; **roll, pitch and yaw** for rotations about the three axes (see Figure 7-9). For example, ship rolling can be reduced by fitting stabilizers. However, such decisions should be based on the use of good seakeeping design.

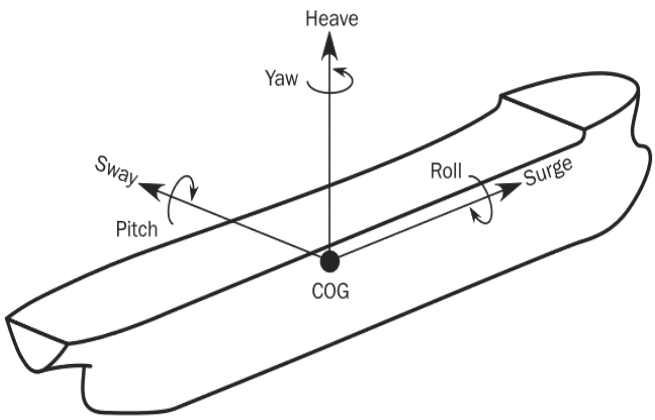


Figure 7-9 Ship motions

Among ship motions**, roll, pitch and heave** are oscillatory motions and they are the most significant form concept/preliminary design perspective. Other motions can be either dealt with separately in maneuvering and resistance analyses or can be coupled with the formerly mentioned motions in seakeeping analysis.

Definition of roll motion. If ϕ is the inclination to the vertical at any instant, see Figure 7-10, and the ship is stable, there will be a moment acting on it tending to return it to the upright. For small disturbances the value of this moment ($\Delta \cdot GZ$) will be proportional to ϕ and given by:

$$Displacement \times GM_T \times \phi = \Delta \cdot GZ \qquad (7\text{-}3)$$

Where GM_T is the transverse metacentric height.

This is the condition for simple harmonic motion with a period T_ϕ defined by:

$$T_\phi = 2\pi(\frac{k_x^2}{gGM_T})^{0.5} = \frac{2\pi k_x}{(gGM_T)^{0.5}} \tag{7-4}$$

where k_x is the radius of gyration about a fore and aft axis. This period is independent of ϕ and such rolling is said to be isochronous. The relationship holds for most ships up to angles of about 10 degrees from the vertical axis.

The greater the GM_T (see Lecture 5, Section 1) the shorter the **period of rolling**. A ship with a short period of roll is said to be stiff and one with a long period termed tender. Most people find a longer period motion more comfortable.

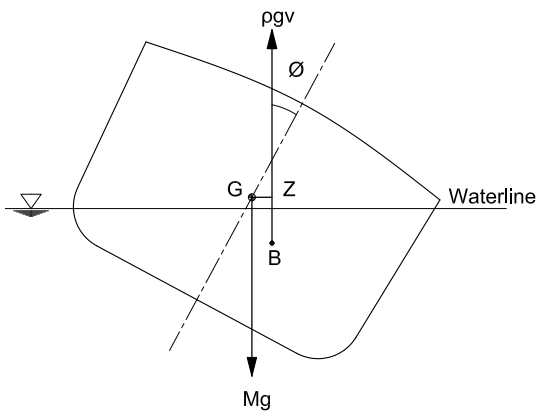


Figure 7-10 Rolling motion (v is the volume of displacement)

Definition of pitch motion. The ship pitching motion is analogous to rolling but around the transverse axis. This is controlled by a similar equation to that for roll; in this case the pitching period T_θ is defined by:

$$T_\theta = \frac{2\pi k_y}{(gGM_L)^{0.5}} \tag{7-5}$$

where k_y is the pitching radius of gyration and GM_L is the longitudinal metacentric height. As the longitudinal metacentric height GM_L is much larger than the transverse metacentric height GM_T, the period of pitching is much smaller than that of rolling.

Definition of heave motion. If z is the downward displacement at any instant, see Figure 7-11, there will be a net upward force on the ship tending to reduce the magnitude of z. This force is a function of waterplane area A_w and can be obtained by $\rho g A_w z$. Hence, the heaving motion period can be defined by:

$$T_z = 2\pi(\frac{\nabla}{gA_W})^{0.5} \tag{7-6}$$

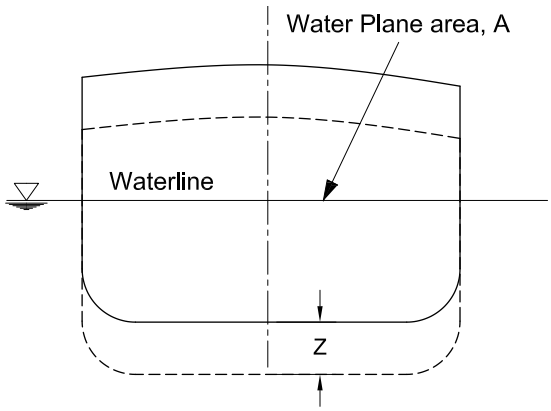


Figure 7-11 Heaving motion

Added mass is defined as the effective increase in mass of a hull, due to the entrained water, when in motion. **Added mass and damping** may influence ship motions and their periods. Added mass values vary with the frequency of motion. Typically, the effect for rolling is to increase the radius of gyration by about 5%. In heaving its influence is greater and may amount to as much as an apparent doubling of the mass of the ship. Damping leads to reduction of ship motion amplitudes over time.

Ship motions that influence design loads are mainly pitch and heave. If we consider quasi – static analysis, i.e. we ignore inertia forces and assume that the ship balances on a trochoidal wave the buoyancy forces will vary in comparison to still water by virtue of the different draughts at each point along the length due to the wave profile and the pressure changes with depth due to the orbital motion of the wave particles. Clearly this is a situation that can never occur in practice but the results can be used to indicate the maximum bending moments the ship may experience in waves. Accordingly, the choice of wave height is important and two conditions may be considered namely **hogging** (where the wave crest is amidships) and the **sagging** (where wave crests are at the ends of the ship); see Figure 7-12.

The bending moments obtained include the still water moments. However, it is useful to separate the two as, whilst the still water bending moment depends upon the mass distribution besides the buoyancy distribution, the bending moment due to the waves themselves depends only on the geometry of the ship and wave.

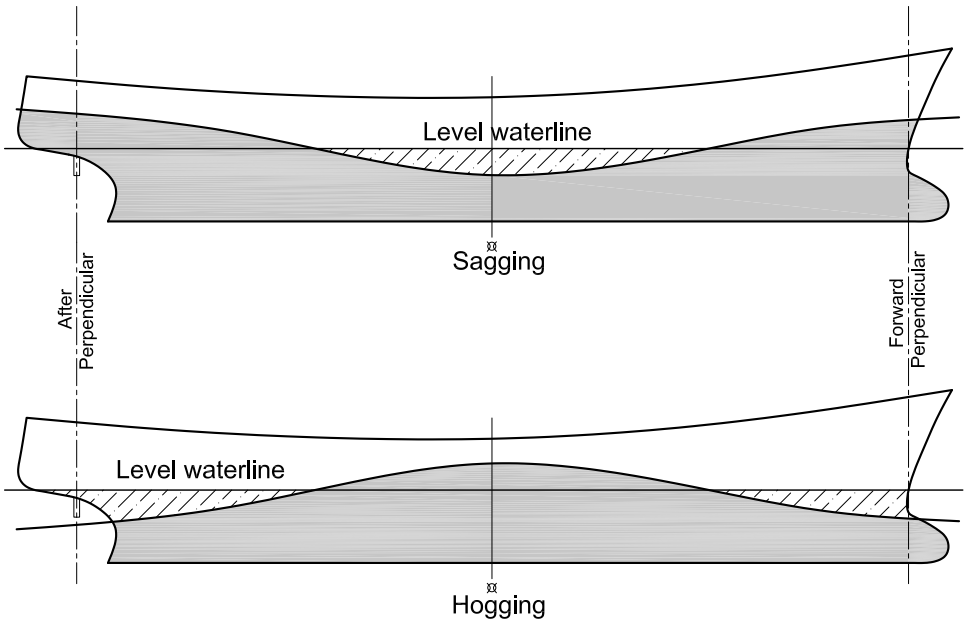


Figure 7-12 A ship on waves (hogging and sagging)

Typical curves of wave induced forces are shown in Figure 7-13. Both shearing force and bending moment must be zero at the ends of the ship. The shearing force rises to a maximum value at points about a quarter of the length from the ends and is zero near amidships. The bending moment curve rises to a maximum at the point where the shearing force is zero, and has points of inflexion where the shearing force has a maximum value. The influence of the still water bending moment on the total moment is shown in Figure 7-14. For a ship with a given total mass and still water draughts, the wave sagging and hogging moments are effectively constant for a given wave. If the still water moment is changed by varying the mass distribution the total moment alters by the same amount. Whether the greater bending moment occurs in sagging or hogging depends on the type of ship depending, inter alia, upon its block coefficient (C_B). It is noted that for ships with low C_B the sagging bending moment is likely to be greater than the hogging. This trend inverts as C_B coefficient increases.

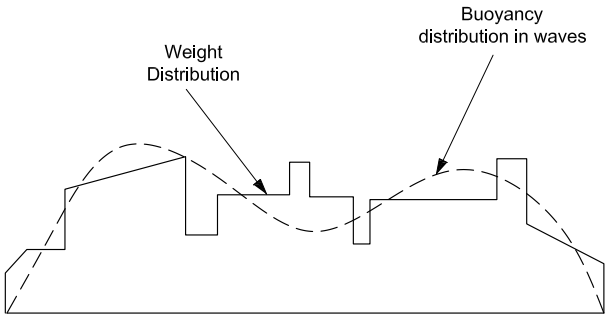


Figure 7-13 Buoyancy and mass distributions

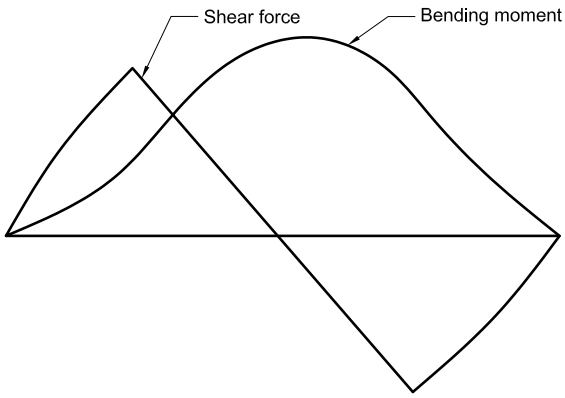


Figure 7-14 Bending moment and shear force distributions in waves

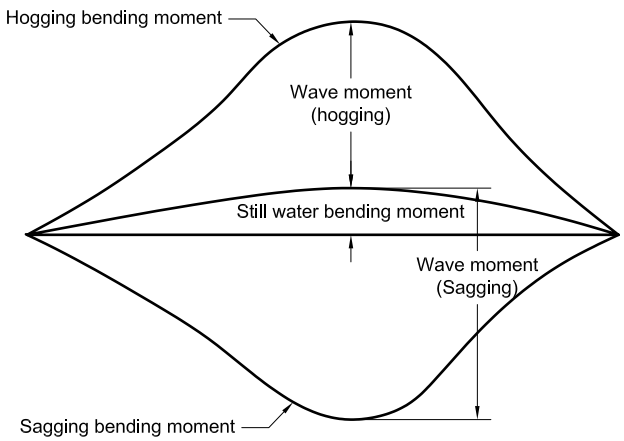


Figure 7-15 Still water versus wave bending moments

6. Section modulus

Having determined the shear forces and bending moments it is necessary to find the stresses in the structure. Midship section is the most important plot that describes the structure of the ship and its main component. The midship section plot shows the scantling of the main members like shells (bottom and sides), deck, longitudinal bulkheads, stiffeners and girders. Therefore, we can obtain from it the horizontal and **vertical section modulus** which determines the longitudinal and transverse strength of the vessel.

This section usually extends one forth length of the ship forward and aft amidship. It starts to change gradually towards the forward and aft body while the main structural members are kept the same. Once we get to the engine room and forward the collision bulkhead, we usually have different construction and frames due to the different nature and loads of these sensitive areas. The zero-shear force is usually located at the midship area where the shear

curve intersects with the baseline and change its sign. Therefore, the moment reaches its peak amidship. In consequence, adequate **midship section modulus** is necessary to withstand the high moment in this area that usually comes from the different distribution of the cargo loads and buoyancy forces.

If we assume that ship hull is a beam for which plane sections remain plane at any longitudinal position of the ship's length, the bending moment is M, and the bending stress σ at vertical distance z from the neutral axis is defined as:

$$\sigma = \frac{M \times z}{I} \tag{7-7}$$

where I is the second moment of area about the neutral axis of the section. Z is the maximum value of z, I/Z is known as the **section modulus**. Section modulus is needed to convert bending moments into stresses. The most important section to be considered at preliminary design stage is the mid ship section. This is the section where the ship experiences maximum bending moments. Typically, the members concerned are the longitudinally effective members namely: side and bottom plating, keel, deck plating, deck and side longitudinal stiffeners and longitudinal bulkheads. The section modulus is evaluated in tabular format (see Table 7-1). To achieve this an **A**ssumed **N**eutral **A**xis (**ANA**) is chosen at a convenient height above the keel. Accordingly, the area of each element above and below the ANA, the first and second moments about the ANA and the second moments about each element's own centroid are calculated. The differences of the first moments divided by the total area gives the distance of the true NA from the ANA. The second moments of area give the moment of inertia about the ANA and this can be corrected for the position of the true NA. This is shown in the section example (Figure 7-16) and the sectional modulus calculations in Table 7-1).

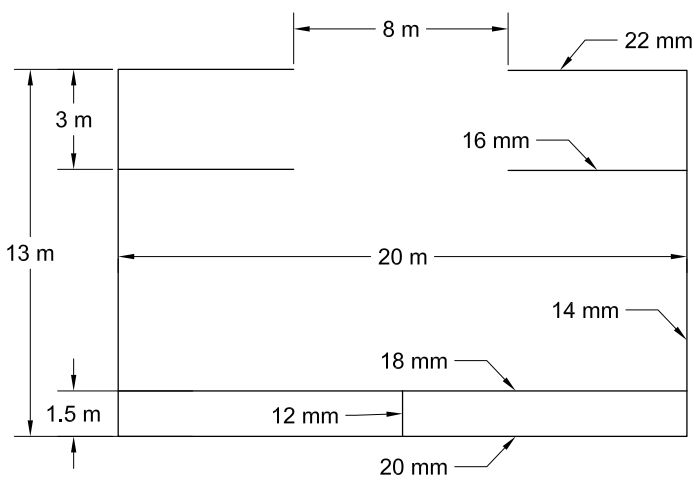


Figure 7-16 Idealized main frame

Table 7-1 Sectional modulus table

Item	Scantlings	Area (m^2)	Lever about keel (m)	Moment about keel (m^3)	2nd moment of Inertia (m^4)	2nd Moment of inertia about own centroid (m^4)
Upper deck	6 x 0.022	0.132	13	1.716	0	0
Second deck	6 x 0.016	0.096	10	9.600	0	0
Side shell	13 x 0.014	0.182	6.5	7.690	2.563	2.563
Tank top	10 x 0.018	0.180	1.5	0.405	0	0
Bottom shell	10 x 0.020	0.200	0	0	0	0
Center girder	1.5 x 0.006	0.009	0.75	0.005	0.002	0.002
Summation		0.799		4.136	40.008	2.565

The height of the NA above the keel:

$$h_{NA} = \frac{4.136}{0.799} = 5.18\ m \tag{7-8}$$

Second moment of area of half section about keel:

$$I_{keel} = 40.008 + 2.565 = 42.573\ m^4 \tag{7-9}$$

and about neutral axis

$$I_{NA} = 42.573 - 0.799(5.18)^2 = 21.163\ m^4 \tag{7-10}$$

For the whole section the section modulus value at the deck Z_{deck} and keel Z_{keel} are:

$$Z_{deck} = \frac{42.326}{7.82} = 5.41\ m^3 \tag{7-11}$$

$$Z_{keel} = \frac{42.326}{5.18} = 8.17\ m^3 \tag{7-12}$$

7. Modes of structural failures

Naval Architects tend to avoid structure failures by considering the potential limit states and failure modes associated with their designs. Whereas the scope of this course is not to define in detail issues associated with structural failures it is considered essential to be able to identify at least the following (basic) types of failure modes:

- **Material yield.** This limit stress level is termed yield stress. It is the stress at which material starts to plastically deform. At a higher stress level, known by the ultimate stress, structural fracture occurs. Although the aim of a successful structural design is to prevent yield in its members, localized yield in some portions of the structure is acceptable.

- **Buckling Failure.** When compressive loads act on a structural member, the structure may experience an in-plane deformation called buckling at a stress level lower than the material yield strength. Material buckling load is a function of the member geometry and material properties. The most common example of an instability failure

is the buckling of a simple column under a compressive load that equals or exceeds elastic buckling criteria. A plate in compression also will have a critical buckling load whose value depends on the plate thickness, lateral dimensions, edge support conditions and material elasticity modulus.

- **Fatigue Failure.** It occurs at a stress level lower than the ultimate stress and as a result of a cumulative effects of loads on a structural member exposed to many cycles of stress. Theoretically, each cycle of stress causes some small but irreversible damage within the material and after the accumulation of such damage, the ability of the member to withstand loading is reduced below the level of the applied load.

- **Brittle fracture** relates with small cracks that may suddenly grow and lead to a catastrophic failure. Brittle fracture is mainly associated with the fact that below a certain temperature the ultimate tensile strength of a material (e.g. steel) dramatically diminishes. The originating crack is usually found to have started as a result of poor design or manufacturing practice.

- **Collision and Grounding**. IMO has developed some requirements regarding collision and grounding especially for ships carrying dangerous or pollutant cargoes such as tankers and ore carriers. The primary requirements for such ships are to arrange a double bottom of minimum height given by the IMO rules and double sides of minimum width to reduce the outflow of pollutant cargoes in ship collision or grounding accident.

8. Structural design assessment procedures

Structural design assessment procedures are mainly developed by Classification Societies and aim to ensure that high standards of safety, quality and reliability at the design stage and during construction. Compliance with the procedures may, upon application from the Shipowner, lead to what is known as a Classification Society notation or descriptive note for inclusion in a Class Society's ship registry. Such procedures require combination of Finite Element Methods to model the ship structure, linear hydrodynamic models to model the influence of waves and broad knowledge on marine structures, ship design and ship building (e.g. LR, 2020). They may apply at detailed design stage but for the case of innovative vessels they may be used to monitor design development early on in the design. Procedures considered more vital to the safety of a ship are mandatory while those which serve to further enhance the safety of a ship are optional.

Structural design assessment procedures focus on structural integrity and are used to **evaluate global and local structural response due to static and dynamic loads, strength and fatigue assessment, shipbuilding construction monitoring.** The application of the procedures in this way ensures that:

- The critical design areas are identified early in the design phase;
- Structural details are designed to minimize the inclusion of stress concentrations;
- The steel weight distribution may be optimized;
- The construction tolerances will be applied to the critical areas during construction to reflect the increased diligence and care taken during the design stage;
- The Shipowner's commitment to safety is demonstrated.

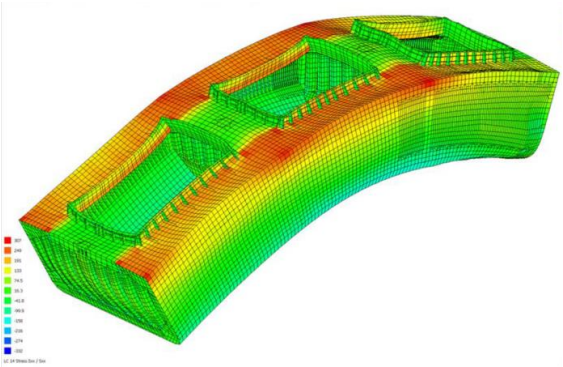


Figure 7-17 Finite Element analysis Application; structural response of a three-cargo holds FE model of bulk carrier ©Marin Palaversa

9. Shipbuilding materials

Structural design of a marine structure or vehicle, floating, submerged or fixed, includes the structural layout and determination of geometrical properties, commonly known as scantlings, of each structural element, each element being interconnected with other elements. The basis of this design is the mechanical properties of the material used such as yield strength, ultimate strength, compressive strength, elongation characteristics and plastic deformation, fracture and fatigue characteristics and other properties. Selection of construction material for marine fixed, floating platforms, ships and submarines is an important aspect of structural design. Materials depend on the following items:

- **Strength-to-weight ratio**. Marine structures and vehicles are generally weight sensitive. The displacement for a vessel being constant, higher weight of material means lower payload. Submersibles and submarines are particularly weight sensitive. In vehicles and structures where strength of the platform is a major consideration, such as deep-diving submarine or decks of large ships, higher strength to weight (or density) ratio means lower material weight.

- **Fracture (or notch) toughness.** This is a measure of material's ability to absorb energy before plastic deformation leading to fracturing. This also means ability of a material to resist brittle fracture in the presence of a notch.

- **Fatigue strength**. Fatigue failure can occur in a material due to low-cycle highstress fatigue, high-cycle low-stress fatigue or corrosion fatigue leading to stress corrosion cracking. The mechanism of fatigue is complex, failure being initiated due to generation of a small crack which grows to a major failure under repeated cyclic loading.

- **Ease of fabrication, weldability and ease of maintenance**. Welding causes a lot of problems in high-strength steels, aluminium and titanium. An additional problem is hydrogen induction into the metal leading to hydrogen embrittlement.

- **Cost and availability.** Cost of material depends on unit cost of material and the quantity of material used. Generally, in steels of various types, unit cost is quite high so that a small reduction in weight may not have significant effect on cost. So using higher strength steels is expensive and they can be used only if other technology considerations predominate. Titanium alloy is very strong though very expensive and used in submarine construction. Aluminium alloy are much lighter than steel though unit cost is higher.

Key materials to be considered as part of this selection process are :

- **Mild Steel** metallurgical variants have been used for shipbuilding construction since the end of the 19th century. They are cheap, available and tolerant with respect to quality deficiencies during fabrication and small damage during operation. Additionally, it has a relatively high strength to weight ratio (compared to wood for instance), a good reserve strength after serious damage, and easy to repair after damage. Steel characteristics have been improved over decades to obtain better properties such as increasing the yield strength and reducing the critical temperature to avoid brittle fracture. Structural steel in marine construction is designated as Grade A, B, D or E which have gone through a process of deoxidation by thermomechanically controlled processes (TMCP) or have been cooled by a process of normalization (N) or have been control - rolled (CR). High strength steel is obtained by changing the carbon percentage in steel and using special heat treatment. High-tensile steels for ship structures are generally specified at three levels of yield strength – 32, 36 and 40 (representing yield strength 355 N/mm^2; ultimate strength 490 – 620 N/mm^2) with four designated grades – AH, DH, EH and FH based on increasing notch toughness.

- **Aluminum alloys** that have nearly the same strength of the traditional mild steel. In recent years, aluminum alloys have found extensive use in marine applications. Mainly hulls of small boats such as commercial pleasure craft (planning boats), sailing craft, personnel and work boats, fishing vessels, survey boats and naval boats have been made of aluminum. Superstructures and deck houses of large commercial vessels and

many naval vessels, marine fittings (e.g. hatch covers, ladders, railings, gratings, windows and doors) are also important applications. Aluminum alloys are highly ductile materials and, if not properly stiffened, may be prone to large deflections. They have lower fracture toughness making them unsuitable where such requirements are essential. Aluminum alloy welding has to be done with care. Since strength of welded aluminum is less than non-welded plate, defects in welds cannot be afforded. If an aluminum alloy and steel are joined as would be required for aluminum deck house on steel hull, aluminum will waste away due to galvanic action, and so, the aluminum and steel must be separated at the joints by non-metallic separators. One of the main disadvantages of use of aluminum as structural material such as partition bulkheads is that aluminum deforms easily and melts when exposed to fire for a long time. Since fire hazard increases with aluminum, it cannot be used in fire-prone areas.

- **Fiber Reinforced Plastics (FRP)** are widely used for high-speed boats, re-creational craft and novel hull forms. The material consists of reinforcing fibers of glass or carbon embedded in a matrix; a polyester for instance. Such a material is light compared to steel, has a relatively high strength useful for ship construction and relatively low cost. Small sailing boats and luxury yachts use composites because they can be shaped very easily in complex three-dimensional forms such as superstructures. Another advantage of composites are the smooth finish and easy maintenance. The main disadvantage of FRP is its poor resistance to fire and potential emission of noxious gases. Application of GRP/FRP and composites on ocean going hull forms would lead to increased fire safety and dry-docking requirements. As engineering application, it is placed in the distant future.

10. Questions

1. Name and sketch the main structural elements of hull girder.
2. Name and sketch the main structural elements of hull girder and describe what is their main role in load-carrying mechanism.
3. Describe the main structural elements of a ship and how they participate to the load-carrying mechanism of a ship. What are the loads ship experiences?
4. Describe the load carrying mechanism of a ship.
5. What is the load-carrying mechanism of ship structure? What does hierarchy mean in this context?
6. What main dimensions are the most important ones in terms of hull girder strength?
7. What are the main elements of ship structural design process?
8. Describe the hierarchy of a ship structural design.
9. Define at least six different categories or types of structural loads.
10. What happened in the picture below? Analyze the situation from shipbuilder's point-of-view.

Figure 7-18 Ship failure ©mptconsult

Lecture 8
Powering, Machinery, and Equipment

Ships are self-powered systems of systems. Their machinery produces energy needed for propulsion, manoeuvring, accommodation, anchoring, mooring and if applicable cargo handling equipment. Onboard machinery must have a high power to weight ratio to ensure efficient ship propulsion. To ensure profitable shipping operations propulsion / power generation systems and their fuels tanks should also accommodate for as low space as practically possible. Within this context it is envisaged that energy efficiency and environmental friendliness should always counterbalance sound safety standards. Study of a ship's operational profile is fundamental to the above (Figure 8-1). It helps determine the ship's power demand under real environmental and operational conditions i.e. from port and in transit to docking and over a period of time of casual operations. This information may be used to estimate propulsive efficiency and compliance against IMO emission regulations.

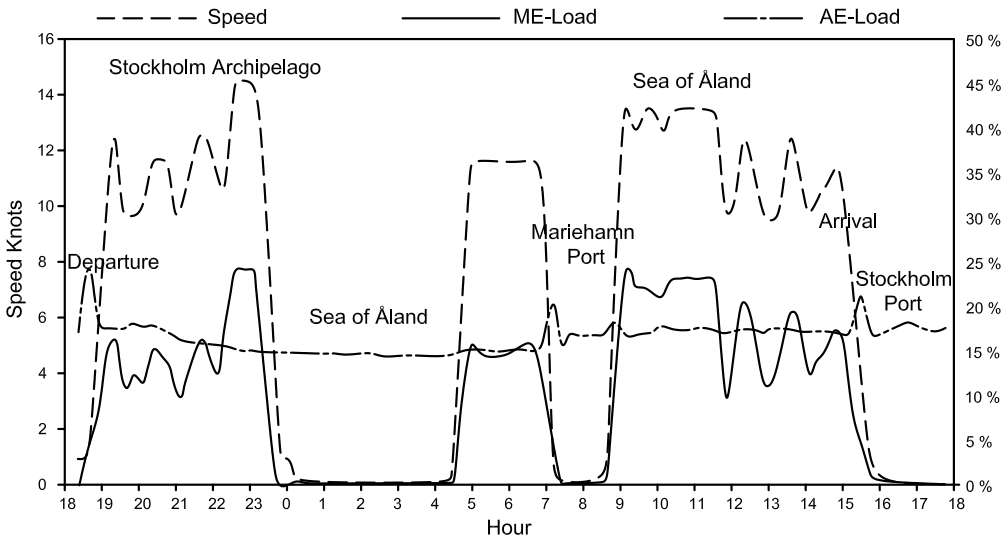


Figure 8-1 Example of an operating profile of a ship (Baldi, Ahlgren, Nguyen, Thern, & Andersson, 2018)

This section provides a brief introduction on basic machinery (engines), fuels, propulsors (propellers, azimuths, pods) and equipment (mooring, anchoring, evacuation) found on ships. Since our focus is on principles that may directly influence concept ship design discussion on the complete range of machinery, equipment and component items (e.g. electrical generators, piping, sewage, ballast refrigeration and air conditioning systems, firefighting /protection, deck machinery and cargo handling equipment, etc.) are not presented. The keen reader could find concise information on ship knowedge items in (Dokkum K. V., 2016) and (Taylor, 1996).

1. A note on available energy sources

The energy used for marine propulsion can be derived from various sources depending on a ship's main machinery systems. Traditional **fuel oil products** are petroleum products classified as : (a) **MDO** (Marine diesel oil) - a blend of heavy gas oil that may contain very small amounts of black refinery feed stocks, with low viscosity up to 12 centistokes so heating for use in internal combustion engines is not necessary ; (b) **IFO** (Intermediate fuel oil) is a blend of gasoil and heavy fuel oil, with less gas oil than marine diesel oil; (c) **HFO** (Heavy fuel oil) - pure or nearly pure residual oil, with very high viscosity. These products are the most polluting in nature. As the IMO has recently implemented stricter measures for emission requirements, including a Sulphur Oxide maximum of 0.5%, the usage of HFO is already being heavily discouraged. In the next century, the IMO has a goal to eliminate greenhouse gas emissions completely. Taking into account the large share contribution of shipping to the in the worldwide transport market (80% of world trade by volume, 3% of global greenhouse gas emissions and contributing to air pollution close to coastal areas and ports), the gradual adoption of alternative fuels by shipping is expected to would have a significant positive immediate environmental impact.

Energy source	Fossil (Without CCS)					Bio	Renewable [3]		
Fuel	HFO + scrubber	Low Sulphur fuels	LNG	Methanol	LPG	HVO (advanced biodiesel)	Ammonia	Hydrogen	Fully electric
High priority parameters									
Energy density	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟠	🔴
Technological maturity	🟢	🟢	🟢	🟡	🟡	🟢	🟠	🟠	🟡
Local emissions	🟠	🟠	🟢	🟢	🟢	🟠	🟡	🟢	🟢
GHG emissions	🔴	🔴	🟠 [2]	🟠	🟠	🟢	🟢	🟢	🟢
Energy cost	🟢	🟢	🟢	🟡	🟢	🟠	🔴	🔴	🟠🟡🟢 [4]
Capital cost									
converter	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟢
storage	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🔴	🔴
Bunkering availability	🟢	🟢	🟢	🟡	🟡	🔴	🟠	🔴	🟠
Commercial readiness[1]	🟢	🟢	🟢	🟢	🟢	🟡	🟠	🔴	🟠🟡🟢 [5]
Other key parameters									
Flammability	🟢	🟢	🟢	🟢	🟢	🟢	🟠	🔴	🟢
Toxicity	🟢	🟢	🟢	🟡	🟢	🟢	🔴	🟢	🟢
Regulations and guidelines	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🔴	🟢
Global production capacity and locations	🟢	🟢	🟢	🟡	🟢	🟠	🟡	🟡	🔴

[1] Taking into account maturity and availability of technology and fuel.
[2] GHG benefits for LNG, methanol and LPG will increase proportionally with the fraction of corresponding bio- or synthetic energy carrier used as a drop-in fuel.
[3] Results for ammonia, hydrogen and fully-electric shown only from renewable energy sources since this represents long term solutions with potential for decarbonizing shipping. Production from fossil energy sources without CCS (mainly the case today) will have a significant adverse effect on the results.
[4] Large regional variations.
[5] Needs to be evaluated case-by-case. Not applicable for deep-sea shipping.

Figure 8-2 DNV GL's interpretation of results and evaluation of status of viability for different alternative fuels (internally rated), within selected assessment parameters (i.e. potential barriers). 2020 compliant conventional fuels have also been included for reference and for these the given colour is based on a simplified assessment by (DNV, 2019).

The obvious alternatives are liquified natural / petroleum gas products (LNG / LPG), biofuels, hydrogen fuel cells, methanol, ammonia, renewable energy technologies (e.g. wind, solar; see), batteries, nuclear. There are various factors that influence design and operations and should be considered while choosing the energy source of a vessel. In brief key factors are energy density, availability, price. Figure 8-2 outlines comparison of some of those based on a study by (DNV, 2019).Today, LNG is the most promising alternative fuel in the sense that it is socially acceptable, resources are available and engine technology is well under development. Notwithstanding exploration of new resources, improved international port / bunkering infrastructure and novel LNG based engines will have to develop further for this energy source to prevail. Some wind and solar energy solutions applied on existing ships are shown in Figure 8-3.

(a) Merchant ship with Flettner rotors ©theconversation

(b) Wind-powered vessel usign sails technology ©Wallenius Marine

Figure 8-3 Wind assisted propulsion solution

2. Basic engine types

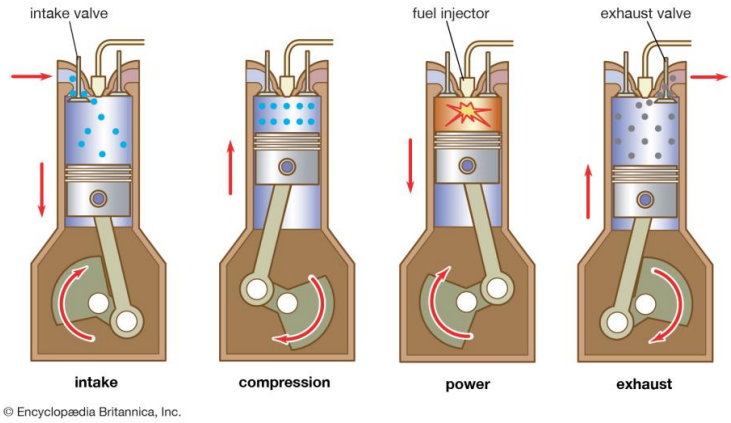
The **diesel engine** is a type of internal combustion engine which ignites the fuel by injecting it into hot, high-pressure air in a combustion chamber, Figure 8-4. Diesel cycle engines are characterized by the direct injection of fuel into the combustion chamber. The fuel is ignited by the high temperatures arising from the large mechanical compression of the air prior to fuel injection. The power delivered from an engine depends on the torque (*T*) it can develop at a given rotational speed (angular velocity, ω) and the rotational speed itself:

$$P = T \times \omega = T \times 2\pi \frac{rpm}{60} \tag{8-1}$$

Similarly, to all internal combustion engines the diesel engine operates with a fixed sequence of events, which may be achieved either in four strokes or two, a stroke being the travel of the piston between its extreme points. Each stroke is accomplished in half a revolution of the crankshaft. **Diesel engines can be classified on the basis of their rotating speed** (low speed engine <400 rpm; medium speed engine: 400-1200 rpm; high speed engine >1400 rpm) **and their operating principle** (two-stroke; four-stroke). For an overall comparison see Table 8-1.

Steam turbines have until recently been the first choice for very large power main propulsion units. Their advantages of little or no vibration, low weight, minimal space requirements and low maintenance costs are considerable. A steam turbine can be provided for any power rating likely to be required for marine propulsion. However, the higher specific fuel consumption when compared with a diesel engine offsets these advantages. Refinements such as reheat have narrowed this gap. Steam, after expansion in the high-pressure turbine, is returned to the boiler to be reheated to the original superheated temperature.

A steam turbine generates mechanical work from the energy stored in steam. The steam is used to move the pistons at very high pressure (approximately 60 bar at 510°C). The high-pressure steam from the boiler is expanded in nozzles to create a high-velocity jet of steam. The nozzle acts to convert heat energy in the steam into kinetic energy. This jet is directed into blades mounted on the periphery of a wheel or disc, see Figure 8-5. The steam does not blow the wheel around. The shaping of the blades causes a change in direction and hence velocity of the steam jet. Steam turbines use various choices of fuel like, diesel, LNG or nuclear. In general, their fuel efficiency is low (i.e. in the range of 230g/kW-290g/kW) which depends on the circulation and the power of the engine. This way of producing energy is also very bulky and heavy as it requires more equipment, but it is technologically simple and reliable.



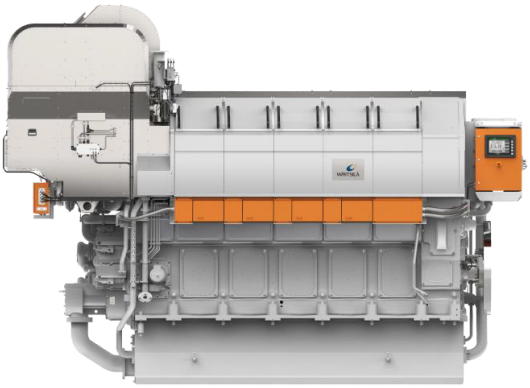


Figure 8-4 Demonstration of 4 stroke diesel engine ©Wärtsilä

Table 8-1 Comparison of diesel engine types

Engine type	**Low speed (2 stroke)**	**Medium speed (4 stroke)**	**High Speed (4 stroke)**
Rotational speed (rpm)	60-250	400-800	>1400
Fuel Efficiency (SFC) (g/kWh)	160-180	170-190	220-240
Power range (MW per cylinder)	0,7-4	0,4-1,3	0,005-0,375
Weight (kg/kW)	20-40	8-20	4-7
Price (USD/kW)	400-500	200-300	200-300
Usage	Common on large cargo ships	Common on passenger ships, RORO ships and icebreakers	Common on fast ships, naval ships, small vessels and used as emergency generators on bigger ships.

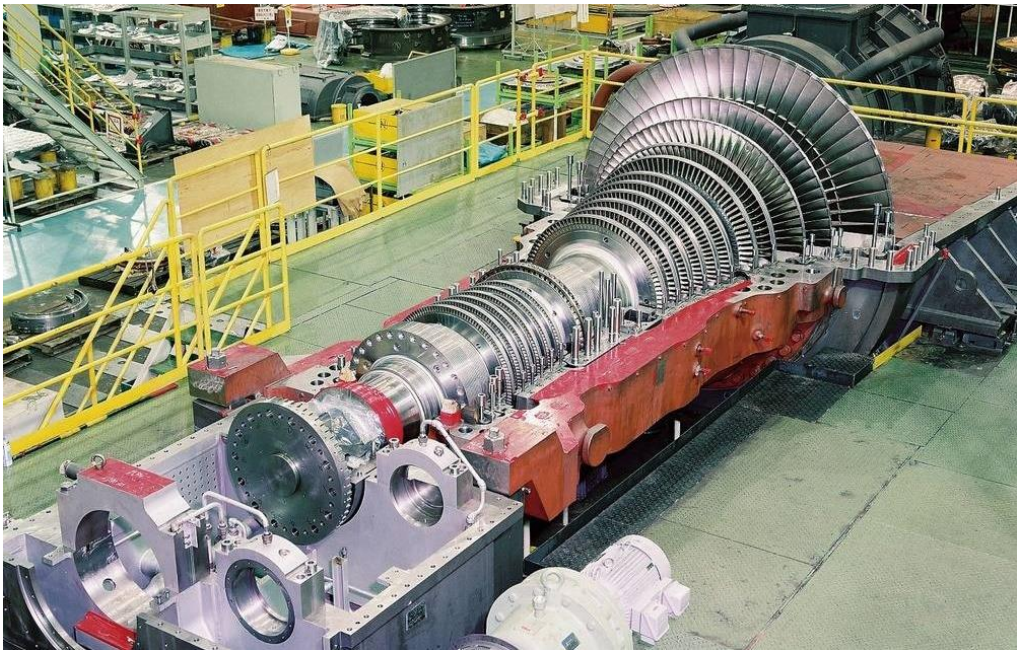


*Figure 8-5 Steam turbine (©*MHI*)*

In **gas turbines,** see Figure 8-6 and Figure 8-7, the air is compressed to a high pressure and energy is added by spraying fuel into the air. This combustion process produces energy which rotates the shaft to drive the compressor. The excess energy is then used to produce thrust or work via an independent turbine that helps rotate the ship's propeller. Gas turbines have relatively low fuel efficiency (approx. 220-260 g/kWh depending on operating conditions) and require the use of high-quality Marine Gas Oil. The weight to power ratio is low in the range of 0,8-1,2 kg/kW and 10-30 MW/unit. However, it is light, small, and generally susceptible to fewer breakdowns. It is environmentally friendly, but the fuel consumption is high; hence economic feasibility is questionable.

The power that is produced by the main power generating engine must be transferred to the propeller by a transmission system. There are various methods to do this namely, mechanical system, electric system, and hydraulic system. **Mechanical transmition systems** have a direct transmission where the rotated shaft is directly running the propeller or the power produced is transmitted through a gearbox where the gear ratios are used to change the speed of the propeller without changing the speed of the engine. In **electrical transmission** the engine runs a generator which is then transferred through a switchboard to ta motor running the propellers. This is used in passenger and cruise ships because there are demands for electricity for the hotel operations and a varying ships speed is seen. Icebreakers require high torque which makes an electric motor the ideal transmission unit. It is also used in ships that require a lot of electric energy due to the equipment onboard. **Hydraulic transmission** systems are similar to mechanical systems with a gearbox where the gearbox is replaced with the hydraulic vane pump. The pump draws hydraulic fluid from the storage tank and delivers

it to the direction control valve at high pressure. This control valve determines the direction and volume of fluid needed for the rotation of the hydraulic motor which in turn drives the propeller.

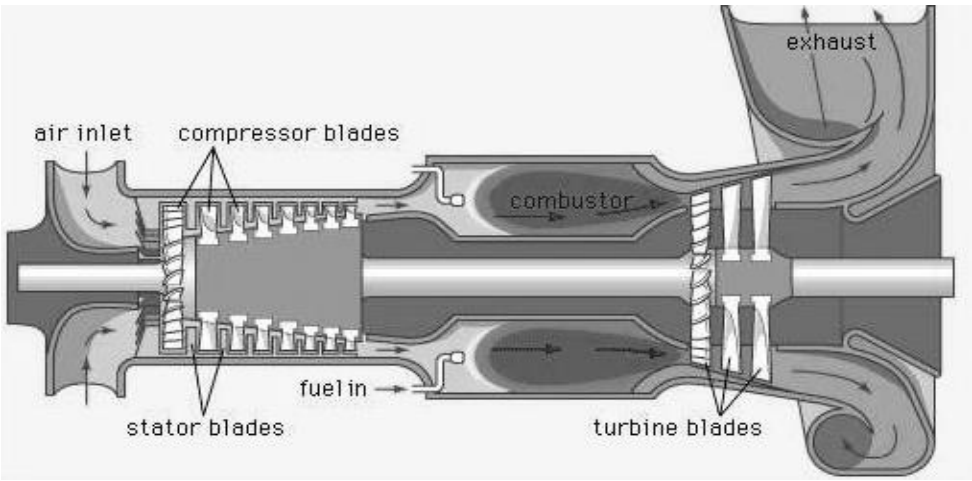


Figure 8-6 Energy conversion process in a Gas turbine (©Britannica)

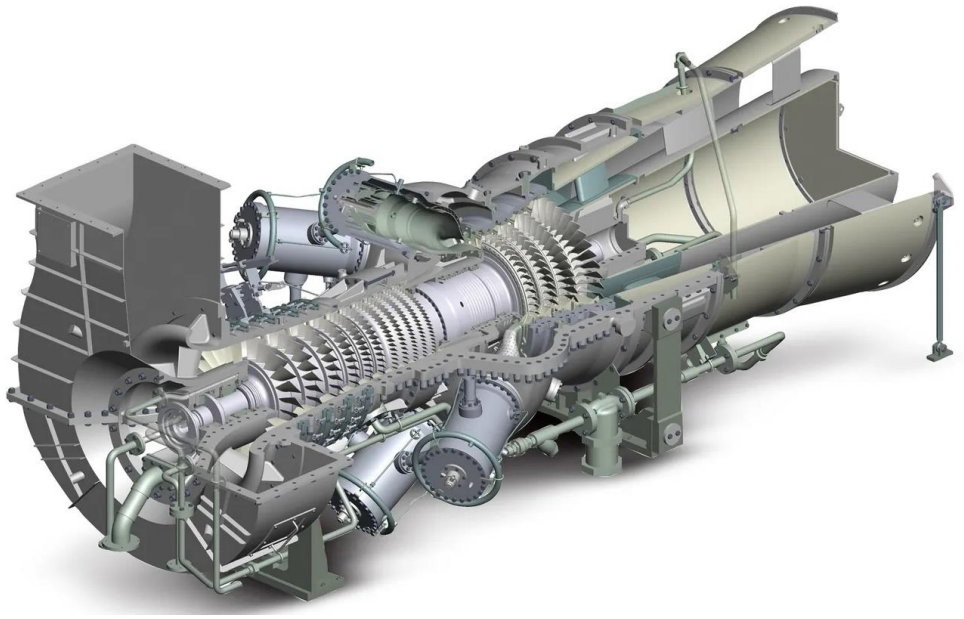


Figure 8-7 3D demonstration of Kawasaki 1 MW class M1A -17 gas turbine (©Turbomachinerymag)

3. Introduction to ship resistance

A ship must be designed to propel through water with maximum efficiency ideally via use of minimum power. Hence, the magnitude of resistance on the ship's hull, R_T, is naturally paramount for the power required to move the ship If the naked hull of the vessel is driven through water by a device which does not interfere with the hull, then we get the **total resistance** R_T. **Ship effective power** is defined as the power required to overcome this resistance at the given speed of the vessel (V). It is defined as:

$$P_E = R_T \times V \tag{8-2}$$

R_T comprises of **frictional (R_F), residual (R_R) and air resistance (R_A)** components. Thus,

$$R_T = R_F + R_R + R_A \tag{8-3}$$

The influence of frictional resistance depends on the thin water viscosity boundary layer generated around the hull surface as the ship progresses in waves. The magnitude of residual resistance describes the energy lost by the ship setting up waves, eddies and by the viscous pressure resistance, which all depend on the hull lines. For slow moving ships such as tankers and bulkers, the frictional resistance is often of the greatest influence ($70 - 90\%$) whereas for fast going ships, such as panamax container carriers, the frictional resistance may account for as little as half of the combined resistance. It is not possible to make a perfectly streamlined design above the water form as there are difficulties of fabrication and these difficulties are not justified by the amount of resistance reduced. Thus, eddies are formed due to the discontinuities in a ship's superstructure and because the streamlines are broken. Air resistance normally represents about 2% of the total resistance, however, with a significant increase up to approx. 10% for ships with large superstructures such as container ships with containers stacked on deck. If wind resistance is considered, the figures may increase. There are various methods to measure hull resistance (Holtrop & Mennen, 1978), Taylor & Getler etc.). However, each of these methods have a limited range and are valid only for certain speeds and hull forms. Ice resistance in areas where the sea freezes over and is dominant for icebreakers.

4. Ship resistance estimation using Holtrop method - example.

Calculate the total resistance of a ship with principal particulars outlined on Table 8-2 at a design speed of 25 $knots$ (12.86 m/s). Other characteristics of the vessel have been assumed or calculated for you in Table 8-2 to simplify the problem.

Table 8-2 Ship Principal particulars

Item		Value	Unit
Length between perpendicular	$\boldsymbol{L_{PP}}$	205	m
Breadth	$\boldsymbol{B}$	32	m
Draft	$\boldsymbol{T}$	10	m
Longitudinal center of Buoyancy	$\boldsymbol{LCB}$	2.02 (aft Amidships)	%
Prismatic Coefficient	$\boldsymbol{C_P}$	0,583	-
Block Coefficient	$\boldsymbol{C_B}$	0.572	-
Volume of Displacement	$\boldsymbol{\nabla}$	37500	m^3
Midship Coefficient	$\boldsymbol{C_M}$	0.980	-
Waterplane Coefficient	$\boldsymbol{C_{WP}}$	0.570	-
Transverse area of the Bulbous bow	$\boldsymbol{A_{BT}}$	20	m^2
Stern shape parameter	$\boldsymbol{C_{stern}}$	10	-
Draught Forward	$\boldsymbol{T_f}$	10	m
Draught Aft	$\boldsymbol{T_a}$	10	m
Height of center of A_{BT} above basis	$\boldsymbol{h_B}$	4	m
Immersed transom area	$\boldsymbol{A_t}$	16	m^2
Wetted surface area	$\boldsymbol{S}$	7205.004	m^2
Appendages wetted surface Area	$\boldsymbol{S_{APP}}$	50	m^2

Table 8-3 Additional dimensionless wave resistance factors according to (Holtrop & Mennen, 1978)

	Bare hull form factor	Appendage factor (twin screw rudder)	Coefficients for the wave resistance computation, function of hull form							Wake (propulsion system)	Thrust deduction fraction
Item	$(1+k_1)$	$(1+k_2)_{eq}$	c_1	c_2	m_1	m_2	λ	c_5	d	w	t
Value	1.156	1.5	1.398	0.7595	-2.1274	-0.17087	0.6513	0.9592	-0.9	0.2584	0.1747

Hull viscous resistance (R_v) is the component of water resistance due to viscosity; the water particles exert frictional drag on the ship's hull. It comprises the frictional drag due to the surface of the hull and another sub-component due to the local flow field as a result of the ship's form and this is known by the form effect. This component can be solved using the following equations:

$$R_v = 0.5(1+k_1)\rho S V^2 C_F \tag{8-4}$$

$$C_F = \frac{0.075}{(log(Re)-2)^2} \tag{8-5}$$

Where C_F is the frictional coefficient according to the IITC 1957 line formula which is a function of the Reynold's number $Re = VL/v$. $(1+k_1)$ is the form factor multiplied by the frictional drag gives the viscous resistance:

$$Re = \frac{12.86 \times 205}{1.1897 \times 10^{-6}} = 2215805332 \tag{8-6}$$

$$C_F = \frac{0.075}{(log(2215805332) - 2)^2} = 0.001390 \tag{8-7}$$

$$R_v = 0.5 \times 1.156 \times 1025 \times 7381.45 \times (12.86)^2 \times 0.00139 = 1005.29 \text{ KN} \tag{8-8}$$

Appendage resistance is the viscous resistance of the appendages attached or fitted to the hull. Appendages include any part that stick out of the bare hull below the waterline (e.g. rudders, thrusters, bilge keel, etc.). It has the same equation as the hull viscous resistance (with separate combined form factor for all the appendages).

$$R_{App} = 0.5\rho S_{App} V^2 (1 + k_2)_{eq} C_F = 0.5 \times 1025 \times 50 \times (12.86)^2 \times 1.5 \times 0.00139 = 8.83 \text{ KN} \tag{8-9}$$

The ship when moving in water generates a typical wave system which contribute in the total resistance and known by <u>*wave-making resistance*</u>. You can imagine it as the energy absorbed in forming such waves. It is given by the following equation:

$$R_W = c_1 c_2 c_5 \nabla \rho g \ exp(m_1 Fn^d + m_2 \, cos(\lambda Fn^{-2})) \tag{8-10}$$

$$c_1 = fn(L, B, T, i_E), c_2 = fn(A_{BT}, B, T, T_F, h_B), \text{and } c_5 = fn(A_T, B, T, C_M) \tag{8-11}$$

$$m_1 = fn(L, T, \nabla, B, C_P), m_2 = fn(L/\nabla^{1/3}, C_P, Fn), \lambda = fn(L/B, C_P), \text{and } d = -0.9 \tag{8-12}$$

To simplify the problem these coefficients have been calculated for you in Table 8-3.

$$\begin{aligned} R_W = 1.398 \times 0.7595 \times 0.9592 \times 37500 \times 1025 \times 9.81 \times exp(&(-2.1274 \\ &\times 0.2868^{-0.9}) + (-0.17087 \times cos(0.6513 \times 0.2868^{-2}))) \\ &= 557.1 \text{ KN} \end{aligned} \tag{8-13}$$

The **bulbous bow resistance** is an additional part of the hull at the bow that contributes in reducing wave making resistance by initiating waves that cancel out the waves produced by the hull's pressure points. However, bulbous bow is considered as an additional wetted

surface which increase the frictional drag. The additional resistance due to the presence of the bulbous bow is given by:

$$R_B = 0.11\, exp(-3P_B^{-2}) Fn_i^3 A_{BT}^{1.5} \rho g/(1 + Fn_i^2) \tag{8-14}$$

Where P_B is a coefficient measures the immersion of the bow and Fn_i is the Froude number based on immersion and are given by:

$$P_B = 0.56\sqrt{A_{BT}}/(T_F - 1.5h_B) \tag{8-15}$$

$$Fn_i = V/\sqrt{g\left(T_F - h_B - 0.25\sqrt{A_{BT}}\right) + 0.15V^2} \tag{8-16}$$

$$\therefore P_B = 0.56 \times \sqrt{20}/\left(10 - (1.5 \times 4)\right) = 0.6261 \tag{8-17}$$

$$Fn_i = 12.86/\sqrt{9.81(10 - 4 - 0.25 \times \sqrt{20} + 0.15 \times (12.86)^2} = 1.5084 \tag{8-18}$$

$$R_B = 0.11\, exp(-3 \times 0.6261^{-2}) \times 1.5084^3 \times 20^{1.5} \times 1025 \times 9.81/(1 + 1.5084^2) = 0.0491 \text{ KN} \tag{8-19}$$

Ships are often designed with transom stern for reduced length and wider deck aft. The flow around the transom stern differs from the cruiser (rounded) stern. Transom stern immersion induces some eddies downstream and consequently increases the pressure resistance known as **transom stern resistance.**

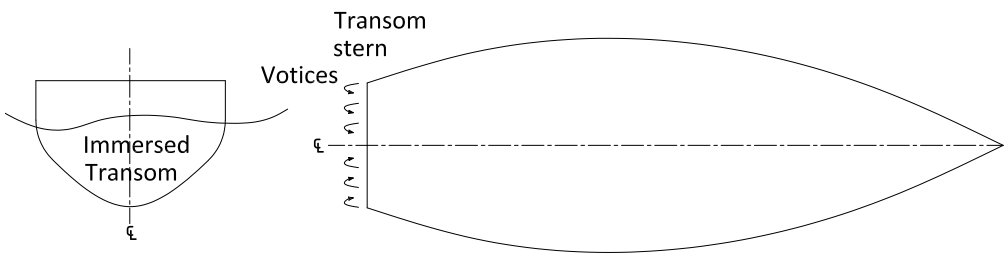


Figure 8-8 Transom stern vortices

Transom immersion resistance R_{TR} is obtained using the following equations:

$$R_{TR} = 0.5\rho V^2 A_T c_6 \tag{8-20}$$

$$c_6 = 0.2(1 - 0.2Fn_T) \qquad \text{for } Fn_T < 5$$
$$c_6 = 0 \qquad \text{for } Fn_T \geq 5 \tag{8-21}$$

$$Fn_T = V/\sqrt{2gA_T/(B + BC_{WP})} = 12.86/\sqrt{2 \times 9.81 \times 16/(32 + 32 \times 0.57)} = 5.144 \tag{8-22}$$

$$\therefore c_6 = 0$$
$$\therefore R_{TR} = 0 \tag{8-23}$$

Mainly, the following equations depend on model tests in towing tanks. There must be a correction for the model test resistance values when correlate to the full-scale. The reason behind that is the additional resistance on the full-scale due to the difference in the surface roughness between the model and the ship, and the difference in the still-air resistance. This resistance is termed as **model testing induced resistance** and is given by:

$$R_A = 0.5\rho S V^2 C_A \tag{8-24}$$

where C_A is the $Correlation\ allowance$:

$$C_A = 0.006(L+100)^{-0.16} - 0.00205 + 0.003\sqrt{L/7.5}C_B^4 c_2(0.04 - c_4) \tag{8-25}$$

$$c_4 = T_F/L \ \text{ for } T_F/L \leq 0.04 \tag{8-26}$$

$$c_4 = 0.04 \ \text{ for } T_F/L > 0.04 \tag{8-27}$$

$$T_F/L = 0.0488, \ \therefore c_4 = 0.04 \tag{8-28}$$

$$\therefore C_A = 3.525 \times 10^{-4} \tag{8-29}$$

$$\therefore R_A = 0.5 \times 1025 \times 7381.45 \times (12.86)^2 \times 3.525 \times 10^{-4} = 221 \text{ KN} \tag{8-30}$$

The <u>*total resistance*</u> is the summation of the previous components:

$$R_T = 1005.29 + 8.83 + 557.1 + 0.0491 + 221 = \mathbf{1793\ KN} \tag{8-31}$$

5. Ship propulsion

The force required to propel the ship is obtained by causing a stream of water (and possibly air) creating a thrust in the opposite direction to that of the ship motions. We can use wind power (e.g., fletner rotors, sails) to propel the ship forward (Figure 8-3). **Marine propellers** are made from corrosion-resistant materials (e.g. alloy of aluminum and stainless steel). Other popular materials used are alloys of nickel, aluminium and bronze which are 10~15 % lighter than other materials and have higher strength. Propellers are be classified on the basis of **number of blades** or by **blade pitch** (see *Table 8-4*, *Table 8-5*, and Figure 8-9). **Screw propellers** are the most common type of propulsion device used. They consist of helicoidal surfaces (blades) that rotate through the water. This rotational motion creates a pressure difference between the forward and rear surfaces of the propeller blades which produces thrust pushing the ship forward. They can turn clockwise or anti-clockwise. In modern passenger ships and LNG carriers we find a twin propeller specification; i.e. 2 propellers are used to produce the thrust. Most marine screw propellers have fixed blades and produce only a certain thrust and torque at a certain rpm. Controllable/variable pitch propellers have blade

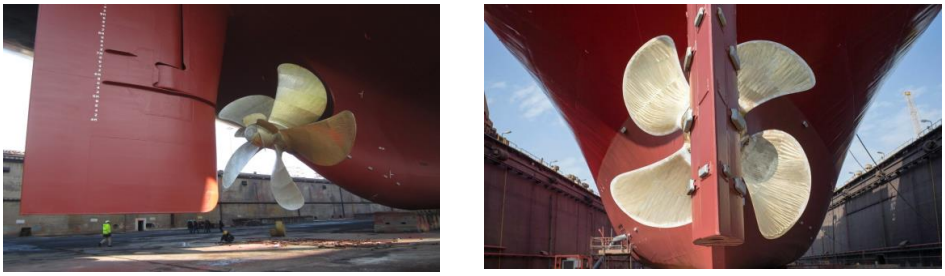
adjustment capability; i.e. they can produce varied thrust / torque at the same rpm by adjusting the pressure difference between the blades.

Table 8-4 Propeller classification based on number of blades

Propeller type	Technical Characteristics Characteristics
3 blade propeller	• The manufacturing cost is low • Material: aluminium alloy • Gives a good high-speed performance • The acceleration is better than other types • Low-speed handling is not much efficient.
4 blade propeller	• The manufacturing cost is higher than 3 blade propellers • Material: stainless steel alloys • Good strength and durability • Good low-speed handling and performance • Good holding power in rough seas • Good fuel economy
5,6 blade propellers	• Manufacturing cost is higher • Vibration is minimal • Excellent holding power in rough seas • Low pressure field over the propeller decreases

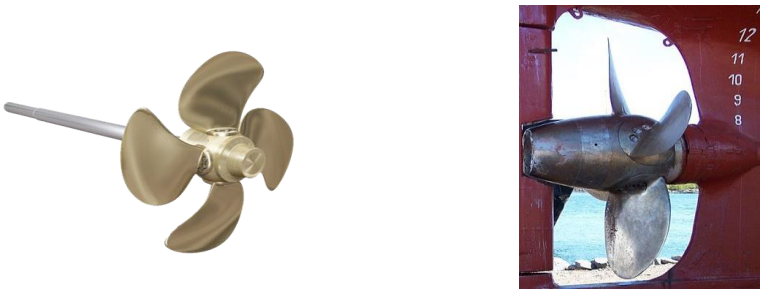
Table 8-5 Propeller classification based on pitch

Propeller type	Technical Characteristics	Advantages	Limitations
Fixed Pitch	Blades permanently attached (casted) to the hub	Reliable as the system doesn't incorporate any mechanical and hydraulic connections	Fitted in ships of limited maneuverability demands
Variable pitch	Blade rotation and pitch variation possible	Good maneuverability and engine efficiency	High risk for oil pollution as hydraulic oil in the boss mechanism used for controlling the pitch may leak out



(a) Single screw propellers (5 and 4 blades) ©ship-technology ©rivieramm

(b) Twin screws propeller ©dreamstime



(c) Controlable/ variable pitch propeller ©Stahlkocher

Figure 8-9 Some ship propellers

Azimuth thrusters or pods are propulsive devices with full rotational capability (360°) and enable excellent ship manoeuvrability. **Mechanical transmission thrusters**, connect a motor inside the ship to the outboard unit by gearing. The motor may be diesel or diesel-electric. Depending on the shaft arrangement, mechanical azimuth thrusters are divided into L-drive and Z-drive. An L-drive thruster has a vertical input shaft and a horizontal output shaft with one right-angle gear. A Z-drive thruster has a horizontal input shaft, a vertical shaft in the rotating column and a horizontal output shaft, with two right-angle gears. In **electrical transmission pods**, an electric motor is fitted in the pod itself, connected directly to the propeller without gears. The electricity is produced by an onboard engine, usually diesel or gas turbine. ABB Group's Azipod was the first product using this technology Figure 8-10. They have good hydrodynamic performance, low vibrations, and ergonomics as they have an inbuilt transmission system which is usually electric. However, their cost is high and their

efficiency low as compared to traditional mechanical transmission systems. They are commonly used on passenger ships, ice going ships and supply ships as these require high manoeuvrability.

Azipod CO for ship applications (Power 1.5-4.5 MW)

Azipod XO for ship applications (Power 7-22 MW)

Azipod DZ for high thrust applications (Power 1.5-7 MW)

Azipod CZ for high thrust application (Power 1.5-4.7 MW)

Azipod VI for different Ice classes for (Power 5-17 MW)

Azipod ICE for different ice classes (Power 2-5 MW)

Figure 8-10 ABB Azipod thruster (©ABB)

Rudders are devices used for steering and manoeuvring a vessel. They are hydrofoils pivoting on a vertical axis located normally at the stern behind propeller(s) to produce a transverse force and steering moment about the ship centre of gravity by deflecting the water flow to the direction of the foil plane. Some key rudder types are shown on Figure 8-11.

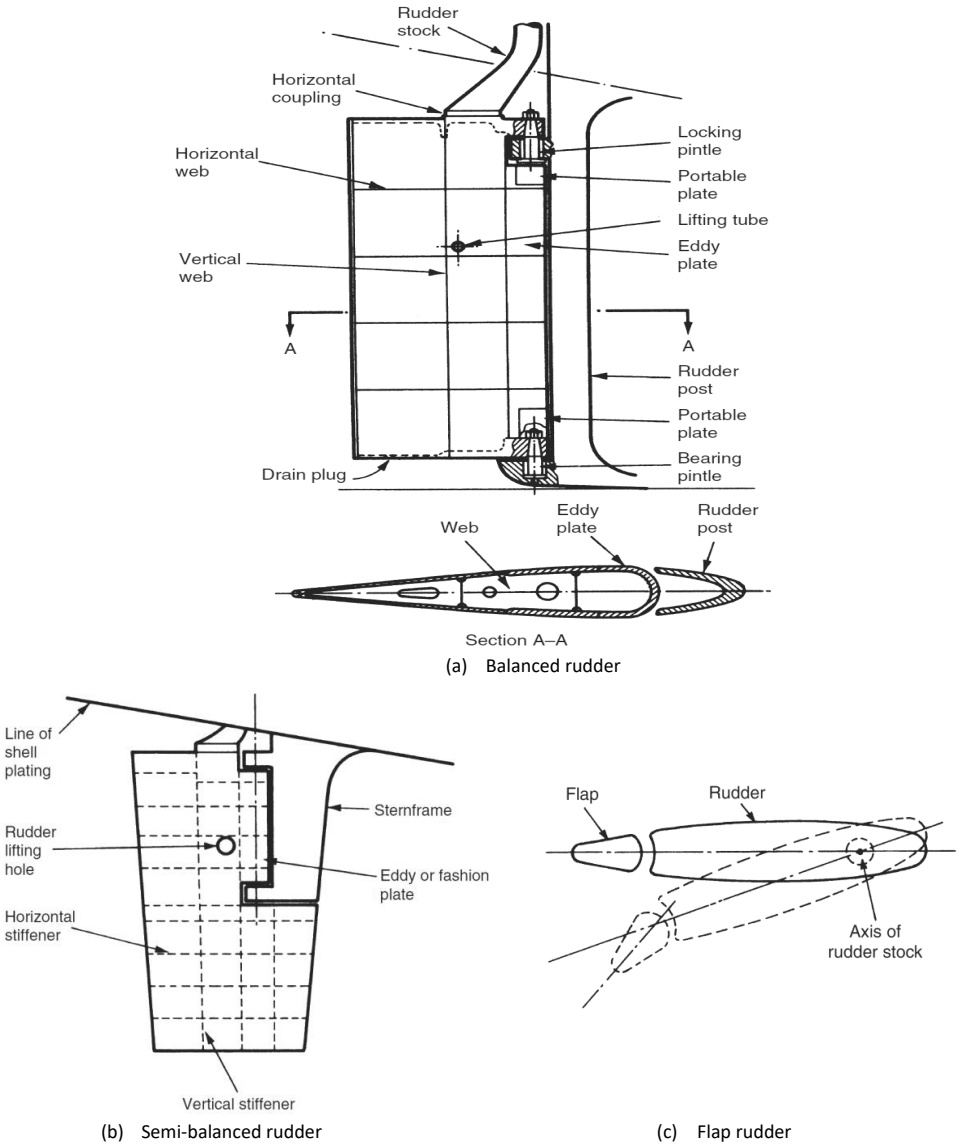
Characteristics of the rudder types are as follows:

- Balanced rudder—requires little steering energy
- Semi-balanced rudder has good hydrodynamic properties, facilitates maintenance of the propeller shaft, and can return to the centreline orientation on its own if the steering gear fails
- Flap rudder—designed for improved maneuverability

Rudder effectiveness can be improved by improving the rudder arrangement in the propeller stream, increasing the rudder area, selecting a better rudder type (e.g., spade rudder instead of semi-balanced rudder, high lift profiles or flap rudders), using a steering gear which allows larger rudder angles than the customary 35 deg. or by implementing shorter rudder steering time by introducing a more powerful hydraulic pump in the steering gear. Rudders are one of

the areas where extra investment spent on getting the right equipment can pay back. One of the basic problems is deciding whether to optimise the rudder for the service speed or for low-speed manoeuvring. Many rudder configurations can meet guidelines for turning circles and zig zag manoeuvres, but still, they are not optimum for the ship service profile. For ships like VLCCs and container vessels, the majority of service is course keeping. Consequently, rudder angles during normal course keeping and manoeuvring operation are limited to 35 deg. For some service profiles good slow speed performance is very important and high rudder operating angles will give greater benefit.

Thrusters in way of a ship's bow or stern are transversal propulsion devices built into or mounted to either the bow or stern of a ship or a boat to make her more manoeuvrable. Practically they are used to allow ships to be more independent from tugs, give them more maneuverability at low speeds (e.g. when maneuvering in ports). There are three general types of thruster devices namely: (a) the lateral or **tunnel thruster**, which consists of a propeller installed in a athwartship tunnel; (b) the **jet thruster** which consists of a pump taking suction from the keel and discharge to either side and (c) the **azimuthal thruster**, which can be rotated through 360°. Bow thrusters make docking easier, since they allow the captain to turn the vessel to port or starboard side, without using the main propulsion mechanism which requires some forward motion for turning. Modern large ships (e.g. passenger) might have multiple bow thrusters and stern thrusters. Large vessels usually have one or more tunnel thrusters built into the bow, below the waterline. An impeller in the tunnel can create thrust in either direction which makes the ship turn. Most tunnel thrusters are driven by electric motors, but some are hydraulically powered. These bow thrusters, also known as tunnel thrusters, may allow the ship to dock without the assistance of tugboats, saving the costs of such service. During vessel design, it is important to determine whether tunnel emergence above the water surface is commonplace in heavy seas. Tunnel emergence hurts thruster performance and may damage the thruster and the hull around it. The general arrangement and hull form of new buildings incorporating thrusters can be modified significantly in order to increase hydrodynamic efficiency. A key advantage is that they tend to suffer less from vibration and noise and are therefore well suited for use on passenger vessels. Since thrusters are steerable, using them may also eliminate the ship rudder, see Figure 8-12 and Figure 8-13.



(a) Balanced rudder

(b) Semi-balanced rudder

(c) Flap rudder

Figure 8-11 Typical ship rudders (Tupper, 2013)

Figure 8-12 Bow thrusters @lloydmarchand

Figure 8-13 Azimouth thrusters ©nauticexpo

6. Powering calculations (Continue previous example)

The propulsion system interacts with the ship's hull in forming the flow around them. The flow induced to the propeller is changed due to the hull form. On the other hand, the flow around the hull is affected by the propeller existence behind it. The traditional way of dealing with this complex hydrodynamic problem is to consider them separately in analysis, design, and testing, then to introduce some efficiencies to account for this interaction. The general form of calculating the power is *force × speed*. If we consider only the hull towed in a tank by some external force, thus, the power required to move the ship at the design speed mentioned above is known by the effective power, which is the product of total resistance R_{total} and ship speed V:

$$P_E = R_{total} \times V = 1793 \times 12.86 = 23058 \text{ KW} \tag{8-32}$$

Let us consider now the propeller operating in open water without the hull. The power produced by the propeller is the thrust power. Thrust power is the product of propeller thrust T and ship speed as follows:

$$P_T = T \times V \tag{8-33}$$

However, this is not real, as the flow speed directly upstream the propeller differs from the ship speed due to the ship's wake, and the speed directly upstream the propeller (on the suction side) is called the speed of advance V_A and the thrust power is: $P_T = T \times V_A$. The relationship between the ship speed and the speed of advance is connected with a term called the wake fraction (w), and it indicates how much the wake is affecting the flow velocity directly before the propeller:

$$w = 1 - \frac{V_A}{V} \tag{8-34}$$

$$V_A = (1 - 0.2584) \times 12.86 = 9.537\ m/s \tag{8-35}$$

It can be calculated numerically or by using empirical formulae in preliminary design approaches. The empirical formula used to obtain the wake fraction is a function of some parameters as shown:

$$w = fn(C_V, L, B, C_P, D, T_A, C_B, C_{stern}) P_T = T \times V \tag{8-36}$$

On the other hand, the thrust measured when the propeller is behind the hull is higher than the total resistance without the propeller. So, the propeller induces some additional resistance due to some reasons (the propeller increases the flow velocities in the aftbody which increases friction and reduces pressure behind the hull which increases the pressure resistance). The term that connects the relation between the total resistance and the thrust is known by the thrust deduction factor:

$$t = 1 - \frac{R_T}{T} \tag{8-37}$$

Hence, the thrust deduction factor $t = fn(LCB, C_P, L, B, D, C_{stern})$. The difference between the effective power P_E and the thrust power P_T combines together the wake effects and the thrust deduction effects. The ratio between them is called the hull efficiency:

$$\eta_H = \frac{P_E}{P_T} = \frac{R_T \cdot V}{T \cdot V_A} = \frac{1 - t}{1 - w} = \frac{1 - 0.1747}{1 - 0.2584} = 1.11 \tag{8-38}$$

Noted that this efficiency can be more than unity, that's because those two factors- previously mentioned, can have some beneficial effects on the power.

The power delivered from the shaft to the propeller is expressed by the torque Q and propeller rotation speed n (rpm):

$$P_D = 2\pi \cdot n \cdot Q \tag{8-39}$$

The losses between the delivered power and the thrust power are expressed in terms of the behind hull efficiency $\eta_B = P_T/P_D$. This ratio is different when the propeller is considered alone without the hull which is known by the open water efficiency (η_o). The factor that accounts for the differences between the case where the propeller is behind the hull and the open water condition is known by the relative rotative efficiency η_{RR}:

$$\frac{P_T}{P_D} = \eta_o \times \eta_{RR} \tag{8-40}$$

The relative rotative efficiency η_{RR} can be obtained using a regression formula which is a function of the blade area ratio A_E/A_o (a propeller characteristic), C_P and LCB:

$$\eta_{RR} = fn(A_E/A_o, C_P, LCB) = 0.9931 \tag{8-41}$$

The delivered power P_D is less than the brake power of the engine due to losses in shafts and bearings. So, the ratio between the delivered power and the brake power represents the shaft efficiency η_s which can be assumed as 98%.

$$\eta_s = \frac{P_D}{P_B} = 98 - 98.5\% \tag{8-42}$$

The brake power is what you need for your design and it is the main aim of this analysis. Using the brake power, you can select the prime movers of your ship project.

$$P_B = \frac{P_E}{\eta_H \eta_o \eta_{RR} \eta_s} = \frac{R_T \cdot V}{\eta_H \eta_o \eta_{RR} \eta_s} \tag{8-43}$$

The final step to calculate the brake power is to obtain the open water efficiency. Usually this needs open water tests. There are some equations used to estimate the open water efficiency and the other propeller characteristics by polynomial representation of the test results. Propeller design is an iterative process and you shall first estimate some main characteristics such as the diameter or the rpm, then calculate the torque coefficient, the thrust coefficient, and the open water efficiency, and finally to compare the thrust produced to the thrust required for your hull. If the thrust produced is lower than the required, you shall start another calculation process. You can find more details in propeller design using methodical series. For this example, propeller main characteristics are given as follows:

Table 8-6 Example of a propeller main characteristics

Item	Value	Unit
Number of Blades Z	5	-
Propeller diameter D	8	m
open water efficiency η_o	0.6461	-

Eventually, the brake power:

$$P_B = \frac{P_E}{\eta_H \eta_o \eta_{RR} \eta_s} = \frac{23058}{1.11 \times 0.6461 \times 0.9931 \times 0.98} = 33035.42 \text{ KW} \tag{8-44}$$

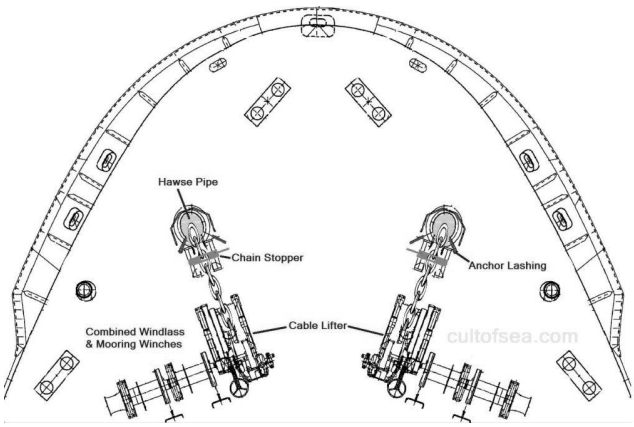
Noted that we assume there is no losses between the shaft and the engine, so the shaft power is equal to the brake power.

7. Ship Equipment and components – brief reference

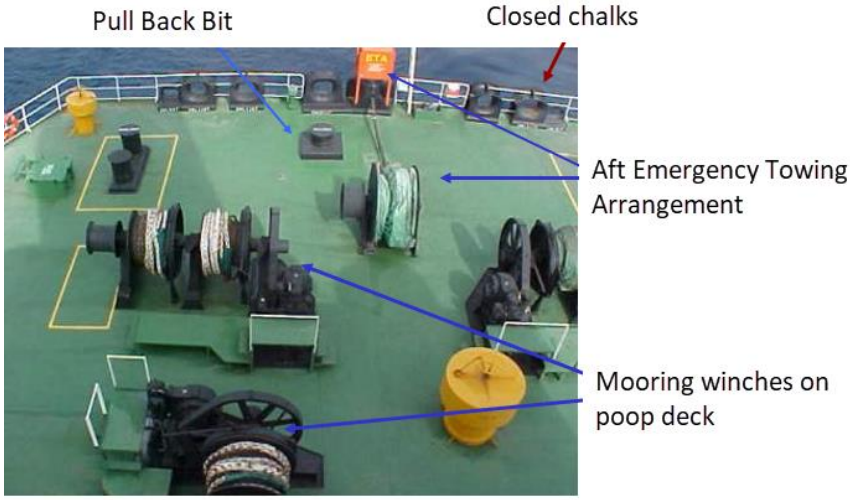
Ship anchoring and mooring are important activities of a marine platform at the port or in shallow waters. The crew of the ship normally do the needful in this respect using ship's mooring ropes, anchor chains, associated machinery such as anchor windlasses, mooring winches, capstans and mooring fittings on deck such as bitts or bollards and fairleads and chocks of various kinds. Normally, on a ship these deck machinery and fittings are provided in way of the bow on the forecastle deck and in the aft on the poop deck (see Figure 8-14). It is a regulatory requirement that the space in these areas is enough not only to house the machinery and equipment, but also provide enough space for ropes and chain to pass conveniently for enough working space.

There are two basic anchor types namely **stockless** and **stock.** A ship anchoring system is control from the bridge and consists of the anchor, anchor chain and anchor handling equipment. The overall purpose of the system is to maintain a ship's position so that she does not drift off due to wind/currents and/or waves. To ensure high operational reliability all ships have 2 bow anchors. When launched together they help reduce ship yaw via equal weight distribution. Inland water way ships also have a stern anchor. The force on an anchor is horizontal acting along the bottom of the seabed otherwise (e.g. if the force is vertical) ship heaving and uprooting of the anchor from the seabed may occur (see Figure 8-15). The weight of the anchor is measured in tons and is decided based on the ship size. The holding capacity of an anchor is measured by the anchors holding power which is the force exerted on the anchor by the ship. The chain is also an integral part of this system. It must be long enough to support the force of the ship and this affects the holding capacity of the anchor. The chain should also act on the anchor horizontally and must dampen the stopping forces. The handling system consists of various parts namely the chain locker, the brakes for the capstan, guiding and controlling mechanisms.

In a merchant vessel, if cargo handling gear is provided on the upper deck space must be provided for housing and working of the cargo machinery such as cranes and derricks and also space for hatch cover panels when open. Arrangements should be such that the hatches can be opened and closed conveniently as per the recommendations of the supplier so that cargo movement (loading and unloading) can be done efficiently. Access of crew members from accommodation to work space on deck must be available in all weather conditions.



Typical forecastle deck arrangement ©Cultofsea



Poop (Aft) deck arrangement ©knowledgeofsea

Figure 8-14 Typical mooring arrangements.

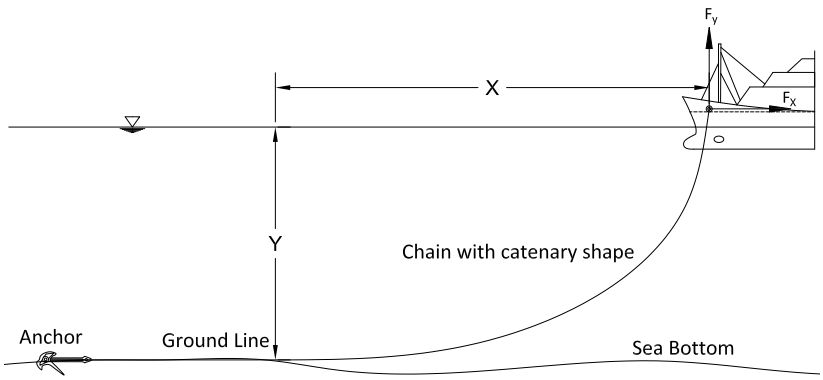
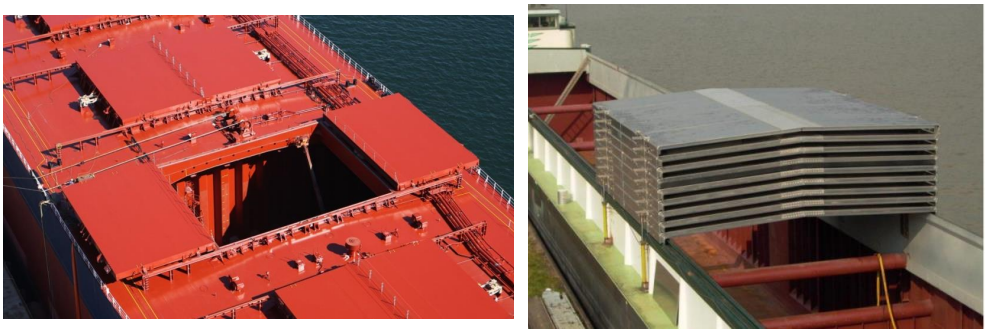


Figure 8-15 Basic dynamics of ship anchorage system

Doors and hatches provide access to enclosed compartments and tanks. **Watertight doors** are designed to prevent water leakage under constant water pressure and are generally located between separate watertight compartments. **Weathertight doors** are intended to seal the accommodation (superstructure) or a compartment from ingress of water or flooding during bad weather, but they cannot remain water tight when submerged / under long-lasting water pressure. Hatch covers in cargo ships are generally weathertight. Examples of watertight and weathertight doors are shown in Figure 8-16.

Watertight doors© gard.no

Manholes ©Mariners Planet, © thormarine.



Different types of hatch covers (Roll on Roll off on the left, ©macgregor, and stacking cover on the right, © blommaertalu.be

Figure 8-16 Ship doors and hatches

Mooring systems are auxiliary to anchoring and are used to guide a ship to her correct quay location and to hold her fixed in the lateral and in longitudinal directions. They are designed such that the forces acting on the ship by waves, winds and currents are counterbalanced. Thus, changes in a ship's draught, heel and trim needs to be accounted for while designing the system. The components of a mooring system are called **mooring lines**. **Breast lines** are perpendicular to the quay and may be added to counteract high environmental forces such as winds and waves. **Spring lines** prevent a moored ship from moving along the quay and provide longitudinal fixing. Most of the mooring lines are made from synthetic materials like nylon, polyester and polypropylene. They are stored on reels and can be used to tow the ship too if separate towing lines are not present. The line is handled with capstans or winches and the direction of the pull force is adjusted with rollers and chokes. The track of the line should always be minimized, and the total number of lines is adjusted so that least number of lines are needed to keep the ship in place. It is regulatory requirement to keep all lines in direct sight of the operator.

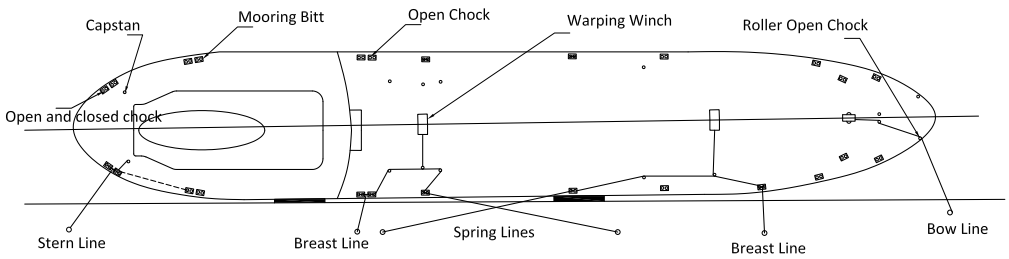
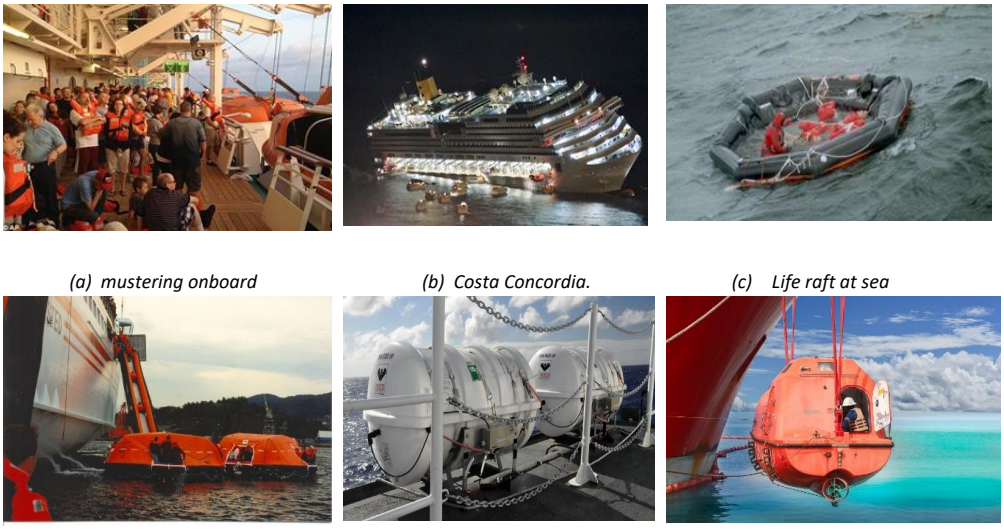


Figure 8-17 Mooring of a ship to a dock

Ship evacuation systems are very important part of safe operations/design and they are regulated in accordance with IMO SOLAS requirements. Evacuation system components include escape routes, muster stations, lifeboats/rafts and their launching mechanisms, life vests and last but not least evacuation procedures. To date, most fatal accidents during evacuation have been caused due to failures in lifeboat release mechanisms. The rescue of the evacuation personnel must be planned too and communication to the maritime emergency services must be done. There are various requirements for lifesaving appliances, such as minimum capacity for lifeboats and minimum amount of extra liferafts based on the number of person onboard. Other requirements are the angle of clearance of the lifeboats, such that the ship can heel 20 degrees without impeding the usage.



(a) mustering onboard *(b) Costa Concordia.* *(c) Life raft at sea*

(d) Evacuation slide *(e) Ship life rafts* *(f) Launching of a life boat*

Figure 8-18 Demonstration of ship lifesaving equipment (©shoretension website)

8. Questions

1. Name the components of a ship propulsion system and give examples of those.
2. What are the main parts of diesel-electric propulsion system?
3. Define the main engine for 15,000 TEU container ship. Justify you selection.
4. Name the most important differences between a slow speed diesel engine and a medium speed diesel engine. Give examples of the advantages and disadvantages in each case.
5. Explain what we mean by ship operational profile and how it influences power plant design. List 3 of the most potential energy sources for a passenger ship. Discuss them from viewpoint of SWOT analysis (strength, weakness, opportunity and threat).
6. What are the benefits of Azipod-system in large passenger ships?
7. Explain the benefits and weaknesses of podded propulsion systems.
8. Name the most important lifesaving appliances in ships.
9. Shallow-draft vessels have often rudders with a long profile but a low height. Characterize their use and the distinctions when compared to a rudder of a ship with bigger draught, a rudder with a shorter profile and greater height.
10. Describe the forces and principles acting on the ship when anchored.

Lecture 9
Ship weight Calculations

1. Ship Classification systems

Ship systems and their components provide detailed technical information needed for weight assessment, price estimation and production planning. Ship classification systems have been developed to provide to the yards and to the companies involved in the management and operation of ships tools to support ship specifications, estimates of light ship weight, ship building (or repair) costs and systematically sort listed information on the procurement of materials, equipment and services. In brief, there are three basic ship classification systems namely: (a) **MARAD (**MARitime Administration) used by the U.S.A. administration; (b) **SWBS-** Ship Work Breakdown Structure, used by the USA Navy and (c) **SFI–** developed by the Norge Skips Forsknings Institutt (NSFI) of Norway, and is now property of XANTIC (www.xantic.net).

SFI is the most widely used classification system for the maritime and offshore industry. It consists of a technical account structure covering all aspects of ship/rig specification, and it can be used as a basic standard for all systems in the shipping/offshore industry. In shipbuilding, the grouping system can help shipyards to estimate the weight of system components hence the ship's lightweight and deadweight, and for price estimation purposes. In operations, it helps shipping companies to control purchasing, accounting, maintenance, technical records, etc., by tying them together.

The SFI group system introduces of 3-digit decimal classification. Accordingly, the ship is divided into 10 main groups (ranging from 0 to 9). Of those only main groups 1-8 are in use. Group 0 and 9 are used for classifying other main components that are not covered under the SFI standard. Each of the main groups (1digit) is composed of 10 sub – groups.

The main groups are as the follows:

- **Group 1:** general costs and details that cannot be assigned to any of the following groups such as general arrangement, launching, and drydocking.
- **Group 2:** hull, superstructure and material protection of the vessel.
- **Group 3:** cargo equipment and machinery including the loading and unloading equipment.
- **Group 4:** ship specific equipment and machinery (navigational equipment, maneuvering machinery, anchoring equipment and communication equipment).
- **Group 5:** equipment serving crew and passengers such as the lifesaving appliances, furniture, catering equipment, and sanitary systems.

- **Group 6:** machinery main components including main engines, auxiliary systems, propellers, boilers, and generators.
- **Group 7:** equipment serving main machinery such as fuel and oil lubrication systems, starting air systems, exhaust systems, and automation systems.
- **Group 8:** ship Common Systems such as ballast and bilge systems, firefighting and electrical distribution systems.

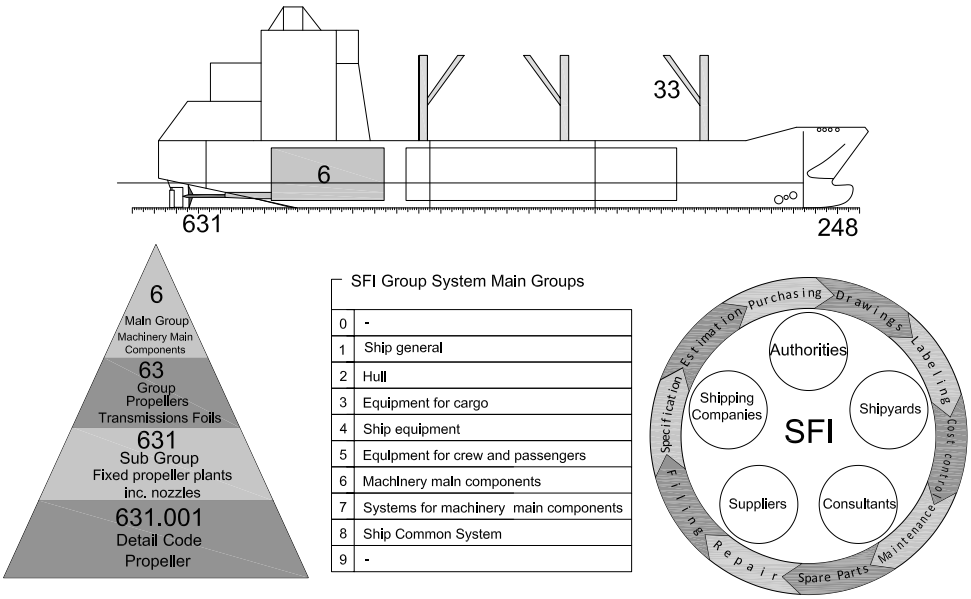


Figure 9-1 The SFI classification system

2. Classification of weights

It is necessary to allocate ship weights in order to facilitate data gathering, reporting and analysis of ship weights. The traditional way of weight classification is to divide the ship's total displacement into lightship weight (W_{LS}) and total deadweight (*DWT*). The lightship weight is defined as:

$$W_{LS} = W_S + W_M + W_O + W_{margin} \tag{9-1}$$

where: W_S is the structural weight; W_M is the propulsion machinery weight; W_O represents the outfitting weight and W_{margin} is the Margin or reserve.

The ship's deadweight is defined as:

$$DWT = DWT_C + DWT_{FO} + DWT_{LO} + DWT_{FW} + DWT_{C\&E} + DWT_{PR} \tag{9-2}$$

where DWT_C is the cargo deadweight; DWT_{FO} is the fuel oil weight; DWT_{LO} is the lube oil weigh; DWT_{FW} is the Fresh Water, $DWT_{C\&E}$ represents the weight of crew and their effects and DWT_{PR} is the weight of provisions.

As the payload and the income of the vessel are sensitive to the ship dead weight, the shipyard must adhere to the **contract dead weight** that is specified in the contract between the shipyard and the owner. The deadweight acceptance and rejection limit must be specified in this contract. The acceptance limit is a specific value of deadweight below it a shipyard has to compensate the owner. The compensation value should also be specified in the contract which is usually expressed in (€/ton). The dead weight rejection limit is the value of the dead weight, specified in the contract, below which the owner can reject the ship.

3. Preliminary Weight Calculations

Weight calculation process in the early design stage is very important to determine the ship's total weight, weight distribution and center of gravity. These parameters are important for quoting prices and carrying out the preliminary stability, seakeeping, resistance and strength analysis. Estimation of weight at early design stages requires the use of parametric models based on information of similar vessels either from literature or using a shipyard's database. An important part of this estimation is to decide on the relevant independent variables that are correlated with weights and their centers. The accuracy of the estimated weight should improve while progressing in the ship design and building processes, as the weight estimation methods become more accurate and based on firm drawings. Eventually, the official weight calculation should indicate exactly the weight of the vessel and should be validated by conducting draught survey and inclining experiment after launching the ship (see Lecture 5, Section 7).

In the preliminary estimation of the ship weight, it is common practice to split the weight into separate groups, like structure weight, machinery weight, equipment weight and outfitting weight; and then estimate the weight of these parts separately. The structure, machinery and outfitting preliminary weight estimations are explained in the following sections.

The **structural weight** consists of the weight of the basic hull to its depth amidships, the weight of the superstructures, extensions of the hull above the basic depth amidships (e.g. forecastle and the poop deck) and the weight of deckhouses. Because superstructures and deckhouses have an important effect on the estimation of the ship's vertical and longitudinal centers of gravity it is important to capture the designer's intent in relation to the existence and location of superstructures and deckhouses as early as possible in the design process. An approach to this has been traditionally proposed by Watson and Gilfillan using the so-called modified Lloyd's index/numeral E_N (**E**quipment **N**umerical):

$$E_N = L(B+T) + 0.8L(D-T) + 0.85\sum_{i=1}^{N_1} h_{1i} l_{1i} + 0.75\sum_{i=1}^{N_2} h_{2i} l_{2i} \tag{9-3}$$

where N_1, h_1 and l_1 are the number, height and length of deckhouses, while, N_2, h_2 and l_2 for superstructure.

This number is an area type independent variable. The first term represents the area of the bottom and the two sides of the hull below the waterline. The second term represents the area of the two sides above the waterline which are 15% lighter since they do not experience hydrostatic loading. The third term is the sum of the profile areas (*length x height*) of the superstructure elements. The fourth term represents the sum of the profile areas of the deckhouse elements which are relatively lighter because they are not influenced by wave loads and have a width less than the ship's beam.

Watson and Gilfillan also introduced the following regression-based equation as a function of the equipment number:

$$W_S = K\,E^{1.36}[1 + 0.5(C_B - 0.7)] \tag{9-4}$$

where C_B is the block coefficient at 80% of the depth. The factor K varies with the ship type as shown on Table 9-1. It is noted that this estimation corresponds to the case of a vessel made 100% from steel.

Table 9-1 K factor (Thomas, 2003)

Ship type	K mean	K range	Range of E
Tankers	0.032	± 0.003	$1500 < \mathrm{E} < 40000$
Chemical tankers	0.036	± 0.001	$1900 < \mathrm{E} < 2500$
Bulk carriers	0.031	± 0.002	$3000 < \mathrm{E} < 15000$
Container ships	0.036	± 0.003	$6000 < \mathrm{E} < 13000$
Cargo	0.033	± 0.004	$2000 < \mathrm{E} < 7000$
Refrigerator ships	0.034	± 0.002	$4000 < \mathrm{E} < 6000$
Coasters	0.030	± 0.002	$1000 < \mathrm{E} < 2000$
Offshore supply	0.045	± 0.005	$800 < \mathrm{E} < 1300$
Tugs	0.044	± 0.002	$350 < \mathrm{E} < 450$
Fishing trawlers	0.041	± 0.001	$250 < \mathrm{E} < 1300$
Research vessels	0.045	± 0.002	$1350 < \mathrm{E} < 1500$
RO-RO ferries	0.031	± 0.006	$2000 < \mathrm{E} < 5000$
Passenger ships	0.038	± 0.001	$5000 < \mathrm{E} < 15000$
Frigates/corvettes	0.023		

In commercial classification **machinery weight** includes only propulsion machinery; the prime mover, reduction gear, shafting and propeller. Watson and Gilfillan suggested a division of machinery weight into main engines W_{ME} and the remaining items W_{rem}. This approach is

advantageous because it is usually possible to select the main engine early in the design process.

$$W_M = W_{ME} + W_{rem} \tag{9-5}$$

If the engine weight is unknown, the following regression equations should be used to deduce both the main engine and the rest of the machinery components according to the equation:

$$W_{ME} = \sum_i 12(MCR_i/N_{ei})^{0.84} \tag{9-6}$$

In the above, i subscript represents the index of multiple engines respectively running at a maximum continuous rate MCR_i in the order of N_{ei} rpm. The overall weight of the remaining items varies with the total plant MCR as follows:

$$W_{rem} = c_m(MCR)^{0.7} \tag{9-7}$$

where MCR is in KW and $C_m = 0.69$ bulk carriers, cargo vessels and container ships; 0.72 for tankers; 0.83 for passenger vessels and ferries, and 0.19 for frigates and corvettes. It is noted that for modern diesel electric engines Watson proposed the following equation for the total machinery weight:

$$W_M = 0.72(MCR)^{0.78} \tag{9-8}$$

Outfitting weight includes the weight of the electrical plants, auxiliary systems – such as HVAC, joiner work, furniture, electronics, paint, etc., and hull engineering– such as bits, chocks, hatch covers, cranes, windlasses, winches, etc. Watson and Gilfillan introduced the following equation to estimate outfitting weight:

$$W_o = C_0 LB \tag{9-9}$$

where C_o is the outfitting weight coefficient. It is a function of the ship type and length and its values can be obtained from Figure 9-2.

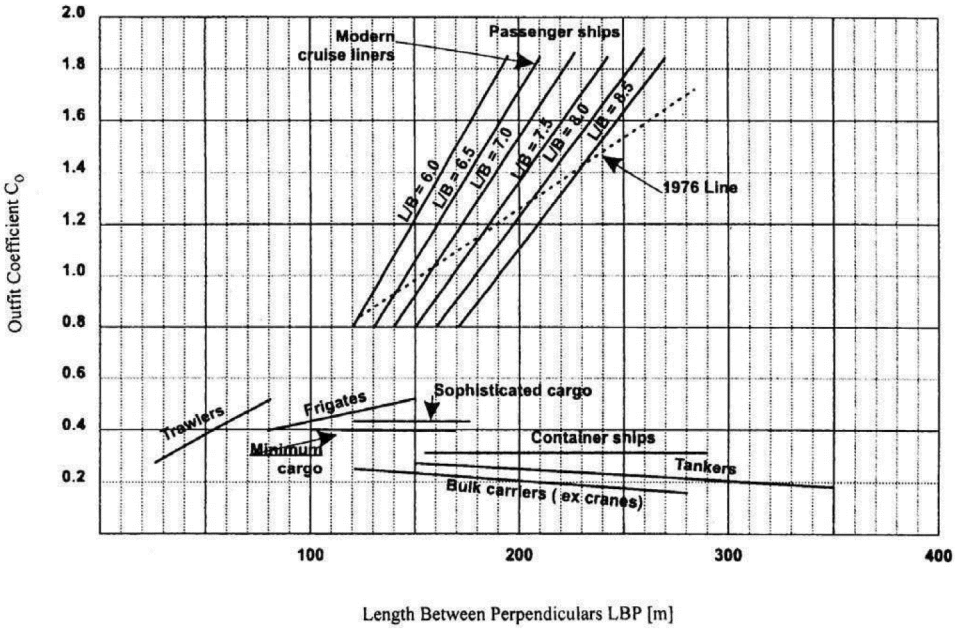


Figure 9-2 Outfit coefficients (Thomas, 2003)

Cargo deadweight is usually an owner requirement, or it can be estimated from analysis of the hull capacity. The remaining deadweight items can be estimated in the same way as the lightship weight. Based on the selection of the main machinery and the prime mover of a vessel, the specific fuel consumption rate (SFR) for propulsion plant is provided. Accordingly, fuel weight can be estimated as:

$$W_{FO} = SFR \times MCR \times range/speed \times m\,arg\,i\,n \tag{9-10}$$

For diesel engines, SFR is $0.00019\ t/KWhr$ and 10% addition is allowed to account for shipboard operations. For gas turbines SFR is $0.000215\ t/KWhr$. Overall, the SFR design margin might be between $5 - 10\%$. While, $range/speed$ should give the time before refueling. In practice a ship would not reach her maximum continuous rate except for worst service conditions. Thus, this estimation may be seen as overconservative.

The **lube oil weight** depends on the type of machinery used and is usually derived based on existing vessel records. On the other hand, the **weight of fresh water** depends upon the designer's intents relative to onboard distillation and storage. For example, modern commercial vessels often carry the water that would be needed over the entire voyage. Naval vessels and cruise vessels because they have much higher capacity demands they can distill water onboard. On the basis of using 45 gallons per person per day, the total water tankage weight would need to be:

$$W_{FW} = 0.17 \quad ton/(Person \times day) \tag{9-11}$$

the above would be satisfactory for 10 days storage with distillation and 45 days storage without distillation onboard.
The **weight of the crew and their effects** can then be estimated as:

$$W_{C\&E} = 0.17 \qquad ton/person \tag{9-12}$$

And finally, the **weight of provisions** can be estimated using:

$$W_{PR} = 0.01 \qquad ton/(person \times day) \tag{9-13}$$

Alike weight estimation, **centers estimation** in the early stages of design can use parametric models. For example, the vertical / longitudinal centers of gravity (VCG_{hull}/ LCG_{hull}) of the basic hull can be estimated using equations proposed by Kupras:

$$\begin{aligned} VCG_{hull} &= 0.01D[46.6 + 0.135(0.81 - C_B)(L/D)^2] + 0.008D(L/B - 6.5) \quad \text{for } L \leq 120m \\ VCG_{hull} &= 0.01D[46.6 + 0.135(0.81 - C_B)(L/D)^2] \quad \text{for } L > 120m \end{aligned} \tag{9-14}$$

$$LCG_{hull} = -0.15 + LCB \tag{9-15}$$

where both LCG and LCB are expressed in percentage of the ship's length with positive results demonstrating the positioning of centers forward of amidships.

The VCG of machinery is given as a function of the inner bottom height h_{db} and the height of the over-head of the engine room D' as given by Kupras:

$$VCG_M = h_{db} + 0.35(D' - h_{db}) \tag{9-16}$$

The longitudinal center of the machinery weight depends upon the overall layout of the vessel. For machinery aft vessels, the LCG_M can be taken near the after end of the main engines.

The vertical center of the outfit weight is typically above the main deck and can be estimated using an equation proposed by Kupras:

$$\begin{aligned} VCG_o &= D + 1.25 \quad \text{for L} \leq 125 \text{ m} \\ VCG_o &= \text{D}+1.25+0.01(\text{L-125}) \quad \text{for } 125 \text{ m} < \text{L} \leq 250 \text{ m} \\ VCG_o &= \text{D}+2.5 \quad \text{for } L > 250 \text{ m} \end{aligned} \tag{9-17}$$

The longitudinal center of the outfit weight depends upon the location of machinery and deckhouse. The remainder of the outfit weight is distributed along the entire hull. A percentage of distributing the outfit weight and the longitudinal center of gravity is proposed by Lamb as follows:

$$LCG_0 = \begin{array}{ll} 25\%W_o & \text{at } LCG_M \\ 37.5\%W_o & \text{at } LCG_{dh} \\ 37.5\%W_o & \text{at amidships} \end{array} \tag{9-18}$$

where LCG_{dh} is the longitudinal center of the deckhouse.

4. Discussion on uncertainties in weight estimation

From the aforementioned methods we can notice that there are different sources of uncertainties and risk factors embedded in the weight estimation process, either in the preliminary design or even in the final weight estimation. The main sources of these uncertainties are:

- Innovative and novel ship designs and ideas
- Lack of the available data of similar ships and the lack experience of the designer and the shipyard.
- Small Deadweight/Displacement ratio, like in cruise vessels and ice breakers. Therefore, relatively small mistakes might have huge consequences on the weight estimation.
- An unclear division of responsibilities between designer and builder.
- A highly competitive shipbuilding market situation
- Economic troubles at the shipyard

These risk factors can be minimized by different methods, such as using statistics of similar ships, repeating the calculation using different methods, etc. However, it appears necessary to have margins on power, weights, water, space and other quantities. Small margins may lead to a situation where the design fails to meet its requirements. On the other hand, if the margin is too large, the vessel will be over-designed resulting in waste and potentially the designer's failure to be awarded the contract. Most current contracts include penalties if the vessel does not make design speed or some other requirements such as the deadweight. For lightship weight at early design the margin may be 3-5%.

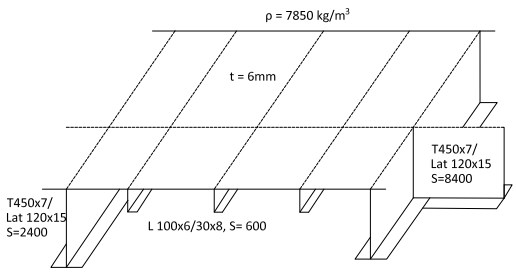
The weight calculation errors may be critical in cases where the ratio between deadweight and displacement is small—such as in icebreakers. Weight calculation errors may also be critical in cases where ratio between outfitting weight and total weight is large—such as in cruise ships. This risk of calculation errors can be minimized by; order of magnitude assessments, use of statistics of similar ships and compare them with the ship estimated weight, repeating the calculation using different methods and compare between them, or using adequate reserve weights and "scantling reserves." The reserve weight may be used to change the location of the center of gravity, for instance, reducing the KG to improve the ship

stability or changing the longitudinal location to adjust the trim. The lightweight often increases during the building, so the reserve weight should take into account this potential increase. Reserve weight is also beneficial if the owner needs some modification on the design during the building process. The lightweight reserve can vary depending on the ship type, the shipyard experience, and ship owner.

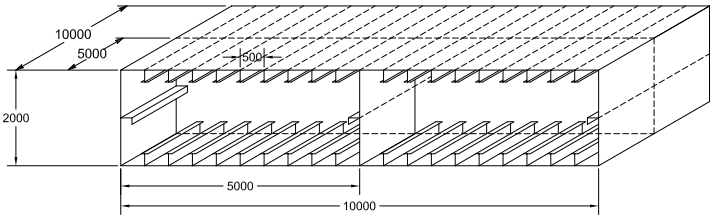
The preliminary design is usually followed by intermediate and final or official weight estimation. These advanced estimations are carried out using weight coefficients based on final drawings and general arrangement and the measured weights of the systems components. Eventually, the shipyard usually carries out post-calculation to study how the weight changed during the building process and compares these data with the actual value of the weight and its centroids obtained from the inclining experiment.

5. Questions

1. A mass of 6 tonne is moved transversely through a distance of 14 m on a ship of 4300 tonne displacement, when the deflection of an 11 m pendulum is found to be 120 mm. The transverse metacenter is 7.25 m above the keel. Determine the height of the center of gravity above the keel.
2. Estimate the outfitting weight of a cruise ship of 150 m length, 25 m breadth, and 9 m draught using Watson and Gilfillan parametric model.
3. A ship has the following characteristics: L=100 m, B=20 m, T=7 m, D=10 m, and displacement of 11480 tonne. Estimate (a) the center of gravity of the hull ; (b) the center of gravity of the machinery (given that double bottom height=0.7 m and height of the engine room= 5m) ; (c) the center of gravity of the outfitting.
4. You are required to estimate the main machinery weight for a preliminary design of a bulk carrier. The self-propulsion performance has been estimated and result in the maximum continuous rate=3 MW and an estimated rpm of 300.
5. What is the purpose of weight calculations when designing and building a ship? Describe different stages of weight calculations, the aim of those and discuss their limitations in terms of accuracy.
6. Calculate the weight of deck with area 1000 m^2 manufactured from the panel presented below.



7. Calculate the weight of the double bottom section illustrated below. The steel density is 7850 kg/m^3.



Solid floor spacing = 5000 mm
Solid floor plate thickness = 10 mm
All T 250x12/140x10
All L 200x80x10
All plates thicknesses t = 12 mm

8. Explain for what purpose the SFI Coding and Classification System and how it can be applied in the context of ship weight calculations.
9. What are the sources of uncertainties and risk factors of the weight estimation process?
10. What are the weight reserves and reserves in the vertical center of gravity? How and why do they vary in the preliminary design and at delivery time?

Lecture 10
Economic Assessment

1. Cost Categories

Engineering economic studies almost always involve an estimate of invested costs. For cost estimation and analysis, several costs are categorized into two main groups; the shipbuilding cost and the running or operating cost. The prime cost of a project is usually the single largest, hence most important, factor. Operating costs are to be further divided into voyage costs and daily costs. Although this information is out of the naval architects' responsibility, it is necessary to know how different costs are categorized and estimated.

Shipbuilding Costs. In preliminary design, naval architects usually have to choose between several alternatives based on ship performance and economics. This means that economics estimation models should be as simple as possible so that comparing different alternatives will be easy. Most of the cost estimating techniques fall into two major considerations; the **functional capability related costs** (e.g. costs related to deadweight and speed), or the **costs associated to technical characteristics** (e.g. major dimensions and power). The second family of techniques is usually more aligned to design.

Shipbuilding costs associated with functional capabilities can be estimated as follows:

$$P = C(DWT)^B \tag{10-1}$$

where C is a coefficient and B is an exponent typically about $0.7 - 0.8$. Both coefficients are derived from databases including information on similar vessels.

When technical characteristics are used as costing basis then lightship weight W_E is considered and the following equation is used:

$$P = C(W_E)^{0.87} \tag{10-2}$$

Overhead costs comprise all the costs necessary for running the shipyard but cannot be associated with any ship under construction. There are two basic kinds of overhead costs, those that are not related to how busy the yard is which are fixed overhead costs and those that vary with the level of activity of the yard and are termed variable overhead costs. Examples include salaries for administration staff and managers, cost estimators, and watchmen. Bills for electricity, real estate taxes, income taxes, and depreciation also are included in these costing items. In addition, overhead costs in many estimation models are considered to be a percentage of the labor costs.

Material costs are sometimes generalized and more accurately called outside goods and service costs as many shipyards use subcontractors.

Nowadays, the worldwide shipbuilding competition has led shipyards to try reducing ship - building costs for profitability and increase the probability of acquiring more contracts. There are various means of reducing shipbuilding costs such as reducing labor costs or man-hours. However, there is an indirect yet efficient solution in reducing shipbuilding costs. New technologies and methods of production such as automated production of stiffened panels and laser cutting based on CAD designs may help reduce production costs. Even though the volume of ships being built simultaneously might be relatively low, in most cases, the volume of similar intermediate products is considerable. For example, if a yard is building a few ships all at once in a given time, they might have a steady weekly demand for structural stiffeners and stiffened panels.

For predicting **operating costs**, a basic step is to analyze the time involved in a typical round-trip voyage; the operational profile of such a ship. An imaginary representation of a typical voyage would include the estimated times. **Voyage costs** are those that are affected by the voyage in which the ship is engaged (e.g. fuel and lubricating oil). Fuel costs per trip are usually multiplied with the estimated number of trips per year and the result is the annual fuel costs. The same procedure is followed when estimating the annual costs of the lubricating oil. A separate profile should be used to estimate the amount of fuel required for generators as the variation of the main engines' power requirement differ from those of the electric generators. Other costs such as port or canal fees, tug service, pilotage fees vary widely and are difficult to generalize. For instance, pier charge may be based on the ship's length, and pilotage fees may depend on the draft. However, perhaps a one parameter can be used to relate all these costs which is usually the net gross tonnage or the cubic number. Another important category is the cargo handling costs, which depends on whether or not it is included in the shipping contract. If it were be included, then it would be considered as voyage costs. In addition to cargo handling costs and associated with it, there are also brokerage fees, cargo damage claims and hold cleaning costs. **Daily costs** are those that continue year around regardless of the voyage. Among the daily costs, are the crew wages and their benefits. In the past, crew numbers were related to the ship's size and power. Nowadays, they are independent of ship's size and power, and the trend has been to reduce the crew number onboard, and alternatively, they depend on the shipowner's vision on his business and his willingness to invest in automated equipment, more reliable components, and minimum maintenance equipment. In addition to their daily wages, there are many benefits paid to the crew. An example is the wages paid to the crew in their vacation times, as in ship operations there may be crew rotation schemes. There are also sick benefits, payroll taxes, and repatriation costs (travel costs from the ship to their homes and vice versa). One other important running cost, while not quite operational, is the periodic maintenance cost. The periodic maintenance cost includes cost of dry-docking for repairs, generally occurring every 2.5 or 5 years.

2. Economic key performance indicators (KPIs)

As previously mentioned, in early design stages, there is a series of alternative designs and a decision has to be made on which of them is the best alternative operationally and economically. In an economic basis, there is no universally agreed upon technique for weighing the relative merits of alternative designs. That's because the criteria of a successful design might be affected by the shipowner's perspective. For example, business managers may agree the aim of designing a commercial vessel is to maximize profitability, but they may fail to agree how to measure profitability. On the other hand, government officials who are responsible for designing non-commercial vessel such as military vessels may find it difficult to decide on an alternative. Accordingly, several economic KPIs might be used, each of which has its benefits and the role of a designer is to know how to handle each of them. Noted that only two out of several known KPIs are discussed in this section.

The $\boldsymbol{Net\ Present\ Value}$ (NPV) is one of the most popular and easiest measures of merit to understand and use. NPV requires an estimate of the future revenues and it assigns an interest rate for discounting future cashflows. NPV is simply the present value of the projected cash flow including investments. Costs and revenues are projected on an annual basis over the lifetime of ship and the net cash flow is calculated (accounting for capital repayments including resale value, income and expenditure). These annual uniform cash flows (A) are then discounted back using interest rate r and over the ships lifetime n (number of years). The net present value is given by:

$$NPV = A\frac{(1+r)^n - 1}{(1+r)^n} - P \tag{10-3}$$

If P is a single lump investment NPV is calculated for each alternative and the higher the NPV, the better the alternative. Noted that if *NPV* is a negative value, the project would be rejected.

Example 1

A ship design alternative (A) has an estimated uniform cash flow of €2 million, a ship's expected lifetime of 25 years and a lump investment of €5 million. Another alternative (B) has a uniform cash flow of €1.5 million, an expected lifetime of 30 years and a lump sum of €3 million. The minimum required interest rate is 12%. State which of the two alternatives is the best using NPV.

Solution. Using equation (10-3) the following values for each alternative can be obtained in a tabular format:

Table 10-1 Solution of example 1

Project	Annual Cash flow (€)	Lifetime (years)	Interest rate (%)	Lump sum (€)	NPV (€)
A	2 M	25	12	5 M	10.7 M
B	1.5 M	30	12	3 M	9.1 M

Since project (A) has a higher NPV value, then it is the best alternative. Perhaps the annual cash flow is complex and non-uniform, and in such cases, NPV can be found using a year-by-year table in which each single future cash flow to be returned as a present value at the year zero using the following equation and the net present value can be then obtained as follows:

$$P = F(\frac{1}{(1+r)^n}) \tag{10-4}$$

where F is the future cash flow of each year n. Consider, for example, a project that is expected to involve the investments and after-tax returns shown in this diagram:

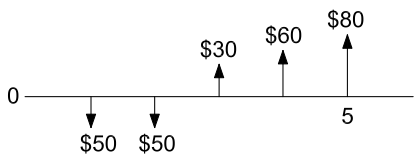


Figure 10-1 Sample of cash flow

Table 10-2 Annual cash flow

Year	Cash flow	PW @ 9%
1	€50	$-€50/(1+0.09)^1 = -€45.87$
2	€60	$-€60/(1+0.09)^2 = -€50.5$
3	€30	$€30/(1+0.09)^3 = €23.17$
4	€60	$€60/(1+0.09)^4 = €42.51$
5	€80	$€80/(1+0.09)^4 = €51.99$
		Net present value = €21.30

The **required freight rate (RFR)** provides a criterion which does not require an estimation of the revenue. It is the rate the shipowner must charge the customer if the shipowner is to earn a reasonable return on the investment. The theory is that the owner who can enter a given trade route with a ship offering the lowest RFR will best be able to compete. It establishes a freight rate by calculating annual costs (operating voyage, cargo handling, capital and repayments) and dividing them by the annual tonnage of cargo to be transported. The required freight rate is; therefore, a relative unit transport cost and its lowest value provides the most economical solution. It is therefore a good method for comparing various designs.

Beware, however, of the fluctuations of fuel and interest rates, particularly if they are important factors in the design. This measure could be applied to different types of cargoes such automobiles per year for a ferry, tons of fish per year for a trawler, passengers per year for a passenger ship, and so forth. Assuming a single invested amount P at year zero, uniform annual operating costs A, annual tons of cargo C, interest rate r and a ship's lifetime n, the equation for the required freight rate becomes:

$$RFR = [P(\frac{r(1+r)^n}{(1+r)^n - 1}) + A]/C \tag{10-5}$$

Example 2
Assume a proposed ship that can move 3.5 million tons of cargo over a given trade route each year. Its estimated first cost is €40 million, and its economic life is 20 years. the annual operating costs are estimated at €2.5 million. The owner stipulates a yield of 12%. What is this ship's required freight rate?

Solution. Using givens in the example, the required freight rate can be obtained as follows:

$$RFR = [€40M \times (\frac{0.12(1+0.12)^{20}}{(1+0.12)^{20} - 1}) + €2.5M]/3.5M\ ton = €2.24/ton \tag{10-6}$$

3. Shipyard Practice

It should be obvious for a designer that the shipyard capabilities and facilities affect several choices in design and construction. For example, small shipyards may do not have the capabilities and the workmanship for producing complex curvature-shaped ship, in such case, the choice of a planning hull is more considerable. It is also wrong to assume that the same design can be built with the same productivity and efficiency in different shipyards unless they are identical.

The **layouts of shipyards** have been developed over decades as both the ships being built, and the shipyard technology have changed. Such a shipyard layout should suit the environment surround the shipyard. The natural land topography found along riverbanks or sea cost influenced the shipyard layout. There are two basic examples of shipyard layouts shown in (Figure 10-2 and Figure 10-3). Some shipyards were established beside restricted water yet deep frontage. This layout is known by the narrow straight-line flow arrangement. Where there were steep hills or rocky nature of the land on which the shipyard is built, shipyards were squeezed onto the banks or shore and stretched along them to provide the needed land area as shown in (Figure 10-3). This type of layout is called the lateral wide or turning flow arrangement. It is clear in this type that the material flow is not ideal especially with shipyards that use large block construction. Where the river is not wide the building berths/launch-ways were set at an angle to the river in order to build and launch as large a

ship as possible. Where the river is even narrower, shipyards used side launching instead of end lunching.

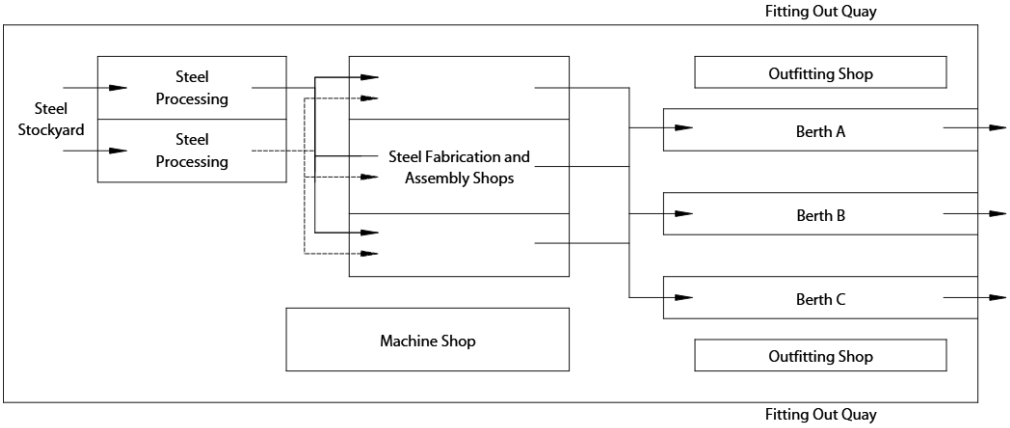


Figure 10-2 Straight line flow arrangement. Image credits: (Thomas, 2003)

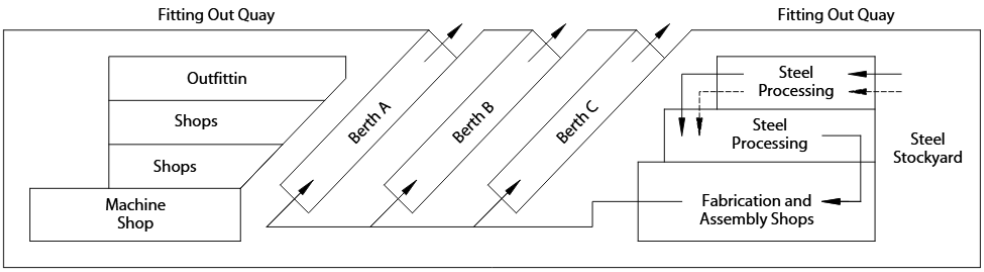


Figure 10-3 lateral wide or turning flow arrangement. Image credits: (Thomas, 2003)

In general, there are two basic forms of organization; the functional organization and the product organization. Other forms of organization are hybrid such as matrix organization. The functional organization gather resources into common activities. For instance, engineers and production workers are organized per function to produce a ship. On the other hand, the product organization is based on group-technology concept; multiple product line. The functional organization is the better when only one or a few ships are built in such a shipyard. Traditionally, the shipbuilding community looks at the ship as an entire end product. However, modern shipyards nowadays breakdown the ship into subassemblies together create a larger assemblies (blocks) and which are assigned for production to the most cost-effective producers inside the shipyard or by using subcontracting. Although the shipyard can gain a lot of benefits from hiring subcontractors, there are several challenges the shipyard should predict and deal with. The challenges are: delivery problems and delays due to negligence of the subcontractor or force majeure reasons, transportation challenges, like the transportation of big blocks that are built in workshops far from block assembly site, quality/performance issues, especially due to lack of experience, communications, information flow, cultural/language issues, and intellectual property rights issues.

Block assembly is a module-based assembly which uses prefabricated blocks, created in shipyard facilities before being transported to the dock. Block assembly greatly improved shipyard efficiency as the material can be sent to many different facilities at once, speeding up the building process. Grand blocks should be assembled as large as possible before entering the dock, to maximize efficiency. Block division of the ship, therefore, is an important consideration which includes the alignment and maximization of structural division and the overall layout and weight carrying capacity of the shipyard. Figure 10-4 shows the process of block-based construction. The block assembly process makes it clear that outfitting is more efficiently done in earlier stages, where the working condition and transport of material is much better, decreasing building time. Modularization of outfitting is therefore another important part of increasing shipyard efficiency. Outfitting components such as piping, cabin blocks, and machine modules can be prefabricated.

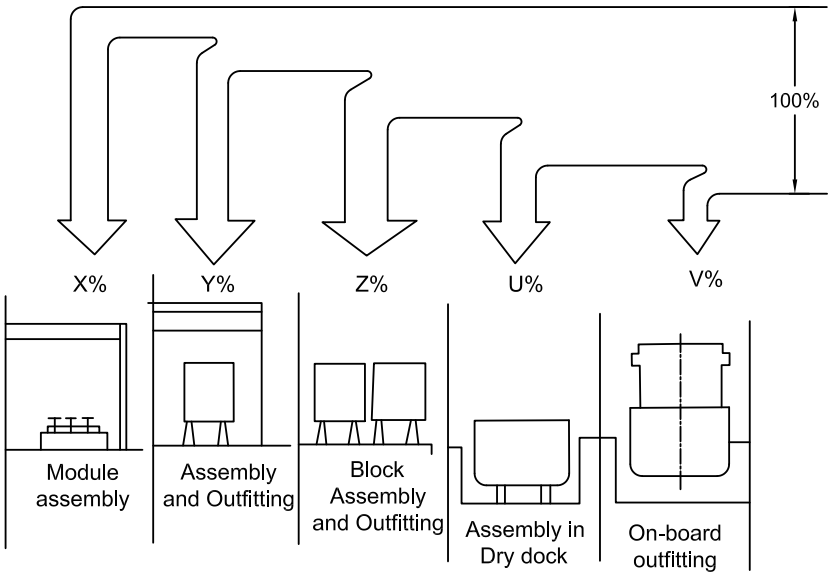


Figure 10-4 Block Construction Process

As the shipbuilding cost is mainly reduced through shipyard efficiency, it is practical to determine a measure for shipyard efficiency. The efficiency can be measured as the amount of production per number of employees. The “compensated gross- tonnage” (CGT) can be used also to measure the efficiency of the shipyard. It is a measure of shipbuilding output which takes account of the work content of the ship. It is calculated by multiplying the gross tonnage of a ship by an appropriate conversion ship factor for that ship type. The comparisons of shipbuilding output working on different types of ships cannot be measured by deadweight or gross registered tonnage as some ships had a higher work content per gross ton than others. Therefore, we use the CGT instead.

Another key method for reducing shipbuilding cost is through new technologies. New technologies implemented at shipyards include laser scanning and CAD models. Laser scanning enables reverse engineering and quality control. It is adopted in some 3-D printers, in rapid prototyping, in machines for material processing, in laser engraving machines, etc. CAD programs have a significant influence on the marine industry in both the design and production stages. The CAD models also have application for refit projects, digital prototyping, finite element analysis and virtual reality. However, most of these measures focus on design which is only a small part of the total cost of building a ship. System integration of different software in ship design is increasingly important as software becomes more integral to the engineering process.

4. The shipbuilding contract

A contract for building of ship/ships is a consequence of a decision by the shipowner to acquire a vessel or a series of vessels to achieve the objectives of his organization. Examples of these objectives are a favourable return on investment, a public service (ferries, research or rescue ships), acquiring a transportation link through a larger logistics system, or scientific research.

After the decision to acquire a new vessel is made, there are basic follow-on steps necessary. An important step is to decide on the ship's technical specifications and technical drawings which define the physical ship that will meet the owner requirements. This step forms the contract specification part in the shipbuilding contract. Besides, there are also non-technical decision to be made such as selecting the naval architectural company or consultancy office to develop the technical requirements, identifying qualified shipyards to be invited to submit bids or proposals, selecting the flag of registry and the classification society that will be involved in ship design, construction, and operation.

Contract Specifications and Contract Plans define the unique features of a vessel and other non-unique features that are not already addressed by the appropriate regulatory requirements and classification rules. Generally, there are three main types of specification to be defined:

- Design and end product specifications,
- Performance specifications,
- Procedural specifications.

The contract specification may have more than one type of specification and may include the three types as this part comprises all the different aspects of such a ship. A design or end product specification is a representation, by either drawings or verbal descriptions or both, of what that aspect of the ship should look like upon completion. For example, contract specifications may define the type, composition and colour of the coatings, as well as perhaps

the manufacturer, and then go on to define the thicknesses of each of the primer, undercoat and topcoat. In addition, contract plans may define the final hull form of the ship. A performance specification, on the other hand, does not in any way describe what the object will look like, but instead will describe how it is to perform. A specification for the ballast pumps on a ship, for example, could state that the two ballast pumps shall each separately be capable of pumping into and out of the ship's ballast tanks a certain number of tons of ballast water per hour. A procedural specification usually supplements one of the two other forms of specification by defining part of the procedure that is to be followed in achieving the other part of the specification, either in the design process or the construction stage. An example of a construction procedural specification pertains to coatings: the design specification for the coatings, may be supplemented by a procedural specification that requires the Contractor to apply the coatings in accordance with the practices recommended by the coating manufacturer pertaining to surface preparation, air temperature, steel temperature, relative humidity, direct sunlight, wind speed, etc. It is necessary to know that there are some main specifications must be included in a shipbuilding contract whatever the type of specification they lie in. There are for instance the ship's main dimensions, deadweight, capacity, sea trial speed, and limit for noise and vibration.

5. Questions

1. A €5 M investment on a ship promises annual returns of €700,000 over 20 years. Find the net present value based on 9% interest.
2. Find the NPV at 8% for this cash flow: €1000 expense now, €2000 expense a year from now, €2000 income two years from now, and €2000 income three years from now.
3. Find the required freight rate for a dry bulk carrier that has an initial cost of €80 million, annual operating costs of €1.85 million, and an annual transport capacity of 4.25 million tons. The ship's life is 20 years, and the interest rate is 14%.
4. Suppose that certain end-of-year cash flow are expected to be $1000 for the second year, $2000 for third year and $3000 for the fourth year and that if the interest is 15% per year. It is desired to find the equivalent present worth value.
5. If a certain machine undergoes a major overhaul now, its output can be increased by 20% which translated into additional cash flow of $20000 at the end of each year for 5 years. If i = 15% per year, how much can we afford to invest to overhaul this machine?
6. Explain the methods used to reduce shipbuilding costs. How does shipyard organization play into these methods?
7. Find the required freight rate of a ship that carries 2 million tons of cargo yearly, has an initial cost of €100 million, a lifetime of 20 years, and 12% interest rate.
8. List and explain the main shipbuilding costs
9. List and explain the main operating costs
10. What parts of preliminary design are needed to prepare a contract? Explain the importance of performance criteria in the contract?

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Shipping is responsible for 90% of world trade. The design, equipment and function of ships are subject to constant evolution that intensified recently because of emerging sustainability and safety requirements, the changing patterns of world trade and technological evolution. It is becoming increasingly evident that the Naval Architects and Marine Engineers of the future will be less tied to conventional ship types, will work in less deterministic ways and will have to adapt to market demands. Yet good understanding of the basics shall remain essential. With the above in mind, this set of lecture notes outlines some of the Principles of Naval Architecture and Marine Engineering for use in concept ship design. The material presented can be used by undergraduate students or early stage postgraduate students of Marine Technology.

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