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DIPLOMA THESIS

PRELIMINARY DESIGN OF RO-PAX FERRY

Panagiotis Antoniadis

Supervisor:

George Zaraphonitis, Professor

Examination Committee:

Konstantinos Anyfantis, Assistant Professor

George Papadakis, Assistant Professor

George Zaraphonitis, Professor

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Summary

Ship design is admittedly an arduous procedure, requiring in-depth knowledge of the naval architects to achieve an efficient and techno-economically optimal design. Parametric ship design and design optimization consist powerful tools in facilitating the ship design procedure as current developments in computer hardware and software enable their application into the early ship design process with increased accuracy and acceptable computational demands.

In this diploma thesis, the preliminary design of a large ro-pax ferry is conducted, derived from a newly developed parametric model developed by NTUA-SDL, which can generate ship designs within a range of sizes, as well as properties of the hull form (C_B, LCB) and of the general arrangement (number of passengers and / or vehicles). An optimization study is carried out and the basic particulars of a techno-economically optimal design for a realistic operational scenario are determined. This design is then elaborated. A preliminary general arrangement plan is developed, aiming to clarify several design aspects not addressed extensively by the parametric model and the optimization procedure. Subsequently, the optimal design is further assessed in terms of intact and damage stability by providing detailed loading characteristics and finally, in terms of structural integrity by dimensioning the main structural components of the ship's hull both in longitudinal and transverse directions. Both the parametric model and the stability assessment are set up in the well-known naval architectural software NAPA, by utilizing appropriate macros developed by NTUA-SDL using the programming language NAPA Basic. The development of the general arrangement plan is handled fully in the CAD-type software AutoCAD. Regarding the structural analysis, the software MARS2000, provided by Bureau Veritas (BV), is utilized along with the computational capabilities of the Microsoft Excel Spreadsheet software.

More specifically, this thesis is comprised of six chapters.

Chapter 1 provides an introductory description of ro-pax ships and their unique design characteristics. Chapter 2 introduces the concepts of parametric ship design and design optimization while providing a brief presentation of the parametric model developed by NTUA-SDL. Ultimately, an optimization case study is described, the outcome of which constitutes the main subject of the thesis. Chapter 3 elaborates on the details of the general arrangement plan of the optimal ship design described in Chapter 2, while in Chapters 4 and 5 the intact and damage stability of the optimal ship is assessed in greater detail, provided the thorough arrangement of the ship's expected loading conditions. Finally, Chapter 6 aims to determine the ship's main structural components and provide preliminary structural plans of certain transverse sections.

Περίληψη

Η σχεδίαση ενός πλοίου είναι, ομολογουμένως, μία επίπονη διαδικασία, η οποία απαιτεί εις βάθος γνώση του αντικειμένου από τους ναυπηγούς ώστε να πετύχουν μία αποτελεσματική και τεχνοοικονομικά βέλτιστη σχεδίαση. Η παραμετρική σχεδίαση και βελτιστοποίηση αποτελούν πολύτιμα εργαλεία που συμβάλλουν στη διαδικασία σχεδίασης ενός πλοίου, καθώς οι πρόσφατες τεχνολογικές εξελίξεις επιτρέπουν την εφαρμογή τους στα πρώτα στάδια της σχεδίασης, προσφέροντας έτσι αυξημένη ακρίβεια με αποδεκτό υπολογιστικό κόστος.

Στην παρούσα διπλωματική εργασία πραγματοποιείται ο προκαταρκτικός σχεδιασμός ενός μεγάλου επιβατηγού – οχηματαγωγού (Ε/Γ – Ο/Γ) πλοίου, που προέρχεται από ένα νεοανεπτυγμένο παραμετρικό μοντέλο που αναπτύχθηκε από το Εργαστήριο Μελέτης Πλοίου (NTUA-SDL), το οποίο μπορεί να παράξει σχεδιάσεις πλοίων σε μια σειρά μεγεθών και ιδιοτήτων της γάστρας (C_B, LCB) και της γενικής διάταξης (αριθμός επιβατών και / ή οχημάτων). Πραγματοποιείται μία εφαρμογή βελτιστοποίησης και προσδιορίζονται τα βασικά στοιχεία μιας τεχνοοικονομικά βέλτιστης σχεδίασης για ένα ρεαλιστικό σενάριο λειτουργίας. Στη συνέχεια, η σχεδίαση αυτή αναλύεται. Παράγεται ένα προκαταρκτικό σχέδιο γενικής διάταξης που αποσκοπεί στην αποσαφήνιση πολλών πτυχών του σχεδιασμού που δεν αντιμετωπίστηκαν εκτενώς από το παραμετρικό μοντέλο και τη διαδικασία βελτιστοποίησης. Στη συνέχεια, η βέλτιστη σχεδίαση αξιολογείται περαιτέρω ως προς την άθικτη ευστάθεια και την ευστάθεια έπειτα από βλάβη παρέχοντας λεπτομερή χαρακτηριστικά φόρτωσης του πλοίου και τέλος, ως προς την δομική ακεραιότητα διαστασιολογώντας τα κύρια δομικά στοιχεία της γάστρας του πλοίου τόσο στη διαμήκη όσο και στην εγκάρσια διεύθυνση. Τόσο το παραμετρικό μοντέλο όσο και η αξιολόγηση της ευστάθειας του πλοίου πραγματοποιούνται εντός του γνωστού ναυπηγικού λογισμικού NAPA, χρησιμοποιώντας κατάλληλα macros που αναπτύχθηκαν από το Εργαστήριο Μελέτης Πλοίου (NTUA-SDL) χρησιμοποιώντας τη γλώσσα προγραμματισμού NAPA Basic. Η ανάπτυξη του σχεδίου γενικής διάταξης πραγματοποιείται στο σύνολό του με το λογισμικό τύπου CAD AutoCAD. Όσον αφορά τη δομική ανάλυση, χρησιμοποιείται το λογισμικό MARS2000, που παρέχεται από τον νηογνώμονα Bureau Veritas (BV), σε συνδυασμό με τις υπολογιστικές δυνατότητες των υπολογιστικών φύλλων Microsoft Excel.

Πιο συγκεκριμένα, η εργασία αποτελείται από έξι κεφάλαια.

Το Κεφάλαιο 1 παρέχει μια εισαγωγική περιγραφή των Ε/Γ – Ο/Γ πλοίων και των ιδιαίτερων χαρακτηριστικών τους. Το Κεφάλαιο 2 εισάγει τις έννοιες της παραμετρικής σχεδίασης και βελτιστοποίησης, ενώ παρέχει μια σύντομη παρουσίαση του παραμετρικού μοντέλου που αναπτύχθηκε από το Εργαστήριο Μελέτης Πλοίου (NTUA-SDL). Τέλος, περιγράφεται μια εφαρμογή βελτιστοποίησης, το αποτέλεσμα της οποίας αποτελεί το κύριο αντικείμενο μελέτης της διπλωματικής εργασίας. Το Κεφάλαιο 3 αναλύει τις λεπτομέρειες του σχεδίου γενικής διάταξης του βέλτιστου πλοίου που περιγράφεται στο Κεφάλαιο 2, ενώ στα Κεφάλαια 4 και 5 η άθικτη ευστάθεια και η ευστάθεια έπειτα από βλάβη του βέλτιστου πλοίου αξιολογούνται λεπτομερέστερα, υπό την προϋπόθεση του αναλυτικού ορισμού των αναμενόμενων καταστάσεων φόρτωσης του πλοίου. Τέλος, το Κεφάλαιο 6 στοχεύει στον προσδιορισμό των κύριων δομικών στοιχείων του πλοίου και στην παροχή προκαταρκτικών κατασκευαστικών σχεδίων στοχευμένων νομέων (τομών) του πλοίου.

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Nomenclature

Latin symbol	Description
A	Attained subdivision index
A_c	Partial attained subdivision index at loading condition c, c = S, P, L
A_i	Partial attained subdivision index at loading condition i, i = S, P, L
A_{sh}	Net shear sectional area
B	Beam / breadth (moulded)
C_B	Block coefficient
C_M	Midship section coefficient
C_P	Prismatic coefficient
C_{WP}	Waterplane coefficient
CO_2	Carbon oxide
d	Mean draught
d_L	Light service draft
d_P	Partial service draft
d_S	Subdivision draft (same as T_{max})
D	Depth to bulkhead deck (Chapter 2)
D	Depth to strength deck (Chapter 6)
DWT	Deadweight
FSM	Free surface moment
GM	Metacentric height
GM_0	Initial metacentric height
GT	Gross tonnage
GZ	Righting lever
KG	Height of center of gravity above baseline
l_{wl}	Steady wind heeling lever
l_{w2}	Gust wind heeling lever
L	Rule length according to the “Rules for the Classification of Steel Ships, Bureau Veritas, January 2021”
L_{PP}	Length between perpendiculars
L_{WL}	Length of ship at waterline

LCB	Longitudinal center of buoyancy
LCG	Longitudinal center of gravity
M_R	Heeling moment
MCR	Maximum continuous rating
N_{CR}	Number of relevant intact stability criteria
N_{LC}	Number of examined loading conditions
NO_X	Nitrogen oxide
NPV	Net present value
NPV1	Net present value assuming unlimited demand (linear correlation between supply and demand)
NPV2	Net present value assuming maximum demand 40% above baseline
NPV3	Net present value assuming maximum demand 20% above baseline
ODS	Ozone-depleting substances
p_i	Probability that only the damage case i – consisting of a particular compartment or a group of adjacent compartments – is flooded after damage
R	Required Subdivision Index
RFR	Required freight rate
s_i	Probability that the ship survives (does not sink or capsize) following the flooding of the examined compartment i – or a group of adjacent compartments –
SHP	Calculated propulsion power (service speed, design draft, calm sea, clean hull)
SO_X	Sulfur oxide
T	Draft / draught (moulded)
TCG	Transverse center of gravity
V	Service speed
VCG	Vertical center of gravity
VCG_i	Vertical center of gravity in each loading condition i = 1, …, N_{LC}
$VCG_{max,i}$	Maximum allowable vertical center of gravity in each loading condition i = 1, …, N_{LC} to satisfy stability regulations
w	Net section modulus

Greek symbol	**Description**
Δ	Displacement
ΔVCG_i	Difference between $VCG_{max,i}$ and VCG_i in each loading condition i = 1, …, N_{LC}
ΔVCG_{intact}	Intact vertical center of gravity margin
φ	Righting lever angle
φ_0	Angle of heel under the action of steady wind
φ_1	Angle of roll under wave action
φ_f	Angle of down-flooding

List of Abbreviations

Latin symbol	**Description**
BV	Bureau Veritas
CFD	Computational Fluid Dynamics
CPP	Controllable Pitch Propeller
DDN	Deck Down
DO	Diesel Oil
DUP	Deck Up
DWT	Deadweight
EEDI	Energy Efficiency Design Index
EU	European Union
FW	Fresh Water
FSM	Free Surface Moment
GA	General Arrangement
HFO	Heavy Fuel Oil
HHSD	Height Horizontal Subdivision Downwards
HHSU	Height Horizontal Subdivision Upwards
IACS	International Association of Classification Societies
ILLC	International Load Line Convention
IMO	International Maritime Organization
IS	Intact Stability
LCB	Longitudinal Center of Buoyancy
LCG	Longitudinal Center of Gravity
LNG	Liquified Natural Gas
LO	Lubrication Oil
MARPOL	Marine Pollution
MCR	Maximum Continuous Rating
NPV	Net Present Value
NTUA-SDL	National Technical University of Athens – Ship Design Laboratory
ODS	Ozone-Depleting Substances
RFR	Required Freight Rate

Ro-Pax	Roll on – Roll off / Passenger
Ro-Ro	Roll on – Roll off
SG	Specific Gravity
SHP	Shaft Horsepower
SOLAS	Safety Of Life At Sea
TBA	Transverse Bulkhead Aft
TBF	Transverse Bulkhead Forward
TCG	Transverse Center of Gravity
VAR	Various
VCG	Vertical Center of Gravity
WB	Water Ballast
WOD	Water On Deck

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1. Design Characteristics of Ro-Pax Ferries

This first chapter provides an overview of the design of modern ro-pax ships, particularly of conventional (monohull, displacement), closed-type ferries[1]. Subchapter 1.1 presents some general information. Subchapter 1.2 discusses the procedure of determining the main dimensions, while Subchapter 1.3 analyzes the main elements and particularities of their hull form. Subchapter 1.4 summarizes the most crucial safety issues concerning ro-pax ships and Subchapter 1.5 briefly presents the basic rules and regulations that affect their design.

1.1. Introduction

Passenger ships comprise an essential means of maritime transport, described as vessels intended for transportation of more than 12 passengers and are categorized into pure passenger ships and ro-ro passenger ferries (or ro-pax) [1]. The term ″roll on – roll off″ refers to the loading and unloading of vehicles (private cars and/or trucks) by their own means, through external ramps at the stern and sometimes at the bow or the sides of the ship. Thus, the existence of at least one large vehicle deck – referred to as the main ro-ro deck – (practically extends through the entire length and breadth of the ship) is expected, allowing the unobstructed movement of vehicles inside the ship. Larger ro-pax ferries are equipped with multiple vehicle decks, upwards or downwards of the main ro-ro deck, connected with fixed or – more commonly – hoistable internal ramps. In some cases, platform – or hoistable – decks are installed to adjust the payload to seasonal demand variations, videlicet lowered at half the deck height when the demand for private car transportation is high, converting one ro-ro deck for trucks into two decks for private cars. An additional distinguishing characteristic is the large extent of superstructures, both in terms of deck area as well as in the number of decks, enabling the accommodation of a large number of passengers and providing a high level of passenger comfort.

It is a relatively new ship type, used in short-sea liner shipping in conjunction with transportation of vehicles. Their development can mainly be attributed to the large growth of road transport, having displaced large pure passenger ships – or ocean liners – as a means of transport, which today exist only as cruise ships (partly due to tourism), while, for longer routes, passenger ships have been replaced altogether by the development of air transportation [1].

The size and layout of ro-pax ships vary according to the routes and duration of service for a particular vessel. The size of a ferry is usually measured in terms of overall length, passenger/vehicle capacity or gross tonnage (GT). Typical sizes range from around 30m to over 200m in overall length and from 150 to over 70.000 GT [2]. In comparison with cargo ships of similar size, their payload is much smaller – a natural corollary considering that both passengers and vehicles constitute a relatively «lighter cargo» –, along with a higher value of stowage factor (ratio of volume capacity to deadweight), meaning that the ship's maximum capacity in terms of volume is reached before exceeding the maximum allowable draft. Therefore, passenger ships are classified as volume carriers, in contrast with displacement carriers such as tankers and bulk carriers [3].

[1] Ferries with fully enclosed main ro-ro deck.

Finally, in comparison with other conventional ship types, passenger ferries are among the most demanding in terms of design. The two major challenges both stem from the presence of passengers on board.

Specifically, a high service speed is essential to be competitive as a means of passenger transport. Ro-pax ships typically operate at speeds ranging from 23 to 31 knots, corresponding to Froude numbers over 0.3 (example in Figure 1-1), while passenger ferries of unconventional design (catamaran, hydrofoils, hovercrafts, etc.) can exceed 35 to 40 knots. However, this trend has been halted; namely, the stabilization of the service speed, both for the sustentation of a reasonable operating cost, as to remain an affordable means of transport, and for minimum environmental impact [1]. These challenges call for improved hydrodynamic design of the hull and efficiency of the propulsion system (propellers – engines), hence restriction of fuel consumption. In a final note, the implementation of EEDI (Energy Efficiency Design Index) by IMO (International Maritime Organization) is expected to lead to a progressive reduction of the ships' installed power, thus a reduction of service speed [1].

In addition, the required level of safety is extremely high, as large numbers of passengers are carried, without any special training in case of an emergency, in contrast with cargo ships where only the crew is embarked, having completed persistently training. For this reason, regulations regarding intact and damage stability, fire protection and other safety issues are much more rigid than those of a cargo vessel.

Figure 1-1: Ro-pax ferry Blue Star Myconos operates at a service speed of 26.5 knots (along with a length of 141 m), corresponding to a Froude number of 0.37. Source: www.attica-group.com.

1.2. Main dimensions

The general principles governing the selection of the main dimensions (length L, breadth B, draft T, depth D) are discussed in this subchapter. The procedure of determining the main dimensions resides in a combination of the shipowner's requirements – consisting of transport capacity, service speed, construction standards of a recognized classification society, etc. – and some basic factors, such as the ship's hydrodynamic performance, satisfactory stability, adequate structural strength, minimized construction cost, etc. [3]. Typically, improper selections of the basic dimensions are almost impossible to be corrected retrospectively; they generally lead to uneconomic and/or technically insufficient solutions.

The ship's length is a function of displacement and speed. Ro-pax ships are generally slender, meaning their length is large compared to the displacement volume (slenderness coefficient $L/V^{1/3}$ values between 6.2 – 6.9 for ferries with length greater than 100 m [3]). For constant displacement and relatively high Froude numbers – where ro-pax ships are generally operating and wave-making is dominant –, increased slenderness leads to reduced wave resistance, but at the same time increased wetted surface and thus frictional resistance. However, increased length generally reduces the consequent overall resistance. Naturally, as the ship's length is a function of displacement and speed [3] (associated with Froude number), having a significant influence on the lightship weight, hence on the building cost, a continuous increase of its value for constant displacement outweighs its benefits. These issues, along with possible navigational constraints mentioned below, set limits to the slenderness of the ship.

Compliance with demanding stability requirements is mainly achieved by increasing the ship's breadth. This results in length to beam ratios comparable to those of cargo ships (consequent values ranging from 5.9 to 6.2 for ferries with length greater than 100 m [3]), despite the large differences in terms of slenderness coefficient. Additionally, ro-pax ships are classified as linear dimension ships (in addition to volume carrier's classification) in the sense that their beam changes aperiodic, with a step approximately equal to the width of a lane [3].

The draft of ro-pax ships is generally small, with values of the ratio B/T ranging from 3.7 to 4, significantly higher than those considered ″optimal″ regarding both the minimization of the total resistance and the higher efficiency due to the possible fitting of a large diameter propeller – not generally concerning ro-pax ships which are equipped with two propellers – [3]. This is attributed to the low weight of the transported cargo (passengers and vehicles), in combination with the requirement for a large beam (a consequence of demanding stability regulations). Limitations to the maximum draft are also set, similarly to other main dimensions, by possible navigational constraints.

Finally, the selection of the ship's depth is crucial for two main reasons; the available volume and height below the freeboard deck for machinery installations and cargo stowage. In ro-pax ships' case, the large number of accommodation decks increases the total depth of the ship, which, in combination with the low draft translates to increased air draft. This statement is amplified by the need of a relatively high position of the bulkhead deck [3]. Nevertheless, as the available height of decks is determined by the cargo's standard dimensions and loading-unloading method, the position of the bulkhead deck must be relatively low to enable fast and convenient loading and unloading of vehicles, but high enough to protect the main ro-ro deck from flooding in case of damage resulting in a hull breach.

The main dimensions L, B, and T are often affected as well by the topological limits of the route (dimensions of canals, ports, channels, and confined waters) that the ship needs to pass through. The restrictions are mostly referring to allowable drafts (e.g. Panama Canal and Suez Canal) [3].

1.3. Hull form

In general, the hull form of a ro-pax ship deviates from that of a low-speed cargo vessel (i.e. tanker, bulk carrier). Some complexities are introduced due to the demand for high service speed with a reasonable operating cost (e.g. improvement of hydrodynamic performance – generally by optimizing the hull form – leading to the reduction of fuel consumption at high speeds).

The selection of the block coefficient (C_B) is effectively influencing the selection of all the hull form coefficients (prismatic coefficient C_P, midship section coefficient C_M and waterplane coefficient C_{WP}) either through their comparable values (the case of the prismatic coefficient C_P) or through empirical and semi-empirical calculations. Ro-pax ships generally have low values of block coefficient (C_B), ranging from 0.5 to 0.6 [3], corresponding to more hydrodynamically optimal designs, as in high Froude numbers a decrease of the block coefficient increases the wetted surface, to which the frictional resistance is proportional, but at the same time decreases the dominant wave resistance. Such low values are attributed to the reduced exploitation of the lower deck spaces in both the stern and bow, mainly because of the sharp entrance of the waterlines in these regions.

The longitudinal center of buoyancy (LCB) is affected by the desire to minimize total resistance and most prominently, wave resistance. Essentially, if the position of the longitudinal center of buoyancy is stationed excessively forward of the amidships, it will trigger the generation of intensive waves around the bow shoulders, albeit for an extreme position aft of the amidships, the efficiency of the propeller is in jeopardy, as phenomena of flow separation and creation of vortices are frequently encountered. In the case of ro-pax ships, characterized by high values of wave resistance associated with relatively high Froude numbers, typical positions reach values of 2.5% to 3.0% L_{PP} aft of amidships, to minimize the transverse bow wave, which contributes to the wave resistance [3].

Moving towards the bow, the most prominent hull characteristic is the bulb. Ro-pax ships are usually equipped with wedge-shaped – referred to as ″goose-neck″ – bulbs which pierce the design waterline. At relatively high Froude numbers, the major advantage of a bulbous bow is the generation of an independent wave system, which starts with a wave crest and, if configured appropriately, reduces the height of the bow wave and the corresponding resistance [3]. Also, a resulting positive effect of the bulb is the increased efficiency of the propeller (reduction of the required thrust and degree of loading of the propeller). However, the implementation of a bulb increases the wetted surface of the ship for a given displacement, and consequently the frictional resistance.

Figure 1-2: Bulbous bow of ro-pax ferry Blue Star Delos. The aforementioned independent bow wave system is shown. Source: www.attica-group.com.

Regarding the stern, a central skeg is usually encountered. Above the waterline, the maximum beam is usually maintained throughout the entire stern area up to the transom resulting to the maximization of the available deck areas. This allows for the installation of ramps, needed for the loading/unloading of vehicles, and improves stability. Aft of the transom, an extension of the hull called ″ducktail″ is often found. Its effects comprise of an increase to the waterline length (decreasing the effective Froude number) and consequently the ship's resistance, and an additional contribution to the hull's buoyancy which reduces the dynamic trim towards stern which is developed at high speeds.

Figure 1-3: Typical stern design and ducktail addition in ro-pax ship Blue Star 1. Source: www.attica-group.com.

1.4. Safety issues

The design of ro-pax ships comes with certain innate problems which can jeopardize their safety and have in fact led to tragic accidents in the past (for example, Herald of Free Enterprise (1987) [4], Estonia (1994) [5]). The elements which make ro-pax ships unique and constitute important safety issues are presented below [6]:

- The lack of internal bulkheads / low freeboard in the main ro-ro deck; As mentioned already, transverse bulkheads cannot extend above the main ro-ro deck, which is located relatively close to the waterline. Thus, in the event of a hull breach, a sudden inrush of water could rapidly flood the unobstructed length of the main ro-ro deck, jeopardizing the survivability of the ship (e.g. a very large free surface will be generated, the effect of which to the ship's stability can be detrimental). Furthermore, the lack of bulkheads means that fire can spread very quickly.
- Cargo access doors; The cargo access doors at the stern – or the bow or the sides – of the ship represent potential weak spots, as over the years such doors can become damaged or twisted, especially when the door also serves as a ramp.
- Stability; The movement of cargo on the vehicle deck can affect the intact stability of the ship, causing her to list. The sudden inrush of water following damage to the hull or failure of watertight doors can even be more serious (and rapid). Moreover, the fact that ro-pax ships have extensive superstructures compared with other types of ships means that they can be more easily affected by wind and bad weather.
- Cargo stowage and securing; This applies to cargos transported inside a trailer, but also to the vehicles themselves. Potential results of cargo breaking loose if it is not correctly stowed and secured, will be increased list, spillage of dangerous substances or even damage to the ship's structure.
- Life-saving appliances; The high sides of the ro-pax ships pose problems regarding the usage of life-saving appliances· for example, as lifeboats are located high on the superstructures, at large heeling angles (listing of the ship), are difficult to launch. This problem is moderated today due to the partial replacement of lifeboats by liferafts.
- The crew; The aforementioned safety factors indicate that ro-pax ships are highly sophisticated, and therefore requiring cautious handling. As a result, they are exceptionally vulnerable to human error.

Of course, accidents are usually caused by an unfortunate combination of more than one factor. The most important accidents being the sudden and catastrophic capsizing of the roll-on/roll-off passenger ferry Herald of Free Enterprise (March 1987) and the even more tragic loss of the Estonia (September 1994). In the first case, the accident occurred because the bow door was left open when the ship left port allowing water to enter and flood the car deck. The accident resulted in the deaths of 193 passengers and crew members [4]. In the second case, the under-designed lockings and hinges of the bow door failed due to rough weather. Subsequently, the large inflow of water on the car deck quickly created a very large free surface which resulted in the ship capsizing within minutes and 852 lives being lost [5].

Figure 1-4: Herald of Free Enterprise with her bow door raised. Source: www.allpoetry.com.

Figure 1-5: MS Estonia with her bow door raised. Source: www.thesun.ie.

1.5. Regulatory framework

The entirety of the ship's life cycle, including its design, construction, operation, maintenance, and recycling, is governed by a set of rules and regulations imposed by the International Maritime Organization (IMO), other international organizations (e.g. by the EU), flag administrations and the classification societies in which the ships are classed. Most of them aim to protect human life and the environment. Those set by the IMO, mainly through international conventions are of paramount importance· Safety of Life at Sea (SOLAS), Marine Pollution (MARPOL), International Load Line Convention (ILLC), International Code on Intact Stability (Res. MSC.267(85)) etc. Similarly, this applies to the class rules, which are set by classification societies and have to do with the ship's construction (materials, global and local strength), machinery, electrical installations, welding, etc. [6].

Regional and national regulations often also apply, for example the European Union Stockholm agreement – or Directive 2003/25/EC –.

A brief presentation of some of the most important rules and regulations regarding the safety of human life and environmental protection follows (the presentation is in no way exhaustive).

Arguably, the basic pillars of safety for a passenger ship are stability and fire protection.

Stability can be distinguished into intact and damage stability. The relevant regulations are critical and must be examined from early stages of the design, as they affect the main dimensions and the watertight subdivision of the ship. Intact stability is covered by IMO's intact stability code (2008 IS Code), specifying various criteria to be satisfied for a loading condition to be considered acceptable. These include general criteria regarding properties of the righting lever curve (GZ–φ), the severe wind and rolling criterion (weather criterion – IMO Resolution A.562 –), as well as additional requirements for passenger ships specifying maximum heeling angles due to crowding of passengers to one side of the ship and due to turn [10].

Regulations concerning damage stability include the probabilistic assessment method specified by SOLAS, requiring investigation of multiple damage scenarios – referred to as damage cases – to determine the probability of survival after damage (attained subdivision index, A), which must be at least equal to a minimum allowed value (required subdivision index, R). For large passenger ships, SOLAS incorporates also some supplementary deterministic requirements in the probabilistic model to ensure survival after minor side and bow damages. The aforementioned are defined in Chapter II-1 of SOLAS [7]. Finally, the Stockholm Agreement – or the European Union Directive 2003/25/EC – imposes deterministic requirements for ro-pax ships sailing between to/from designated ports in the European Union, regarding survivability in damaged condition, assuming significant accumulation of water on ro-ro decks [9].

Regarding fire protection, various prescriptive requirements are defined in Chapter II-2 of SOLAS [7], pertaining to all ship spaces, and in particular the accommodation decks (halls, dining rooms, lounges and similar permanently enclosed spaces). These requirements include but not limited to thermal subdivision requirements, tank arrangement constraints, required firefighting equipment, etc. In terms of the general arrangement, each deck is subdivided into main vertical and horizontal zones by thermal and structural boundaries, referred to as ″A″ class divisions – and more specifically ″A-60″ class divisions –, designed to delay the spreading of fire. In general, the maximum allowable length of a main vertical zone is 48 m, provided that its total area does not exceed 1600 m^2 on any deck. Increased fire protection is also required for spaces with large ignition probability (e.g. galleys), as well as for spaces that are vital for the safe operation and evacuation of the ship (e.g. wheelhouse and stairways). Other spaces, specified accordingly by the regulations, are also transversely and horizontally subdivided by thermal barriers.

It is worth mentioning additional regulations imposed by SOLAS [7], regarding the safety of human life. Regarding evacuation of the ship in case of emergency, the regulations require the complete evacuation of the vessel in a well-defined time, thus affecting the arrangement of accommodation spaces. Furthermore, large passenger ships must be able to return to port by their own means after one-compartment damage, according to ″safe return to port″ requirements. Finally, the installation and usage of life-saving appliances are well-defined in SOLAS, such as the required capacity of lifeboats and liferafts on board.

Environmental protection is the second major concern after the safety of human life. This issue has become increasingly important in recent years, with the introduction of regulations in MARPOL Chapter VI [8] regarding the reduction of pollutants (NO_X, SO_X) and total prohibition of ODS (Ozone-depleting Substances) from ships. An important implication of these regulations, having taken effect from 1 January 2020, regarding ship design, is the reduction of SO_X emissions (global sulphur limit). Recent solutions include switching to higher-quality and low sulphur fuels (commonly referred to as distillates), installing exhaust fuel cleaning structures (frequently referred to as scrubbers), retrofitting present vessels to operate as liquefied natural gas (LNG) powered vessels [11].

The other important addition of MARPOL Chapter VI [8] is the adoption of the Energy Efficiency Design Index (EEDI), aiming to promote the use of more energy-efficient (less polluting) equipment and engines, expressed in the form of CO_2 emitted per unit of transport work, scilicet reducing CO_2 emissions from ships in operation. Its calculation is obligatory for ships constructed after 2013 or having undergone an extensive conversion. It is being implemented in three phases/levels, tightened incrementally every five years – having started from January 2015 –, hence requiring more efficient ships in comparison with an initial reference EEDI line (phase 0) which was determined from a regression analysis of operating ships, representing the state of the industry at that time.

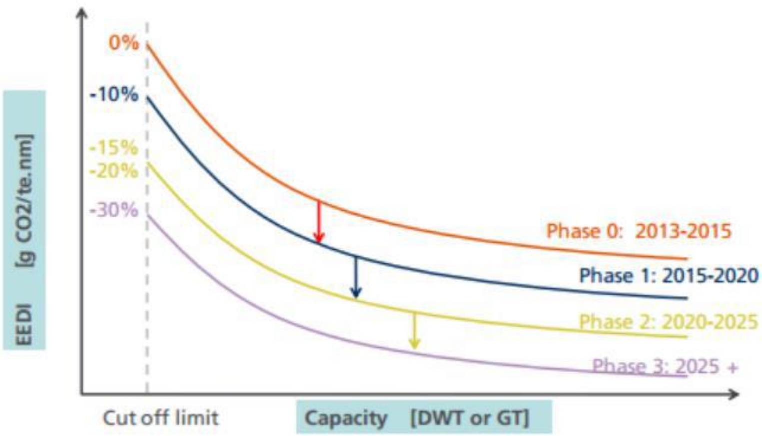

Figure 1-6: EEDI compliance phases.

Finally, as mentioned above, the classification societies, primarily concerning IACS (International Association of Classification Societies), impose supplementary requirements, mainly attributed to the ship's structure. For example, the survey of the hull girder strength and structural members scantling by determining minimum allowable dimensions and/or thickness of each structural member of the ship according to its expected loading.

2. Parametric Ship Design and Optimization

Chapter 2 deals with the main principles of parametric ship design and optimization in the endeavor of achieving the design of an optimal ship. Subchapter 2.1 presents the traditional phases of a ship's design. Subchapter 2.2 provides an introduction to the main principles of parametric ship design and optimization. Subchapter 2.3 elaborates on the construction of a functional parametric model, presenting both the steps for the generation of an appropriately defined geometric model and the consequent calculation methods for the evaluation of the parametric ship design. Ultimately, Subchapter 2.4 describes the formulation of a ship design optimization problem, assuming realistic owner's requirements, elaboration on the criteria utilized for the selection of the optimal ship derived from a pool of feasible designs generated by the parametric model and a brief presentation of its characteristics.

2.1. Main phases of ship design

During the design of a ship, the naval architect faces the challenge of translating a set of owner's requirements into a functional and techno-economically optimal (or near-optimal) vessel. This implies that the main technical and economic ship characteristics are determined by optimization, especially those affecting the cost of shipbuilding (and indirectly the cost of acquisition) and the economy of operation. It is evident that the complexity of the problem prohibits addressing it fully at once. In general, ship design is decomposed into four basic phases [3]:

a. Concept Design – Feasibility Study; In this first design phase, a rough estimation of the main technical characteristics of the ship (main dimensions, block coefficient, propulsion power) transpires corresponding to the ship owner's requirements.

b. Preliminary Design; This stage revolves around the further elaboration of the ship design steps partly addressed in the first phase. Specifically, detailed calculations for the main dimensions and other basic characteristics (block coefficient, propulsion power, etc.) are performed with the purpose of accurately determining these ship's main characteristics, so as to satisfy the owner's requirements and to correspond to an optimal solution with respect to a set economic criterion. The outcome of the preliminary design is the reliable estimation of all important technical characteristics of the ship, as well as the building and operational costs. The feasibility study (first phase) and the preliminary design (second phase) are often jointly referred to as the ″basic design″.

c. Contract Design; Where detailed calculations are performed and naval architectural drawings (e.g. general arrangement plan) are elaborated with the required accuracy for the shipbuilding contract between the shipyard and the owner to be formed. This design phase involves a detailed description of the ship's hull form, the exact estimation of the powering, seakeeping (behavior of the designed ship in waves), the analysis of her manoeuvring properties, consideration of alternative propulsive systems, details of her structural design, design of the auxiliary/supply networks (electric, hydraulic, piping systems etc.) and finally, a more precise estimation of the individual ship weight components, of lightship weight and the corresponding centroids.

d. Detailed Design; This last stage includes the design of each element of the ship's structure, equipment and machinery, in order to provide the necessary drawings to the manufacturer or the supplier of each element.

The above traditional methodology is illustrated in the well-known design spiral, introduced by J.H. Evans in 1959 [12]. The design spiral emphasizes the sequential and iterative nature of the process required to assemble an ″optimal″ ship through the various design steps. Notably, the first loop corresponds to the concept design, loops 2-4 to the preliminary design while loop 5 to the contract design. These loops lead to the final design phase; the detailed design [3].

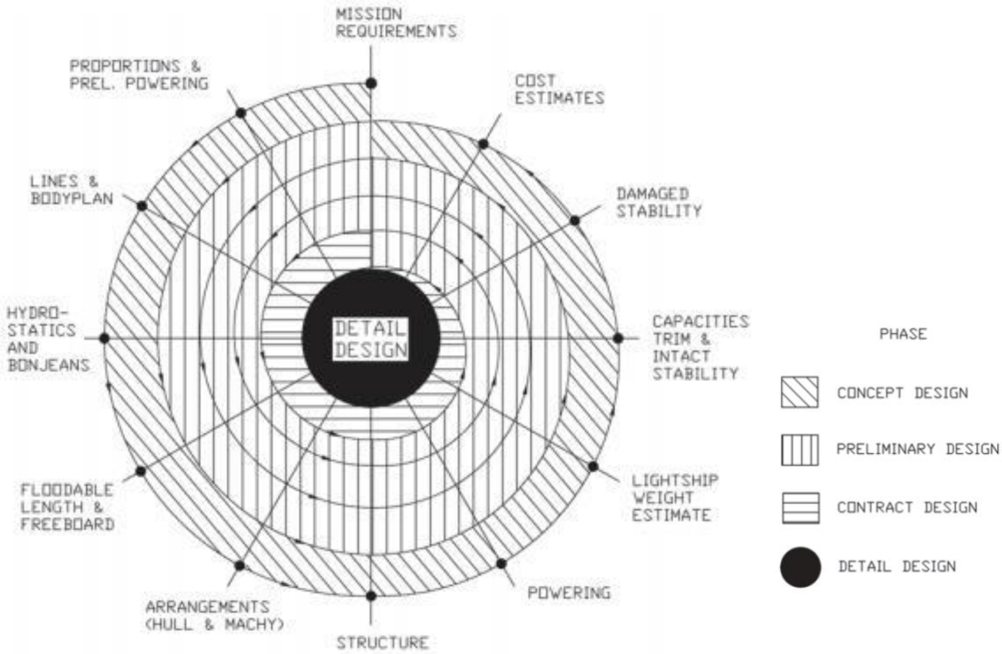

Figure 2-1: Design spiral [12].

2.2. Introduction to parametric ship design

The traditional methodology, composing the design spiral displayed in the above Figure 2-1, includes various design steps, each with its own difficulties and distinct characteristics. The ship is often described as a complex system integrating a variety of subsystems and their components, for example, subsystems for cargo storage and handling, energy/power generation and ship propulsion, accommodation of crew/passengers and ship navigation [13], thus the endeavor of reaching an "optimum" solution subject to specific owner's requirements through these traditional "relational or empirical methods" (consisting namely of semiempirical methods and statistical data of existing vessels regarded as successful designs) is evidently arduous. Additionally, the iterative nature of ship design, as explained above, intensifies the vulnerability of the final design to less optimal solutions due to crucial decisions made by the designer at the initial design stage, based on very limited information [14].

An integrated design methodology based on the "parametric method", where a parametric model is constructed, namely to seek the best combination of main dimensions and main design characteristics through an optimization procedure in order to produce truly optimal designs, facilitating the fast exploration of a series of design alternatives, would be of great assistance to the designer [1]. In contrast with the manual process described above, innately coupled with the design process is design optimization, namely the identification of the best solution out of a series of feasible ones on the basis of a criterion, or rather a set of criteria [13].

Inherent to ship design optimization are the conflicting requirements resulting from the design constraints and optimization criteria (objective functions, i.e., minimization of propulsion power, lightship weight, building cost, etc.), reflecting the interests of the various stake holders: ship owners/operators, ship builders, classification societies, etc. Thus, to conform with a specific set of requirements (usually the shipowner's requirements), it is essential for the ship to be optimized for cost effectiveness, for highest operational efficiency – or lowest Required Freight Rate (RFR) –, for highest safety and comfort of passengers/crew, and for minimum environmental impact. Even aspects of ship engine emissions and air pollution need to be considered (see Subchapter 1.5) [15]. As deduced from the above, the requirements are clearly conflicting, hence the necessity of automatic calculations through a parametric model, in search of the optimal ship design, is clear.

An example of a “near-optimal” design, achieved through the traditional design methods, replaced by a truly optimal, achieved through exhaustive optimization calculations utilizing computer hardware and software tools integrated with powerful hardware and software design systems, is presented in the following Figure 2-2, thus underlining the usefulness of the “parametric method”.

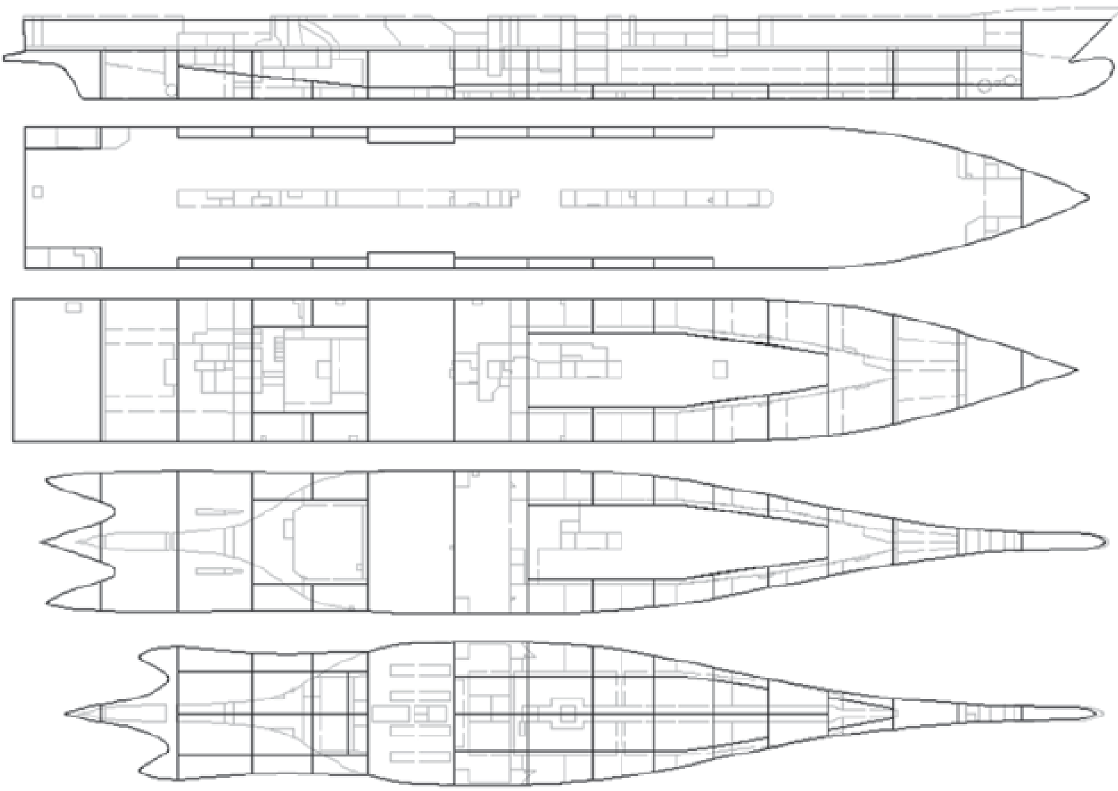

Figure 2-2: Comparison of compartmentation of optimal (dark line) vs. initial (grey) Ro-Ro passenger ship design [16].

2.3 Parametric model description

Before presenting the procedure of the parametric modeling, it is crucial to underline that the detailed presentation of the tools (calculation methods, software tools, etc.), which comprise the parametric design method is not incorporated in this thesis – mainly addressed briefly or only by term –, as its main concerns are the design steps taken after the delivery of the optimal ship.

2.3.1 Geometric model

An application of the “parametric method” described in the previous subchapter, focused on ro-pax ships’ parametric design, was developed by NTUA-SDL (NTUA Ship Design Laboratory). The methodology for the parametric design of ro-pax vessels has been developed within the well-known commercial ship design software NAPA, utilizing a series of appropriate macros able to generate the ship’s hull form and internal layout according to a selected set of design parameters which have been assigned with the required values. Additional macros or external software tools have been developed and linked to the design application for the assessment of the technical and economic performance of each design. A representative example of such external software tools is CAESES®, a state-of-the-art process integration and design optimization environment developed by FRIENDSHIP SYSTEMS. It integrates first-principles analysis software from various disciplines relevant to ship design and combines them with advanced multi-disciplinary and multi-objective optimization methods [17].

The first step of the parametric design procedure is the development of the geometric model, identified as the definition of the hull form, which is generated based on a set of design variables, namely the main dimensions and global hull form characteristics (C_B and LCB), along with their appropriate range of variation, ensuring the generation of feasible and efficient hull forms. Additional parameters are introduced to control local hull form details, such as the shape (either conventional or goose-neck type) and size of the bulbous bow, or the existence of a propeller tunnel, a duck tail or a stern wedge. It should be mentioned that a typical hull of a modern ro-pax ferry is generally generated, with a flared bow and a goose-neck bulb, no or very small parallel midbody and a buttock-flow stern with a skeg.

It is emphasized that, by default, the frame spacing is set at 800 mm, while the web frame spacing at 2,400 mm (three times the ordinary frame spacing).

The cross-sections of a typical hull form, created by a parametric design application are presented in the following Figure 2-3.

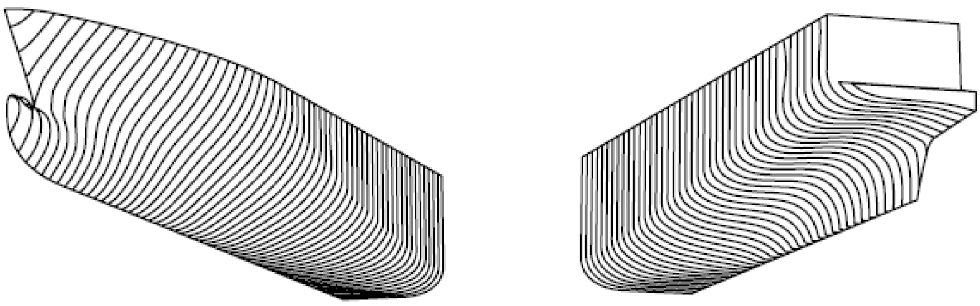

Figure 2-3: Transverse sections of a typical parametric-generated hull form (left: fore-body transverse sections, right: aft-body transverse sections) [14].

Following the construction of the ship's hull form, the geometric modeling is temporarily interrupted as parameters concerning her powering (resistance, propulsion and selection of main engines) are introduced and are calculated at specified service speed(s)[2]. These calculations affect directly the internal compartmentation as it needs to be ensured that the engine rooms are sufficiently spacious, according to the dimensions of the selected machinery components (main engines, reduction gears, etc.) and this is actually the reason why the resistance and propulsion calculations are carried out at this point of the procedure. Specifically, the towing resistance can be calculated using either of two alternative methods; the Holtrop method [19] or the a priori calculation of the resistance – utilizing external CFD tools. Additionally, the propulsion power of the ship is estimated by the Holtrop method [19] and B-series open water efficiency polynomials derived with multiple regression analysis [20]. Finally, the selection of the ship's main engines is decided from a list of potential prime movers covering the limitations established by the ship particulars for a range of design speeds. Thus, four 4-stroke diesel (or dual-fuel) engines are selected, with their maximum continuous rating determined based on the previously defined (required) propulsion power, the maximum consumed power of the shaft generators and an appropriate power margin. It is noted that the power of the shaft generators and the power margin are user-defined parameters [18].

Recommencing the geometric modeling, the definition of the ship's internal layout occurs. All designs can be divided into three main regions. The lower region consists of the double bottom and two additional decks (decks 1 and 2) and it is occupied mainly by machinery and auxiliary spaces, various tanks (e.g. ballast water, fuel oil, etc.), void spaces and most prominent the engine rooms and lower holds for private cars. It should be noted that the main engines are arranged in two engine rooms, the length of which is derived from the size of the main engines, as a means of compliance with "safe return to port" regulation for passenger ships, as mentioned in Subchapter 1.5. Moving upwards, the middle region consists of the main and upper ro-ro decks (decks 3 and 4), while the upper region houses the superstructure – consisting of three additional decks (decks 5 to 7) – that provides the required accommodation and public space areas. The first step towards the construction of the internal layout is the definition of the watertight subdivision below the main ro-ro deck (deck 3), namely the transverse and longitudinal bulkheads, and decks.

Starting from the main transverse bulkheads, a default arrangement was assumed corresponding to a "baseline design" with a length between perpendiculars of 180m [18]. For deviations from that reference design, the transverse bulkheads, thus the size and number of resulting compartments, can be either lengthened and shortened (in the first case) or increase and decrease (in the second case). The primary constraints causing such alterations concern the aft and fore limits of the engine rooms, as well as the position of the collision bulkhead specified by SOLAS [7]. Regarding the first constraint, the aft limits of the engine rooms are additionally restrained by the elevation of the ship's hull due to the "buttock-flow" stern, while the fore limits by the consequent lane capacity reduction of the lower holds as well as the increased length of the shafting system.

[2] The option for different design speeds for day and night trips is included, if applicable for the operational profile of a ship (this option was not included during the design of the optimal ship).

Concerning the deck heights in the lower region (up to deck 3), desired values are supplied by the user. Generally, the decks are flat horizontal surfaces with the exception of "steps" at the engine rooms, due to the size of the main engines or the necessary alignment of the shafting system with them. Similarly to transverse bulkheads, several constraints imposed either by SOLAS [7], such as the minimum double bottom height, or by the hull form itself, mainly the elevation of the stern, or even by the main engines' height, shift the deck heights accordingly, until all constraints are satisfied. It is noted that the relevant distance between decks remains constant.

Finally, the lower decks are subdivided into three transverse zones by two symmetric longitudinal bulkheads, which follow the hull form geometry. The distance of the bulkheads from the ship's side shell can be modified by the user as a percentage of the beam, ranging from 15% (if the Stockholm Agreement does not apply) to 25% [18].

Moving upwards, the definition of the ship's middle region takes place. The number of vehicle decks and the type of vehicles (mix of private cars and/or trucks) carried on each of them are controlled by a series of user-defined parameters, in accordance with the size of the designed vessel. As mentioned above, the generation of a main and upper ro-ro deck is common practice. Additionally, a hoistable platform can be arranged on top of the upper vehicle deck, which can be lowered to convert the trailer deck into two private car decks. General arrangements containing either or both of central and side casings can be modelled, according to the user's specifications.

The upper region is an assembly of an appropriate number of decks, providing the necessary space for the accommodation of passengers and crew – ensuring their comfort while on board –, public facilities and the required installation of life-saving equipment (e.g. lifeboats and/or liferafts), according to passenger transport capacity specified by the user and the required crew number. Thus, the main compartments of the superstructure are defined accordingly and the ship is divided into main vertical zones as specified in SOLAS [7] (addressed in Subchapter 1.5).

The geometric modeling is completed by defining suitable surface objects, representing structural entities of the ship (e.g. bottom and side plating, decks, bulkheads and the primary supporting members). These objects are utilized in the next phases of the design procedure for the calculation of areas and weights.

Overall, the ship designs derived from the parametric model are comprised of the same configuration concerning the regions specified above.

The aforementioned steps concerning the generation of the hull model followed by the specification of its internal layout are summarized in the following Figure 2-4.

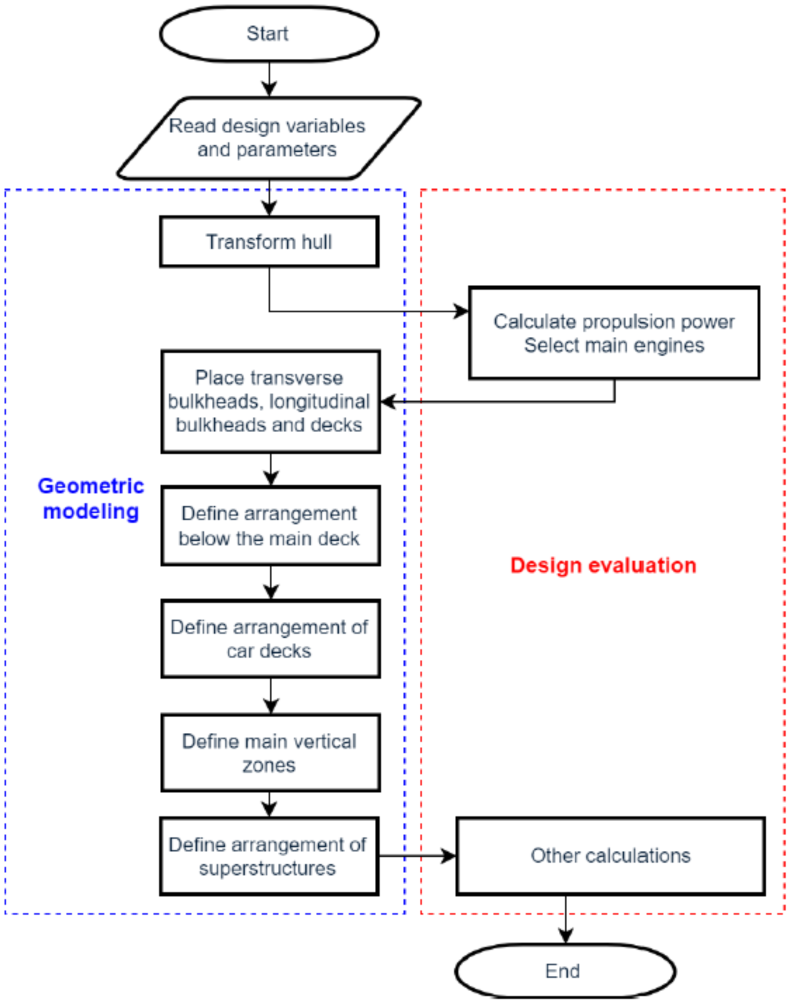

Figure 2-4: Flowchart of modeling process with emphasis on the geometric model [18].

2.3.2 Evaluation methods

The steps concerning the calculation methods for the evaluation of various quantities/characteristics of the ship's design, as specified below, are summarized in the following Figure 2-5. The assembly of Figures 2-4 and 2-5 constitute the main pillars of the endeavor to achieve an optimal design.

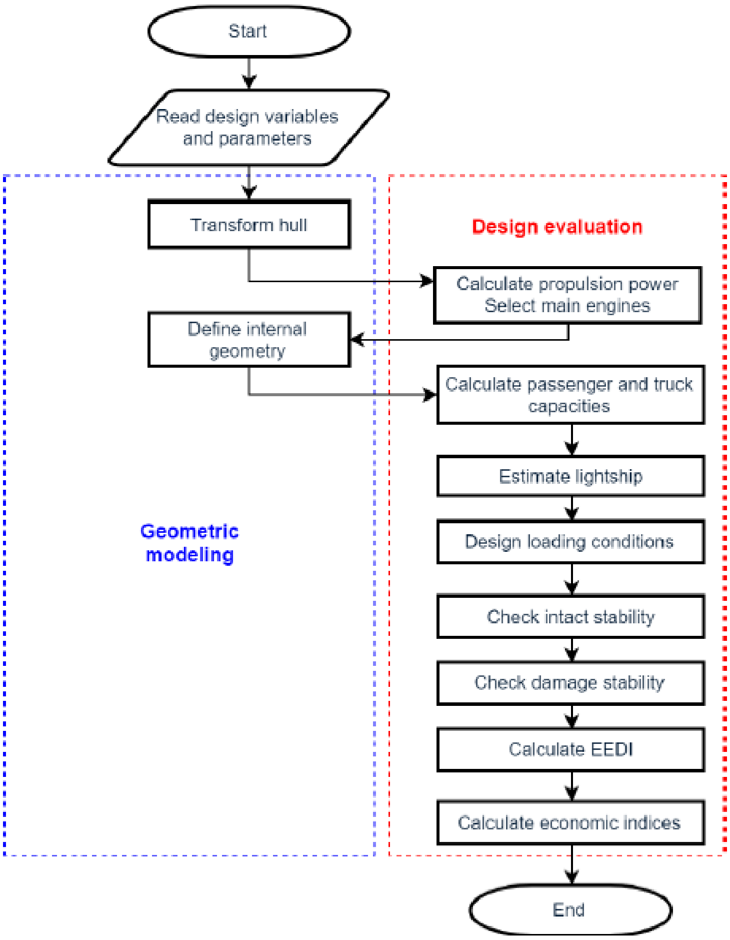

Figure 2-5: Flowchart of calculations and interaction with geometric modeling [18].

An introduction of the evaluation methods used in the parametric design has transpired in the previous subchapter, concerning the determination of the ship's powering, namely her towing resistance, propulsion power and selection of propellers and main engines. To complete the ship's design, a series of additional quantities has to be defined.

Firstly, the definition of the ship's cargo capacity, videlicet the vehicle capacity (assembly of trucks and/or private cars) is accomplished by utilizing a NAPA macro developed at NTUA-SDL. Thus, regarding the main vehicle deck, the macro receives as input the geometry of the ro-ro rooms, the dimensions and weight of the trucks, the web height at the sides of the ro-ro decks and the required margins from the webs and the casings (irrespective of the selection of central or side casings), and calculates the truck capacity, expressed in lane meters, for each ro-ro deck, along with the corresponding weights and their centroids [18]. Similarly, the private car capacity of the lower holds is estimated. For the upper ro-ro deck, in case of employment of the arranged hoistable platform, the private car capacity is estimated using the calculated number of trucks, as described above, and an assumed private car – truck projected area ratio [18].

Concerning the passenger capacity, default values of area coefficients (passengers / m^2) are applied on each deck of the superstructure, derived from existing large ro-pax vessels [18].

Furthermore, the estimation of the ship's lightship weight is crucial for the correct determination of the ship's floating position and stability, as well as for its building cost. The ship's lightship weight is subdivided into the following main categories: steel, outfitting and machinery. The steel weight is obtained mainly by direct calculation, namely based on the predefined surface objects, where several weight coefficients (tonnes / m^2), derived from existing vessels, are assumed for the structural elements of the ship's hull. However, the weight of some elements is calculated separately (i.e., struts, rudder and rudder stock, etc.) by utilizing suitable formulae. Moreover, the machinery weight is decomposed into several sub-items (main engines, reduction gears, shafting, bearing, propellers, gensets, etc.). Relevant empirical expressions have been developed for the estimation of the corresponding weights and their centroids, not including the weight – and centroid – of the main engines which is precisely known from the manufacturer data. To conclude, the outfitting weight is subdivided into various categories (deck equipment, ramps, life-saving appliances, accommodation, etc.), which are also further decomposed into sub-categories (e.g. deck equipment into mooring, towing and anchoring). These are calculated based on a variety of methods, including among others, empirical formulae, direct calculation from manufacturer data and appropriately defined area coefficients (mainly for accommodation areas).

The aforementioned lightship weight analysis has been implemented on existing vessels with ample lightship data, resulting to deviations not exceeding ±2% [18], while several correction factors were calculated for both the lightship weight and its centroid, thus improving the method's accuracy.

A stability analysis verifying regulatory compliance for intact and damaged condition is conducted. Primarily, the ship's loading conditions, expected in her life-cycle, are defined, mainly concerning loading cases in both departure and arrival condition with 100% passenger capacity and total or fraction of the total or even zero vehicle capacity. Intact stability analysis is based on the requirements of IMO's intact stability code (Resolution MSC. 267(85)) and additional criteria for passenger ships, while the damage stability analysis on regulations imposed by SOLAS or regional agreements (Stockholm Agreement – or Directive 2003/25/EC – concerning Water On Deck (WOD)). A series of macros has been prepared to control the process flow, while the actual stability analysis is automatically performed by NAPA. The contents of the aforementioned regulations, regarding the ship's stability, are addressed in detail in Chapters 4 and 5.

A design characteristic, emphasizing its significance in recent years, is calculated thereupon. The energy efficiency design index (EEDI), expressing the produced emissions for a given transport work rate, is assigned with a value utilizing a simplified formula for ro-pax ships with conventional diesel propulsion (disregarding efficiency technologies) [18] [21].

Finally, the assessment of the ship's economic performance is divided into two main categories: the building cost, and annual income and operating expenses. The building cost is estimated based on unit cost coefficients for the lightship components. Another coefficient is introduced to cover non-weight costs. Default values have been assigned to these coefficients, but their values can be freely altered by the user if more accurate data are available [8]. Regarding the operating cashflow, the calculations are based on the ship's operational profile specified by the user (length of route, service speed, fuel price, number of trips per week in the lower, medium and high season, the desired passenger and vehicle capacities along with the corresponding passenger's fare and vehicle freight for each of the three operating seasons, annual insurance and maintenance costs, etc.), including also a percentile increase to account for various other costs. The user defines also the expected years of operation and an interest rate. Therefore, the vessel's economic performance is assessed using the net present value of the investment (NPV).

2.4 Case study: Ro-pax ferry optimization

2.4.1 Formulation of the optimization problem

The developed parametric model is put into practice for a ferry service between Piraeus and Chania corresponding to a route of 165 nm. Both daytime and nighttime trips are arranged for a service speed of 24 knots, corresponding to approximately 7 to 7.5 hours of voyage. Appropriate time frames were considered for embarkation and disembarkation of passengers and vehicles, as well as maneuvering while approaching or departing from both ports. The ship will be operated year-round, considering a high season of six weeks with six roundtrips per week, a medium season of twenty weeks with three roundtrips per week, and a low season of twenty-four weeks with three roundtrips per week resulting in a total of 168 roundtrips per year. Appropriate occupancy rates for passengers, private cars and trucks for each of these three periods have been assumed for the calculation of annual revenues.

For the chosen application case a set of the most important owner's requirements concerning transport capacity have been selected based on equivalent vessels. Thus, the following Table 2-1 is constructed:

Table 2-1: Owner's requirements affecting ship design and economic life-cycle.

Constraint specification		**Value**	**Unit**
Capacity	Number of passengers	≥ 1600	-
	Lane meters for vehicles	≥ 1750	m
Service speed (calm sea, clean hull, 80% MCR)		24	knots

In addition, the design parameters characterizing the design under optimization are introduced. These include the ship's main dimensions and hull form characteristics, as they were not specified by the shipowner's requirements in the above Table 2-1. Specifically:

- The length between perpendiculars (L_{PP}), ranging from 155 m to 170 m. The length of the ship is the most important design variable and must obviously be optimized, as it affects virtually all values of interest.
- The beam (B), ranging from 25 m to 27.5 m, corresponding to lane capacities of either 7 or 8 lanes. Further deviation from the above maximum value is expected to lead to increased propulsion power and building cost. The ship's stability is highly affected by her breadth, emphasizing its importance.
- The block coefficient (C_B), ranging from 0.57 to 0.62, mainly affecting the hydrodynamic performance of the vessel.

Suitable optimization constraints were introduced to distinguish feasible and infeasible designs. The most important constraints, resulting from relevant regulations (mainly the international SOLAS and MARPOL conventions), evidently concern the vessel's intact and damage stability, while particular significance was given to its environmental footprint. As a temporary safeguard against possible inaccuracies in the surrogate model for the damage stability assessment, suitable safety margins were introduced: The intact stability requirements should be met with a GM margin of 0.05m, meaning that the actual GM in all loading conditions tested ought to be greater by at least 0.05m than the one required by the intact stability criteria (IMO Intact Stability Code (2008)). Similar constraints apply to the GM margins of SOLAS Chapter II-1 Regulations 8.1 and 8.2/3, as well as for Stockholm Agreement. For the attained subdivision index (A-index) and the three partial indices a safety margin of 0.01 was introduced, i.e., all feasible designs need to meet the following inequality constraints:

$$A - R \geq 0.01$$

$$A_i - 0.9 \cdot R \geq 0.01$$

where A_i is the partial A-index at subdivision, partial and light service draught. The values of the abovementioned safety margins can be modified by the user.

Regarding, the environmental impact of the designs, an appropriate EEDI margin of 0.1 g/(t·m) – for phase 2 corresponding to the time period from 01/01/2020 to 31/12/2024 – was introduced, meaning that the attained/calculated EEDI shall be smaller by at least 0.1 g/(t·m) than the one required by the regulations. It is evident that if any errors are encountered during the design procedure, that particular design is considered infeasible.

It is emphasized that the definition of the quantities encountered during the optimization process, mainly concerning the intact and damage stability of the ship, is incorporated in Chapters 4 and 5.

2.4.2 Optimization results

Therefore, an optimization study was carried out to identify optimal ro-pax designs, fulfilling the owner's requirements and the specified constraints. The objective is to identify the optimum combination of main particulars (length between perpendiculars, beam, design draught and block coefficient) that maximizes the vessel's economic potential expressed by its Net Present Value (NPV).

A total population of 946 ships was produced. Overall, approximately 48.6% of the generated designs are feasible, translating into 460 feasible and 486 infeasible designs. By analyzing the relative results, it is concluded that the most critical constraint of the optimization problem is MARPOL's energy efficiency design index (EEDI), with only 68.71% of the designs passing, while the most trivial is Regulation's 8.1 margin, with a compliance percentile of 100%. Specifically, the percentages of feasible designs in terms of each of the constraints are presented in the following Table 2-2. It is noted that the values of Table 2-2 are only taking into consideration the designs with no errors during the optimization procedure.

Table 2-2: Influence of constraints on the number of feasible designs.

Constraint	Feasible designs	Percentage of total population
A-index margin	817	86.36%
Partial A-indices margin	907	95.88%
EEDI margin (phase 2)	650	68.71%
Regulation 8.1 margin	946	100.00%
Regulation 8.2/3 margin	762	80.55%
Stockholm Agreement (WOD) margin	756	79.92%
Lane meters	907	95.88%
Number of passengers	908	95.98%

A series of scatter diagrams, presenting relationships between the various technical and economical values of interest, followed by some relevant comments, is presented. Blue coloring denotes feasible designs, while red coloring designs which violate at least one constraint and are therefore infeasible.

Figures 2-6 and 2-7 present the influence of the length between perpendiculars and beam on the net present value and the building cost respectively. The net present value is examined under three different scenarios, assuming linear correlation, in the first case, and non-linear correlation, in the remaining cases, between the ship's size and occupancy rates, affected by the market's demand. Regarding the last two scenarios, the profit corresponding to the increase of the transport capacity (payload) – contrary to the first case in which as the transport capacity is increasing, the profit is increasing linearly – is limited by the demand for this transport capacity; meaning that by increasing the transport capacity of the ship, the increase of the effective capacity[3] may not exceed 40% – and 20% respectively – of the initial transport capacity. Thus, each scenario is more conservative, in terms of profit, regarding the ship's operation.

Thus, the length of the ship is positively correlated with the net present value of the investment in all cases, while observing a relative stabilization of its value at the more conservative scenarios. Similarly, the building cost is higher in longer designs. All feasible designs have lengths between perpendiculars above 164 m, associated with both greater net present values and building costs. This contradiction is mainly attributed to economies of scale; namely, the costs relevant to pricing and competitiveness, decline as ship size increases. This decline is more pronounced in the case of shipbuilding costs, manning costs and fuel costs [22]. Similar behavior is observed with the beam regarding both the net present value and building cost, except for the most conservative NPV scenario where a negative correlation between the ship's beam and the net present value is observed. This is due to the disproportional increase of annual transportation work and operational and building costs. It should be noted that feasible designs are characterized by a varied range of beams, in contrast with their lengths. Finally, as shown in Figure 2-8, a negative correlation between the block coefficient, C_B, and the net present value is observed, which can be attributed to the increased resistance, thus propulsion power, for larger values of the block coefficient. Regarding the building cost, a definite conclusion on the effect of C_B is difficult to reach.

[3] The effective capacity corresponds to the percentage of the actual (transport) capacity that brings profit to the ship's owner.

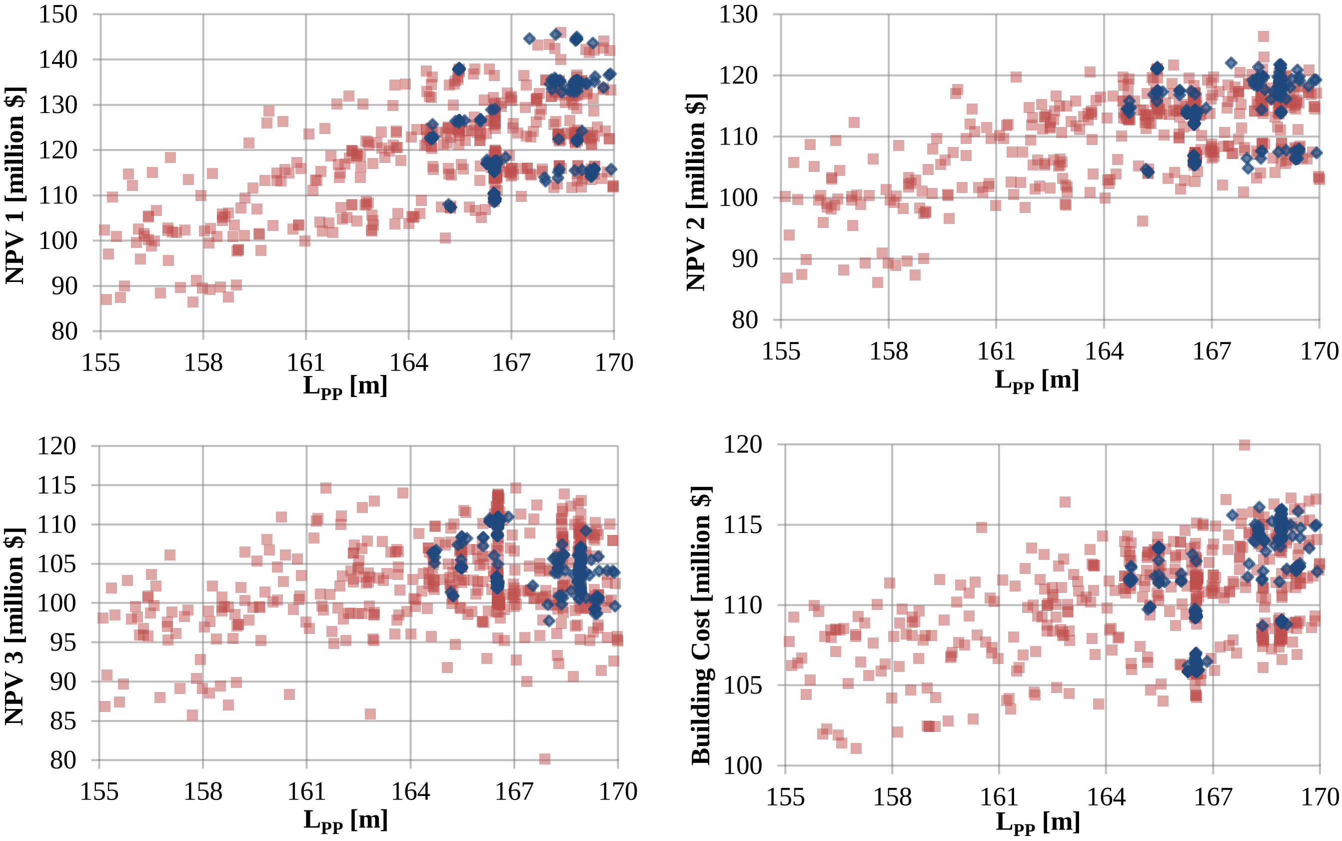

Figure 2-6: Length between perpendiculars relation with main economic indices.

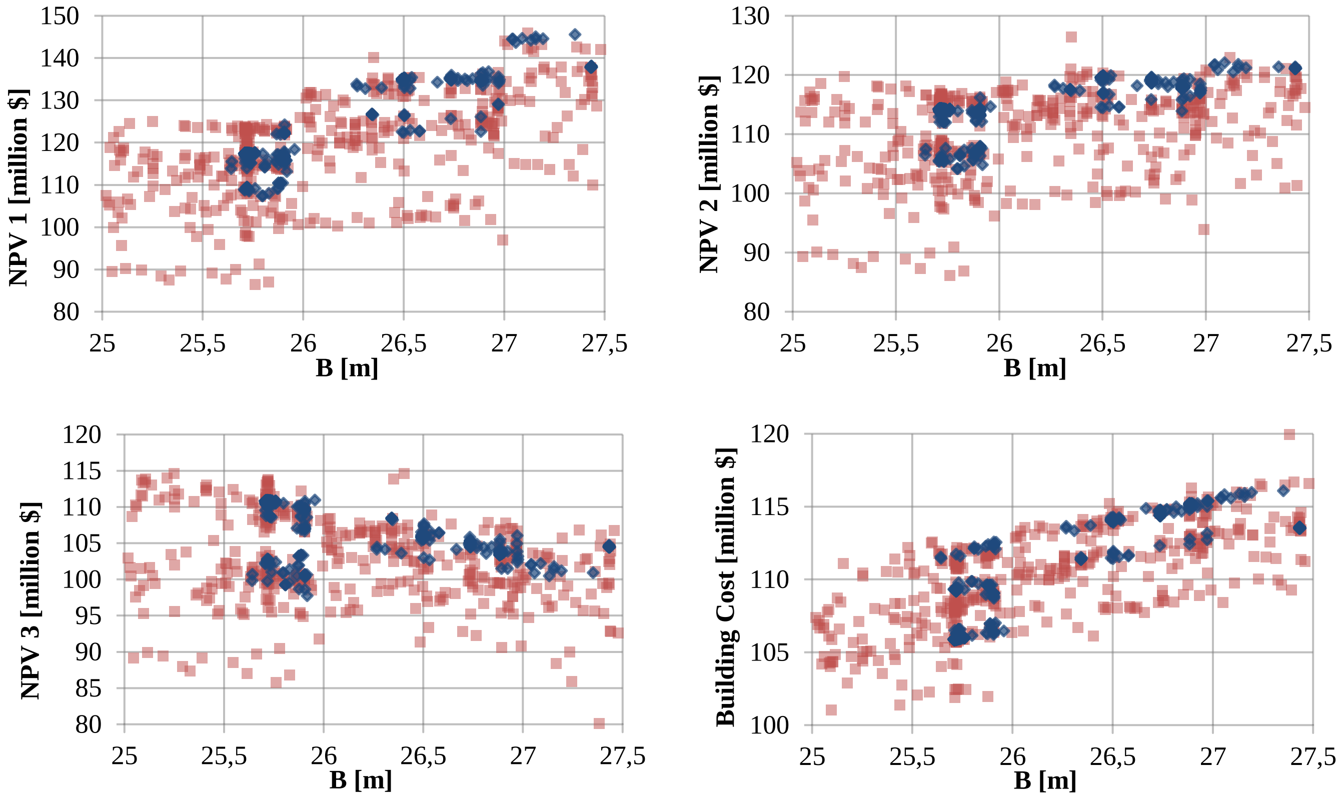

Figure 2-7: Beam relation with main economic indices.

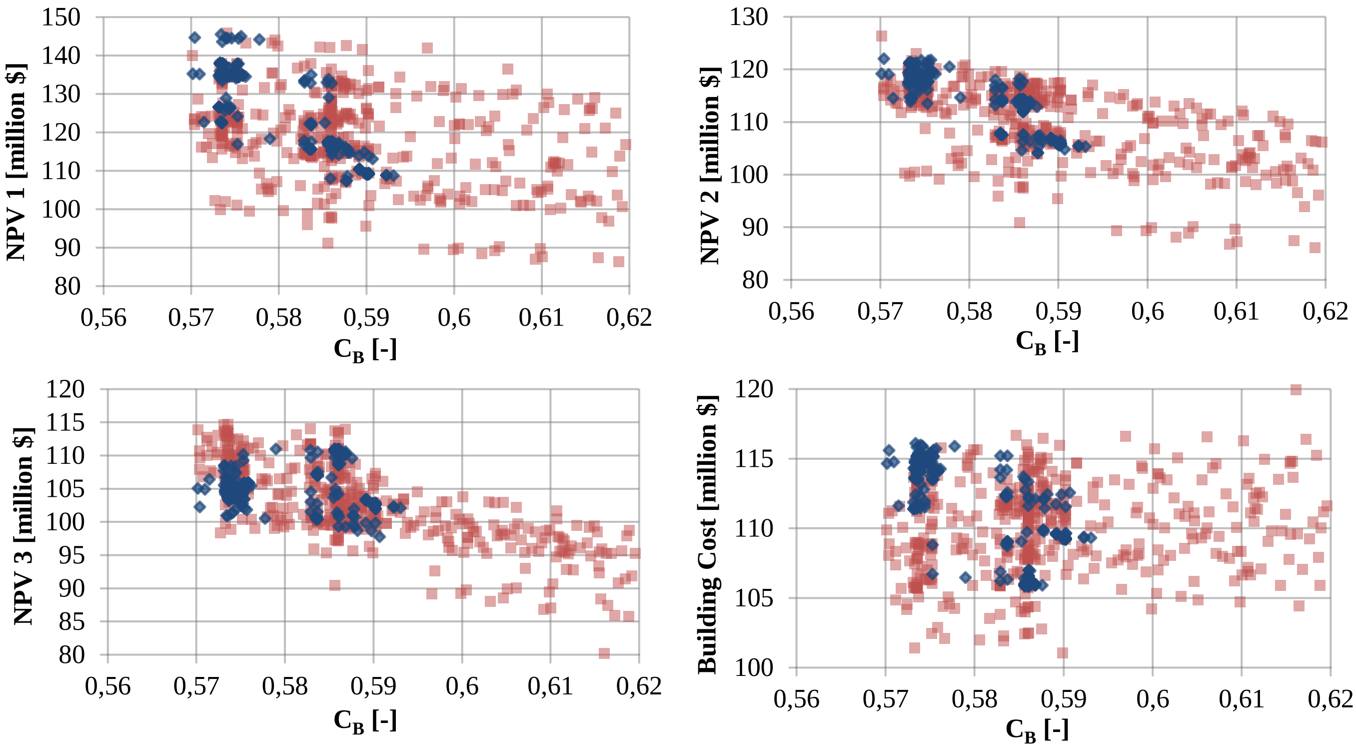

Figure 2-8: Block coefficient relation with main economic indices.

An additional index of the economic performance is the estimated payback period – measured in years –, presented in the following Figure 2-9 in relation with both the length and beam of the designs. It can be concluded that the majority of the feasible designs is assembled at a payback period of approximately 8 to 8.5 years.

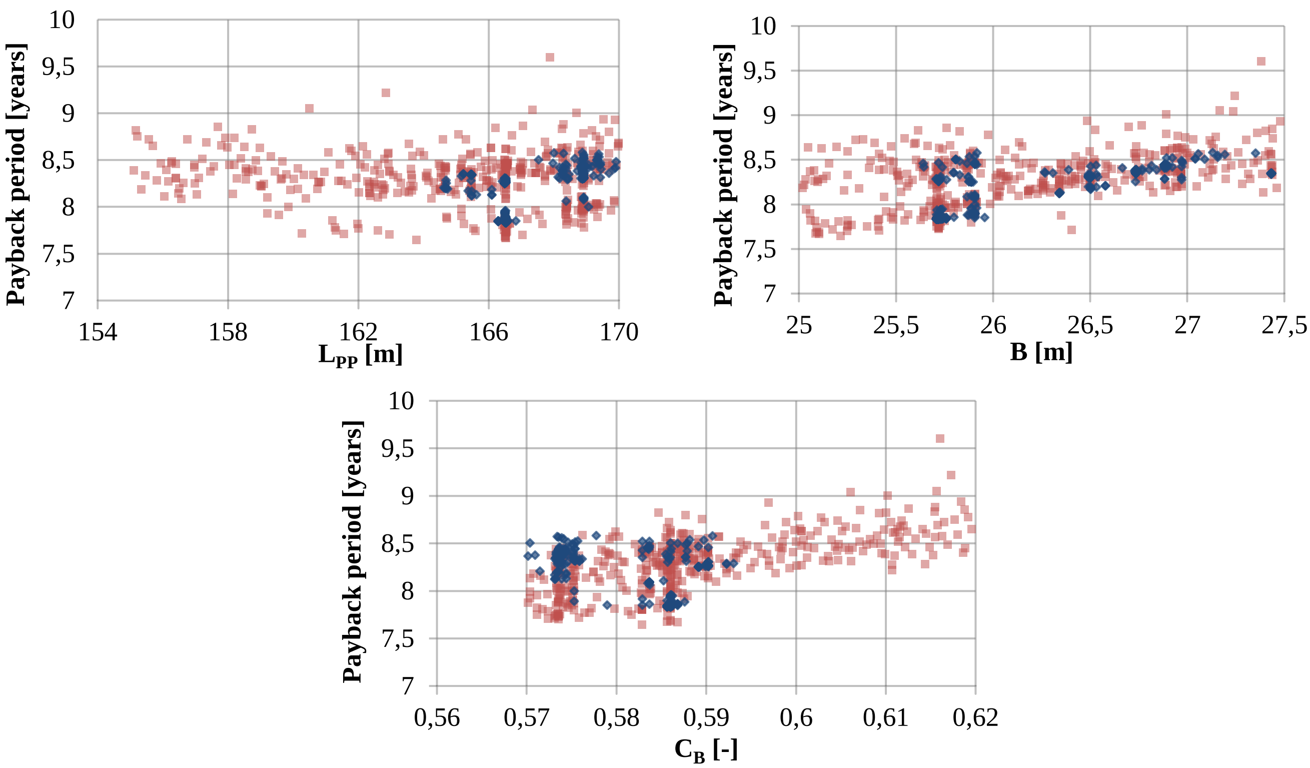

Figure 2-9: Additional design variables scatter diagrams for the assessment of economic performance.

Regarding the designs' compliance with stability requirements, the scatter diagrams in Figures 2-10 to 2-13 below present the stability margins against the relevant design variables (length between perpendiculars, beam and block coefficient). Generally, the most significant criteria are those of A-index margin and Regulations' 8.2/3 margin, as their resulted values are closer to the borderline value of zero. Thus, the following figures focus prominently on their relationship with the relevant design variables. Both the length and block coefficient have no explicit effect on the damage stability requirements, as their values are either relatively stable or scattered in a seemingly random way. Thus, as expected, the designs' beam affects dominantly the compliance with damage stability requirements, and more specifically, its increase comes with substantially improved stability, mainly on the critical criterion of Regulations' 8.2/3 margin, where the resulting values are significantly low for lower beams, reaching almost zero or negative values. As far as concerning the intact stability, expressed by the intact VCG margin – analogous meaning with GM margin –, a similar behavior from all design variables is discerned, hence emphasizing the positive and predominant effect of a larger value of beam. However, the effect of larger values of beams should not be disregarded – namely, the disproportional increase of cargo capacity and operational and building costs, as mentioned above – despite its positive impact on stability requirements.

Ultimately, a common denominator of the diagrams beneath is the behavior of feasible designs; meaning that they are concentrated at certain values of almost all design variables, namely lengths greater than approximately 164 m and block coefficients ranging from 0.57 to 0.59. However, the beams are linearly scattered while having a positive relationship with the values of interest.

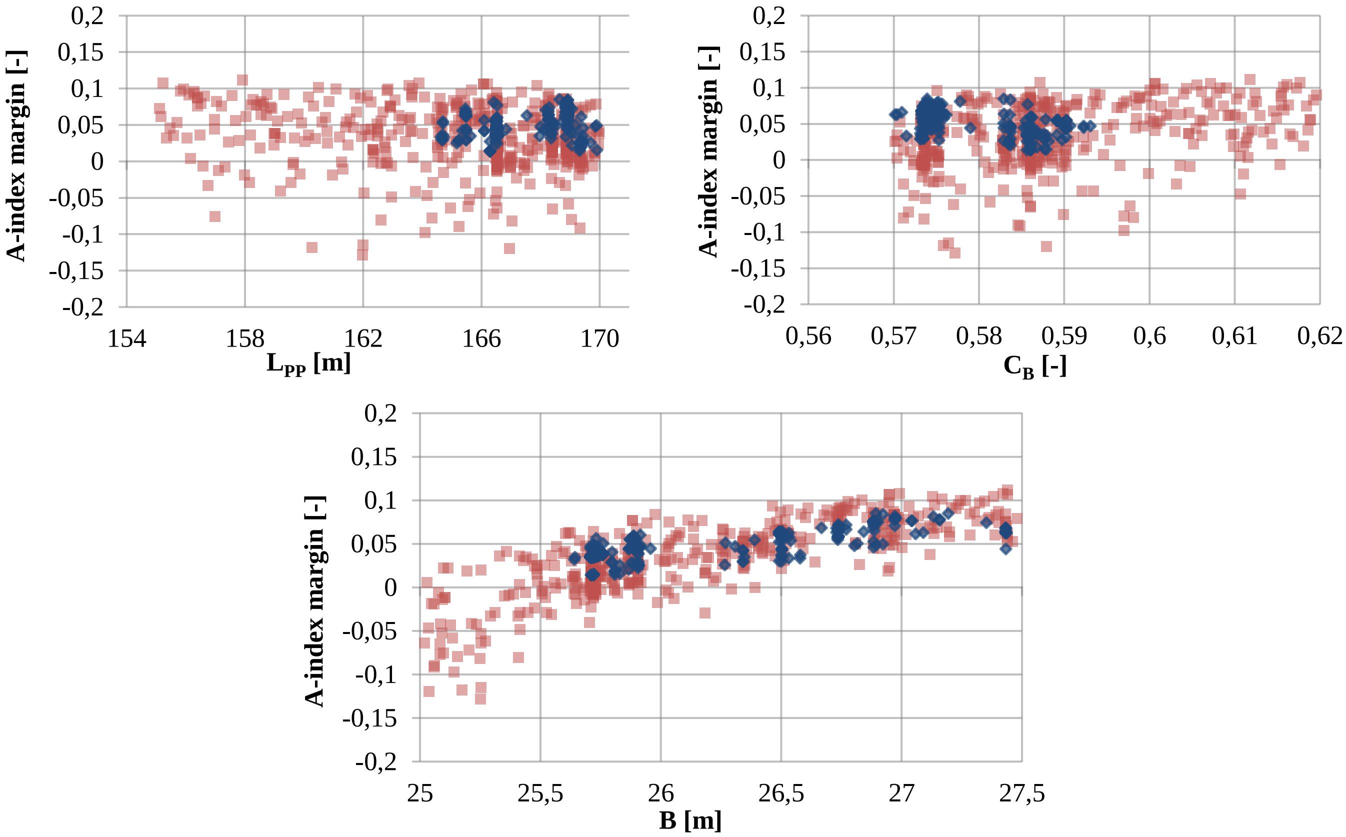

Figure 2-10: Effect of design variables on A-index margin.

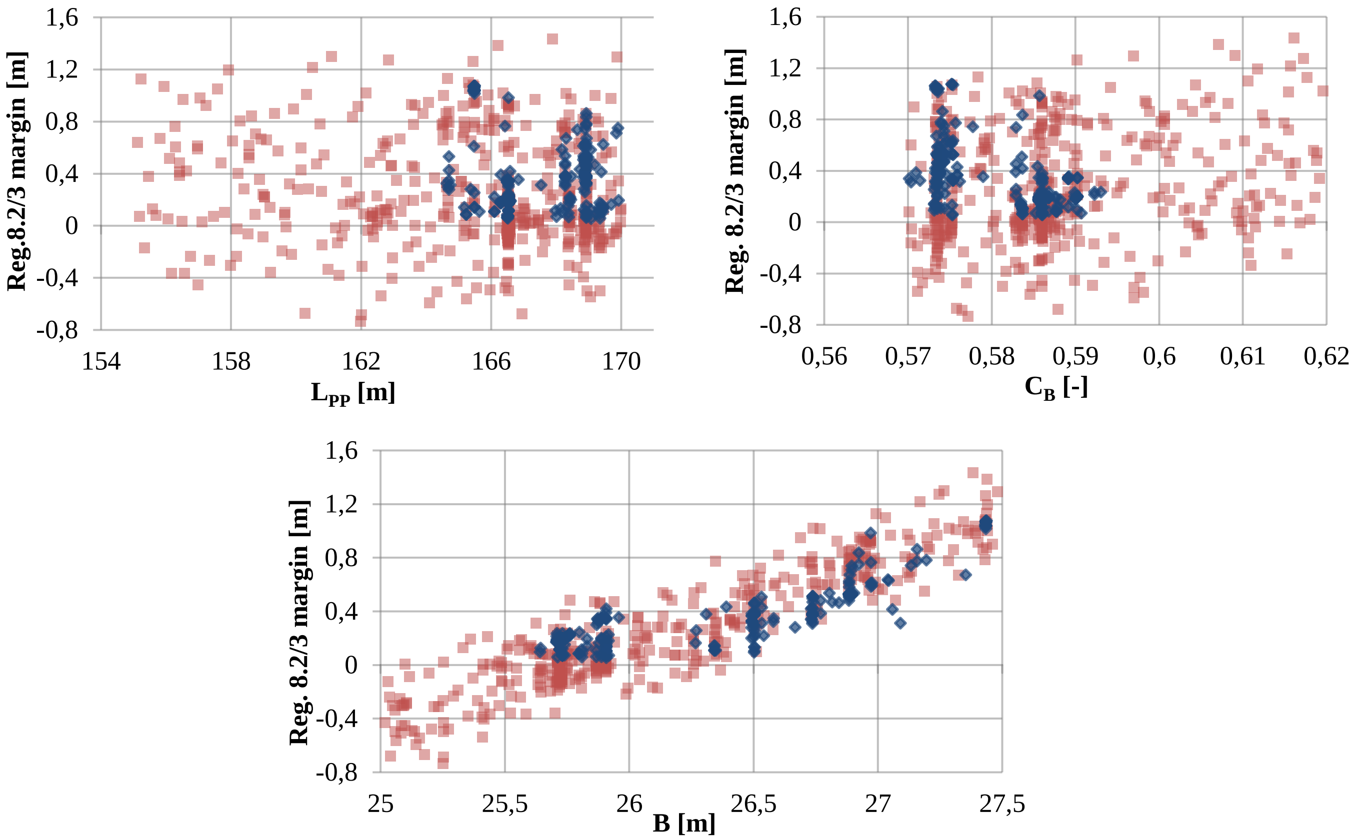

Figure 2-11: Effect of design variables on Regulations' 8.2/3 margin.

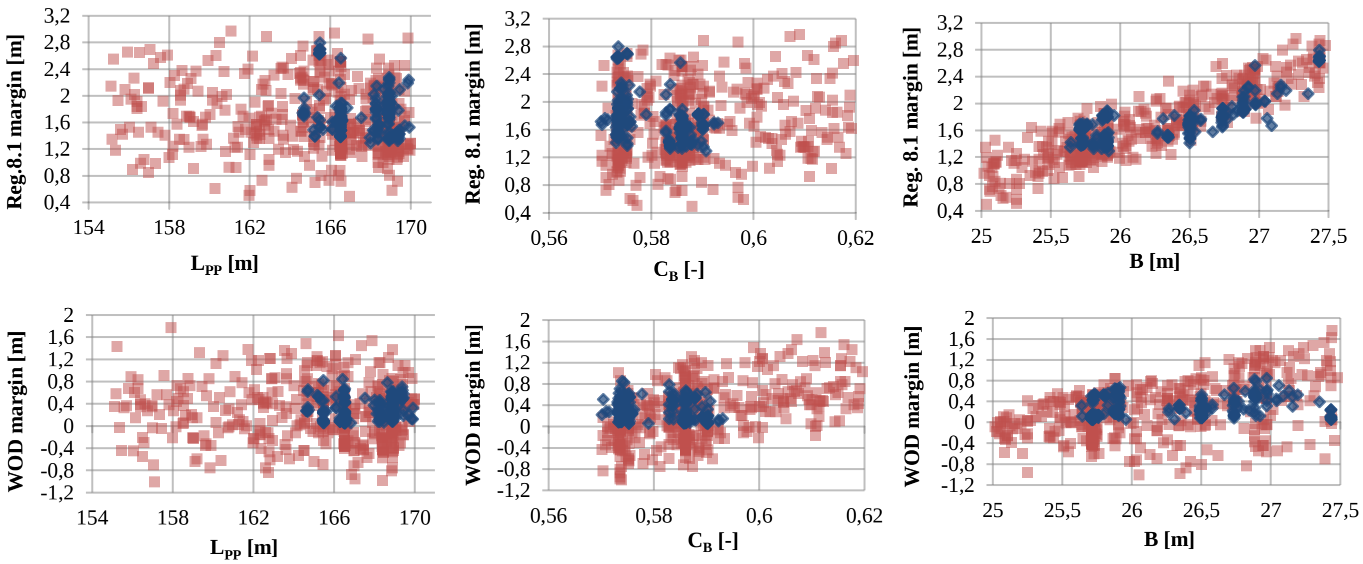

Figure 2-12: Effect of design variables on Regulation's 8.1 margin and Stockholm Agreement (WOD) margin.

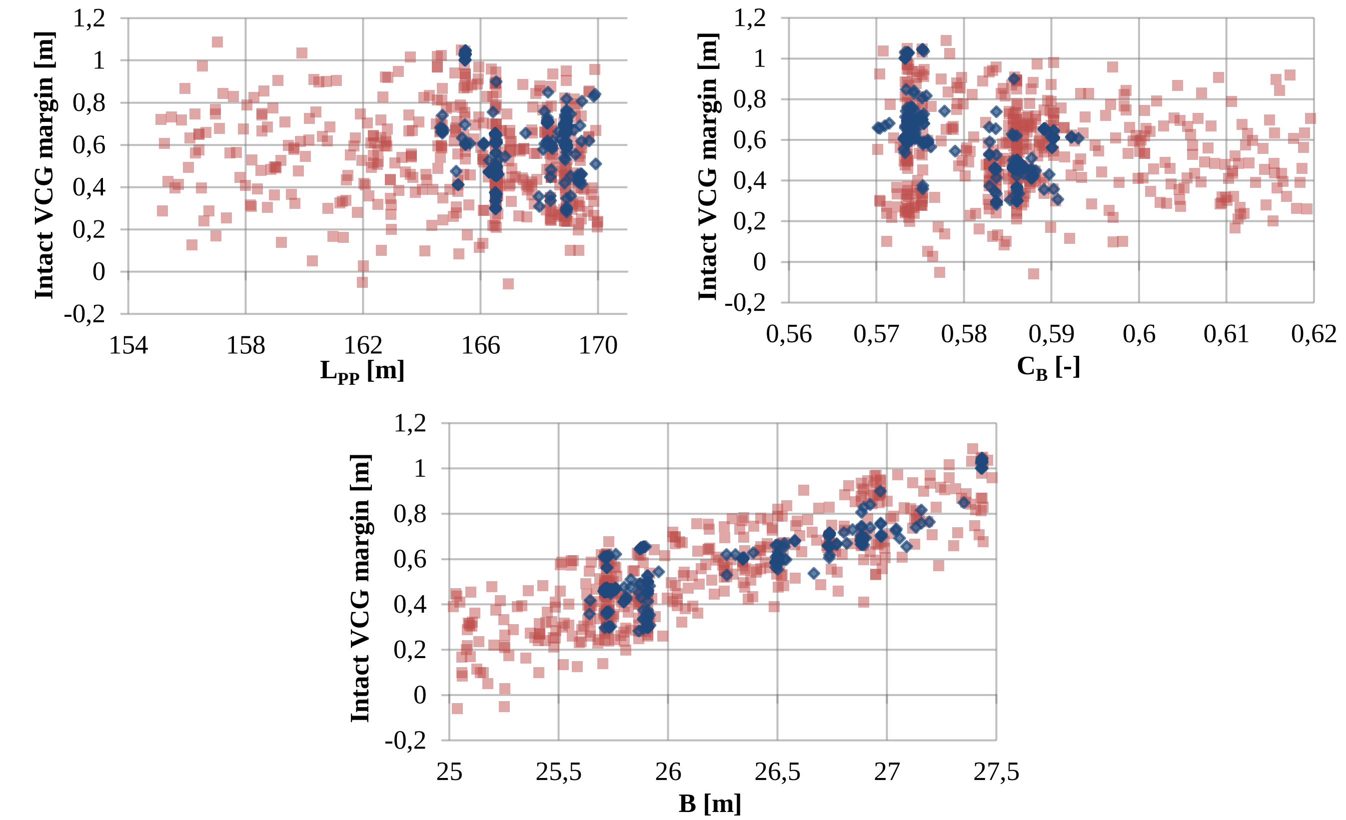

Figure 2-13: Effect of design variables on intact VCG margin.

Figure 2-14 below indicates that although the various stability criteria are positively correlated with each other, this is not always the case: for example, several designs which satisfy sufficiently the intact VCG margin might fail the criterion of A-index margin. Additionally, the majority of feasible designs can be clearly seen, in both diagrams, surrounded by a “cloud” of infeasible designs; meaning that feasible designs possess comparable stability-oriented quantities.

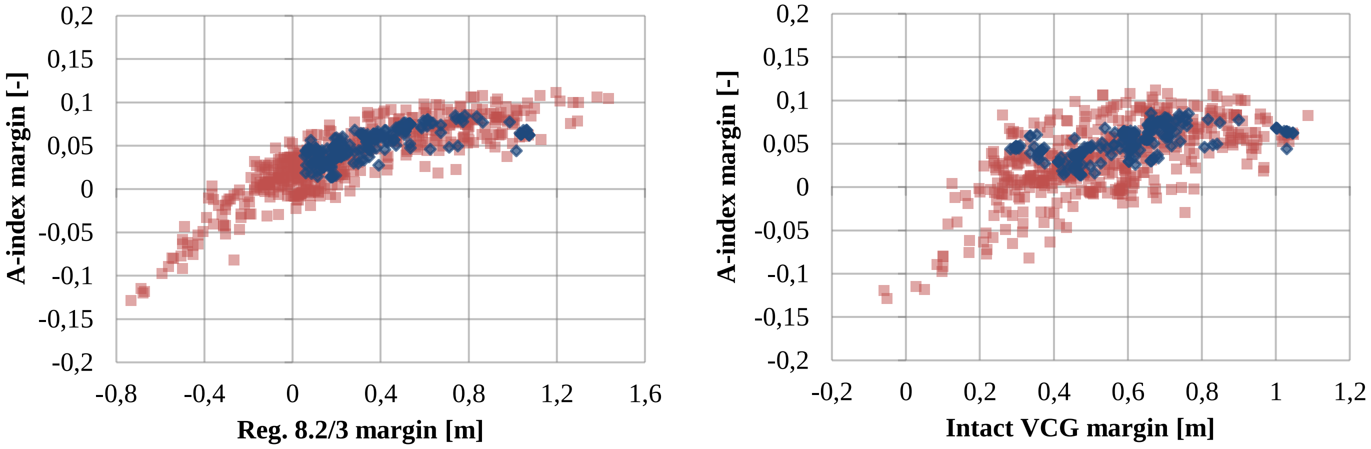

Figure 2-14: Relation between significant stability criteria.

Furthermore, in the following Figure 2-15, the relation of EEDI margin with the various design variables is examined. It is reminded that the EEDI margin constitutes the most critical criterion as approximately only 69% of the total produced designs is characterized as "feasible". This statement is emphasized, as shown below (Figure 2-15) as many designs fail the criterion, corresponding to values considerably less than zero. Regarding the length between perpendiculars, higher values of the EEDI margin are observed for its upper limit, which is attributed to the reduction of the designs' resistance, namely the wave resistance – prominent for the increased Froude numbers in which the designs generally operate –, thus the consequent decrease of the propulsion power facilitates the satisfaction of the criterion. A reliable conclusion on the effect of the designs' beam cannot be reached, in contrast with the effect of block coefficient where a negative correlation with this particular criterion ought to be further elaborated. The compliance with the criterion examined in smaller values of the block coefficient is mainly attributed to, as explained above, the reduction of the designs' resistance due to the slenderness of the hull for high Froude numbers. The selection of smaller values of the block coefficient for ro-pax ships, as mentioned in Subchapter 1.3, is justifiable, as concluded from the figure below (Figure 2-15).

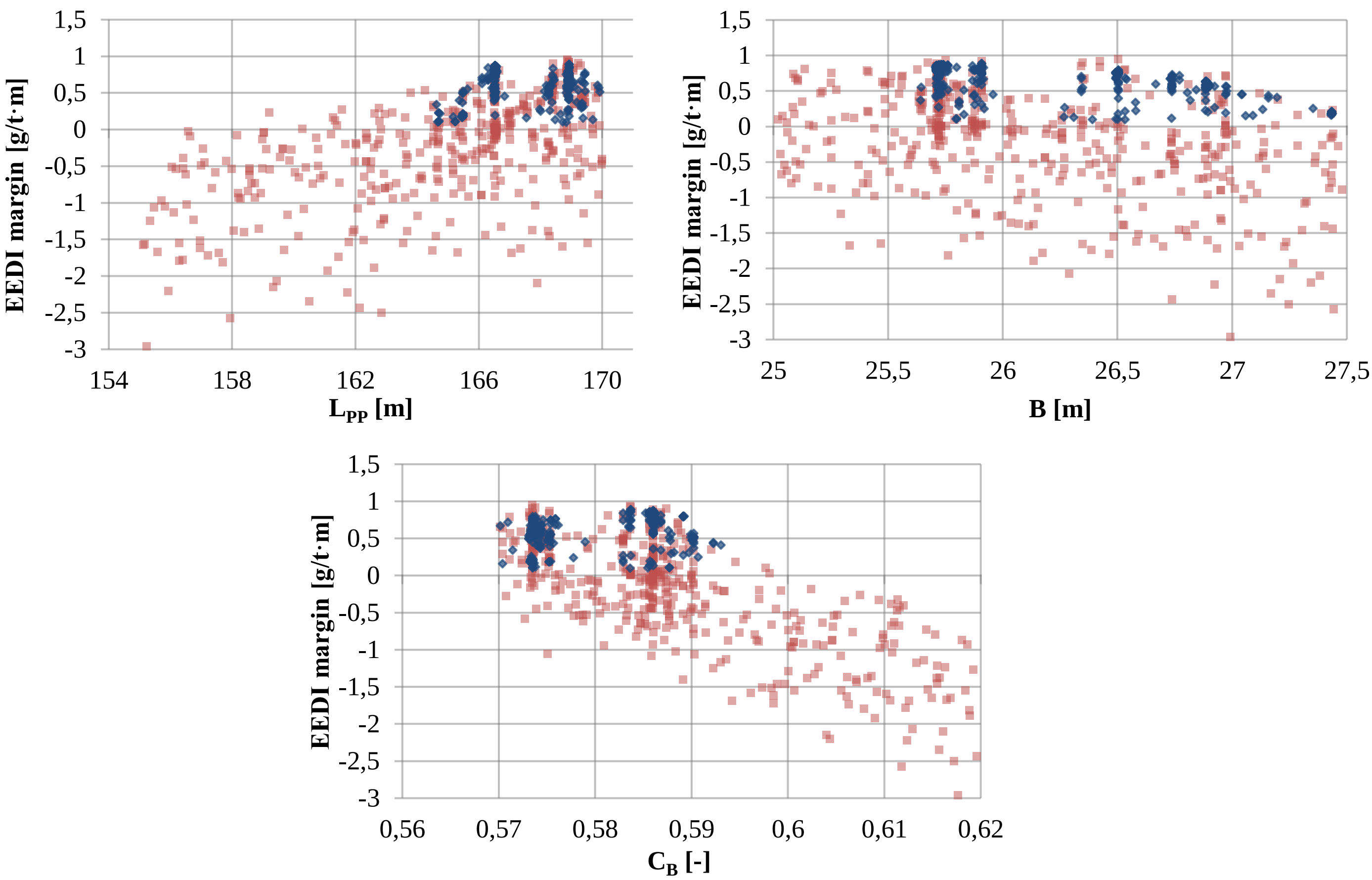

Figure 2-15: Effect of various design variables on EEDI margin.

2.4.3 Selection process of optimal ship design

The optimization procedure resulted in a number of feasible and infeasible ship designs. By examining the output of the parametric model for each design, the selection of the optimal ship, in terms of passenger and vehicle capacity, economic performance, intact / damage stability and environmental footprint is conducted. It is evident that the infeasible designs are automatically excluded from the selection process. The most significant quantities of interest, the careful analysis of which will result in the selection of the optimal ship design, are dominantly the A-index margin and the EEDI margin. Furthermore, the payback period (measured in years) is selected as an index of the economic feasibility of each design. Thus, each quantity was constrained as shown:

A-index margin ≥ 0.04 EEDI margin ≥ 0.5 Payback period < 8

This resulted in the reduction of feasible designs by approximately 95%; namely a total of 22 designs to be assessed. Additional constraints were introduced affecting various quantities of interest leading to the construction of Table 2-3.

A-index margin ≥ 0.04 EEDI margin ≥ 0.5 Regulation's 8.1 margin ≥ 1.5

WOD margin ≥ 0.45 Regulations' 8.2/3 margin ≥ 0.2

Table 2-3: Candidate criteria results.

Candidate name	A-index margin [-]	EEDI margin [gr/(t·m)]	WOD margin [m]	Regulations' 8.2/3 margin [m]	Regulation's 8.1 margin [m]
Nsga2_30_des0170	0.05864	-	0.637	-	1.523
Nsga2_30_des0251	0.04572	-	0.520	-	-
Nsga2_30_des0287	0.04573	-	0.520	-	-
Nsga2_30_des0363	0.04647	-	0.527	-	-
Nsga2_30_des0390	0.04572	-	0.520	-	-
Nsga2_30_des0403	0.0477	0.73733	-	0.340	1.793
Nsga2_30_des0404	0.04548	0.80982	-	0.316	1.766
Nsga2_30_des0409	-	-	0.505	-	-
Nsga2_30_des0419	0.04592	-	0.520	-	-
Nsga2_30_des0424	0.04573	-	0.520	-	-
Nsga2_30_des0443	0.04512	0.743	0.652	0.211	1.555
Nsga2_30_des0453	0.06032	0.67145	0.671	0.227	1.570
Nsga2_30_des0469	0.04547	0.75712	-	0.348	1.805
Nsga2_30_des0470	0.05926	0.66013	0.643	-	1.535
Nsga2_30_des0480	-	0.7283	-	-	-
Nsga2_30_des0606	-	0.73213	-	-	-
Nsga2_30_des0631	0.046	0.82216	-	0.348	1.801
Nsga2_30_des0649	-	0.71736	-	-	-
Nsga2_30_des0681	-	0.83491	-	0.246	1.691
Nsga2_30_des0686	-	0.73592	-	-	-
Nsga2_30_des0725	-	0.79966	-	0.301	1.750
Nsga2_30_des0781	0.04566	0.86164	-	0.418	1.887

By analyzing the data of the above Table 2-3, it is concluded that the most promising ship design is «Nsga2_30_des0453», possessing high values of A-index and WOD (Stockholm Agreement) margins respectively and sufficient margins regarding the remaining quantities of interest. It is emphasized that due to several simplifications during the optimization procedure (i.e. estimation of the designs' lightweight), the attainment of relatively high values of the quantities of interest, prominently those concerning the ships' damaged stability, is crucial for the following design phases.

Consequently, a second optimization procedure was conducted aiming to examine the prospect of the Regulations' 8.2/3 margin increase, as the reliability of the results – namely the achieved stability in case of damage –, as mentioned above, is relatively low in this preliminary design phase. Additional measures were introduced, concerning some design variables, by limiting the limits of their values; specifically, the length between perpendiculars was arranged for the values 166.5m, 167m and 167.5m, the beam ranging from 25.9m to 26.5m and the block coefficient equal to 0.586. Additionally, for each combination of length and beam, two alternative designs were introduced; designs with decreased height and length of the heeling tanks respectively. Therefore, the final optimal design is the one with the decreased heeling tanks height by achieving a Regulations' 8.2/3 margin of 0.41m. The main characteristics of this optimal ship are presented in Table 2-4.

Table 2-4: Characteristics of optimal ship.

L_{PP} [m]	166.5	Lightship [ton]	10373
B [m]	25.9	DWT [ton]	6430
C_B [-]	0.586	SHP [kW]	20565.6
D [m]	9.27	A-index margin [-]	0.0639
Scantling draft [m]	6.54	EEDI margin (phase 2) [gr/(t·m)]	0.6715
Passengers [-]	1688	Regulation's 8.1 margin [m]	1.57
Lane meters for trucks [m]	1805.7	Regulations' 8.2/3 margin [m]	0.41
Lane meters for private cars [m]	371.8	WOD (Stockholm Agreement) margin [m]	0.63

This is a conventional, twin-screw ro-pax ferry with mechanical propulsion, fitted with a main and an upper trailer deck and two lower holds. A hoistable deck is also fitted on the upper trailer deck to provide additional transportation capacity. For loading and unloading of vehicles, the ferry is fitted with two stern ramps, as well as an appropriate stern ramp for the embarkation and disembarkation of passengers. The passenger accommodation spaces consist of two decks, providing sufficient amenities and comfort, and an open deck (sun deck), also containing accommodation areas for the crew.

Finally, a series of scatter diagrams, emphasizing the suitability of the selected ship design, is presented, also providing explicit references to the three similar designs with the alternative heeling tanks dimensions (Figure 2-16). It is noted that only the relation of various quantities of interest with the beam is presented as its effect is significantly higher than the other design variables. This statement resulted from the previously presented scatter diagrams (Figures 2-6 to 2-15).

As concluded from the following diagrams, the optimal ship design possesses high values of the examined quantities and especially in comparison with its similar designs. Regarding Regulations' 8.2/3 margin, higher values are observed for higher values of beam, however the significantly lower values of the EEDI margin render such beams inefficient. Thus, the concurrent satisfaction of both margins transpires in the optimal ship design, where both margins are sufficient for the examined preliminary design phase. Ultimately, a representative example of the economic performance of the selected design is presented, corresponding to the most conservative scenario, where the selected design is ranked among the best design cases, in terms of profit.

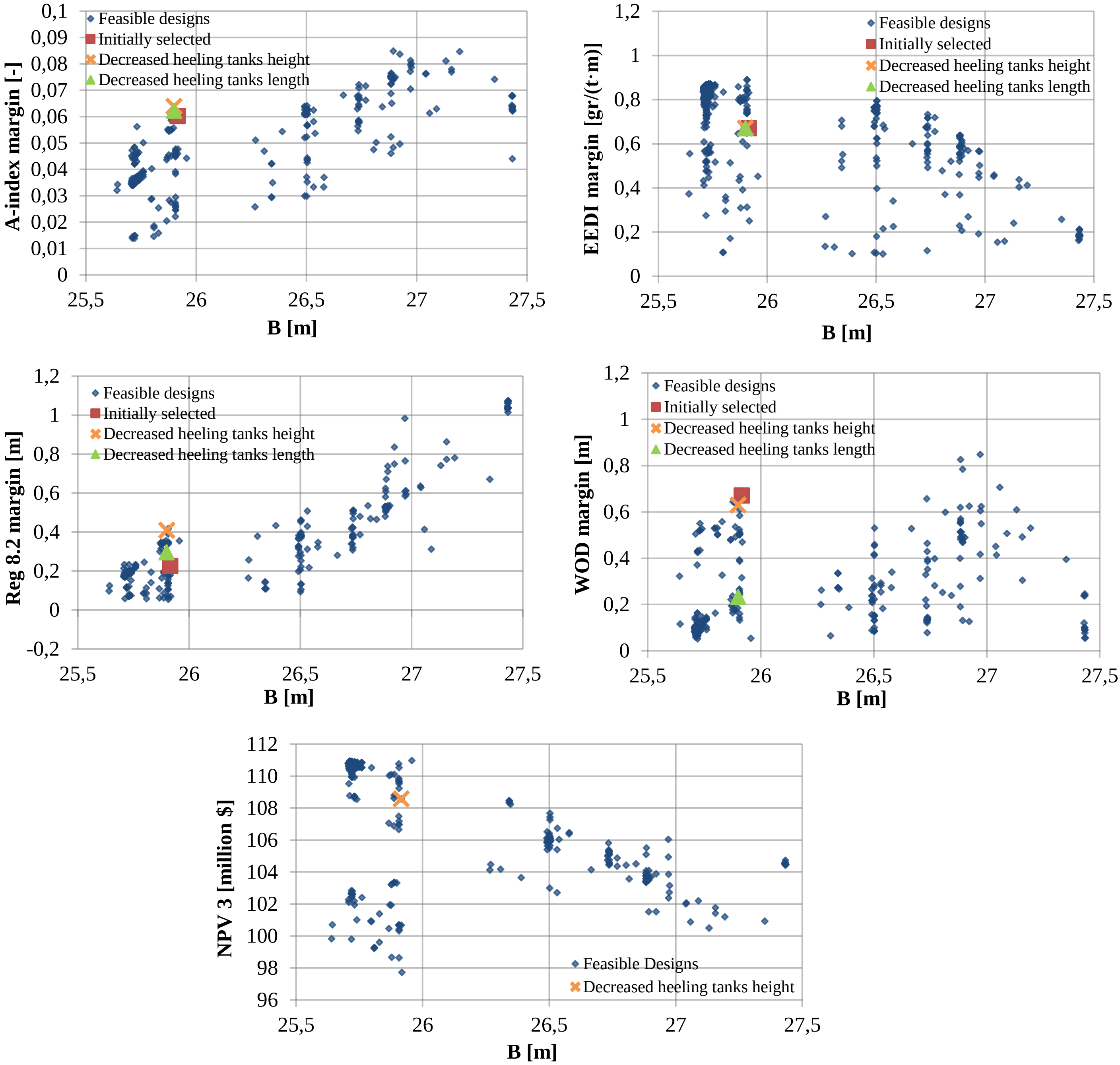

Figure 2-16: Optimal design comparison with the total feasible designs.

3. Development of General Arrangement Plan

This chapter covers various aspects concerning the preliminary general arrangement plan of the optimal ship. The main characteristics of each deck are discussed, thus forming a representative – but in no way exhaustive – portrayal of the ship's arrangement and design.

3.1. Introduction

The general arrangement (GA) plan of a ship involves the arrangement of spaces and the arrangement of the ship's main equipment and outfitting. Generally, it enables the survey of the interior arrangement of the ship and her superstructures, as well as various information regarding the main equipment (main engines, generating sets, etc.) and outfitting (passenger and/or crew cabins, arrangement of public spaces, etc.). The outcome of the procedure for the general arrangement of ship spaces is the subdivision of the ship's enclosed volume in the vertical direction through horizontal decks, transversely and longitudinally through bulkheads and walls into compartments, which serve certain functions, and the determination of communication routes on and between the decks and between the compartments [3].

The general arrangement of a typical ro-pax ship can be divided into three distinct groups: the lower decks, which are mainly occupied by machinery and auxiliary spaces, the ro-ro decks where vehicles (private cars and/or trucks) are loaded, and the accommodation decks on the superstructure. In this case, the first three decks comprise the lower decks, the next two the ro-ro decks, while the last three the accommodation decks and the wheelhouse.

The general arrangement plan, presented in the following subchapters, is derived from the parametric model having taken into account the suggested compartment purposes. It should be noted that as the space planning progressed, various design aspects of the initial design were altered to satisfy various requirements, such as passenger comfort. Specifically, at deck 7, the fore superstructure was widened to accommodate a greater number of crew cabins (Figure 3-16). Furthermore, the longitudinal extent of the fuel oil tanks at deck 1 was reduced as it was concluded that the amount carried was excessive (Figure 3-5).

The designed ro-pax ferry is presented in profile view at the following Figure 3-1, where the deck heights are visible and a preliminary depiction of the compartments' usage is suggested. The presentation of each deck is available following the description of each deck group, as specified above. For reasons of completeness, the entirety of the general arrangement plan is presented at the end of the chapter (Figure 3-17).

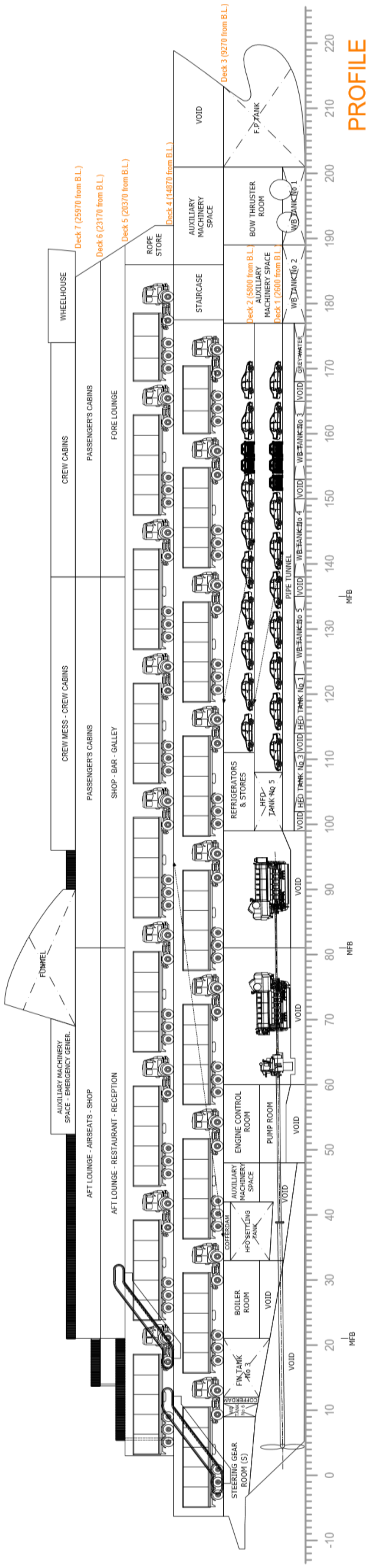

Figure 3-1: Illustration of the ship's profile view.

3.2 Lower decks (double bottom to deck 2)

As seen in the above Figure 3-1, the lower decks reach the bulkhead deck, positioned at a depth of 9.27m, coincided with deck 3 – referred to as the main ro-ro deck –.

Starting from the double bottom, the aft part of the ship contains mainly void spaces except for the four lubricating oil circulation tanks stationed below the ship's engine rooms and specifically, below the main engines. Moving forward, four heavy fuel oil tanks are encountered, which function as storage tanks. The remaining space is occupied by water ballast tanks – aiming to provide appropriate trim to the ship's various loading conditions –, void spaces [4], a grey water tank, each covering the full breadth of the ship, a pipe tunnel [5] and two bow thrusters – fitted in athwartships tunnels near the bow to improve maneuverability –.

Moving upwards (deck 1), the aft part of the ship contains two separate engine rooms as well as other auxiliary rooms (auxiliary machinery spaces, pump room). Generally, passenger ships are equipped with two or four main engines, both for redundancy reasons and because of their increased power requirements. Until recently, all engines were usually placed in a single main engine room. However, with the implementation of regulations 21, 22 and 23 of SOLAS Ch. II-2 [7], regarding the ship's safe return to port under its own means after damage, large passenger ships must be able to survive the flooding of any watertight compartment and be able to return to a port using their own means and at a minimum speed. Thus, this requirement may be fulfilled by dividing the engines between two separate engine rooms. The consequent reduction of useful cargo space is partially retrieved by eliminating the auxiliary engine room and installing the auxiliary engines (generator sets) in the two main engine rooms. However, it should be noted that this solution also increases the cost of the ship and means that there are two adjacent large compartments, jeopardizing her safety in case of side damage resulting in the flooding of both.

Therefore, the two engine rooms are occupied by the ship's main engines, the reduction gears (gearboxes) and the auxiliary engines (generating sets). The selection of the ship's main engines was derived directly from the parametric model, having taken into account the minimization of the specific fuel oil consumption through the calculation of the ship's resistance. As such, four four-stroke, medium-speed dual-fuel engines were installed, providing a total power of 26400 kW. The fact that the main ro-ro deck must be continuous sets a limitation to the maximum vertical extent of the engine rooms, and therefore to the height of the main engines. This is one of the reasons why four-stroke, medium-speed Diesel engines are used in ro-pax ferries rather than two-stroke engines. The design characteristics of the main engines are provided in the following Table 3-1.

---

[4] Apart from protecting the inner compartments in case of flooding, these void spaces enable instantaneous symmetrical flooding to avoid large heeling angles after minor side damages.

[5] The void space running in the midships fore and aft lines between the inner bottom and shell plating forming a space for ballast, bilge and/or fuel lines. Source: Wärtsilä dictionary.

Table 3-1: Design characteristics of the ro-pax ship's main engines [23].

Main Engine Constructor	Wärtsilä
Model	12V31DF
Quantity	4
Cylinder Configuration	12 (V-angle)
Engine Power (Nominal) [kW]	7200
MCR [kW]	6600
Engine Speed [RPM]	750
Dry Weight [ton]	77.7

These main engines are coupled to the propellers with reduction gearboxes – also referred to as marine reduction gears –, as the operating speed of these engines is significantly above a propeller's optimal point. Each marine reduction gear connects two main engines located at different engine rooms, to ensure the powering of the ship in case of failure of one unit or in an event of flooding of one engine room. The selected marine reduction gear is TCH350, by Wärtsilä [24]. Finally, as the arrangement of the main engines (Figure 3-5) dictates that both reduction gears are installed in the aft engine room, appropriate watertight boundaries were introduced in order to ensure the continuation of their operation even after an event of damage (flooding of the aft engine room).

Another important part of the ship's propulsion system is the main propulsion shafting, consisting of the thrust shaft, intermediate shaft and stern tube shaft. The thrust bearing is already integrated into the main engines with the thrust shaft rotating inside [23]. Hence, only the dimensioning of the intermediate and stern tube shafts follows [25] [26] [27]. However, the installation of the marine reduction gears mandates the dimensioning of two additional shafts serving as connections with the main engines.

Table 3-2: Marine reduction gears connection shafts characteristics.

<table>
<tr><td>Diameter [mm]</td><td colspan="2">180</td></tr>
<tr><td>Length [m]</td><td>2.4</td><td>16.64</td></tr>
</table>

Table 3-3: Intermediate shaft characteristics.

<table>
<tr><td rowspan="2">Shaft</td><td>Diameter</td><td>385</td><td>mm</td></tr>
<tr><td>Length</td><td>18</td><td>m</td></tr>
<tr><td rowspan="4">Bearings</td><td>Diameter</td><td>400</td><td>mm</td></tr>
<tr><td>Width</td><td>740</td><td>mm</td></tr>
<tr><td>Height</td><td>734</td><td>mm</td></tr>
<tr><td>Length</td><td>523</td><td>mm</td></tr>
<tr><td rowspan="3">Couplings</td><td>Diameter</td><td>770</td><td>mm</td></tr>
<tr><td>Thickness</td><td>96.25</td><td>mm</td></tr>
<tr><td>Fillet</td><td>30.8</td><td>mm</td></tr>
</table>

Table 3-4: Stern tube shaft characteristics.

Shaft	Diameter	470	mm
	Length	27.17	m
Bearings	Diameter	376	mm
	Width	940	mm
	Height	470.8	mm
	Length	540	mm
Couplings	Diameter	940	mm
	Thickness	117.5	mm
	Fillet	58.75	mm

To conclude the main propulsion system, it is imperative to determine the appropriate propellers for the main propulsion shafting. Ro-pax ships engaged in frequent manoeuvres at limited berthing ports are required to dispose two independent propellers, powered by one or two main engines each [7]. The main reason is redundancy. Moreover, the small ship's draft imposes a limitation to the maximum propeller diameter. In combination with the large delivered horsepower, the use of two propellers is required to achieve higher efficiency and avoid cavitation issues. Controllable pitch propellers (CPP) are preferred in ro-pax ships, enabling the master to optimize the pitch for service speeds lower than the design speed, as well as contributing to excellent steering/manoeuvring capability in ports [3]. The available data from the parametric model specify the main characteristics of the propeller, regarding its geometry and position (Table 3-5).

Table 3-5: Design characteristics of the propellers.

Longitudinal position [m]	3.787
Transverse position [m]	5.183
Hull height at the propeller's longitudinal position [m]	6.313
Diameter [m]	5.224

Concerning the position of the propeller, the data of the above Table 3-5 are considered acceptable, as the necessary clearances both from the ship's hull and the baseline are already addressed during the optimization procedure. Thus, a distance of 10cm from the baseline and a tip clearance of 1.089m from the ship's hull are attained. It is noted that the height difference between the propellers and the engine shafts result in an inclination of the main propulsion shafting of approximately 1 degree, which is common in vessels of this type.

Regarding the transverse distance of the propeller from the centerline, the value of Table 3-5 is altered as the alignment with the main propulsion shafting is not achieved. Hence, a transverse distance of 2.559m is attained, which satisfies the necessary clearance from the ship's hull.

According to SOLAS, a main source of electrical power of sufficient capacity shall provide all electrical auxiliary services necessary for maintaining the ship in normal operational and habitable conditions without recourse to the emergency source of electrical power. Thus, this main source of electrical power must consist of at least two generating sets [7]. The total installed electrical power of the main generating sets must suffice as to cover the worst-case operational condition of the ship.

These operational conditions and their consequent power demands are specified by the parametric model in the following Table 3-6.

Table 3-6: Ship's electrical power demands.

Operational condition	**Engine power [kW]**
Maneuvering	2592.42
At sea	1812.34
At port	1119.63

It is evident that the worst-case operational condition is that of maneuvering. Hence, the number and installed electrical power of the main generating sets shall be determined according to the following requirement:

If any one generating set is rendered inoperative, it will still be possible to supply those services necessary to provide normal operational conditions of propulsion and safety as well as minimum comfortable conditions of habitability. [28]

Considering the above, and with an additional criterion of ensuring minimum CO_2 emissions while operating at port, three (3) generating sets were selected. It should be commented that the same model of generating set was selected so as to facilitate both the maintenance and repair and ensure compliance with the aforementioned requirement. The main characteristics of the selected generating sets are presented below (Table 3-7).

Table 3-7: Technical characteristics of auxiliary engines [29].

Genset Constructor	Wärtsilä
Model	8L20DF (Tier II)
Quantity	3
Number of Cylinders	8 (in-line)
Engine Power [kW]	1480
Engine Speed [RPM]	1200
Electrical Power [kWe]	1420
Frequency [Hz]	60
Dry Weight [ton]	20.8
Fuel Consumption at 100% load [g/kWh]	197.2
Fuel Consumption at 85% load [g/kWh]	196.3
Fuel Consumption at 75% load [g/kWh]	197.2
Fuel Consumption at 50% load [g/kWh]	208.0

To further elaborate on the suitability of these auxiliary engines, the optimal range of operation – combining higher efficiency and lower emissions – is considered between 75% to 90% of the nominal power [28]. On a final note, similarly with the main engines, the generating sets are dual-fuel, so as in the event of conversion of the ship's propulsion system with a different fuel than heavy fuel oil, both the main engines and generating sets will operate efficiently, thus avoiding their costly replacement.

Forward of the engine rooms, the fin stabilizers – utilized in rough sea condition, in order to reduce the effect of rolling –, various tanks for heavy fuel oil and diesel oil as well as water ballast tanks, void spaces and the bow thruster room – constituting a continuation of the compartments in the double bottom – are encountered. It should be commented that after examining the number of trips that the ship can undertake before bunkering – videlicet seventeen (17) trips –, the lengths of the heavy fuel oil and diesel oil tanks were reduced by one web frame (2.4m), thus increasing the longitudinal extent of the lower hold at deck 1 – and consequently, the cargo capacity of the ship –, while the number of trips before bunkering was decreased only by two.

In addition, one relatively small car deck (lower hold) is arranged (Figure 3-2) – with a total vehicle capacity of 40 cars of 4.5m length and 1.8m width –, which is protected in case of side damage by longitudinal bulkheads – formed by the various water ballast tanks and void spaces –. The access to the lower hold is through a fixed internal ramp with an inclination of 10 degrees and length of 18.5m, while the course intended for the circulation of vehicles is semi-elliptical.

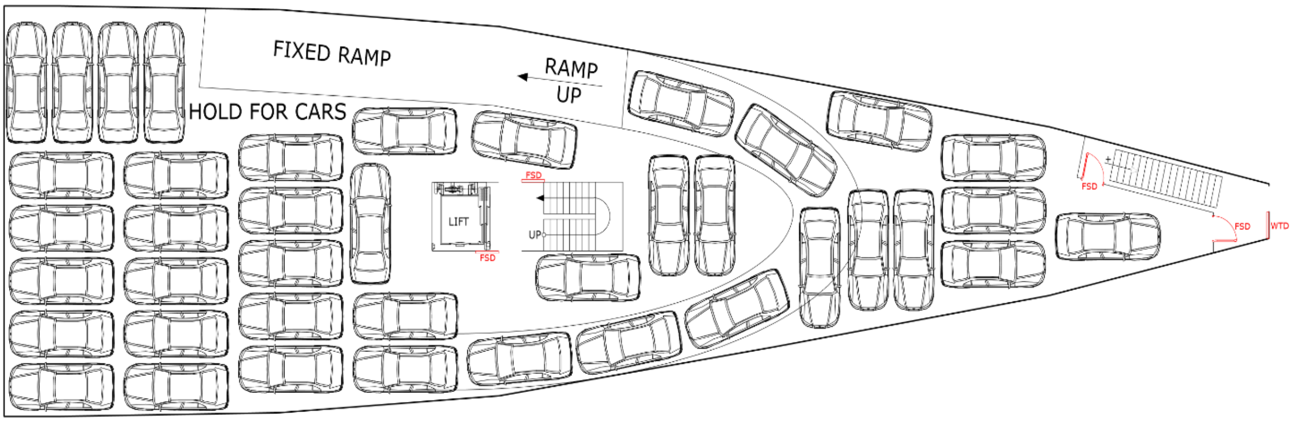

Figure 3-2: Illustration of lower hold at deck 1.

Finally, regarding deck 2, the aft part of the ship contains mainly auxiliary rooms (steering gear room, engine control room, machinery workshop, main switchboard, separator room, etc.) and various tanks (freshwater, water ballast, service and settling fuel oil, and service diesel oil). Platform decks are arranged in way of the engine rooms, enabling easier access to the main and auxiliary engines for the crew. In the fore part of the ship, numerous auxiliary spaces are encountered, such as the refrigerators and stores room, sewage plants rooms, void spaces, while the remaining deck is occupied by several tanks (fresh water, water ballast and heeling tanks) and the second car deck (lower hold). It should be noted that contrarily to both the void spaces and the other water ballast tanks, the heeling tanks are – by definition – two separate symmetric compartments.

Similarly to the lower hold at deck 1, this car deck is arranged with a total vehicle capacity of 36 cars, while the access to the lower hold is through a fixed internal ramp with an inclination of 10 degrees and length of 20m, while the course intended for the circulation of vehicles is almost elliptical (Figure 3-3). The decreased car capacity compared to the lower hold at deck 1 is attributed to the increased length of the underneath car deck following the reduction of the longitudinal extent of the fuel oil tanks.

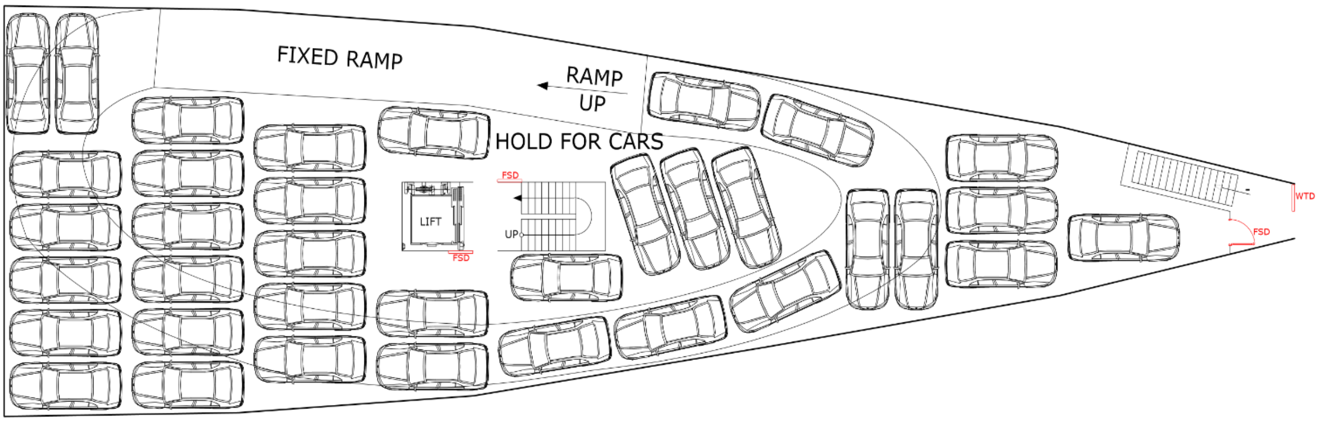

Figure 3-3: Illustration of lower hold at deck 2.

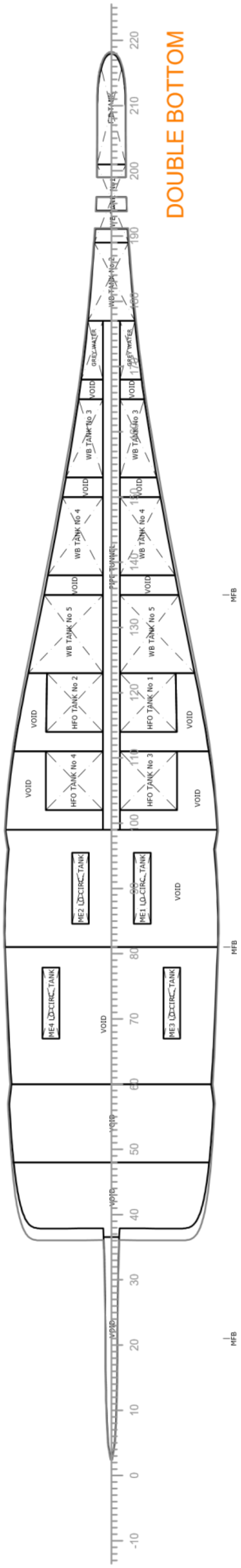

Figure 3-4: Illustration of double bottom.

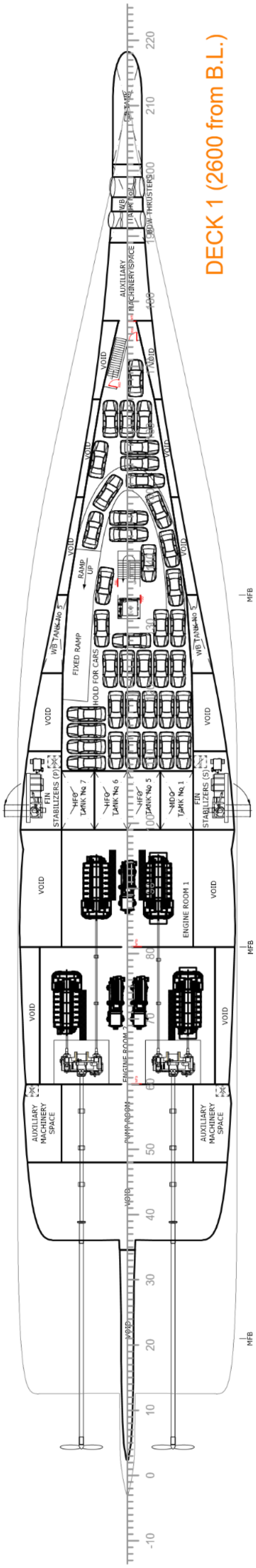

Figure 3-5: Illustration of deck 1.

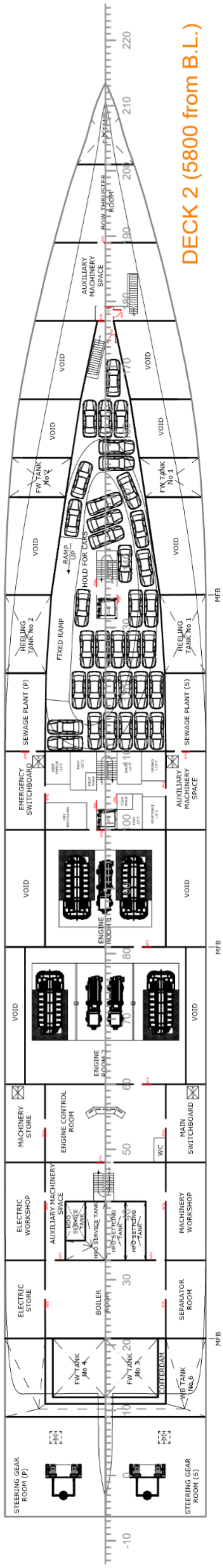

Figure 3-6: Illustration of deck 2.

3.3 Vehicle decks (deck 3 to deck 4)

The first extensive vehicle deck (deck 3) – referred to as the main ro-ro deck – is mainly intended for the carriage of trucks and trailers. The main deck is connected to the other ro-ro decks by fixed or movable internal ramps. For instance, as mentioned above, the access to the lower hold at deck 2 is through a fixed internal ramp, which on the main ro-ro deck is covered with an appropriate ramp cover, so as to enable the unobstructed movement and parking of vehicles. Therefore, since the main ro-ro deck must allow the unobstructed movement of vehicles, the transverse watertight bulkheads cannot extend above it. Thus, the available ro-ro space covers the entire length of the ship almost up to the collision bulkhead (frame #201). Loading and unloading of vehicles take place through two ramps – with an inclination of 7 degrees, length of 10.4m and width of 8m –, located at the stern of the ship, while a third ramp – with an inclination of 7 degrees, length of 9m and width of 3m – is intended for the embarkation and disembarkation of passengers.

The deck is equipped with a central casing, a long and narrow structure that provides a connection between the upper and lower decks – through appropriate staircases and lifts –, ventilation of the lower decks, store rooms and the engine room casing, reaching up to the funnel of the ship. Smaller side casings are installed at the aft part, intended mainly for the embarkation and disembarkation of passengers and for store rooms.

The number of vehicle lanes, utilized mainly for the parking of trucks and trailers, amounts to seven of 3m width – solely dependent on the ship's beam – while the available lane meters total 856.1m, thus permitting the accommodation of 42 trucks of 16m each and 12 trucks of 12m each – assuming the exploitation of the total vehicle capacity of the main ro-ro deck –.

Finally, the fore part of the ship is arranged with an auxiliary space, providing space for the ro-ro deck ventilation fans – also providing connection between the upper and lower decks through a staircase – and a void space.

Moving upwards, the next deck is the upper ro-ro deck (deck 4). Access to the upper ro-ro deck takes place via the main ro-ro deck through an internal – hoistable – ramp with an inclination of 7 degrees and length of 46m. It should be noted that this hoistable ramp is supported by the central casing on one side and ten pillars of 20cm diameter each on the other side. Consequently, the truck lanes of the main ro-ro deck at this longitudinal position create a ″step″, as to maintain their intended width.

The volume between deck 4 and deck 5 is generally intended for trucks and trailers. The number of vehicle lanes, utilized mainly for the parking of trucks and trailers, amounts to seven of 3m width – solely dependent on the ship's beam – while the available lane meters total 866.1m, thus permitting the accommodation of 45 trucks of 16m each and 9 trucks of 12m each – assuming the exploitation of the total vehicle capacity of the upper ro-ro deck –.

The upper ro-ro deck can be split by a hoistable deck (platform), creating two separate decks, converting the available height of deck 4 (5.5m) into two separate deck heights of 3.0m and 2.5m respectively. It is evident that as long as the hoistable platform is lowered, the space underneath is suitable only for the parking of private cars. Thus, the upper ro-ro deck can accommodate 25 trucks of 16m each, 5 trucks of 12m each and 99 cars – assuming the exploitation of the total vehicle capacity of the upper ro-ro deck –, while the hoistable platform holds a capacity of 66 private cars. The access to the hoistable platform is feasible through appropriate flaps – divided by the central casing (seen in the following Figure 3-7) – of 17.5m length, able to perform an inclination of 10 degrees.

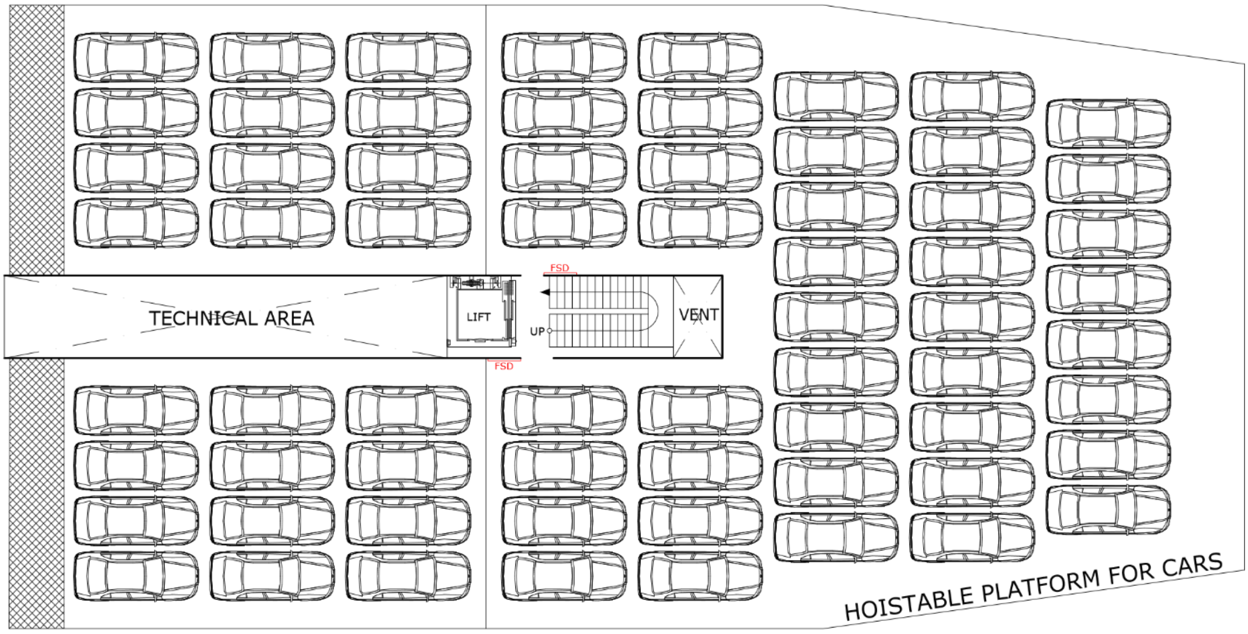

Figure 3-7: Hoistable platform in use.

Similar to the main ro-ro deck, the central casing extends to this deck as well. The passenger access to the accommodation spaces is ensured by one side casing – on the starboard side –, containing staircases and escalators. Both at the bow and stern, the open decks are reserved for mooring (anchoring and towing respectively) equipment.

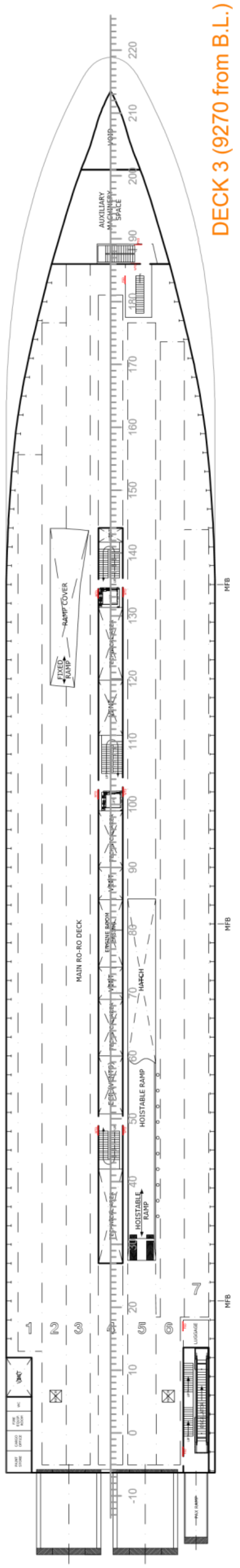

Figure 3-8: Illustration of deck 3/main ro-ro deck (truck lanes).

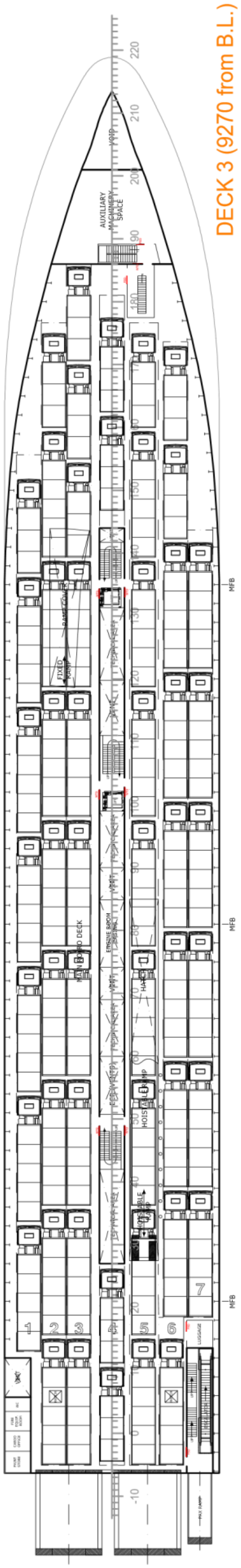

Figure 3-9: Illustration of deck 3/main ro-ro deck (trucks).

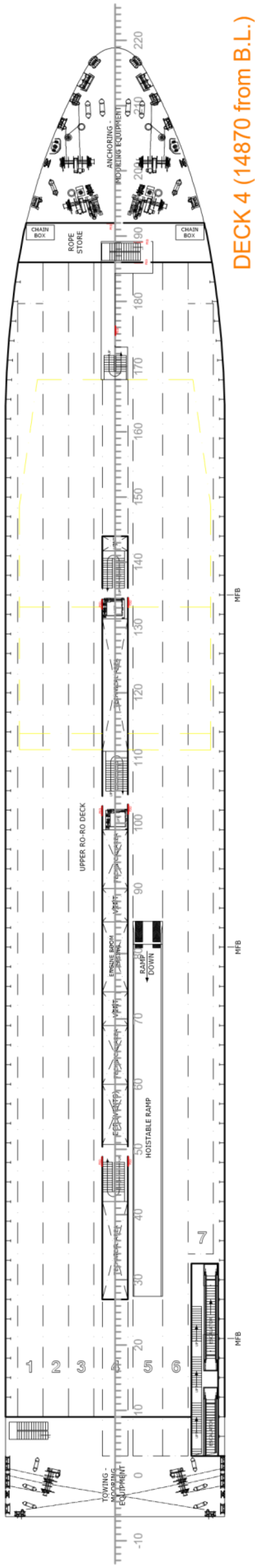

Figure 3-10: Illustration of deck 4/upper ro-ro deck (truck lanes).

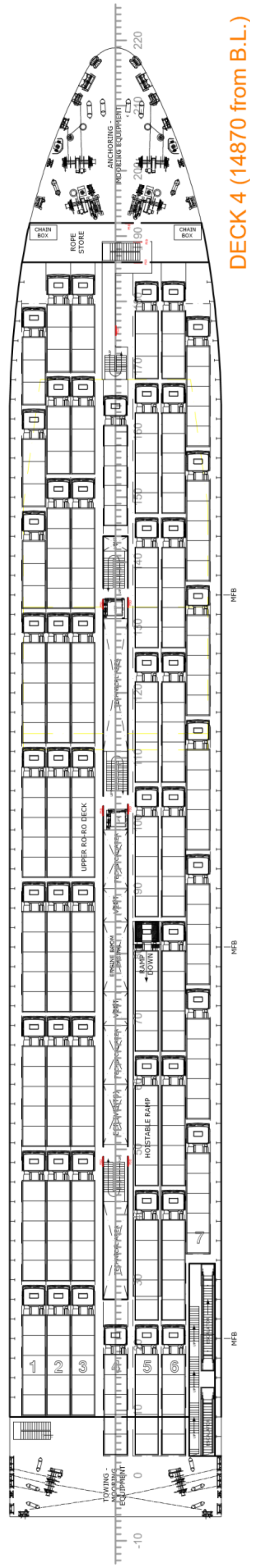

Figure 3-11: Illustration of deck 4/upper ro-ro deck (trucks).

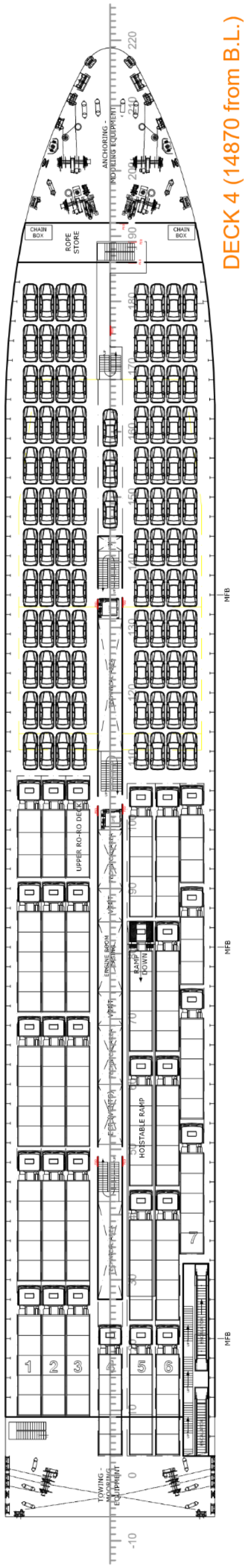

Figure 3-12: Illustration of deck 4/upper ro-ro deck (hoistable platform in use).

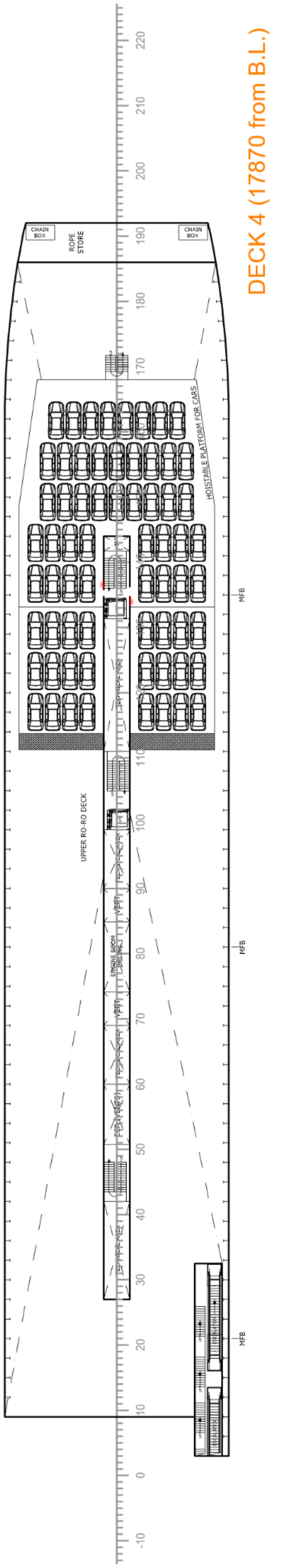

Figure 3-13: Illustration of deck 4/upper ro-ro deck (hoistable platform view).

3.4 Accommodation decks (deck 5 to deck 7)

The upper decks are utilized for the accommodation of passengers as well as officers and crew. Accommodation areas generally include various internal and external public spaces, air seats and cabins. Depending on ship size, trip duration and accommodation standards, the presence of restaurants and galleys, bars, shops, etc. is also possible. The upper decks also house the wheelhouse, life-saving equipment (lifeboats and/or liferafts), the funnel, the emergency generator room and other service spaces.

Each deck is subdivided into main vertical zones by ″A″ class divisions, designed to delay the spreading of fire. As has been mentioned (see Subchapter 1.5), the maximum allowable length of a main vertical zone is 48m, provided that its total area does not exceed 1600 m^2 on any deck [7]. As such, each main vertical zone is close to 48m in length, containing at least one means of escape in case of emergency (staircase), most commonly at its aft limit.

Starting from the first passenger accommodation deck (deck 5), it is occupied by the reception, one aft and one fore lounge, a restaurant, bars and other accommodation spaces (lavatories, shop, galley, lockers). Accommodation areas generally extend to the ship's sides, except for the middle fire zone, where the life-saving appliances (lifeboats and liferafts) are fitted. On this deck, only liferafts are encountered. At the aft part of the ship, an open deck of sufficient space is available for the passengers. The total passenger capacity of this deck is equal to 688.

Moving upwards, the second passenger accommodation deck (deck 6) is arranged with a lounge and air seats at its aft part, while the remaining deck is occupied by passenger cabins of various types and sizes (two-berth, luxury, etc.) amounting to 85. Similar to the deck underneath, additional accommodation spaces are encountered (lavatories, shop, lockers), while the accommodation areas of the middle fire zone retain their reduced width. This reduced part of the ship extends up to deck 7, where lifeboats are positioned. At the aft part, a smaller open deck is available for the passengers, appropriately connected to both the open decks below and above. The total passenger capacity of this deck is equal to 900.

Finally, regarding deck 7, the aft part – referred to as sun deck – is arranged with a spacious area intended to accommodate a large number of passengers. Moving forward, the emergency generator room is encountered. The emergency generating set stationed on this deck provides electrical power so electrical services essential for safety will be ensured in an emergency (lighting in accommodation areas and machinery spaces, fire detection and fire alarm system, steering gear system, etc.). Therefore, the generating set 520W4L20/60Hz (Tier II), by Wärtsilä, was selected with a nominal power of 548kW and a nominal revolution of 900RPM [30]. The funnel is located forward of the emergency generator room followed by the life-saving appliances. In total, six (6) lifeboats were installed. The remaining deck is occupied by crew accommodation (cabins and recreation/communal spaces) and the wheelhouse. The enclosed superstructure remains narrower at the life-saving appliances zone, to facilitate their usage. The total passenger capacity of this deck is equal to 212, while the crew capacity amounts to 99. Thus, the total passenger capacity of the ship is 1800.

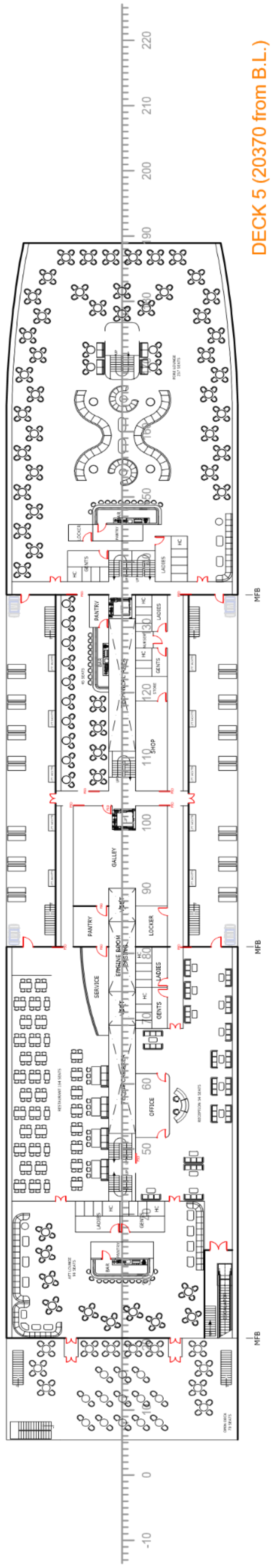

Figure 3-14: Illustration of first passenger accommodation deck (deck 5).

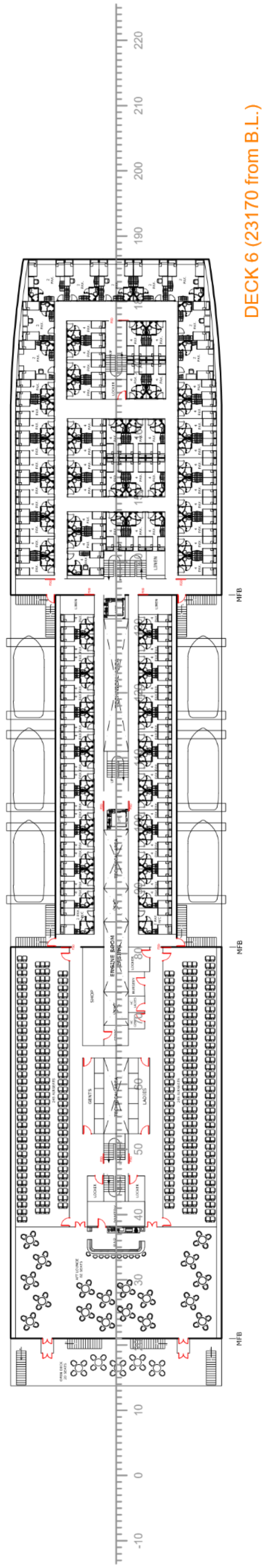

Figure 3-15: Illustration of second passenger accommodation deck (deck 6).

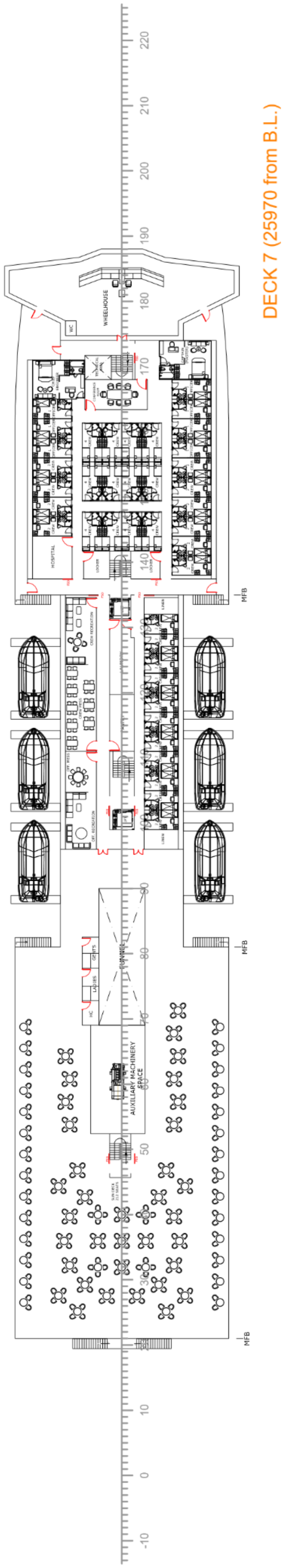

Figure 3-16: Illustration of sun deck/crew accommodation deck and wheelhouse (deck 7).

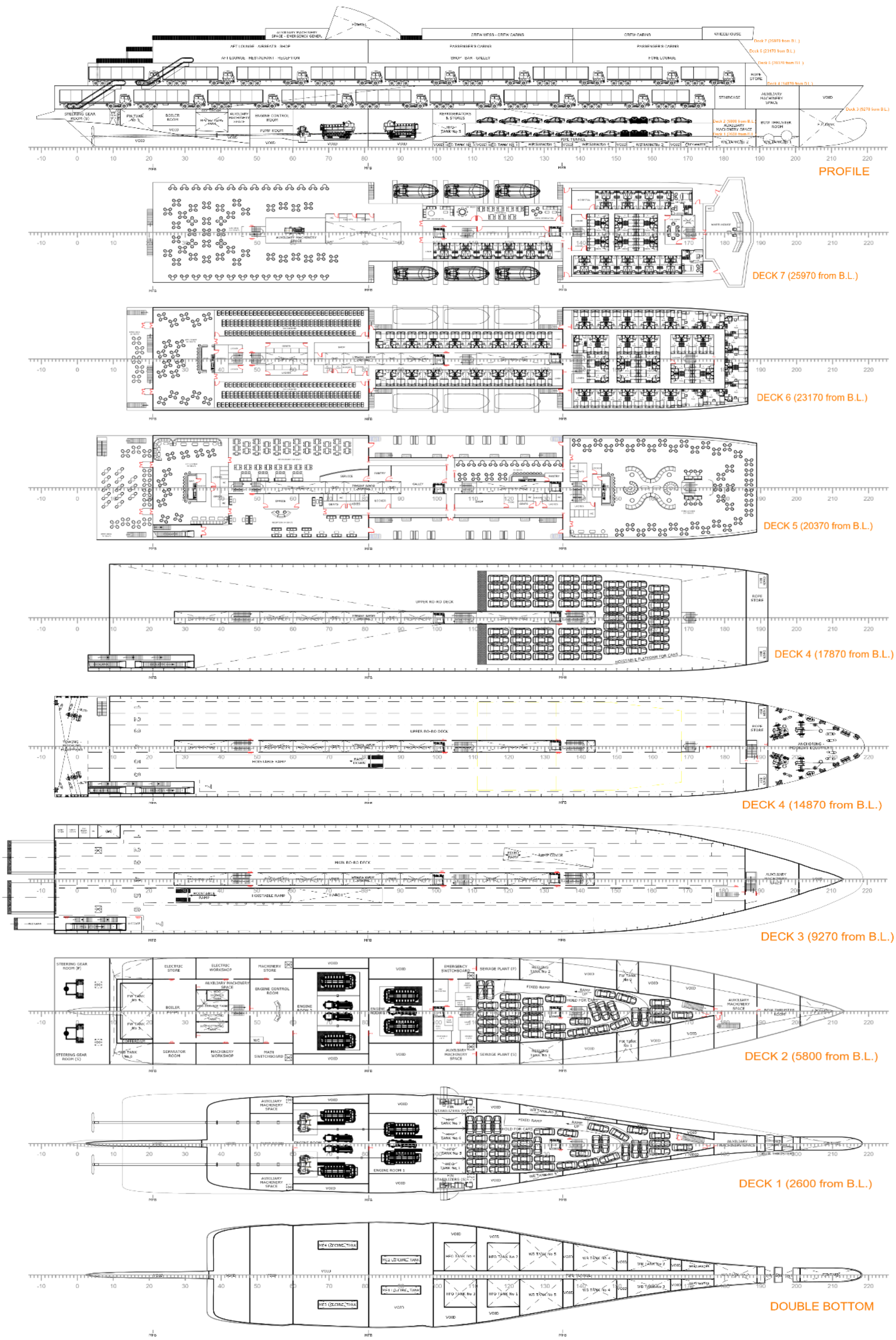

Figure 3-17: General arrangement plan.

4. Intact Stability

This chapter presents the calculation methods and the results for the evaluation of the ship's intact stability. Subchapter 4.1 contains the loading conditions viewed as representative for the ship's life cycle. Subchapter 4.2 refers to the stability criteria used in order to assess the design's adequacy.

4.1. Loading Conditions

The assembly of the loading conditions is formed by utilizing the developed ship model and the predetermined, from the parametric model, lightship weight.

The following representative loading conditions are defined:

- LDS01, LDS02: Design departure, design arrival
  The main and upper ro-ro decks are fully loaded with trucks of 32t (16m) or 24t (12m) each, and the lower car decks fully loaded with private cars of 1.5t each. The ship is also fully loaded with passengers.
- LDS03, LDS04: No cargo IMO departure, no cargo IMO arrival
  The ship is fully loaded with passengers, as in LDS01 and LDS02, though without any vehicles, as specified in IMO's Intact Stability Code (2008).
- LDS05, LDS06: Light design departure, light design arrival
  These loading conditions are based on LDS01 and LDS02 respectively, however with reduced truck capacity by 50% on the main and upper ro-ro decks.
- LDS07, LDS08: No cars design departure, no cars design arrival
  These loading conditions are based on LDS01 and LDS02 respectively, however with the elimination of cars at the lower car decks.
- LDS09, LDS10: Full load departure, full load arrival
  The main and upper ro-ro decks are fully loaded with trucks of the maximum weight (46t (16m) or 34.5t (12m) each), and the lower car decks fully loaded with private cars of 1.5t each. The ship is also fully loaded with passengers.
- LDS11, LDS12: Light load departure, light load arrival
  These loading conditions are based on LDS09 and LDS10 respectively, however with reduced truck capacity by 50% on the main and upper ro-ro decks.
- LDS13, LDS14: Hoistable platform design departure, hoistable platform design arrival
  The upper ro-ro deck is converted into a conjunction of cars and trailers by lowering the hoistable platform, and the two lower car decks are fully loaded with private cars of 1.5t each. The main ro-ro deck is also fully loaded with trucks of 32t (16m) or 24t (12m) each and the number of passengers is in accordance with loading conditions LDS01 and LDS02.
- LIGHT: Lightship condition (not seagoing)

In departure conditions, the filling percentage of heavy fuel oil tanks – as well as diesel oil tanks and fresh water tanks – is calculated per IMO's Intact Stability Code (IS Code 2008) [32] having taken into account the steel reduction for the calculation of the net volume. In arrival conditions, the filling percentage is 10% of the above. Similarly, the filling percentage of lubricating oil tanks, in departure conditions, is governed by IMO's Intact Stability Code [10], however in arrival conditions, the respective percentage is 80% of the above. An additional tank worth mentioning is that of grey water, assumed empty in departure conditions and fully-filled in arrival conditions.

Furthermore, all loading conditions include some ballasting to attain satisfactory trim. It should be underlined that the minimum amount of water ballast tanks was filled, except for the heeling tanks – as the optimization was executed with the default value of 150t in each tank –. In essence, this indicates that this optimal ship is sufficiently designed as it does not require redundant ballasting.

Finally, to realize the loading calculations, it is essential that some parameters are assigned values, as shown in the following Table 4-1. These are required to calculate the weight of vehicles and passengers on board. It is noted that several of them derived from the developed general arrangement plan and as a result, considered representative for the design.

Table 4-1. Parameters regarding the loading conditions.

Weight per passenger – including luggage [kg]	85
Weight per crew – including luggage [kg]	85
Number of passengers	1800
Number of crew	99
Weight of provisions [t]	40
Owner supply [t]	10
Number of cars – lower holds (deck 1)	40
Number of cars – lower holds (deck 2)	36
Number of cars – hoistable platform	66
Number of cars – upper ro-ro deck (deck 4) with hoistable platform in use	99
Weight of cars [t]	1.5
Lane meters – main ro-ro deck (deck 3) [m]	856.1
Number of trucks (16m) – main ro-ro deck (deck 3)	42
Number of trucks (12m) – main ro-ro deck (deck 3)	12
Lane meters – upper ro-ro deck (deck 4) [m]	866.1
Number of trucks (16m) – upper ro-ro deck (deck 4)	45
Number of trucks (12m) – upper ro-ro deck (deck 4)	9
Lane meters – upper ro-ro deck (deck 4) with hoistable platform in use [m]	477.7
Number of trucks (16m) – upper ro-ro deck (deck 4) with hoistable platform in use	25
Number of trucks (12m) – upper ro-ro deck (deck 4) with hoistable platform in use	5
Weight of trucks (16m) [t]	32
Maximum weight of trucks (16m) [t]	46
Weight of trucks (12m) [t]	24
Maximum weight of trucks (12m) [t]	34.5

4.2. Stability Criteria

The evaluation of the ship's intact stability is examined according to IMO's intact stability code (IS Code 2008 - Resolution MSC. 267(85)) [10], for each of the designed loading conditions.

The relevant criteria are as follows:

- The general criteria, regarding the properties of the righting lever curve. In particular:
  1. The area under the righting lever curve (GZ curve) shall not be less than 0.055 meter-radians up to $\varphi = 30°$ angle of heel and not less than 0.09 meter-radians up to $\varphi = 40°$ or the angle of down-flooding φ_f if this angle is less than 40°. Additionally, the area under the righting lever curve (GZ curve) between the angles of heel of 30° and 40° or between 30° and φ_f, if this angle is less than 40°, shall not be less than 0.03 meter-radians.
  2. The righting lever GZ shall be at least 0.2 m at an angle of heel equal to or greater than 30°.
  3. The maximum righting lever shall occur at an angle of heel not less than 25°.
  4. The initial metacentric height GM_0 shall not be less than 0.15 m.

- The severe wind and rolling criterion (weather criterion – IMO Resolution A.562 –). This criterion appraises the ability of a ship to withstand the combined effects of beam wind and rolling.

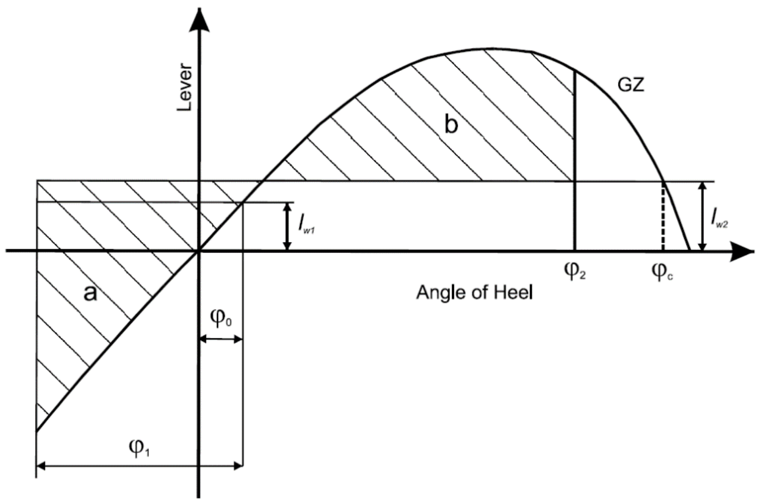

Figure 4-1. Severe wind and rolling.

1. the ship is subjected to a steady wind pressure acting perpendicular to the ship's centerline which results in a steady wind heeling lever (l_{w1}). The angle of heel under the action of steady wind (ϕ_0) should not exceed 16° or 80% of the angle of deck edge immersion, whichever is less.
2. from the resultant angle of equilibrium (ϕ_0), the ship is assumed to roll under the wave action to an angle of roll (ϕ_1) to windward.
3. the ship is then subjected to a gust wind pressure which results in a gust wind heeling lever (l_{w2}).

Under these circumstances, area b shall be equal or greater than area a, as indicated in the above Figure 4-1.

- Special criteria for passenger ships, specifying maximum heeling angles due to crowding of passengers to one side of the ship and due to turn. Specifically:
  1. The angle of heel on account of crowding of passengers to one side shall not exceed 10°.
  2. The angle of heel on account of turning shall not exceed 10° when calculated by the following formula:

$$M_R = 0.200 \cdot \frac{V^2}{L_{WL}} \cdot \Delta \cdot (KG - \frac{d}{2})$$

  where:
  - M_R: heeling moment [kN·m]
  - V: service speed [m/s]
  - L_{WL}: length of ship at waterline [m]
  - Δ: displacement [t]
  - d: mean draught [m]
  - KG: height of centre of gravity above baseline [m]

The intact stability of the ship is primarily assessed by verifying the compliance of all loading conditions with the aforementioned stability criteria. As an additional measure to evaluate the ship's stability, the intact VCG margin is utilized, expressing the minimum distance of the ship's vertical center of gravity from the maximum allowed VCG position, taking into account all loading conditions and relevant stability criteria:

$$\Delta VCG_{intact} = \min_{i=1,\dots,N_{LC}} \{VCG_{max,i} - VCG_i\}, \text{ where } \quad VCG_{max,i} = \min_{j=1,\dots,N_{CR}} \{VCG_{max,ij} - VCG_i\}$$

A summary of all loading conditions is presented in Table 4-2.

Table 4-2. Presentation of designed loading conditions.

Condition	Draft [m]	Draft Aft [m]	Draft Fwd [m]	Trim [m]	DWT [t]	Displ. [t]	GM [m]	ΔVCG$_i$ [m]
LDS01	6.270	6.484	6.056	-0.428	5784.0	16157.1	2.623	1.468
LDS02	5.857	5.804	5.910	0.106	4206.7	14579.8	2.014	0.504
LDS03	5.581	5.855	5.307	-0.548	3386.0	13759.1	3.988	1.993
LDS04	5.146	5.084	5.208	0.124	1808.7	12181.8	3.446	0.841
LDS05	5.793	6.091	5.494	-0.597	4128.0	14501.0	3.125	1.455
LDS06	5.369	5.358	5.379	0.020	2562.7	12935.8	2.564	0.333
LDS07	6.262	6.448	6.075	-0.374	5740.8	16113.9	2.542	1.465
LDS08	5.851	5.769	5.934	0.165	4175.5	14548.6	2.003	0.498
LDS09	6.467	6.668	6.265	-0.403	6498.0	16871.1	2.612	1.480
LDS10	6.060	6.017	6.103	0.086	4920.7	15293.8	1.850	0.694
LDS11	5.932	6.145	5.720	-0.425	4579.9	14952.9	3.051	1.601
LDS12	5.508	5.414	5.602	0.188	3002.5	13375.6	2.487	0.524
LDS13	5.956	6.205	5.707	-0.499	4678.8	15051.9	3.388	1.995
LDS14	5.533	5.483	5.583	0.100	3101.4	13474.5	2.961	0.984
						ΔVCG$_{intact}$ [m]		**0.333**

The resulting range of trims is considered acceptable, while a pattern of trims by the stern in departure conditions and light trims by the bow in arrival conditions is apparent. Generally, the ship's stability is satisfactory and all loading conditions comply with the intact stability criteria. However, it should be commented that the light design arrival condition, LDS06, is viewed as the most critical – the lowest value of VCG margin –, followed by LDS08 (no cars design arrival) and LDS02 (design arrival), where common denominators are their relatively smaller values of deadweight and their trims by the bow.

The detailed presentation of the design departure condition (LDS01) is given in Table 4-3, followed by the intact stability criteria results in Table 4-4, as it is considered a representative loading condition in the ship's life cycle.

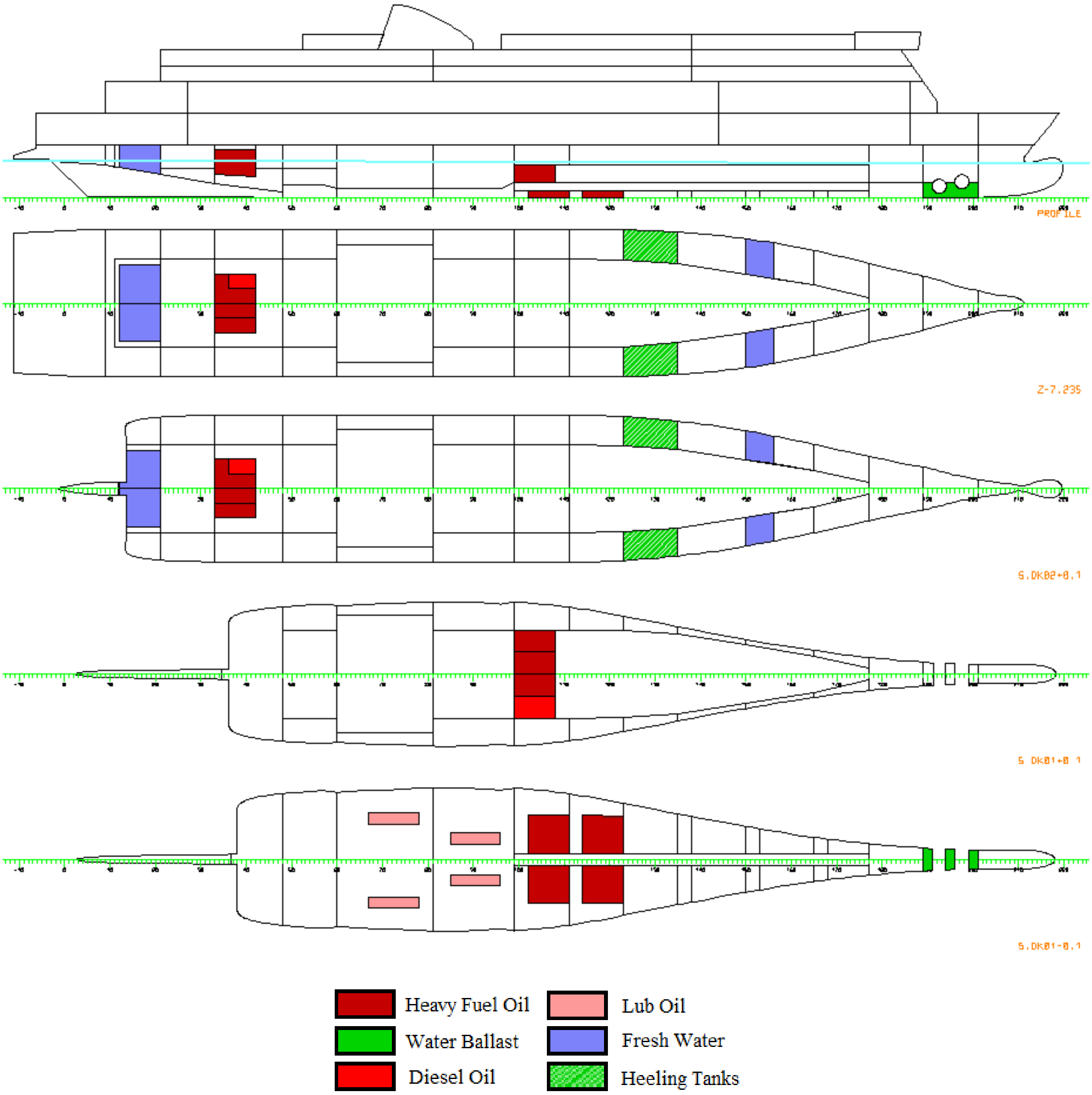

Figure 4-2. Loaded tanks and floating position of LDS01.

Table 4-3. Loading components of LDS01.

Title	Cargo	Fill %	SG [t/m^3]	Weight [t]	LCG [m]	TCG [m]	VCG [m]	FSM [t·m]
Mass Loads - Cargo								
Passengers	VAR	0.00	-	153.0	82.98	0.00	26.97	0.00
Crew	VAR	0.00	-	8.4	106.40	0.00	26.97	0.00
Owner	VAR	0.00	-	10.0	82.98	0.00	23.49	0.00
Provisions	VAR	0.00	-	40.0	90.19	0.00	16.49	0.00
Cars - Deck1	VAR	0.00	-	60.0	108.23	0.00	3.40	0.00
Cars - Deck2	VAR	0.00	-	54.0	109.57	0.00	6.60	0.00
Trucks - Deck 3	VAR	0.00	-	1632.0	72.83	0.00	10.97	0.00
Trucks - Deck 4	VAR	0.00	-	1656.0	79.51	0.00	16.57	0.00
SUBTOTAL	**VAR**	**0.00**	**-**	**3613.4**	**77.76**	**0.00**	**14.16**	**0.00**
Diesel Oil								
R080302	DO	98.0	0.900	77.4	82.80	5.83	4.17	0.00
R120603	DO	98.0	0.900	48.3	31.22	-3.84	6.16	0.00
SUBTOTAL	**DO**	**98.0**	**0.900**	**125.7**	**62.97**	**2.11**	**4.94**	**0.00**
Fresh Water								
R040103	FW	100.0	1.000	104.0	122.41	7.98	7.65	0.00
R040203	FW	100.0	1.000	104.0	122.41	-7.98	7.65	0.00
R140103	FW	100.0	1.000	211.5	13.37	3.36	7.04	0.00
R140203	FW	100.0	1.000	211.5	13.37	-3.36	7.04	0.00
SUBTOTAL	**FW**	**100.0**	**1.000**	**631.0**	**49.31**	**0.00**	**7.24**	**0.00**
Heavy Fuel Oil								
R080101	HFO	98.0	0.980	127.0	85.19	4.09	1.24	0.00
R080201	HFO	98.0	0.980	127.0	85.19	-4.09	1.24	0.00
R080102	HFO	98.0	0.980	84.2	82.80	1.94	5.74	0.00
R080202	HFO	98.0	0.980	84.2	82.80	-1.94	5.74	0.00
R080402	HFO	98.0	0.980	84.2	82.80	-5.83	5.74	0.00
R070101	HFO	98.0	0.980	117.2	94.74	3.87	2.55	0.00
R070201	HFO	98.0	0.980	117.2	94.74	-3.87	2.55	0.00
R120303	HFO	98.0	0.980	81.1	30.05	1.29	8.38	0.00
R120503	HFO	98.0	0.980	78.1	30.04	3.85	8.38	0.00
R120403	HFO	98.0	0.980	106.5	29.47	-1.91	8.38	0.00
SUBTOTAL	**HFO**	**98.0**	**0.980**	**1006.7**	**72.20**	**-0.29**	**3.29**	**0.00**
Lubricating Oil								
R100101	LO	98.0	0.900	15.1	57.94	7.62	1.19	0.00
R100301	LO	98.0	0.900	15.1	57.94	-7.16	1.19	0.00
R090201	LO	98.0	0.900	15.1	72.34	-3.67	1.19	0.00
R090401	LO	98.0	0.900	15.1	72.34	3.67	1.19	0.00
SUBTOTAL	**LO**	**98.0**	**0.900**	**60.4**	**65.14**	**0.11**	**1.19**	**0.00**
Water Ballast								
R060001	WB	0.0	1.025	0.0	102.96	0.0	2.10	0.0
R060103	WB	63.9	1.025	150.0	103.18	9.83	6.22	137.58
R060203	WB	63.9	1.025	150.0	103.18	-9.83	6.22	137.58
R040001	WB	0.0	1.025	0.0	126.87	0.0	1.50	0.0
R050001	WB	0.0	1.025	0.0	114.92	0.0	1.49	0.0
R000003	WB	0.0	1.025	0.0	166.71	0.0	4.77	0.0
R010001	WB	100.0	1.025	46.9	156.05	0.0	1.37	0.0
R020001	WB	0.0	1.025	0.0	146.21	0.0	1.54	0.0
R140003	WB	0.0	1.025	0.0	11.53	0.0	7.26	0.0
SUBTOTAL	**WB**	**16.2**	**1.025**	**346.9**	**110.33**	**0.0**	**5.57**	**275.15**
Deadweight	**-**	**-**	**-**	**5784.0**	**75.19**	**0.0**	**10.66**	**275.15**
Lightweight	**-**	**-**	**-**	**10373.1**	**75.86**	**0.00**	**12.68**	**0.00**
Displacement	**-**	**-**	**-**	**16157.1**	**75.62**	**0.00**	**11.96**	**275.15**

Table 4-4. Stability criteria results for LDS01.

Criterion	Required value	Attained value	Status
Area under GZ curve between 0 – 30 deg	0.055	0.330	OK
Area under GZ curve between 0 – 40 deg	0.090	0.525	OK
Area under GZ curve between 30 – 40 deg	0.030	0.195	OK
Min GZ	0.200	1.131	OK
Max GZ angle	25.000	35.112	OK
Min GM	0.150	2.623	OK
Max heel due to crowding of passengers	10.000	2.105	OK
Weather criterion	1.000	4.009	OK
Max heel due to turning	10.000	3.258	OK

5. Damage Stability

This chapter deals with the evaluation of the ship's damage stability; namely the capability of the ship to retain her floatation, as well as her stability, in the event of flooding following a collision accident.

5.1. Overview

Damage stability calculations are based on methodologies, specified accordingly by regulations (SOLAS [7], Stockholm Agreement [9]), that are categorized as deterministic and probabilistic. In the first case, the evaluation of the ship's damage stability depends on achieving a suitable subdivision of her hull, assuming damage cases with specified dimensions – dependent mostly on her length – affecting either one compartment or a group of compartments, resulting in the satisfaction of certain criteria – mainly concerning the GZ curve and the equilibrium stage after damage –, well established by the regulations. A typical example of the deterministic approach are the regulations of SOLAS 90 – replaced by the probabilistic regulations of SOLAS 2009 for passenger ships –, as well as the Stockholm Agreement (Directive 2003/25/EC) [7] [9].

Contrarily, the probabilistic approach strived for the establishment of a more rational method for the assessment of the ship's damage stability, thus utilizing the probability of survival after damage as a measure of the ship's safety in a damaged condition. This method factors in two main probability categories; the probability that the ship will suffer a certain damage, that affects a particular area of the ship – taking into consideration the damage location and extent – and the probability that the ship survives (does not sink or capsize) following the damage. The main aim of this approach is to ensure that the probability of survival is greater than the minimum allowed value, specified by the regulations. The detailed methodology of this approach is defined in regulations 6 and 7 of SOLAS Chapter II-1 [7] concerning the calculation of the required and attained subdivision indices respectively.

5.2. Subdivision

To resist the effect of damage of the hull, as in a collision accident, and therefore retain the stability and floatability of the ship an appropriate watertight subdivision of the hull is necessary. In general, longitudinal zones are limited by the main transverse bulkheads, transverse zones by the main longitudinal bulkheads and horizontal zones by the decks.

In some cases, other relatively important limits are taken into account, for example, some tank sides or the upper limit of the skeg. Notably, the inner boundary of the cofferdam was taken as a longitudinal limit as its flooding is relatively inconsequential.

Hence, the watertight subdivision of the ship's hull is depicted in Figure 5-1, followed by the presentation of the boundaries implemented in each damage case (compartment or group of compartments) in Table 5-1.

Figure 5-1. Subdivision of ship's hull.

Table 5-1. Details of subdivision of ship's hull.

ZONE	TBA	TBF	LBP	DDN	DUP	X1	X2	BP	HHSD	HHSU
Z01	DAMHULL	7.2	0	s.i.skeg	s.dk03	-9.056	7.20	0.000	6.629	9.27
Z02	7.2	16.8	-6.77	s.i.skeg	s.dk03	7.2	16.8	6.111	5.657	9.27
Z03	16.8	26.4	S.LBHAFT.P	s.i.skeg	s.dk03	16.8	26.4	5.186	4.027	9.27
Z04	26.4	38.4	S.LBHAFT.P	s.i.skeg	s.dk03	26.4	38.4	5.180	2.444	9.27
Z05	38.4	48	S.LBHAFT.P	s.dk01	s.dk03	38.4	48.0	5.180	2.200	9.27
Z06	48	64.8	S.LBHER.P	s.dk01	s.dk03	48.0	64.8	2.590	1.700	9.27
Z07	64.8	79.2	S.LBHER.P	s.dk01	s.dk03	64.8	79.2	5.180	2.546	9.27
Z08	79.2	86.4	S.LBHFWD.P	s.dk01	s.dk03	79.2	86.4	5.180	2.600	9.27
Z09	86.4	88.8	S.LBHFWD.P	s.dk01	s.dk03	86.4	88.8	5.180	2.600	9.27
Z10	88.8	98.4	S.LBHFWD.P	s.dk01	s.dk03	88.8	98.4	5.245	2.600	9.27
Z11	98.4	108	S.LBHFWD.P	s.dk01	s.dk03	98.4	108.0	5.239	2.600	9.27
Z12	108	120	S.LBHFWD.P	s.dk01	s.dk03	108.0	120.0	5.482	2.600	9.27
Z13	120	132	S.LBHFWD.P	s.dk01	s.dk03	120.0	132.0	5.493	2.600	9.27
Z14	132	141.6	S.LBHFWD.P	s.dk01	s.dk03	132.0	141.6	5.210	2.600	9.27
Z15	141.6	151.2	-	s.dk01	s.dk03	141.6	151.2	-	2.600	9.27
Z16	151.2	160.8	-	s.dk01	s.dk03	151.2	160.8	-	2.600	9.27
Z17	160.8	DAMHULL	-		s.dk03	160.8	175.793	-	-	9.27

5.3. Initial Loading Conditions

Damage stability calculations are conducted for the three initial conditions which are defined in SOLAS Chapter II-1 Regulation 2 [7]. They are being selected as the most representative of all the loading conditions. Specifically, the full load condition, with the ship at her deepest subdivision draft, d_S, assumed at even keel, the light service draft d_L – with the ship at her minimum draft – and at the actual service trim, and the partial service draft, calculated as $d_P = d_L + 0.6 \cdot (d_S - d_L)$, at even keel. The metacentric heights of these loading conditions are determined by those of the previously designed loading conditions, including an appropriate safety margin. It should be mentioned that the weighting factor of each condition is measured accordingly, assuming that in the ship's life cycle, the anticipated service condition is the deepest subdivision draft d_S 40% of the time, the light service draft d_L another 20% and the partial service draft d_P the remainder 40%.

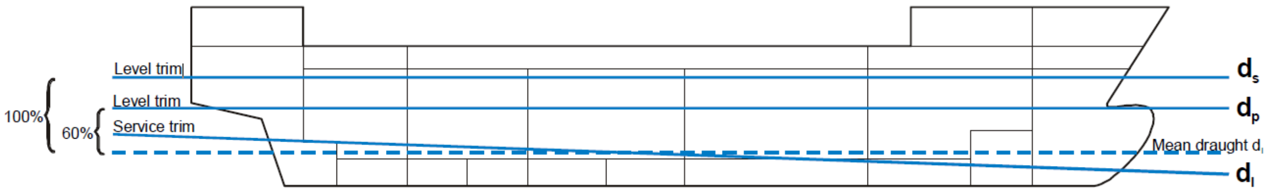

Figure 5-2. Illustration of the initial loading conditions used in the damage stability calculations.

Table 5-2. Loading conditions for damage stability calculations.

Initial Loading Conditions	T [m]	GM [m]
d_L	5.146	2.883
d_P	5.938	1.571
d_S	6.467	2.562

5.4. SOLAS Regulations 6 & 7: Required and attained subdivision index

Regulations 6 and 7 of SOLAS Chapter II-1 [7] prescribe the application – as mentioned above – of a probabilistic model to assess a ship's damage stability. Specifically, regulation 6 describes the method for the calculation of the required subdivision index R, which is the minimum allowed probability of survival, and regulation 7 defines the requirements for the calculation of the attained subdivision index A, expressing the probability that a ship survives after damage and its relation with the required index R. As such, the main requirement is $A \geq R$.

The required subdivision index R is a function of the number of persons on board, whereas the attained subdivision index is a weighted average of three partial indices, A_S, A_P and A_L, referring to the aforementioned loading conditions.

Each partial index is expressed by the following formula:

$$A_c = \sum_{i=1}^{i=t} p_i \cdot s_i$$

where:

- c represents one of the three loading conditions (S, P, L).
- i constitutes each investigated damage case (compartment or group of compartments) under consideration, as defined in Subchapter 5.2.
- t is the number of damages to be investigated to calculate the value of A_c for each loading condition.
- p_i is the probability that only the damage case i – consisting of a particular compartment or a group of adjacent compartments – is flooded after damage, disregarding any horizontal subdivision.
- s_i is the probability that the ship survives (does not sink or capsize) following the flooding of the examined compartment i – or a group of adjacent compartments –. In essence, this indicates that if the value of s equals 0, the ship will certainly sink or capsize, if the value of s equals 1, the ship is sure to survive, whereas for intermediate values of the probability s, the ship's probability to survive equals s.

Where horizontal watertight boundaries are fitted above the waterline under consideration, the s-value calculated for the lower compartment or group of compartments shall be obtained by multiplying the value by the reduction factor v_m, which represents the probability that the spaces above the horizontal subdivision of the compartment i – or a group of adjacent compartments – will not be flooded.

It should be underlined that SOLAS 2020 [7] specifies stricter requirements for the calculation of the s-factor when an examined damage impacts large open vehicle spaces, commonly encountered in RoRo-Passenger ships.

In addition to the abovementioned requirement $A \geq R$, each partial index must not be less than $0.9 \cdot R$: $A_c \geq 0.9 \cdot R$ (c = S, P, L).

Table 5-3. Results of regulations 6 & 7.

Initial Loading Conditions	T [m]	**A-index**	**A-index**	**R-index**	**Status**
-	-	**Including intermediate stages**	**Final stage only**	**-**	**-**
d_L	5.146	0.97917	0.97917	0.86362	OK
d_P	5.938	0.85885	0.86456	0.86362	OK
d_S	6.467	0.90902	0.90902	0.86362	OK
Total	-	0.90298	0.90527	0.86362	OK

As concluded from the above Table 5-3, the attained subdivision index A derived only from the final equilibrium phase is relatively greater than the one that takes into account the intermediate stages of flooding. Essentially, this difference suggests that the ship is more susceptible to sinking or capsizing while the flooding is in progress.

In conclusion, it is evident that the margin of 0.0394 between the values of A-index and R-index is abundant, as the majority of the existing ships is designed with a much lower margin. However, the ship's design is in a preliminary stage, not taking into account several details (e.g. asymmetric flooding, the definition of escape routes, etc.) that will certainly affect, and most probably decrease the value of the A-index. Hence, an appropriate safety margin is considered essential to ensure the compliance with the regulation's requirements in the final stages of the design.

5.5. SOLAS Regulations 8 & 9

The probabilistic model is supplemented by some deterministic requirements for passenger ships, defined in SOLAS Chapter II-1 Regulations 8 and 9 [7]. In particular:

- Regulation 8.1: Passenger ships carrying 400 or more persons must retain watertight subdivision abaft the collision bulkhead ensuring that the survival probability s_i equals 1 for damage involving the breach of all compartments within 8% of the subdivision length measured from the forward perpendicular for the three loading conditions used to calculate the attained subdivision index A.
- Regulations 8.2/3: Passenger ships carrying 36 or more persons must survive side shell damages of a certain extent – specified by the regulation – with a survival probability s_i of not less than 0.9 for the three loading conditions used to calculate the attained subdivision index A.

Table 5-4. Results of regulations 8.1 & 8.2/3.

Initial Condition	T [m]	Actual GM [m]	Reg 8.1 Min. GM [m]	Reg 8.1 Status [-]	Reg 8.2/3 Min. GM [m]	Reg 8.2/3 Status [-]
d_L	5.146	2.883	0.586	OK	1.535	OK
d_P	5.938	1.571	0.360	OK	1.403	OK
d_S	6.467	2.562	0.371	OK	1.640	OK

- Regulation 9: Ships with unusual double bottom arrangements – parts of the double bottom not extended for the full width of the ship – must be able to survive minor grounding damages of a certain extent with probability s=1. Vessels of this type are generally not expected to confront problems with this regulation. Consequently, it was omitted for this design stage.

5.6. Stockholm agreement (WOD)

Undoubtedly, the most dangerous problem for a ro-ro ship with an enclosed ro-ro deck is that posed by the effect of a build-up of a significant amount of water on deck. A such, for ships undertaking regular scheduled international voyages between to/from designated ports in the European Union, the Stockholm agreement – or Directive 2003/25/EC – sets further damage stability criteria in addition to IMO's requirements. Under this agreement, the specific stability standard is directly related to the sea area in which the vessel operates and more particularly to the significant wave height recorded in the area of operation; the significant wave height of the area, where the ship operates, determines the height of water on the car deck that would arise following the occurrence of accidental damage [9].

It demands that for damages including the first ro-ro deck above the design waterline, the provisions of SOLAS 90 Regulation II-1/B/8.2.3 relating to watertight subdivision and stability in damaged condition be satisfied when taking into account the effect of a hypothetical amount of sea water which is assumed to have accumulated on the ro-ro deck. The amount of assumed accumulated sea water ranges between 0 and 0.5 m, depending on the residual freeboard after the damage and the significant wave height in the region the ship operates, as shown in Figure 5-3 below.

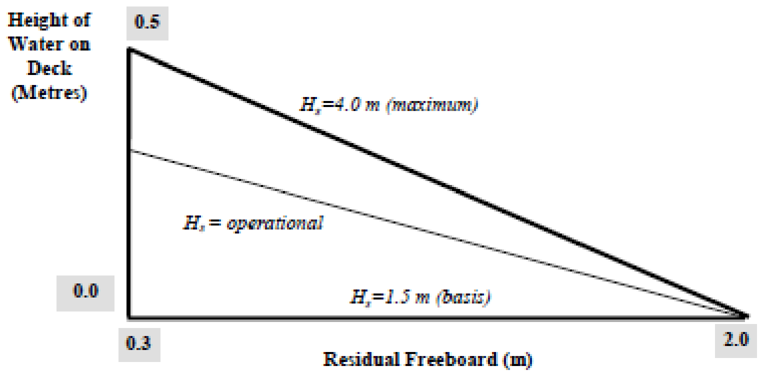

Figure 5-3. Relation between height of water on deck to the residual freeboard and the significant wave height.

Table 5-5. Results of Stockholm Agreement.

Initial Conditions	T [m]	Actual GM [m]	1-Comp. Min. GM [m]	WOD1 Status [-]	Multi-Comp. Min. GM [m]	WOD2 Status [-]
LDS01	6.270	2.623	1.162	OK	1.737	OK
LDS02	5.857	2.014	1.051	OK	1.433	OK
LDS03	5.581	3.988	1.215	OK	1.649	OK
LDS04	5.146	3.446	1.214	OK	1.592	OK
LDS05	5.793	3.125	1.083	OK	1.502	OK
LDS06	5.369	2.564	1.091	OK	1.474	OK
LDS07	6.262	2.542	1.078	OK	1.640	OK
LDS08	5.851	2.003	1.042	OK	1.423	OK
LDS09	6.467	2.612	1.305	OK	1.950	OK
LDS10	6.060	1.850	0.948	OK	1.343	OK
LDS11	5.932	3.051	1.037	OK	1.473	OK
LDS12	5.508	2.487	1.031	OK	1.388	OK
LDS13	5.956	3.388	1.065	OK	1.530	OK
LDS14	5.533	2.961	1.145	OK	1.512	OK

6. Elaboration on Structural Elements

Chapter 6 refers to the primary selection of the ship's main structural components. To achieve this objective, a preliminary study of the hull girder strength is conducted following the definition and categorization of the elements under which the ship is constructed, both in longitudinal and transverse directions.

6.1. Overview

The structural elements comprising the ship's hull are part of her steel weight. However, a detailed analysis of the steel weight components is not readily available by the results of the parametric model. Thus, the calculation of both the thickness of panels and dimensions of the longitudinal and transverse stiffening utilized in the ship's construction is crucial, as to determine the elements comprising her steel structure.

This calculation is inseparably connected with the evaluation of the hull girder strength; therefore, additional calculations utilizing both global and local strength criteria are performed. For the selection of both the panels and longitudinal stiffening, the software MARS2000 is utilized, provided by Bureau Veritas (BV), where several sections of the ship's hull are modelled and evaluated. In general, the materials under which the hull transverse sections are constructed, are the following:

- grade "A" steel of yield stress 235 N/mm^2, young (elastic) modulus 206,000 N/mm^2 and density 7.9 t/m^3.
- grade "AH-32" steel of yield stress 315 N/mm^2, young (elastic) modulus 206,000 N/mm^2 and density 7.9 t/m^3.
- grade "AH-36" steel of yield stress 355 N/mm^2, young (elastic) modulus 206,000 N/mm^2 and density 7.9 t/m^3.

By defining several aspects of the ship's structure including but not limited to the thickness of panels and dimensions of the longitudinal stiffeners, MARS2000 implements the aforementioned criteria, leading to an iterative procedure of assessing the hull girder strength and modifying the characteristics of its structural elements.

Regarding the transverse stiffening, the structural elements analyzed are the following: side frames, deck beams, girders and floors. As far as the first three are concerned, a detailed calculation of their dimensions was conducted, according to appropriate regulations. Furthermore, the floors were dimensioned according to minimum thickness requirements, except those at the boundaries of fuel oil or ballast tanks (mainly at the aft and fore parts of the ship), where additional calculations were required in order to ensure their adequate dimensioning.

Overall, the assessment of the ship's hull girder strength is performed in accordance with the "Rules for the Classification of Steel Ships, Bureau Veritas, January 2021" [31]. The abovementioned calculations are accompanied by structural plans – presented at the end of the chapter –, showcasing the details of the ship's steel structure (Figures 6-5 to 6-7).

6.2. Panels and longitudinal stiffening

The main input data entered in MARS2000 are presented in the following Table 6-1.

Table 6-1: Ship's main particulars inserted in MARS2000.

Description	Symbol	Value	Unit
Rule length (scantling length)	L	172.372	m
Moulded breadth	B	25.900	m
Block coefficient	C_B	0.586	-
Maximum service speed	V_S	24.000	knots
Aft peak bulkhead (from A.E)	-	4.317	m
Fore peak bulkhead (from A.E)	-	157.917	m
Depth at strength deck	D	20.370	m
Depth at freeboard deck	D_{FBD}	14.870	m
Scantling draught	T	6.470	m
Still water bending moment (hogging condition)	-	0.000	kN·m
Still water bending moment (sagging condition)	-	0.000	kN·m

Regarding the still water bending moments both in hogging and sagging condition, as their values are not yet known, MARS2000 performs the calculations utilizing the permissible rule values; thus, the value of zero is inserted into the software. Additionally, the ship's longitudinal strength is assessed by examining the total height of the hull; namely all the way to deck 5 (first passenger accommodation deck). As such, the strength deck is positioned at 20.37m, as shown in the above Table 6-1. It should be mentioned that the contribution of the superstructure to the longitudinal strength – videlicet, its bending efficiency – is taken equal to zero as it is not contributing to the longitudinal bending of the ship.

To approach as accurately as practically possible the actual hull – thus, the actual steel weight –, 10 transverse sections along the ship's length were examined, corresponding to distances from A.P (aft perpendicular):

- 5.6m (frame #7)
- 29.6m (frame #37)
- 43.2m (frame #54)
- 58.4m (frame #73)
- 75.2m (frame #94)
- 83.25m (~ frame #104 – Midship section)
- 102.4m (frame #128)
- 115.2m (frame #144)
- 128.0m (frame #160)
- 147.2 m (frame #184)

These sections are modelled according to the available ship data, provided by the parametric model and the further elaborated general arrangement plan (see Chapter 3). Therefore, the definition of each section's characteristics is conducted; namely the number and length of panels along with their division into strakes, the thickness and width of each strake, the stiffener spacing, as well as their type and dimensions and finally, the web frame spacing. Regarding the web frame spacing, as stated in Chapter 2, it is set at 2,400 mm (three times the ordinary frame spacing), which is also equal to the selected length of panels.

Furthermore, the width of each section's strakes was selected separately in a range of 1m to a maximum of 3m determined by the width of the corresponding panel. The stiffeners installed are of type "bulb" with dimensions selected according to standard DIN tables. Two exceptions can be found in some sections, as T-shaped stiffeners are installed in appropriate areas.

By specifying the above characteristics, MARS2000 calculates the minimum requirements of thickness for both the strakes and longitudinal stiffeners, as well as the minimum section modulus of each section. It is noted that depending on the selected material of each strake or longitudinal stiffener, an appropriate corrosion addition is automatically added by the software, thus raising the minimum thickness requirement imposed by the rules. The endeavor of compliance with the software's requirements leads to the finalization of both the strakes thickness and longitudinal stiffeners dimensions.

It is emphasized that the panels, as well as, the accompanying longitudinal stiffeners of the vehicle decks; namely the main and upper ro-ro deck and the two lower holds, are defined in accordance with data readily available from an existing vessel, as the calculations necessary for the selection of these structural elements are highly complex and not a subject of this thesis.

To clarify the resulting data from MARS2000, the following figures (Figures 6-1 to 6-4) present the plates thickness, the longitudinal stiffeners scantling dimensions, and the local strength for both the plates and longitudinal stiffeners, respectively, for the midship section.

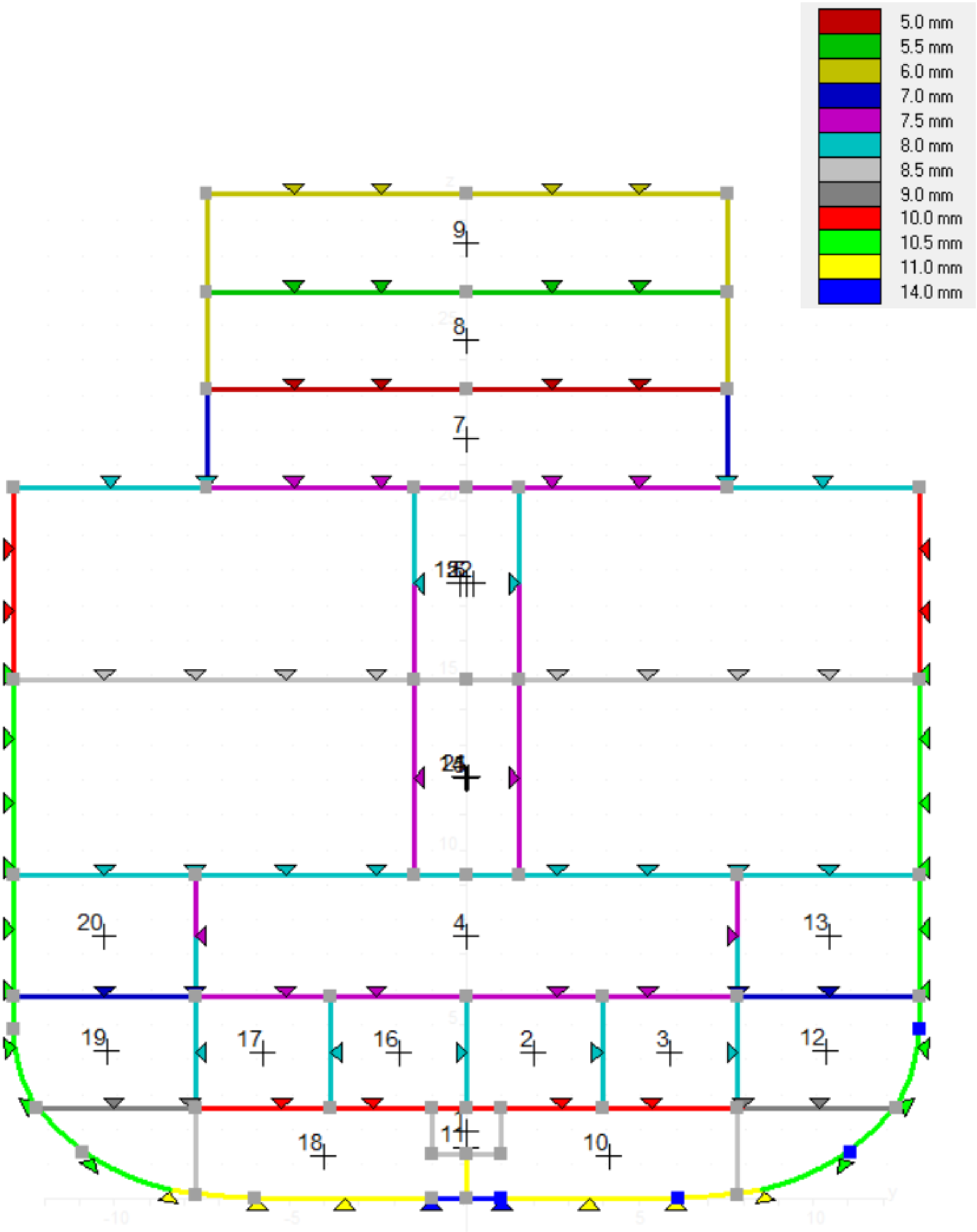

Figure 6-1: Plates thickness at midship section.

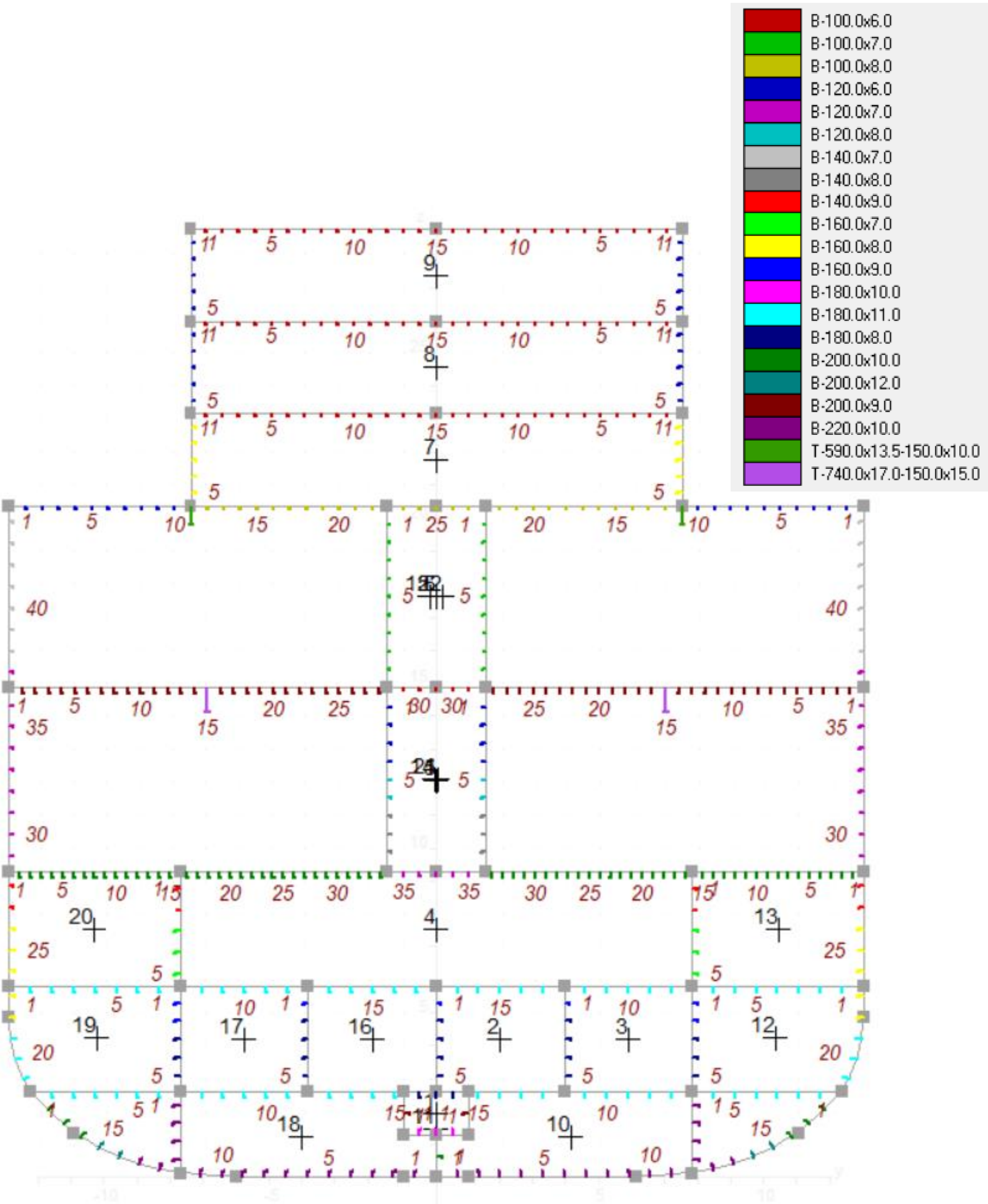

Figure 6-2: Longitudinal stiffeners scantling dimensions at midship section.

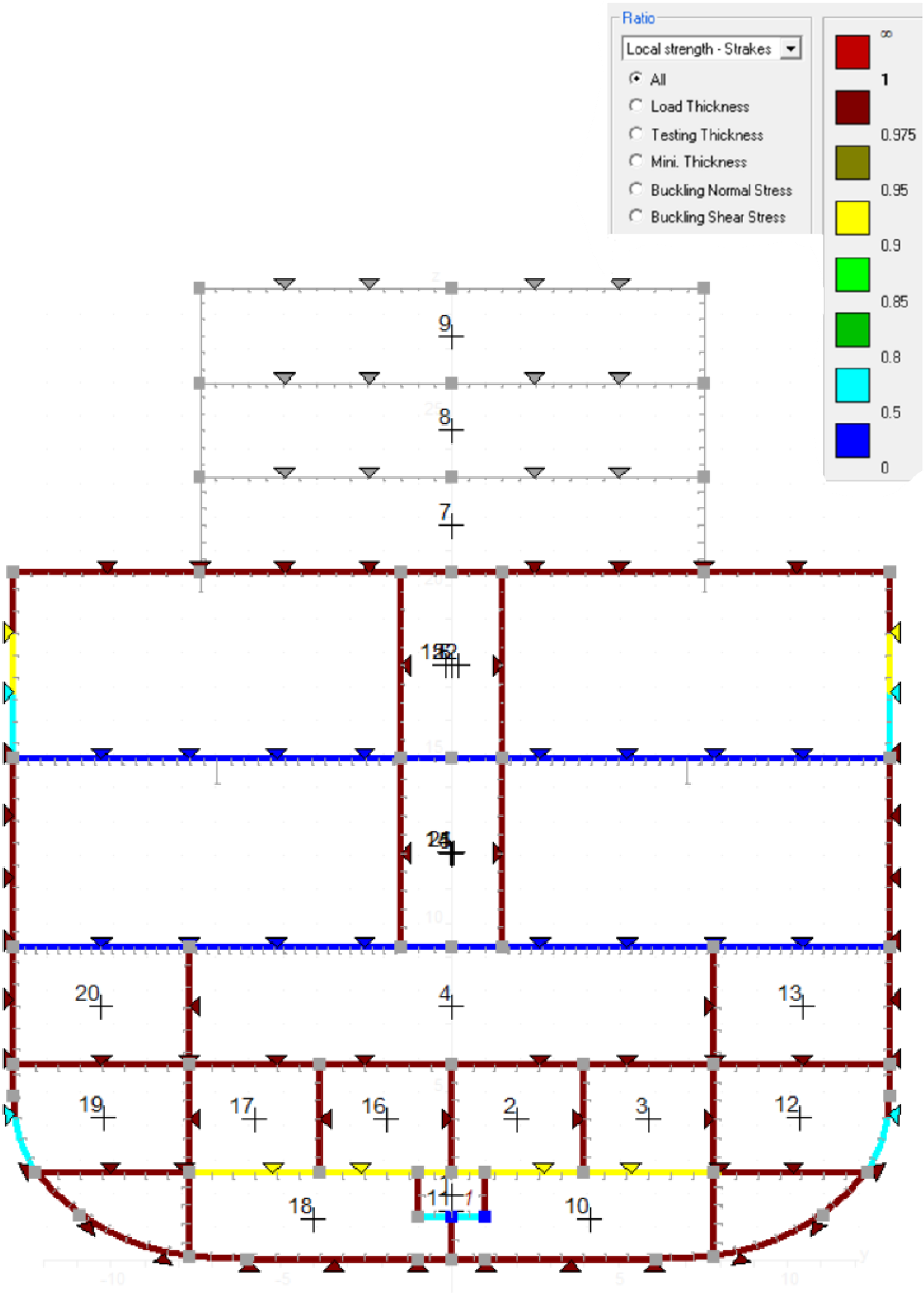

Figure 6-3: Plates local strength at midship section.

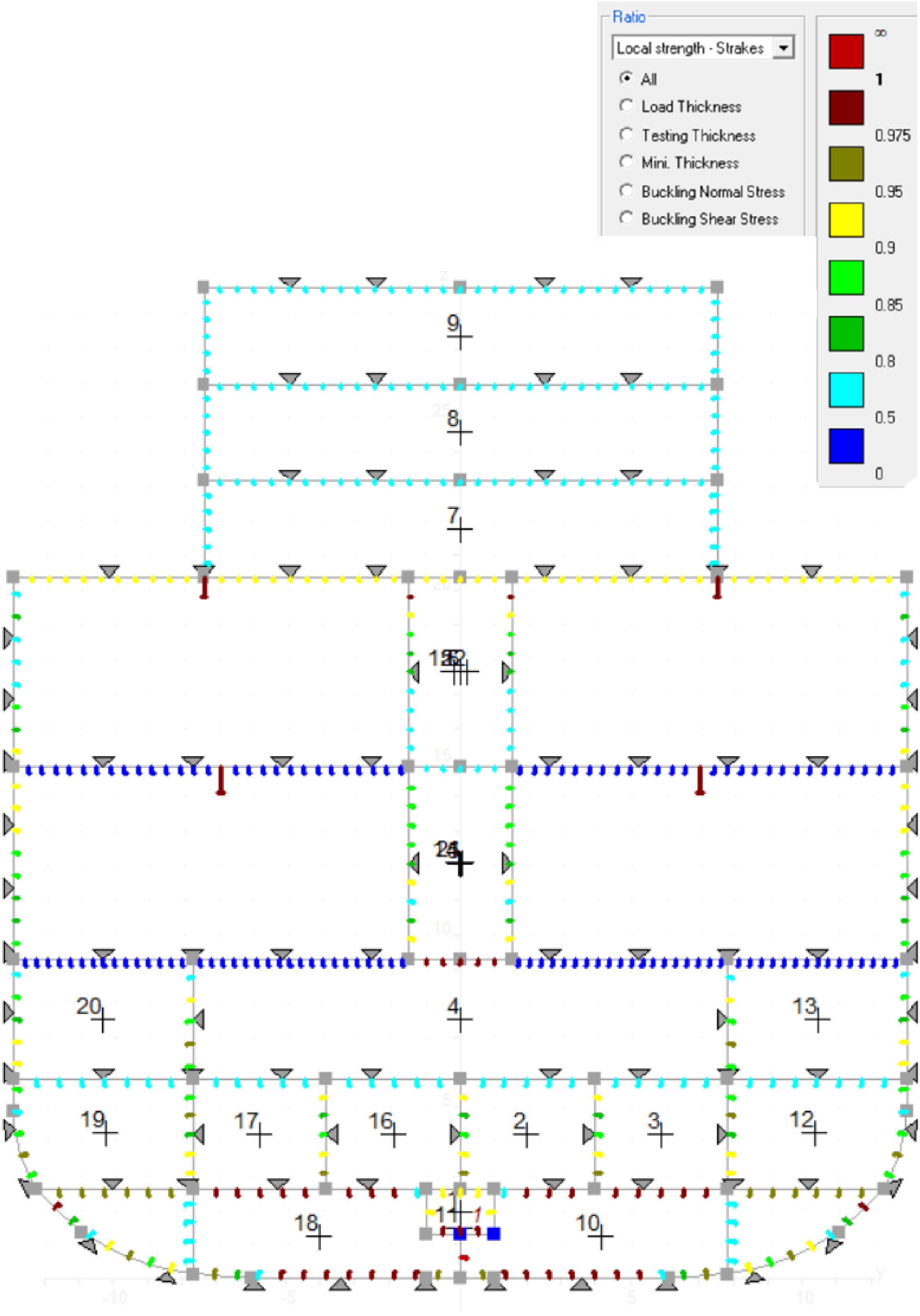

Figure 6-4: Longitudinal stiffeners local strength at midship section.

6.3. Transverse stiffening

As mentioned above, the transverse stiffening of the ship was calculated in accordance with the "Rules for the Classification of Steel Ships, Bureau Veritas, January 2021" [31]. The implementation of these regulations was conducted in detail in Microsoft Excel for a number of selected sections; specifically, the sections at frames #37, #104 (Midship section) and #144.

The methodology followed as to determine the dimensions of the transverse stiffening includes the calculation of the minimum allowable values of net shear sectional area, A_{sh}, and net section modulus, w, for each of the examined sections and their comparison with the values of the primary supporting members dimensions selected by the designer. Finally, an appropriate corrosion addition was introduced in accordance with the regulations [31].

It is emphasized that the primary supporting members – videlicet, the transverse stiffeners – of the vehicle decks; namely the main and upper ro-ro deck and the two lower holds, are defined in accordance with data readily available from an existing vessel, as the calculations necessary for the selection of these structural elements are not a subject of this thesis.

Table 6-2 below displays the dimensions of the primary supporting members taken directly from the aforementioned existing vessel.

Table 6-2: Dimensions of transverse stiffening at vehicle decks.

Transverse stiffener ID	**Dimensions**	**Material**
Deck 2 beam	340x8+150x10	AH-36
Deck 3 beam	590x10+150x10	AH-36
Deck 4 beam	740x10+200x20	AH-36

The following Table 6-3 depicts the dimensions of the selected primary supporting members (transverse stiffeners).

Table 6-3: Final dimensions of transverse stiffening at Midship section.

Transverse stiffener ID	**Number**	**Dimensions**	**Material**
Deck 5 beam	1	590x14.5+150x11	AH-36
Deck 6 beam	1	300x7.5+150x9	A
Deck 7 beam	1	300x7.5+150x9	A
Deck 8 beam	1	300x7.5+150x9	A
Girder deck 1 – deck 2 (C.L.)	1	500x13+150x11.5	AH-36
Girders deck 1 – deck 2	2	500x13+150x11.5	AH-36
Girder deck 2 – deck 3	1	500x13+150x11.5	AH-36
Side frame deck 1 - deck 2	1	590x14.5+150x11	A
Side frame deck 2 - deck 3	1	550x14+150x11	A
Side frame deck 3 - deck 4	1	550x14+150x11	AH-36
Side frame deck 4 - deck 5	1	550x14+150x11	AH-36
Side frame deck 5 - deck 6	1	240x7+150x10	A
Side frame deck 6 - deck 7	1	240x7+150x10	A
Side frame deck 7 - deck 8	1	240x7+150x10	A

6.4. Floors

Floors are part of the transverse stiffening of the ship's hull; however, a separate examination of their dimensions was performed as they are subjected to different regulations. Regarding the thickness of each floor, the minimum allowable value, properly defined in regulations [31], was considered adequate and it was selected for their dimensioning. On the contrary, floors stationed at the boundaries of fuel oil, water ballast or fresh water tanks were further elaborated, as to determine the adequacy of the aforementioned minimum allowable value. In each case, an appropriate corrosion addition was introduced in order to ensure the compliance with the regulations.

The following Table 6-4 presents the floors' thickness of the examined sections; also shown at the structural plans.

Table 6-4: Floors' thickness at the examined sections.

Section frame	Thickness [mm]	Steel type
#37	9.0	AH-36
#104 (Midship section)	9.5	AH-36
#144	10.0	AH-36

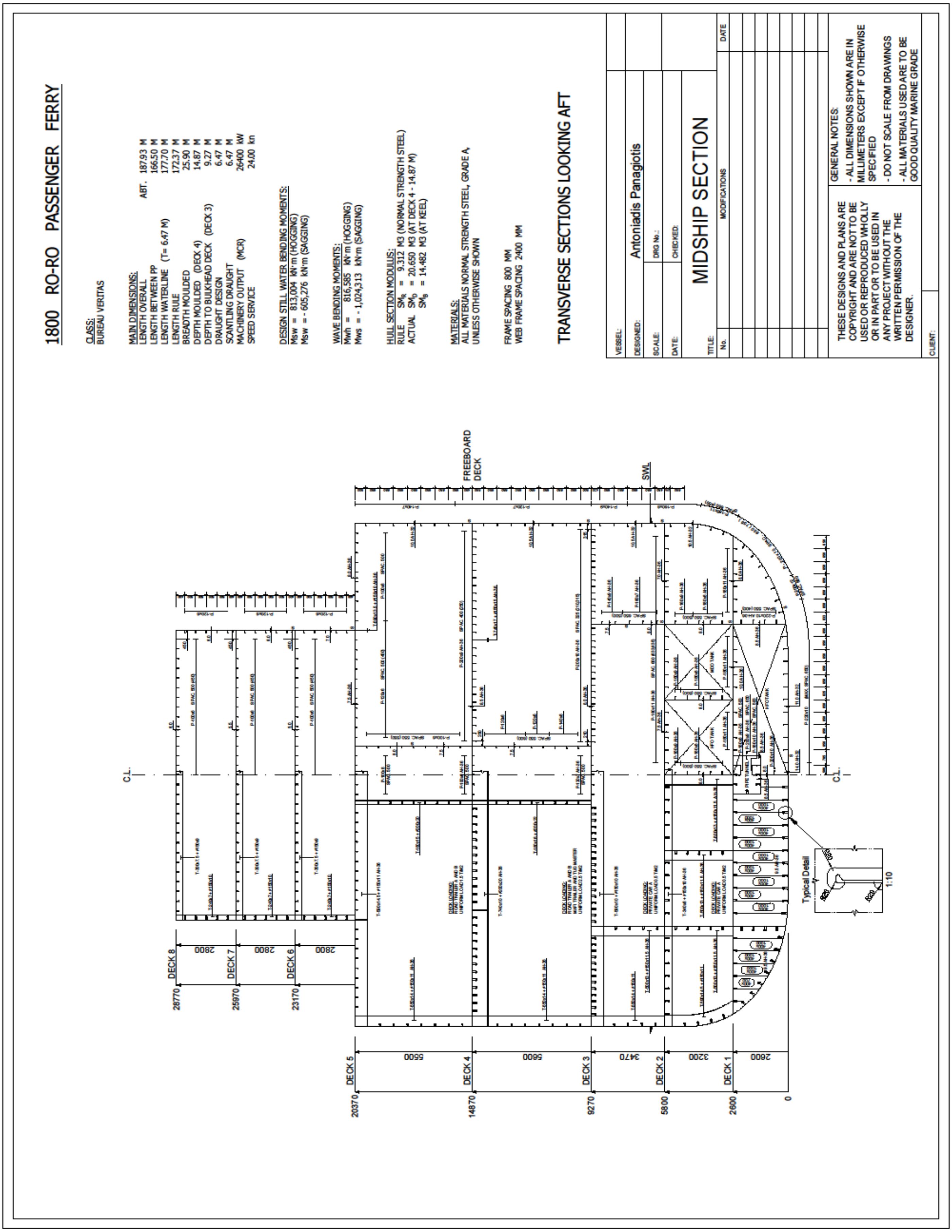

Figure 6-5: Illustration of midship section.

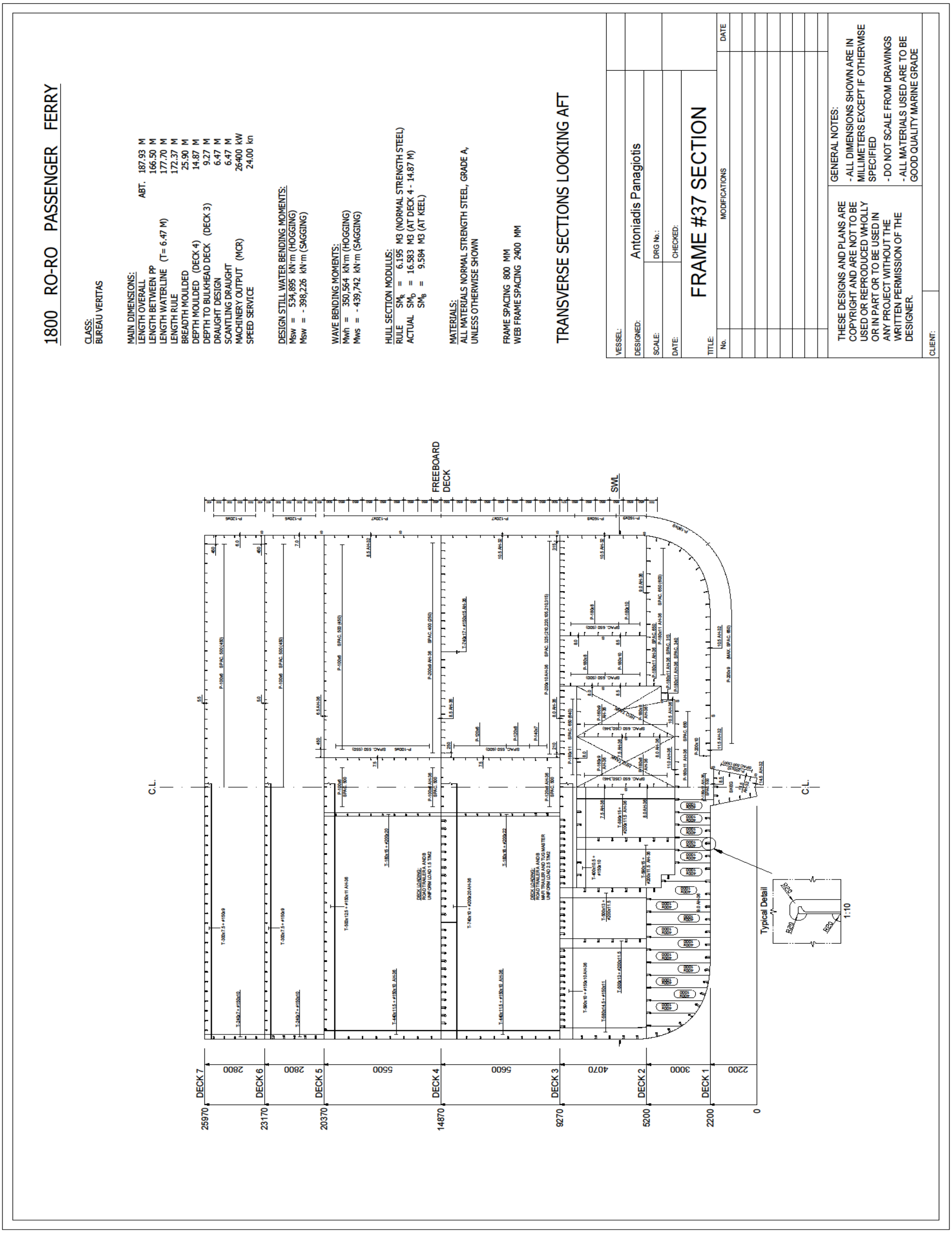

Figure 6-6: Illustration of section #37.

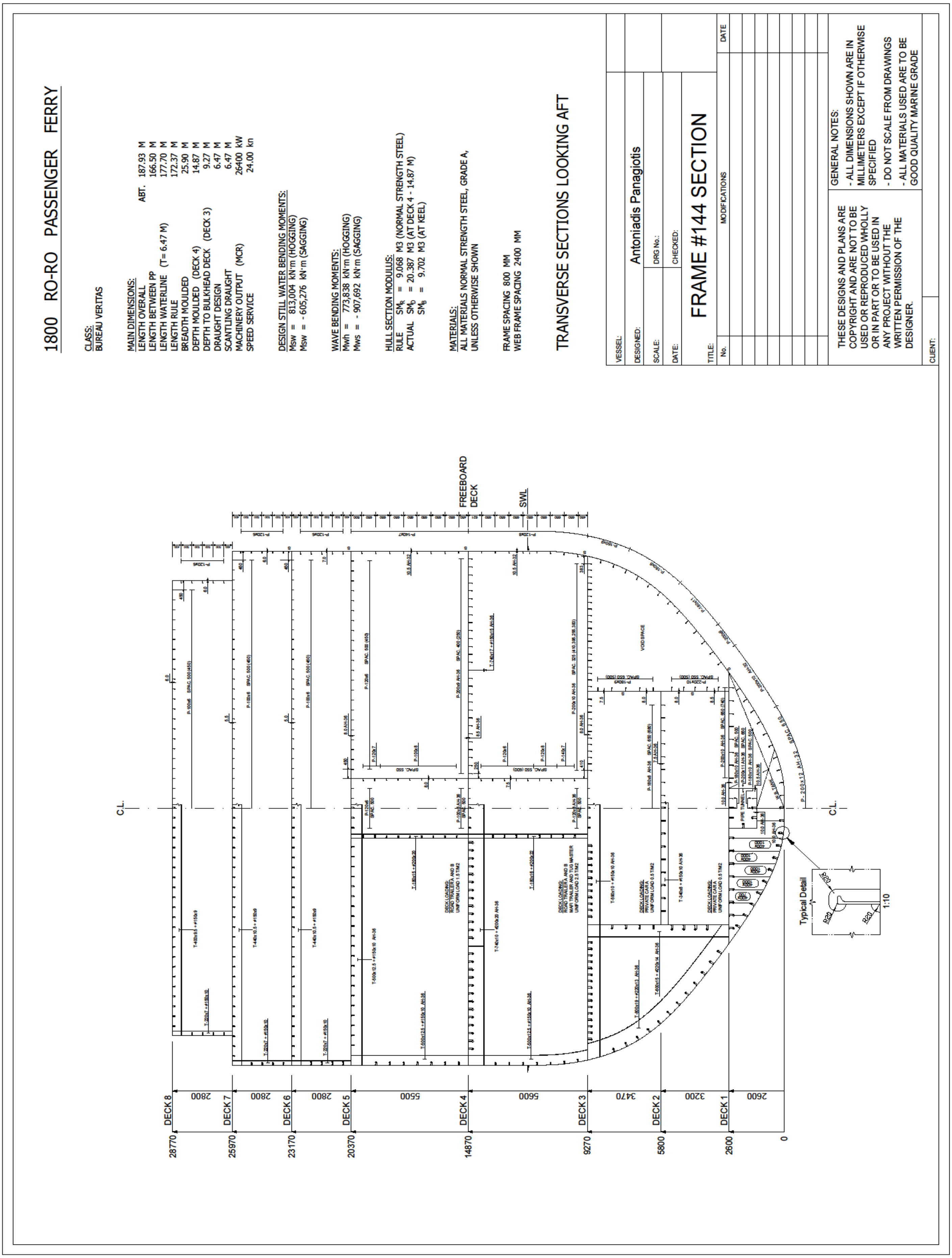

Figure 6-7: Illustration of section #144.

Conclusions and Future Works

This diploma thesis presented the preliminary design of a ro-pax ferry, using the result of a formal design optimization procedure as a starting point.

To sum up the main steps of the preliminary design procedure, initially a selection from a series of feasible designs derived from an optimization procedure with realistic owner's requirements and operational profile was performed. The selected design was then elaborated. A preliminary general arrangement plan was developed, providing several details of the ship's internal arrangement, while taking into account relevant regulations concerning passenger safety. Additionally, a more detailed study on the ship's stability was performed. The expected loading conditions were defined and compliance with relevant intact and damage stability regulations was confirmed. Finally, a preliminary selection of the ship's main structural components (i.e. panels, longitudinal and transverse stiffening) was conducted, taking into account the ship's hull girder strength as well as relevant local loads.

Regarding the results of the optimization procedure, a careful selection of a ship design was required in order to maximize economic potential while conforming with demanding and sometimes conflicting requirements (for example, stability regulations and EEDI). Additional margins should be considered as the results of the optimization procedure may be modified during the detailed design. For example, differences in the attained stability margins were observed, which can be attributed to the more detailed design during the general arrangement plan development. Hence, the higher margin values of the selected ship design were essential to avoid compliance issues with stability requirements.

Concerning the general arrangement plan, the internal arrangement required various modifications, especially in accommodation spaces. For example, the fore superstructure at deck 7 was widened so as to accommodate comfortably the ship's crew. Such alterations called for updated calculations regarding stability. Generally, lower values of safety margins were achieved, however that was to be expected as the calculations were performed at a more detailed design.

Overall, the presented work demonstrated the challenges of ro-pax ferry design, even in the early stages of design. The increased level of safety accompanying the design of such vessels, translating into much more rigid requirements regarding intact and damage stability, fire protection and other safety issues than those of a cargo vessel, forms a complex problem that must be addressed with caution.

There is always room for improvement in the detailing of the ship's design. Particular possibilities for future work are listed below.

- With regard to the general arrangement plan, ship plans regarding passenger safety and fire protection (e.g. fire integrity plan) may be developed, so as to investigate possible modifications in the arrangement of the accommodation spaces.
- Preparation of a detailed techno-economical assessment of the ship's operational profile. Variants of the design may be developed for alternative areas of operation.

- Conversion to LNG-based propulsion. Comparison between conventional and LNG designs and a possible feasibility study of the alternative design.
- Study on hydrodynamic performance of the ship’s bow and optimization of its shape and size.
- Further elaboration on damage stability requirements. Specifically, the evaluation of SOLAS regulation 9, concerning unusual double bottom arrangements, which was omitted in this thesis.
- Detailed calculation of vehicle deck loads and study of their effects on the ship’s structural integrity.
- Detailed study of steel weight components strength both in static and dynamic loads. Utilization of advanced analysis methods (e.g. finite element analysis).

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