INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED23
24-28 JULY 2023, BORDEAUX, FRANCE

COMPLEX SYSTEMS DESIGN: SUSTAINABILITY CHALLENGES FOR SHIPBUILDING

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ABSTRACT

Ships are complex technical systems resulting from large scale and scope projects in which integration plays a key role, particularly because trade-offs have to be made between conflicting objectives.

Merchant ships are usually built with a perspective of twenty-five years of service. Ship owners detail their requirements and ship specifications in line with their strategy to remain competitive on specific segments of the shipping markets. Ships serve and organize global trade flows. The rise in environmental regulations and technological changes generate unprecedented uncertainties for ship owners.

Ships do not follow the usual systems engineering process, as there is no full-scale prototyping. Rules and standards deeply influence the design of ships and limit the possibilities to ’think outside the box’.

The purpose of this paper is to present environmental drivers relating to the operation of the ship which have, or will have, an influence on the way it is designed.

Keywords: Design engineering, Ship, Complexity, Sustainability

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Cite this article: Bouyssou, A., Baumler, R., Öhrwall Rönnbäck, A. (2023) ‘Complex Systems Design: Sustainability Challenges for Shipbuilding’, in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.103

1 INTRODUCTION

Ships are as old as humanity itself (Paine, 2014). Since the move from sail power to mechanical power during the last decades of the nineteenth century (Woodman, 2009), these human-made structures, and their operation, have experienced tremendous transformations under the combined influence of globalization, economic pressures, social progress, as well as technological advancement (Tupper, 2004). This era of unprecedented speed, scale and connectivity in the development of human activities at sea has been coined as the 'Blue Acceleration' (Jouffray *et al.*, 2020). The result is that today's ships are undoubtedly among the most complex, massive and expensive engineering products. Designing and developing vessels involve the coordination of multiple suppliers, stressing the importance of integration (Ahlers, 2004).

It is noteworthy that ships do not follow the usual product engineering process – i.e. planning, concept development, system-level design, design, build, test, production ramp-up (Ulrich, Eppinger & Yang, 2020). Full-scale production for ships begins at the end of preliminary design, contrary to other vehicles. No full-scale prototypes are built and tested before constructing ships. Rather, they are developed on the basis of a system of rules and standards (Drezner *et al.*, 2011). Similar to the civil engineering sector, shipbuilding long depended on empirical knowledge and the impossibility to construct and test full-scale prototypes (identical for large buildings or bridges). On the contrary, newer transport modes (trains, cars, aircrafts) emerged with science and labs. Their reduced sizes allowed the construction of prototypes for testing and improvements.

When compared with other means of transportation, current ships remain giants (cf. Figure 1). The rare engineering constructions overtaking ship size are massive manufacturing sites or record-breaking towers.

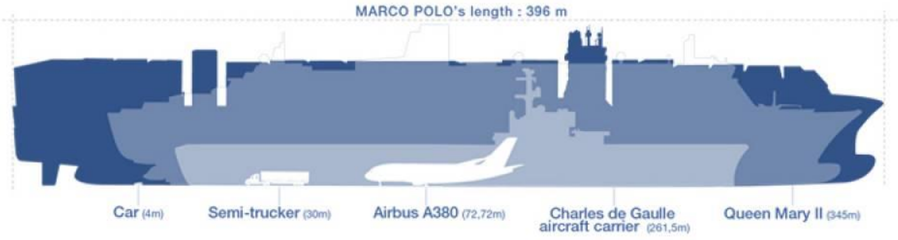

Figure 1: size comparison between the CMA-CGM container ship Marco Polo and other transport units

(source: https://www.meretmarine.com/fr)

To maintain low transportation costs, shipowners target economies of scale with vessel sizes getting larger, thereby imposing new operational and technical requirements (Stopford, 2008). In regard to other engineering products, ships are characterized by a considerable lifespan, beyond twenty years on average (UNCTAD, 2020).

Ships operate amid dynamic and uncertain environments. To perform their functions, they need to resist impacts and continuous stress on their structure. Integrity and stability must be preserved at all times. Therefore, ships are designed and constructed to withstand harsh conditions, including extreme cold and wave impacts. From the design stage, the operation of a particular ship is constrained by strength and stability limits. The crew strives to operate within design limits determined by others. Ship handling by the crew requires specific competences and resilience strategies, i) to adapt to dynamic environments, and ii) to make appropriate decisions when the ship is isolated at sea. Indeed, when at sea, seafarers have to rely upon themselves, using the existing but limited equipment and knowledge available on board.

The high concentration of machines, cargos and human beings on a small area increases risks, for instance fire risks. Hence, seafarers' training and onboard familiarization with emergency procedures are regulated and regularly tested via drills (IMO, 2017, 2020). The practice of safety onboard and the implementation of related processes are of utmost importance, because inattention and errors may lead to loss of life, as well as costly impacts on the marine environment and/or supply chains. Despite their existence, Search And Rescue (SAR) forces are not always able to assist the ship – e.g. in bad weather and sea conditions or when the ship is in a remote location (Futch & Allen, 2019). Ships must be designed to sustain ocean dynamics, ensure survival at sea and allow emergency response by its crew.

In order to complete their transport mission, ships are still bounded by regulations allowing resilience at sea. From a business point of view, ship owners discuss ship design by determining i) the type of cargo to be carried and its volume, ii) the trading route and average speed (Wollert, Lehne & Hirsch, 1992; Watson, 2002). These basic requirements impose technical choices to balance with the regulations. Despite their diversity in sizes and types, current cargo ships share the same features in terms of propulsion (massive diesel engines) and steel hull with ballast tanks to distribute onboard weights (for stability, structural stress management, propeller immersion, efficiency, etc.). Technological choices have environmental impacts all the way from ship construction to ship dismantling, with no exception for ship operation. To reduce these impacts, the international community determined and adopted specific regulations via the International Maritime Organization (IMO).

The overall objective of this paper is to introduce environmental drivers relating to the operation of the ship, to analyze the extent to which such drivers have an impact on the design of ships, and to show that compromises have to be made with economic and regulatory constraints.

2 METHODOLOGY

The present analysis is a desktop study, based on a systematic review of the literature retrieved from the Scopus database.

The related research question was “Are international environmental standards among the key design variables of a ship?”.

The search terms were combined as follows:

- Search No. 1: product AND development AND maritime AND ship AND design AND systems AND engineering, with a result of 21 articles, 6 of which were downloaded and reviewed.
- Search No. 2: product AND development AND maritime AND ship AND design, resulted in 61 articles, 9 of which were downloaded and reviewed.

The articles that best represented the research question were selected from the search results.

A research gap was identified on the subject of design and development of ships with regard to international environmental standards.

3 INTERNATIONAL ENVIRONMENTAL STANDARDS APPLICABLE TO SHIPS

Ship design is an iterative process, framed by national and international regulations, as well as ship owners’ specifications/demands/beliefs. Trade-offs and sacrifices are arbitrated by the buyer – i.e. the ship owner (Mistree, Smith, Bras, Allen & Muster, 1990). Maritime transport is a highly international business, hence most regulations governing shipping and the marine environment are international. The IMO is the specialized agency of the United Nations promoting “safe, secure and efficient shipping on clean oceans”. This motto summarizes the three aspects of sustainability, namely economic, social and environmental. However, to enter into force, maritime instruments require their ratification by countries representing a particular Gross Tonnage (GT) of the world fleet. This provides enhanced power to ship owning nations over the regulatory development and entry into force of maritime instruments (Baumler, Carrera Arce & Pazaver, 2021; Transparency International, 2018). The difficulty of reaching consensus in the midst of divergent national interests generates delays in the adoption of IMO regulations. As a result, i) optimal solutions might have to be disregarded in order to reach a common understanding, and ii) when a convention enters into force, the technological solutions envisaged may already be outdated (Ma, 2010).

3.1 Regulatory environmental drivers

Since the adoption of the International Convention for the Prevention of Pollution of the Sea by Oil (OILPOL) in 1954, and its replacement by the International Convention for the Prevention of Pollution from Ships (MARPOL) in 1973, the IMO adopted a diversity of international rules and standards. In particular, the 1997 Protocol to MARPOL introduced an annex dedicated to the reduction of air emissions from ships in two categories: air pollutants and greenhouse gases (GHG). Ships built after 1 January 2013 must comply with a minimum energy efficiency level called the Energy Efficiency Design Index (EEDI). The EEDI measures the CO2 emitted (g/tonne-mile), taking into consideration ship design and engine performance data. To strengthen the reduction of GHG emissions from shipping, the IMO has adopted its Initial Strategy on Reduction of GHG Emissions from Ships and defined the objective of curbing carbon emissions by 40% by 2030 and 70% by 2050 in comparison to the 2008 levels, defined as a baseline (International Maritime Organization, 2018).

There is a financial hurdle posed on shipowners to comply with additional environmental regulations. Indeed, ship retrofitting and/or the replacement of parts of on-board systems represent significant costs. The objective pursued by shipowners is to operate compliant ships at the lowest cost (Stopford, 2008).

3.2 Other non-regulatory environmental drivers

The greater focus from shipping companies' customers on the carbon footprint across the whole supply chain pressures shipping companies and related industries to research for cleaner maritime transport. There are also environmental pressures from the society. Two examples are i) the Green Ship Campaign (Hydro International, 2007) supported by the Institute of Marine Engineering, Science and Technology (IMarEST) together with Castrol Marine, Eco Ports and ProSea, and ii) the EU-funded Clean Shipping Project in the Baltic Sea region (Clean Shipping Project Platform, 2022).

3.3 Complex nature of shipping

The maritime industry has proved particularly complicated to regulate. As any ancient activity, its regulatory framework evolved from customary law to international law over long time periods. This regulatory structure became even more complex with the inclusion and interrelationship of numerous stakeholders with divergent interests (Boisson, 1999). The operation of the ship itself is far from being simple because ships may be owned by one company, chartered to another one (with varying levels in responsibility according to the charter-party) and operated by a third one. Chosen by the ship owner, the flag determines the regulations applicable on ships and their level of enforcement. Ships may be flagged in any country (Panayides, 2017). The link between beneficial owners and flags is not always visible, allowing unlawful practices and the spread of substandard ships via 'flags of convenience' (Carlisle, 1981). Ship management may also be fragmented into myriad subcontractors or, at least, be divided into two parts: the nautical/technical management[1] and the commercial management[2]. As a consequence, the responsibility for the operation of a ship – nautical management and commercial management – does not always fall upon the owner of the ship. This distribution of actors involved in ship operation and the multiplicity of configurations allow a dilution of responsibilities, as well as possibilities for owners to evade their corporate responsibility (Vuillemey, 2020). The situation may impact the quality of the crew and the maintenance of the ship, causing both safety and environmental risks. As a consequence, enforcing new environmental rules in the shipping industry is a (tremendous) challenge. Considering the weaknesses of flag States, the maritime community developed the concept of Port State Control (PSC) as an additional line of defence to enforce international requirements on foreign vessels calling in national ports. PSC inspections participate in the application of international maritime safety and pollution prevention standards.

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[1] The nautical/technical management refers to the crew, the maintenance of the equipment, the insurance of the vessel, the provision of stores and supplies, etc.

[2] The commercial management relates to the commercial use of the vessel, for example the provision of bunker fuel, the payment of port charges, etc.

4 SHIP DESIGN: A COMPROMISE BETWEEN REGULATORY AND ECONOMIC CONSTRAINTS

Ships are built in the same countries, namely China, South Korea and Japan, according to the same set of standards which, in theory, establish a fair competitive environment (Pettersen Strandenes, 2010). While the IMO develops international regulations, classification societies produce their own classification standards detailing the construction and maintenance of a ship's hull, main and auxiliary engines, as well as electrical and automation equipment. Classification societies have been granted a pivotal role in ship building (IMO, 2020). Reputable classification societies joined in the International Association of Classification Societies (IACS) to coordinate and develop common rules, particularly in terms of ship building (Horn, Arima, Baumans, Bøe, & Ocakli, 2013). Hence, two sets of rules (generally compatible) apply on ships with the consequence for the flag State and classification societies to deliver certificates. Classification certificates are considered as evidences of seaworthiness, for instance in courts. Among the regulations ships have to comply with, some have proven to exert serious detrimental effects on ship design, because they limit designers' freedom.

An indirect hindrance to innovation in ship design is the outdated International Convention on Tonnage Measurement of Ships (1969) (Baumler & Ölçer, 2013). The Tonnage Convention defines a uniform method of measuring a ship's gross tonnage – or ship's magnitude – to establish tax, regulatory thresholds or data management. The Tonnage Convention creates an incentive to shrink unnecessary volumes/spaces to reduce the overall computed tonnage (IMO, 2012). Crews' individual and collective living and working areas on board ships, but also safety and other spaces, are affected. As a consequence, the Tonnage Convention stifles ship designers' creativity because their primary focus is on the reduction of enclosed cubical capacity whereas innovative designs might involve extra volume (IMO, 2012).

5 TWO EXAMPLES OF RESTRICTED INNOVATIONS IN SHIP DESIGN

5.1 Integration of new ballast water management (BWM) rules

By nature of their design, most ships must carry seawater on board to maintain seaworthy conditions. For centuries, ballast came in the form of sand and rocks. However, with the introduction of steel hulls and steam-driven pumps, it became possible to use seawater as ships' ballast. The loading or discharging of ballast tanks allows to distribute onboard weights to maintain proper stability, trim and draught, to adjust list and limit stresses on the hull. Unfortunately, the water pumped in the tanks contains organic and non-organic matter. Aquatic organisms (among them some may be pathogenic), as well as fish eggs and larvae, survive in the water and settle in tank bottoms with sediments. Organisms can also attach to the outside of ships through the process of biofouling, on e.g. the hull, anchor, chain, and propellers. The transfer of biological matter via ballast or biofouling between ports along the ship's voyage may cause severe damage to ecosystems when multiplying into the new biotope and becoming destructive for local habitats and indigenous species. Some of them may also endanger human health or cause infrastructure damage (GEF-UNDP-IMO GloBallast Partnerships Programme & WMU, 2013). The IMO has addressed the risks of ballast waters and sediments with the adoption of the International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004 (BWM Convention). The Convention requires that ballast water is managed to a certain standard. Either ballast water exchange (BWE) in mid-ocean (Regulation D-1) or ballast water treatment (BWT) (Regulation D-2). The Convention also requires that all ballast water management systems (BWMSs) "must be safe in terms of the ship, its equipment and the crew" (Regulation D-3.3). Indeed, some BWMSs utilize, or generate hazardous substances which may threaten human and animal health, ship safety and the marine environment. As a consequence, naval architects and engineers now integrate the ballast water management constraint in design and construction:

- New configuration of ballast tanks to ensure safe and effective BWE at sea, sediment removal and ballast water sampling.
- Dedicated spaces to accommodate BWT plants.
- Effectiveness and ergonomic criteria for BWMSs (e.g. resist the extreme conditions which may result from the ship's motion, facilitate the collection of data, documentation for use, easy basic maintenance for the crew).

- Testing of BWMSs.
- Worldwide availability of spare parts, repair and maintenance services (perspective on the durability and long-term reliability of BWMSs).

Alternative systems fall into two categories (GEF-UNDP-IMO GloBallast Partnerships Programme & GESAMP, 2011): i) no ballast/zero discharge ship designs, and ii) continuous-flow ship designs. For certain ship types, companies such as Det Norske Veritas (DNV) and ClassNK (gCaptain, 2013) developed an innovative crude oil tanker design eliminating entirely the need for ballast water (see Figures 3 and 4).

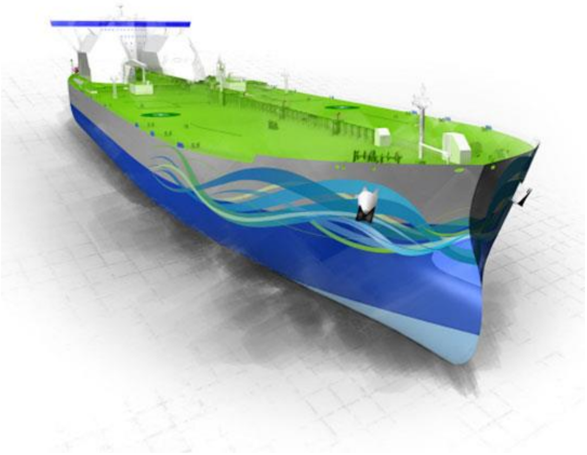

Figure 3: Triality, a DNV's ballast-free VLCC design

(source: http://www.marinelog.com)

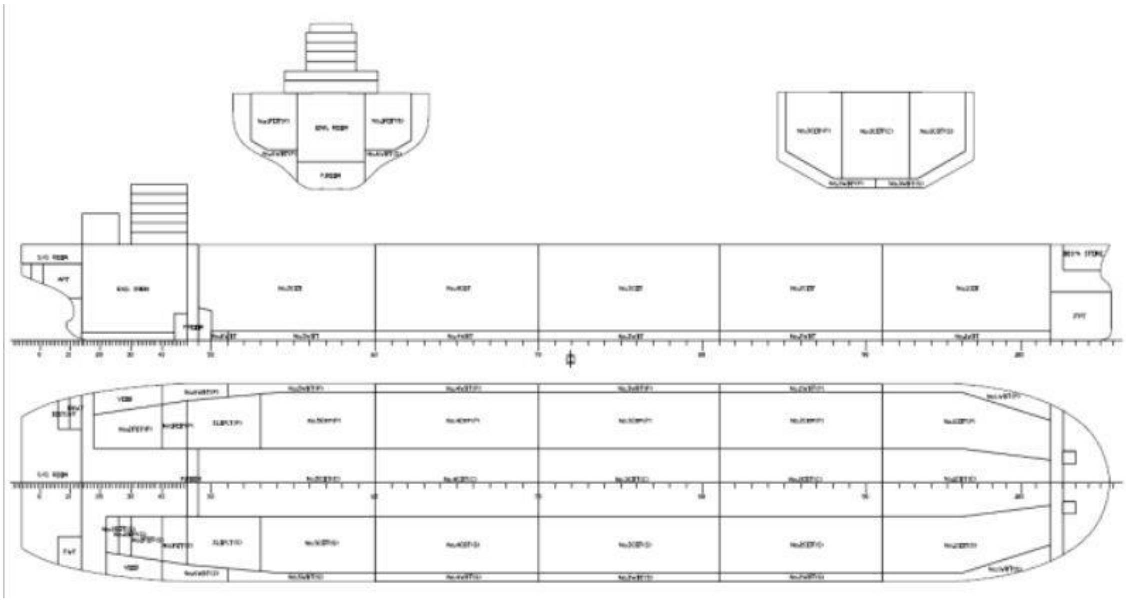

Figure 4: Minimal Ballast Water Ship VLCC design developed by Namura Shipbuilding Co., Ltd. in cooperation with the Shipbuilding Research Centre of Japan

(source: https://gcaptain.com/)

No ship has ever been constructed according to these designs, although providing enhanced environmental protection, because they resulted in increased GT. Thinking the ships of the future makes it necessary to take into account the effects of regulations on the design of ships, address a number of barriers, to open up new possibilities.

5.2 Deployment of wind propulsion

Machines and engines were late inventions in the long history of navigation. For millennia, wind and muscles powered ships. Wind propulsion systems have been the object of thousands of years of development, from old cargo ships to contemporary wind craft racing. The seventy-year transition from sails to engine-powered ships took place in the nineteenth century (Woodman, 2009; Barron, 2016). Today, wind propulsion systems are categorized as innovative mechanical energy efficient technologies to reduce fossil fuels consumption. Various types of devices (sails, rotors, kites, etc.) capture wind energy and generate thrust (Lloyd's Register, 2015). It is estimated that a reduction of 10 to 30% on fossil fuels consumption can be achieved when wind propulsion systems are adapted on existing ships (20% with kites). For newbuilt ships, this reduction may account for 50% of fossil fuels consumption (International Windship Association, 2022). Available options (International Windship Association, 2022; Lloyd's Register, 2015) are categorized as follows:

- Flettner rotors (Figure 5): they are fixed cylinders on the ship's main deck. They increase both the vessel's air draft, and its resistance to motion in the air (which does not go towards energy efficiency).

Figure 5: Flettner rotors fitted on a ship's weather deck

(source: International Windship Association)

- Soft sails: they are traditional / textile sails which can be folded.
- Hard sails (Figure 6): they look like aircraft wings. They cannot be used on certain vessels' routes because they cannot be folded.

Figure 6: Example of ship equipped with hard sails

(source: International Windship Association)

- Kites (Figure 7): they are attached to the bow of the vessel and use wind energy to substitute power from the main engine. As there is a speed restriction, only tankers and bulk carriers (the slowest ships) can be equipped with this system.

Figure 7: Use of kites to move ships

(source: International Windship Association)

- Hull innovation (Figure 8): improvements in ship design allow to take advantage of the wind.

Inspired by airfoil techniques harnessed by the aviation and sailboat industries, *Vindskip*'s wind-powered propulsion enables a 63% reduction in CO_2

Figure 8: Revolutionary innovation in hull design for CO_2-emissions abatement

(source: Vindskip AS)

Wind propulsion systems can be adapted to both existing and newbuilt ships. Wind-propelled ships require the selection of the optimal route depending on season and immediate weather dynamics. Weather forecast and routeing companies already calculate routes, according to wind historical (statistical) data and immediate information, for racing sailing ships and some cargo vessels. However, the last two centuries of economies of scale significantly increased ship size, thereby affecting the capacity of wind propulsion systems to power large vessels. Furthermore, the large mobilization of capital for building large and powerful ships demands a high return on investment. As a result, cargo operations are intensified. These trends prompt two fundamental questions: how to power megaships without fossil fuels? how to maintain large ships at high and stable speed? There is no doubt that regulatory constraints and current shipping structures constraints act in conjunction. Today's owners and operators of large and fast ships may hinder the development of smaller-size ships powered by unreliable but free winds.

Without a massive overall adaptation of the shipping system, wind energy also cannot be imagined as the main propulsion source for the current world fleet. At present, shipping companies and engine manufacturers research and invest in alternative fuels such as biofuels, methanol, ammonia or hydrogen. Many new ships are delivered "ready-to" – i.e. waiting for the upcoming new alternative fuel supply and potentially equipped with wind-power systems. This may create a generation of hybrid ships like those of the nineteenth century (blending coal-power and sails), but on a reverse trend. The use of alternative energy sources should be combined with other energy efficiency technical measures such as hull optimization and/or efficient hull coating to reduce friction/resistance (IMO, 2018).

The Norwegian/Swedish shipping company Wallenius Wilhelmsen developed the concept ship E/S Orcelle, claiming to eliminate negative environmental impact – i.e. no discharge of hazardous substances into the air or into the sea (the only discharges are heat and water), sail-powered with the support of solar energy, wave power and fuel cells, no use of oil and ballast water. Although the company had doubt that such a ship would be built in its entirety, it had nevertheless hope that some of its parts would be further developed in future-generation vessels. This case highlighted that current shipping paradigms relating to economies of scale shape shipbuilding and operation with detrimental impacts on designers' freedom.

6 CONCLUSION

At present, two main trends slow down and restrict exploration and innovation in the design of ships: a poorly-adapted regulatory framework, and shipping structures praising massive and powerful ships. The shipping system remains strongly in the hands of shipowners and is organized according to their interests (Baumler *et al*., 2021). Its current state of inertia prevents the rethinking of established business paradigms and regulations. Without a serious push, and the involvement of non-maritime stakeholders, decarbonization of shipping may be delayed. As a global activity by nature, shipping has 'successfully' navigated, avoiding and postponing environmental constraints adopted at the national level to regulate land-based industries and vehicles. The 'Green Ship' of the future, capable of integrating technological improvements both in cargo-handling and navigational practices, will take shape in achieving social change in the shipping sector. It seems a paradox since maritime transport remains the only transportation mode which proved its capacity to exist and flourish without any fossil fuel.

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