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SAFEDOR – the implementation of risk-based ship design and approval

Christian Breinholt[a], Karl-Christian Ehrke[b], Apostolos Papanikolaou[c], Pierre C. Sames[d,*], Rolf Skjong[e], Tom Strang[f], Dracos Vassalos[g], Thomas Witolla[h]

[a]*Danish Maritime Authority*
[b]*SAM Electronics*
[c]*National Technical University of Athens*
[d]*Germanischer Lloyd SE*
[e] *Det Norske Veritas*
[f]*Carnival Plc*
[g]*University of Glasgow and Strathclyde*
[h]*Meyerwerft*

Abstract

The integrated project SAFEDOR has been completed in spring 2009 and this paper summarizes the achievements. SAFEDOR has been focusing work on the development of a risk-based regulatory framework, a risk-based design framework, advanced probabilistic simulation tools and their integration as well as a series of application examples. The paper outlines the elements of the risk-based regulatory framework incl. approval process, risk evaluation criteria, requirements for documentation and key personnel as well as onboard documentation. Novel risk-based simulation tools and their integration into a design environment are discussed. The paper also highlights the innovative ship designs developed within SAFEDOR and points towards possible future applications. Eventually, future research on risk-based approaches is outlined.

Keywords: Risk; risk-based; risk-based design; risk-based approval

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[*] Corresponding author.
E-mail address: pierre.sames@gl-group.com.

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1. Introduction

Fuelled by expected continuous growth of maritime transport and the need to provide sustainable shipping, economic opportunities drive proposals for ever more innovative ships and shipping concepts. Recent examples include cruise ships with huge shopping malls inside the superstructure and compressed natural gas transporters. Advocating risk-based approaches, ship owners will be able to implement those innovative ships and maritime transport solutions which cannot be approved today because limitations in the current prescriptive rules and regulations. Shipyards and equipment manufacturers will benefit from the introduction of risk-based approaches through enabling novel and optimized ships and systems incorporating new technology, functionality and materials. The benefits arise from the fact that yards acquainted with risk-based approaches are among the first to respond to the demand from ship owners for such novel and innovative ships. In addition, production costs may be reduced through application of risk-based approaches when, e.g., novel systems allow for improved modularization. Thus, risk-based ship design and approval respond to the maritime industries' need to deliver ever more innovative transport solutions to their customers. And, risk-based ship design and approval also responds to the society's need to have increasingly safer transport.

Risk-based ship design introduces risk analysis into the traditional design process aiming to meet safety objectives cost effectively. This is facilitated by use of advanced computational tools to quantify the risk level of a particular design and its variants. Risk is used to measure the safety performance. With safety becoming measurable, the design optimization can effectively be expanded and a new objective – minimize risk – is addressed alongside traditional design objectives relating to earning potential, speed and cargo carrying capacity. Approval of risk-based ships and their systems - conveniently called Risk-Based Approval – is the process to identify and resolve issues relating to the regulatory acceptance of the proposed design. Obviously, the approval process needs to take into account the risk assessment for the ship and its systems and, therefore, a careful review of risk analysis and establishment of risk acceptance criteria are central elements of risk-based approval.

Risk-based approaches in the shipping industry started with the concept of probabilistic damage stability in the early sixties, and risk-based design was later widely applied within the offshore sector and is now being adapted, extended and increasingly utilized within the shipping sector. SAFEDOR (2005) was the first large scale project that developed elements of a risk-based regulatory framework for the maritime industry and corresponding design tools to facilitate first principle approaches to safety, addressing the complexity of a fully comprehensive system. Strategic research objectives were formulated to meet the outlined goals:

1. Develop a risk-based and internationally accepted regulatory framework to facilitate first principles approaches to safety.
2. Develop design methods and tools to assess operational, extreme, accidental and catastrophic scenarios, accounting for the human element, and integrate these into a design environment.
3. Produce prototype designs for European safety-critical vessels to validate the proposed methodology and document its practicability.
4. Transfer systematically knowledge to the wider maritime community and add a stimulus to the development of a safety culture.
5. Improve training at universities and aptitudes of maritime industry staff in new technological, methodological and regulatory developments in order to attain more acceptances of these principles.

The development of SAFEDOR and the progress over its duration was presented by Bainbridge et al. (2004), Christensen et al. (2005), Breinholt et al (2007a and 2007b), Sames (2007) and during the mid-term conference of the project. Further public information (annual reports, newsletters, facts sheets and presentations) is available on the web at www.safedor.org. The following chapters discuss the achievements of SAFEDOR and review the progress towards the above listed objectives.

2. Regulatory framework – the impact of SAFEDOR

The regulatory system within the maritime industry consists of internationally agreed standards at the International Maritime Organization (IMO), regionally agreed regulations and national standards, International Association of Classification Societies' (IACS) Common Structural Rules and Unified Requirements, classification rules of the individual classification societies and other technical standards. The regulatory system is a result of continuous amendment processes. Many amendments are results of major accidents, tending to address the safety deficiencies resulting in the latest accidents – with few systematic proactive elements. At IMO level, SOLAS-I.5 allows for equivalent design of "fitting, material, appliance or apparatus" provided it "is at least as effective as that required by the present regulations." This in principle facilitated risk-based approaches but wide use is not documented. Today, the most widely used and known regulation SOLAS-II.2/17 addresses alternative design and arrangements for fire safety. The associated guideline (IMO 2001) advocates use of engineering analysis.

Within the project SAFEDOR, elementary building blocks for a risk-based regulatory framework for shipping were developed. These comprise the approval processes for ships and ship systems, risk evaluation and acceptance criteria at ship and functional level and requirements for documentation and qualification. Six formal safety assessment (FSA) studies were conducted and submitted to IMO for review by an expert group. Thus, work performed in SAFEDOR towards a modern and risk-based regulatory framework will affect the way risk is managed within rule making at IMO level. The approval processes for risk-based ship and ship systems aim providing a basis for use by approval authorities to ensure that novel and risk-based designs are handled in a safe and efficient manner and to make the approval process more transparent and reliable. The key element of the newly proposed approval processes is an intermediate step called the "Preliminary Approval" which concludes the first phase of the process, see Fig. 2. The preliminary approval allows the client to demonstrate that an independent third party attests to the novel or risk-based design which may be useful with respect to project partners. A summary of the novel approval process with all relevant details is being submitted to IMO (MSC 86).

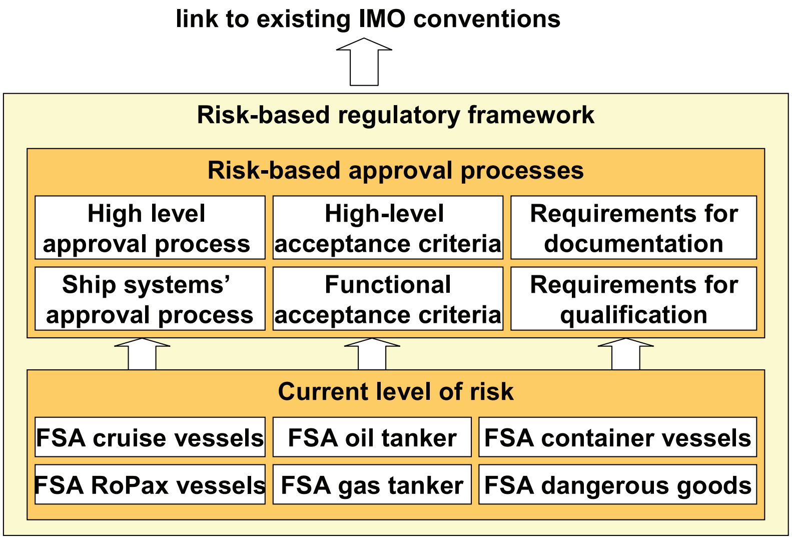


Fig. 1. Elements of a risk-based regulatory framework

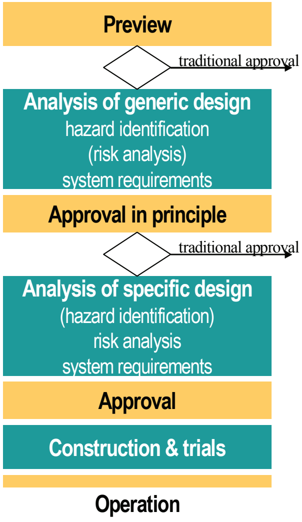


Fig. 2. Approval process for risk-based designs (schematic)

High-level risk evaluation criteria for use within risk-based design and approval were presented by Skjong et al. (2005). These criteria include individual and societal risk acceptance criteria, a cost-effectiveness evaluation criterion related to life saving and appropriate background information to update the criteria. In addition, a new cost-effectiveness evaluation criterion related to environmental protection was developed: Cost of Averting a Ton of oil Spilt (CATS). This new criterion should primarily be used to assess design changes of oil tankers with respect to their cost effectiveness – under the assumption that risk associated with oil transport by tankers is inside an ALARP area. Alternatively, one could use the criterion to enhance the cost-effectiveness evaluation related to life saving by subtracting expected difference in oil outflow times CATS from the differences in costs for a design option. This approach – termed 4Δ-model, was presented by Skjong (2007). With the publication of CATS at IMO (Netherlands 2006), a debate started with Greece (2007) leading the discussion, focusing on the formulation and the value of CATS. The basic idea of CATS was then agreed (IMO 2008). At the last meeting of the Maritime Environmental Protection Committee (MEPC 62 in July 2011), the work on CATS was completed and a spill-size dependent formulation was agreed.

Risk evaluation criteria at ship system and function level are presently not publicly available. An unpublished report from SAFEDOR lists such criteria and proposes a general procedure to derive lower-level risk evaluation criteria (Skjong et al. 2006). This procedure builds upon a risk model for the considered system or function and uses high-level cost-effectiveness criteria to derive target reliabilities, availabilities or failure probabilities. The procedure was successfully applied to hull girders in intact and damaged condition, (IACS 2006), Hørte et al. (2007) and a fuel oil system (Rüde and Hamann 2008).

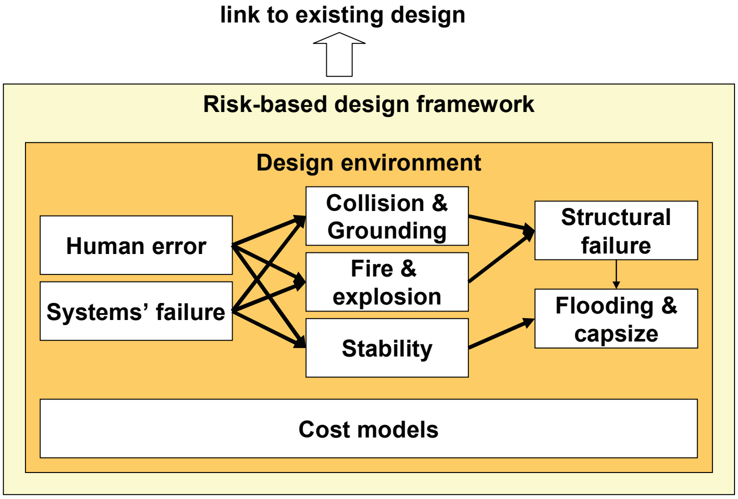
The FSA studies were performed to deliver high-level risk models, identify risk control options and to document the current level of risk per ship type and followed the FSA guidelines (IMO 2002 and IMO 2007). At the moment of writing, five FSA studies have been submitted to IMO addressing container vessels (Denmark 2007b), LNG tankers (Denmark 2007a), oil tankers (Denmark 2008a), cruise vessels (Denmark 2008b), RoPax ferries (Denmark 2008c) and dangerous goods on open-top container vessels

(Denmark 2009). The submitted FSA studies show that all the societal risk profiles of considered ship types are in the ALARP area and, therefore, cost-effective risk control options should be implemented. The FSA studies for the oil tanker, the cruise and RoPax vessels list a number of such measures for consideration by rule makers.

3. Designer's toolbox – new technology from SAFEDOR

Risk-based design is an extension of the traditional design process in that it integrates assessment of the safety performance into the design process. Prevention and / or reduction of risk (to life, the environment and property) are embedded as a design objective, alongside conventional design objectives (such as speed, capacity, etc). SAFEDOR developed this design framework offering an enhanced decision-making to balance traditional objectives – performance and cost – with the new objective – minimize risk (Vassalos 2007). An overview of the elements of the risk-based design framework and the principal linkage between safety performance predictions tools addressing main accident categories is presented in Figure 3. The integrated design environment eventually facilitates exploring the benefits of risk-based ship design with tools linked together and systematic use of optimization capability. Risk-based design couples traditional design with risk assessment, see Figure 4, and for each step in the conventional process, there is a corresponding step in the risk assessment: definition of safety objectives, identification of hazards and safety-critical functions, determination of the safety performance (i.e., calculating risk), evaluation of risk control options and estimating the costs and benefits for the final decision making.

Similar to performance assessment in conventional design, tools are required to assess the risk level. These tools can be expert judgments, databases, simplified formulae or advanced time and probabilistic simulations. The applicability is determined by the stage in the design process and the associated availability of data. In early design, tools for risk analysis are likely simpler and require less data than tools used within the basic or detailed design phases. With every additional tool and refinement, the uncertainty of the analysis is reduced. A risk model is the central element for the analysis and event trees, fault trees, Bayesian networks or analytical models are currently used. The main issue for the ship designer is direct control over the effect of changing key design parameters, i.e., the risk model must be sufficiently detailed in this respect.



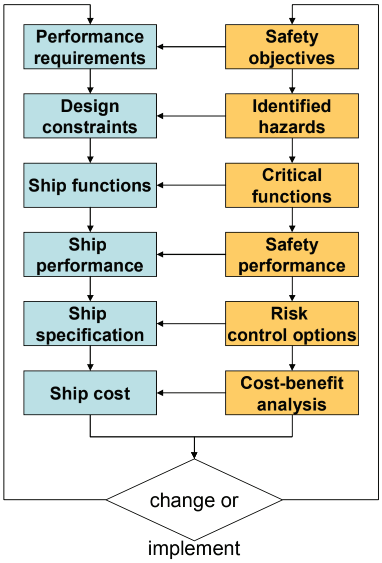


Fig. 3. Elements of a risk-based design framework

Fig. 4. Risk-based design process

Within SAFEDOR, several engineering tools to predict the safety performance of a vessel in extreme and accidental conditions were newly developed or refined. These tools address the main accident categories, as shown in Figure 3. The following developments were performed during the project:

- A Bayesian network was extended to evaluate changes in the causation factor driving from enhanced training and advanced bridge equipment for collision and grounding (Leva et al 2006).
- A new Bayesian network was established to predict the probability of propulsion and maneuvering systems' failure. However, lack of sufficiently validated data on components limited validation.
- A new technique to create fault trees and FMEA tables from system descriptions inside a standard system simulation package (ITI 2002) was developed by Walker and Papadopoulos (2006). Enhancements include entering annotations to systems and components related to failure modes.

- A new approach to assess fire in cargo holds was applied by Povel at al. (2007) by introducing a Bayesian network to evaluate probabilities and consequences of container fires.
- A methodology to assess fire safety for passenger ships was developed by Guarin et al (2007) which offers a probabilistic approach to fire safety similar to the probabilistic approach to damage stability.
- A structural reliability analysis of a damaged ship structure showed that the damaged condition – following a collision – is not a dimensioning case for the hull girder of a tanker (Hørte et al. 2007).
- The probability for intact capsize was predicted with two newly developed algorithms (Jensen 2007 and Spyrou et al. 2007).
- A new method was developed to predict the probability density function for time to capsize for RoPax ferries (Jasionowski and Vassalos 2006). The new method is extremely fast – which allows integration into a design environment - and is still considered to be sufficiently accurate.

4. Ships and their systems – implementing new knowledge

Eight design teams started developing innovative ship concepts when SAFEDOR began. The intention was to focus on design innovations that for formal reasons cannot be approved under the current rules or regulations but are expected to be as least as safe as today’s solutions. Concepts addressed technological, economical and safety aspects for two cruise vessels, a fast full displacement RoPax ferry, a hybrid RoRo/RoPax vessel, a lightweight composite sandwich superstructure for a RoPax ferry, a short-sea LNG tanker, an open-top container vessel and an oil tanker. An overview of the designs is presented in the Annex to this paper. A formal selection of the best designs by a panel resulted in two winning designs which were given additional resources to refine their concepts and prepare for preliminary approval.

The winning design was the lightweight composite sandwich superstructure for a RoPax ferry which exemplifies the use of risk-based approaches to demonstrate safety compliance (McGeorge et al. 2007). The risk model incorporated results from full scale fire tests and advanced computer simulations to show that the risk level for passengers is smaller than for passengers on conventional ferries when appropriate risk control options are implemented. The second winning design was the fast full displacement RoPax ferry which exemplifies the optimization potential for risk-based design and demonstrated the potential of a newly developed tool to predict flooding (Pöyliö and Jasionowski 2007). The risk assessment of a novel subdivision concept also introduced blisters (inflatable buoyancy units above design waterline) as potential powerful risk control options.

Work within SAFEDOR also addressed development of innovative systems focusing on area with high impact on safety, such as an innovative bridge layout, a novel system to distribute electrical power and several new concepts for life saving appliances. Statistics document that many if not most accidents at sea are related to collision and grounding. This resulted in proposals for automatic identification system (AIS) and electronic chart display and information system (ECDIS), the latter supported by an FSA study (Denmark and Norway 2006, Vanem et al 2007). Therefore, the interaction of the crew with advanced equipments was the focal point for the development of the new bridge layout. Six items were sequentially addressed as follows: work environment, man-machine interface, mission related equipment, workstation design, bridge operation and bridge procedures.

The novel system to distribute electrical power (primary power bus) was integrated into a RoPax ferry design and analyzed with respect to its safety compliance (Lühmann 2007). Following early system development activities related to functionality, recent developments focused on hazard identification and risk analysis for the system installed onboard. The analysis comprises the possible failure of the system in normal operation – using newly developed automatic fault tree generator tool - as well as system availability in accidental conditions – also applying a new prediction tool developed within SAFEDOR.

The final step following an accident may be life saving and rescue if the vessel needs to be abandoned. SAFEDOR developed three novel life saving appliances, each focusing on a different scenario and related different survival ranges. The long-range solution focused on a novel launching system to facilitate safe embarkation. The medium-range solution considered a novel onboard stowage to reduce space allocation. The short-range solution addressed safe access and stowage for a complementary life saving system – similar to life rafts. Details of these novel systems were not published for reasons of competitiveness.

5. Qualified engineers – the core of SAFEDOR's success

SAFEDOR started its ambitious path with a partnership comprising 53 European organizations which represent all stakeholders of the maritime industry. In total, about 300 persons were involved at various stages of SAFEDOR and, thus, the knowledge was spread effectively. Indeed, this was one of the reasons for the large partnership of SAFEDOR. Although most partners were building on a decade of intensive research into ship safety, it turned out that some skills were not available as expected and more training was needed.

Qualification requirements for engineers involved in risk-based ship design and approval was distinctly addressed within SAFEDOR. Depending on the process step and level of involvement, four target groups were identified as follows: design engineers, approval engineers, operators and inspectors. The steps in risk-based design and approval were assigned required qualification levels and these were compared with available initial qualifications. A required entry level qualification and desired qualification upgrades were identified for all involved stakeholders as staring point for a personnel training activity.

A number of measures were planned from the beginning of SAFEDOR to enhance knowledge on risk-based approaches within the maritime industry and to add stimulus towards developing a new safety culture. SAFEDOR attracted a large number of people for the annual public conferences. In addition, annual public reports and presentations were provided together with fact sheets for main stakeholders. Two training courses were offered with one focusing on regulators and the second on PhD students and young professionals from all the industry. To complement the material for students and experienced engineers alike, a handbook on risk-based ship design with methods, tools and applications has been published (Papanikolaou 2009).

6. OUTLOOK

With the regulatory framework for shipping changing towards a more goal-based style and new regulations addressing fire safety, damage stability and - in the near future - life saving appliances, the design solution space available to the ship designer is expanded. And, ship designers have now available increasingly sophisticated methods and tools supporting advanced and risk-based ship design and including safety as additional objective into the design process. Risk evaluation criteria are eventually becoming explicit and accepted also at maritime administrations and enable a holistic decision-making. Taken together, all necessary elements and the frame are now available to produce innovative ships with enhanced economics and increased safety.

Although the further development of the Goal-based Standards (GBS) at IMO using the risk-based Safety-level Approach (SLA) is not progressing fast, a clear trend is seen towards using risk analysis in design, approval and rule-making. In this respect, the review of the FSA studies conducted by SAFEDOR at IMO is seen as a large step towards documenting risk levels for shipping at IMO. In parallel, industry has started using the risk-based approach developed in SAFEDOR in a number of new commercial and research projects addressing, for example, the wider use of light-weight materials. And the European maritime industry has identified the implementation of risk-based frameworks as key priority towards 2020 (WATERBORNE 2005).

Risk-based ships are sailing today and their operational aspects are aligned with the current regulatory framework treating risk-based elements as equivalents. Details and reasons for the acceptance of the equivalent are to be communicated to IMO and circulated to IMO Member States. With the advent of more design aspects of a ship becoming risk-based, there is a clear need to ensure complete documentation of all risk-based elements of a ship together with the process and criteria of acceptance should be carried onboard (Strang and Sames 2007). In addition, a proper summary addressing the concerns of surveyors and port state control officers should be drafted.

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Appendix A.

SAFEDOR assembled design teams (comprised of ship owners, ship yards, marine equipment suppliers, design offices and classification societies) to develop innovative ship designs. For each of the eight following designs, a design study, an economic impact study and a safety & environmental impact study were elaborated, see Papanikolaou (2007).

A.1. Cruise vessel – post-panamax size

The design study aimed at optimizing a post-panamax cruise vessel. Innovative aspects included reconsideration of the prescriptive limits for fire load and material certification in public spaces, type, arrangement, position and configuration of innovative LSA, use of stairway enclosures as assembly stations (Safe Area), platform optimisation, based upon the new probabilistic damage requirements, including also a comparison between the IMO Weather Criterion standard methodology and the alternative assessment, and improved navigation / bridge equipment to prevent collisions.

A.2. Cruise Liner

The focus was to design a cruise liner which will be safer than existing ones, in terms of passenger safety and which shall be designed with reduced incidental damages to the environment in case of grounding and collision. And at the same time, to design a vessel more attractive to the cruise industry. Innovative aspects included novel layout with very large fire-curtains, fire zones and watertight compartments, balconies in all passenger cabins, an upper structure working as a lifebelt in case of very large damages, transversal and longitudinal cross flooding through valve operate trunks, and novel machinery locations.

A.3. Fast full displacement RoPax ferry

An existing fast full displacement ferry design was optimised to increase the cargo capacity with the lower hold. A novel watertight compartment arrangement, in order to protect vital ship systems, was developed and inflatable reserve buoyancy was considered on the hull for enhanced survivability. The resultant design showed improved earnings, lower emissions, 45% increase in system's availability in collision and flooding in machinery area and a dramatic risk reduction in collision and flooding scenarios when the inflatable reserve buoyancy was taken into account.

A.4. The 13th passenger (RoRo / RoPax ferry)

The focus was to design a RoPax ferry for about 50 passengers, using risk-based principles and not-SOLAS requirements, which will be as safe as a design using SOLAS but more cost efficient. The additional specific intention was to identify in qualitative terms the safety level of present vessels with 12 passengers. Therefore, a design concept was developed for a RoPAX vessel carrying more than twelve, but not more than fifty passengers, based on an existing modern RoRo ship.

A.5. Lightweight composite sandwich superstructure (for a RoPax ferry)

The focus was to develop an economic lightweight composite sandwich design for a superstructure on a passenger ship through developing a fire risk model and to provide a quantitative measure of the fire risks associated with the new design concept and the economic benefits expected from using it. Design and analysis work included analysis of SOLAS safety objectives and functional requirements as well as identification of challenged rules, identification of hazards and critical fire scenarios as well as development of fire risk model, development of structural model, and evaluation of risk control options.

A.6. Short-sea LNG tanker

The focus was to develop a short sea LNG vessel which can distribute gas to small scale customers using the principia of safety equivalency established in the CNG rules. An equivalent double bottom solution was explored to identify whether it offers the same protection to the cargo tank against indentations and the same energy absorption capabilities as conventional double bottom design. In addition, the implementation of new LNG equipments, such as power connector, gas combustion units, medium pressure, pneumatic cargo valve actuators and argon as inert gas was investigated.

A.7. Open top container vessel

Open top feeder ships are potentially regarded as an effective transport means for short sea shipping service where cargo-handling times are the crucial driving forces. However, open top container vessels face a regulatory disadvantage: bigger tonnage and therefore higher operation costs. Therefore, the design focus was to develop a low gross tonnage and equivalent safe open-top container vessel through challenging rules where necessary to make it more competitive.

A.8. Oil tanker (Aframax size)

The focus was to explore a Double Hull concept, as it is publicly and politically set to be the norm, with the following safety goals: reduction of potential of medium to large amount oil spills, eliminate small size oil spills due to operational incidents/accidents, and to reduce ballast water exchange. The implemented case study focused on the multi-objective optimisation of an AFRAMAX tanker by genetic algorithms, considering a variation of main cargo block parameters to demonstrate the potential of best performing designs with respect to both environmental impact and transport economy.