Ten Lectures on Basic Naval Architecture (1st Edition)

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Preface

Shipping is responsible for 90% per cent 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 textbook briefly outlines Principles of Naval Architecture along the lines of the synonymous MSc course (MEC-E1004) I have been delivering at Aalto University since September 2019. The lecture notes are auxiliary to series of presentations and tutorials delivered at class.

I am grateful to my Teaching Assistant Mr. Zeiad Abdelghafor for helping me to conceptualize this set of lecture notes.

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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 various Classification Societies (e.g. DNVGL, ABS, LR, BV, etc.) 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 and 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 also it is 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) (b)

Figure 1.1 Ship Design Evolution (a) Replica of ancient Greek Trireme Olympias © Hellenic Naval Academy; (b) The Phoenix – World City Cruise ship © Knud E. Hansen

1. The ship design spiral

In Naval Architecture the design spiral (Figure 2.2) 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. Those different stages are defined as follows :

- **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.

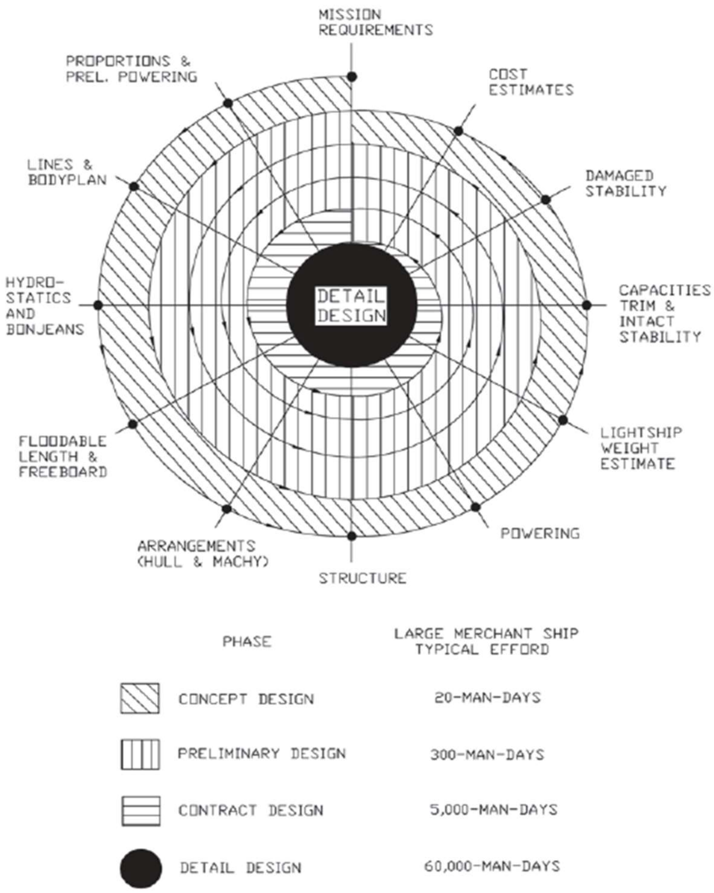


Figure 2.2 Design Spiral (Thomas, 2003)

2. Ship types and mission requirements

At concept design stage, mission requirements should be defined objectively. 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 and examples are explained below. For **naval ships** concept exploration must consider those capabilities and design parameters that are necessary to succeed in operations that may 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 of 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 have to 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 has to 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 such a kind of cargo from point A to point B in a defined time taken into considerations changes in the ship course and the operational area during the ship's lifetime. Besides, achieving this mission should come together with 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). For example, **container ships** use an uninterrupted almost prismatic volume, to allow for easy storage and loading/unloading of containers. Nevertheless, a compromise has to be reached 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 be also 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).

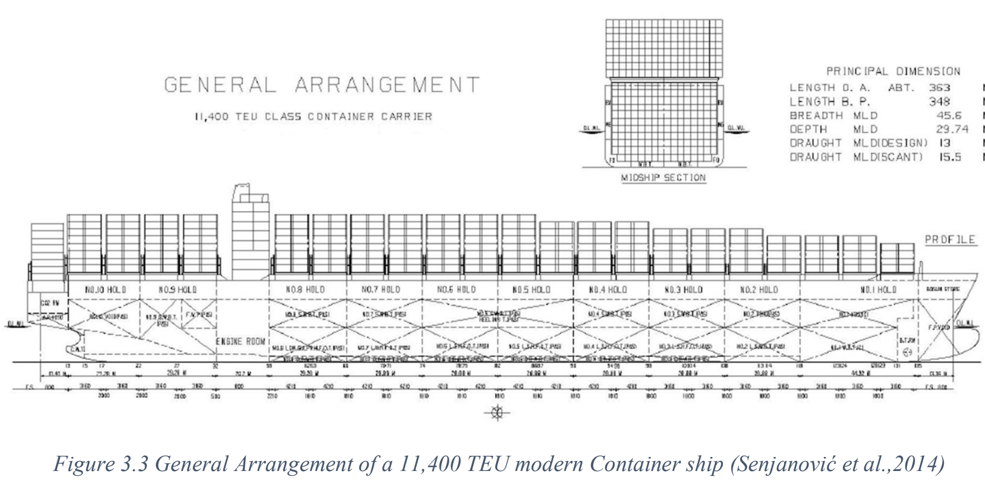


Figure 3.3 General Arrangement of a 11,400 TEU modern Container ship (Senjanović et al.,2014)

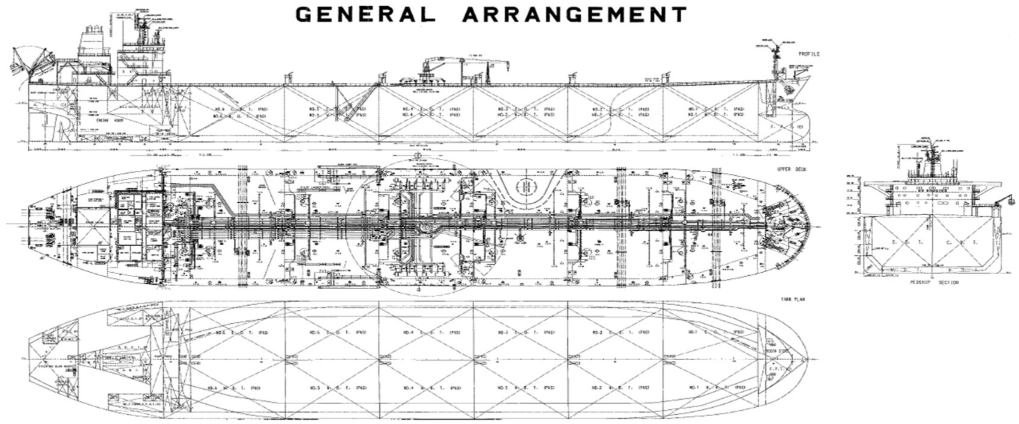
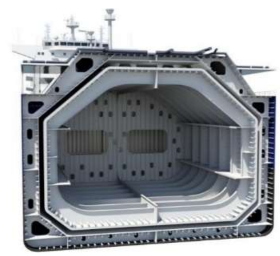


Figure 4.4 General Arrangement of a modern Tanker Ship (Papanikolaou et. al., 2010)

(a)



(b)

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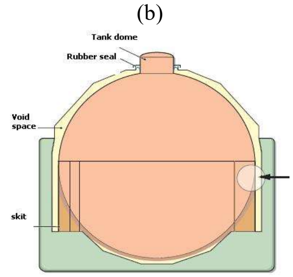
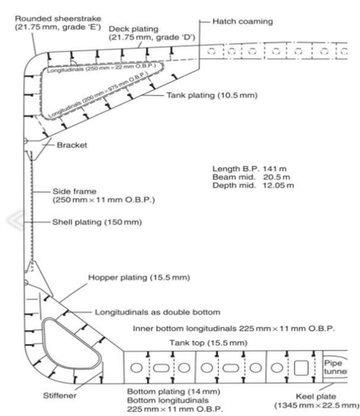


(d)

Figure 5.5 Modern LNG carriers and their containment systems (a) Membrane type LNG ship; (b) Typical Mark III type LNG containment system ; (c) Moss type LNG ship ; (d) Moss Rosenberg type LNG cargo containment system (http://www.liquefiedgascarrier.com/)

(a)



(b)

Figure 6.6 Bulk Carrier concepts (a) Modern Handy-size Bulk carrier from Bluetech Finland Ltd. ; (b) Typical mid-ship section of a bulk carrier (https://www.worldmaritimeaffairs.com/)

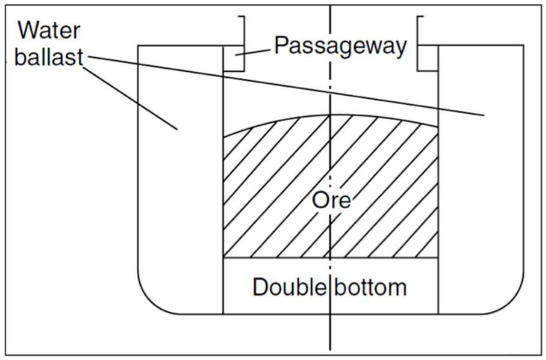


Figure 7.7 Mid ship section of an Oil-Bulk-Ore (OBO) Bulk Carrier (https://www.marineinsight.com/)

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. That's because some non-technical aspects such as the customer experience are difficult to be defined 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.

Figure 8.8 Aerial view of Happag Lloyd Europa 2 cruise ship (© Happag Lloyd)

3. Ship design parameters

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.

In order 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 operate in ice conditions have to 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 increase for 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 1.10).

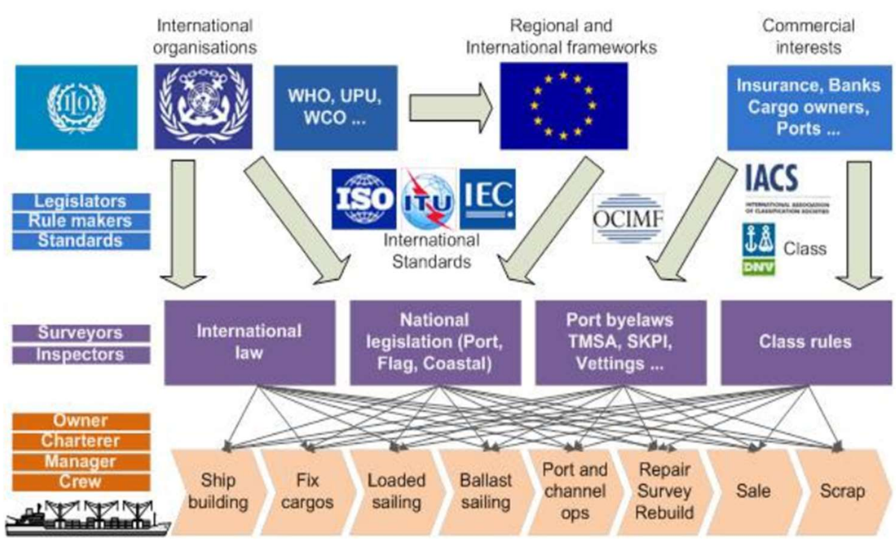


Figure 9.10 The interplay of maritime regulations (Image credit www.marinelink.com)

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. 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)**. 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)[1]. **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.

Figure 10.20 Headquarters of the International Maritime Organisation (IMO), London, UK (https://www.britannica.com)

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 European Maritime Safety Agency (**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

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

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, in occasion consultants, technical advisers and assist the regulators 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, Det Norske Veritas, Nippon Kaiji Kyokai, American Bureau of Shipping, Germanischer Lloyd, 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 CO2 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.

Research Area	Technology	2010-2014	2014-2020	2020-2030
Resistance and Powering	Ship resistance in waves	✓	✓	
	Optimisation	✓	✓	
	Novel Hull forms		✓	✓
Auxiliary propulsion	Novel Propulsors	✓	✓	✓
	Propeller Design methods	✓	✓	
	Propulsor/appendage interactions	✓	✓	
	Retrofit Technology Support	✓	✓	
	Wind Propulsion	✓	✓	
	Propulsor Efficiency Indexing		✓	
Operational Aspects	Operational Optimisation	✓	✓	
	Hull Air Lubrication	✓	✓	✓
	Ice and Cold operations	✓		✓
	Ballast Free operations			✓
Environmental Aspects	Noise & Vibration	✓	✓	✓
	Performance Assessment	✓		
	Acoustic emissions monitoring		✓	✓
Fuels	LNG and CNG as a fuel	✓	✓	✓
	Biofuels, methanol and ethanol		✓	✓
Engineering systems	New diesel engines	✓	✓	
	Heat recovery systems	✓	✓	
	Selective catalytic reduction	✓		
	Fuel water emulsions	✓		
	Exhaust gas recirculation	✓		
	Advanced battery technologies	✓	✓	
	Fuel cells		✓	✓
	Scrubbers	✓	✓	
	Nuclear propulsion			✓
	Tidal stream ships		✓	✓
	wave power propulsion		✓	✓
Corrosions and Coatings	Protective coatings	✓		
	Cathodic Protection Systems	✓	✓	
	Autonomous intelligent systems	✓		
	Antifouling systems	✓	✓	
	Coatings for Ice Class ships	✓	✓	
	Corrosion Monitoring Systems	✓		
	Tank Corrosion Maintenance	✓	✓	
	Coatings Condition Monitoring	✓	✓	
	Effect on high strength steels		✓	
Marine structures	Ship motions and loads	✓	✓	✓
	Climatology	✓	✓	
	Damaged ship structures	✓	✓	
	Crack monitoring	✓	✓	
	Stress monitoring	✓	✓	
	Crack tolerant approaches	✓	✓	✓

Table 1.1 Outlook of environmental technologies for shipping (Hirdaris and Cheng, 2012)

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 marine rules and regulations are developed, applied and how do they influence ship design ?
9. Discuss the importance shipping sustainability and the importance of green technologies on ship design.