Design of a 30 ft high-performance racing yacht

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MASTER'S THESIS

Design of a 30 ft high-performance racing yacht

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Abstract

This Master's Thesis presents the conceptual design of a small high-performance racing yacht, focusing on maximizing performance and compliance with regulations. The design methodology integrates hydrodynamic and aerodynamic analysis, structural optimization, and material selection to balance speed, stability, and durability.

A market study identifies correlations between the main dimensions of similar yachts, later analysing the impact of changing the different dimensions on the resistance and stability of the vessel. A chine is introduced, and its effect on stability is also analysed. The sail set and appendages are optimized using a VPP, with comparisons made to similar yachts to refine the design. From this point forward, the objective of the project is to obtain a more accurate VPP (based on the weight estimation and position of the centre of gravity) and understand the reason behind the discrepancies with similar boats.

The study of the propulsion system, including resistance analysis and propeller dimensions, leads to engine selection. The design and placement of onboard systems ensure peak performance and crew well-being while complying with the requirements. A hotel load of the consumers on board guides battery selection. Lastly, all these systems and equipment are organised so the general arrangement is designed.

The structure is scantled per ISO-12215, including keel and mast supports. Weight estimations in several conditions are used to refine the VPP, and the results are again compared with similar vessels. Finally, the rating and stability of the yacht are analysed to understand performance discrepancies with these designs.

Contents

List of Figures vi

List of Tables viii

Declaration of autorship ix

1 Introduction 1

1.1 Project requirements 1

1.2 Applicable regulations 1

1.3 Design methodology 2

2 Preliminary analysis 4

2.1 Parametric study 4

2.1.1 Regressions 5

2.2 Study of the main dimensions 6

2.2.1 Beam analysis 6

2.2.2 Displacement and draft analysis 9

2.2.3 Midship and prismatic coefficients analysis 9

2.2.4 Conclusions of the study 10

2.3 Navigation areas 10

3 Hull design 11

3.1 Design process 11

3.2 Second dimensions study 12

3.2.1 Results of the second dimensions study 13

3.3 Chine study 14

3.4 Shape refinement 15

3.5 Design completion 15

3.6 Calculations of Naval Architecture 16

4 Appendices and sail design 17

4.1 Appendices design 17

4.1.1 Foil theory 17

4.1.2 Foil section 19

4.1.3 Keel design . . . 20
4.1.4 Rudder design . . . 21
4.2 Sail design . . . 23
4.2.1 Physical theory . . . 23
4.2.2 Sail selection . . . 24
4.3 Velocity Prediction Program (VPP) . . . 25
4.4 Comparison with database boats . . . 26
4.5 Rig . . . 27

5 Resistance analysis and power prediction 30
5.1 Resistance . . . 30
5.2 Required propulsive power . . . 32
5.3 Sizing of the propeller . . . 34

6 Analysis of the systems and GA 36
6.1 Water system . . . 36
6.2 Fuel system . . . 37
6.3 Bilge system . . . 38
6.4 Steering system . . . 39
6.5 Cooling system . . . 39
6.6 Exhaust system . . . 40
6.7 Electrical system . . . 40
6.7.1 Hotel load . . . 42
6.8 General arrangement . . . 43

7 Structure: design and scantling 44
7.1 Scantling of the plating and bulkheads . . . 46
7.2 Scantling of the stiffeners and frame . . . 47
7.3 Keel structure . . . 48
7.4 Mast structure . . . 49

8 Weight estimation 51
8.1 Lightweight . . . 51
8.2 Deadweight . . . 52
8.3 Final calculations . . . 52

9 VPP comparision 54

10 Offshore Racing Congress rating 56

11 Stability analysis 57

11.1 Loading conditions . . . 57
11.2 Application of requirements set by the Standard . . . 58
11.2.1 Minimum righting energy . . . 58
11.2.2 Angle of vanishing stability . . . 59
11.2.3 Stability index (STIX) . . . 59

12 Conclusions 60

Bibliography 62

Drawings 73

Appendices 74

A Sailing vocabulary 74

B Regressions from the database 76

C Beam analysis of the first dimensions study 77

D Regattas database 78

E Results from the chine study 79

F VPP comparision 80
F.1 Comparison between the preliminary VPP of the design yacht and models from the database . . . 80
F.2 Comparison between the more accurate VPP, the preliminary VPP and models from the database . . . 81

G Wageningen b-series propellers 82

H Stucture report 84

I Detailed weight estimation 90
I.1 Structure . . . 90
I.2 Engine and systems . . . 91
I.3 Furniture . . . 91
I.4 Appendices . . . 92

J Stability analysis in detail 93
J.1 Loadcase calculation . . . 93
J.2 Stability graphs and criteria verification . . . 94

List of Figures

4.1 Polar plot of the obtained VPP 26

5.1 Resistance components with respect to Froude 32
5.2 Image that represents the different efficiencies and power to be considered from the propeller-hull interaction [32] 32

9.1 Comparison between the VPPs of the three loadcases represented in a polar plot . . . 54

Lines plan 65
Sail plan & Rig design 66
General Arrangement 67
General Arrangement profile and transverse sections 68
Systems plan 69
Structural layout 70
Structure: Details A-E 71
Structure: Details F-I & Lamination table 72

B.1 Regressions of the first dimensions study 76
B.2 Lwl/Bwl regression of the second dimensions study 76

C.1 Resistance comparison of the beam analysis of the first dimensions study 77
C.2 Stability comparison of the beam analysis of the first dimensions study 77

E.1 Comparison of the Waterplane area between the different studied chine heights 79
E.2 Comparison of the Metacentric height between the different studied chine heights . . . 79

F.1 Comparison between the preliminary VPP of the design yacht and models from the database 80
F.2 Comparison between the more accurate VPP, the preliminary VPP and models from the database 81

G.1 Representation of the study carried out in the B-series of Wageningen propellers for each studied combination of propeller diameter and number of blades 82
G.1 Representation of the study carried out in the B-series of Wageningen propellers for each studied combination of propeller diameter and number of blades [3] 83

J.1 GZ curve of the Maximum load condition 95
J.2 GZ curve of the Minimum operation condition 96
J.3 GZ curve of the Loaded arrival condition 97

List of Tables

2.1 Database of similar boats to the project 5
2.2 Parameters of the database vessels studied in the parametric study 5
2.3 Dimensions of the study boats 6
2.4 Parameters of the study boats 6
2.5 Study appendices dimensions 7
2.6 Verification of dimension and speed requirements for *Delft Systematic Yacht Hull Series* use 7
2.7 Metacentric height obtention for the stability analysis of the study of the dimensions . 8

3.1 Parameters of the database vessels studied in the parametric study with B_{WL} corrected 12
3.2 Dimensions of the second study boats 13
3.3 Verification of the new length-beam ratio requirement for *Delft Systematic Yacht Hull Series* use 13

5.1 Minimum Blade-Area ratio for each studied propeller according to Keller 34

6.1 Hotel load 42

8.1 Lightweight estimation 52
8.2 Total displacement estimation for the condition of all crew at one side of the cockpit . 53
8.3 Total displacement estimation for the condition of two crew inside 53
8.4 Total displacement estimation for the condition of one crew in the fore deck and another in the mast area 53

11.1 Summary of the loading conditions 58

D.1 Regattas in which the database boats participate 78

I.1 Calculation of the weight and centre of gravity of the panels 90
I.2 Calculation of the weight and centre of gravity of the reinforcements 90
I.3 Calculation of the weight and centre of gravity of the additional structural elements . . 91
I.4 Calculation of the weight and centre of gravity of the structure 91
I.5 Calculation of the weight and centre of gravity of the engine and systems 91
I.6 Calculation of the weight and centre of gravity of the furniture 92
I.7 Calculation of the weight and centre of gravity of the appendices 92

J.1 Calculation of the weight and centre of gravity of the Maximum load condition 93
J.2 Calculation of the weight and centre of gravity of the Minimum operation condition . . 93
J.3 Calculation of the weight and centre of gravity of the Loaded arrival condition 94
J.4 Detailed criteria verification of the stability for the Maximum load condition 96
J.5 Detailed criteria verification of the stability for the Minimum operation condition . . . 97
J.6 Detailed criteria verification of the stability for the Loaded arrival condition 98

Declaration of autorship

I declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

Where I have consulted the published work of others, this is always clearly attributed.

Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.

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Date: 14, August 2024 Signature: Clara Monsalve Prieto

1 INTRODUCTION

The objective of this project is to design a new small high-performance racing yacht. The design and construction of a ship is a complex and multifaceted task that requires a careful balance of engineering principles, naval architecture considerations, and operational requirements. The design of a ship includes a wide range of factors like the ship's purpose, intended operations, cargo capacity, speed, efficiency, stability, and safety. Each of these aspects must be thoroughly analysed and addressed to ensure that the resulting ship meets the project's goals while complying with applicable regulations and industry standards. Designing a high-performance racing yacht demands a meticulous approach that carefully balances performance, functionality, and state-of-the-art technology.

Through the project, design software, modelling techniques, and simulation tools to refine the yacht's exterior lines, interior spaces, structural elements, sailing performance, and other critical components are going to be employed.

Some terminology specific to sailing boats is introduced in Appendix A so it can be consulted if needed.

1.1 Project requirements

During this work, it is aimed to design an offshore high-performance racing yacht. The design purpose of such kinds of vessels is to achieve maximum speed in all directions, autonomy, and manoeuvrability, focusing on hydrodynamic forms and a gear that allows a large sail area over unnecessary facilities and equipment in terms of navigability. This is normally related to having appendices with high aspect ratios as well as sails with a generous surface, even though these decisions may produce greater angles of heel.

The target users of this vessel are sailors who want to navigate at high speeds, taking part in offshore regattas while keeping a reduced budget. Due to this last aspect, the waterlength is set to 9 meters, after noticing an increase in interest and market tendency of such boats.

Besides the waterlength there are no other established restrictions, which leads to a thorough study of all the other dimensions and parameters.

1.2 Applicable regulations

The racing yachts are designed exclusively for competing. As there are all kinds of models, designs, brands and lengths, in order to compete between them, a performance compensation system is needed, called *ratings*. The rating is a system of compensation for the performance of sailboats depending on time, by means of which, a sailboat with better features will have to cross the regatta course in less time than another one with worse features. Nowadays, three rating systems are mainly used: ORC, IRC and RI. In the case of One Design (OD) competitions, in which all vessels are the same, with the same specifications, these ratings are not needed. Therefore, it is important to highlight that rating systems can be crucial in the design process of new sailboats, taking into consideration doing an optimization process according to the rating in which they will compete. For the design vessel, the Offshore Racing Congress (ORC) is selected as the rating system, since it is a highly regarded and widely used system for rating the performance of sailing yachts in racing conditions and similar boats are certified within this system. The World Sailing Offshore Special Regulations (OSR), which govern offshore racing for monohulls and multihulls, structural features, yacht equipment, personal equipment and training; also has to be taken into consideration for designing offshore racing yachts.

In order to commercialize a boat in Europe, it has to be certified (CE certification) as complying with one of the design categories established in the European Recreational Craft Directive. The design category of a boat defines the wind and sea conditions for which the boat has been designed. In this case, as for similar boats, the design category will be A, Oceanic navigation. The boats of this category have great autonomy, with unrestricted navigation, can withstand winds greater to force 8 in the scale Beaufort (more than 40kn of sustained wind) and must resist the barrage of waves of more than 4 meters high [28].

Since the vessel is designed for offshore regattas, some implied restrictions have to be met:

- Fresh water, food and energy supply for the duration of the trip
- Space to store all the necessary security equipment required to have the oceanic category
- Have a propeller on board that allows it to navigate in ports and places of restricted manoeuvre without the use of sails
- Will be equipped with a toilet
- Will have a sewage discharge system compatible with MARPOL
- Will carry all safety and rescue devices required under current legislation

1.3 Design methodology

The development of this project follows the design spiral, based on an analysis of vessels of similar characteristics to generate a database and obtain the main dimensions. The forms of the vessel are then created, taking into account functionality and design. Next, the appendices and sails are also designed bearing in mind similar vessels and trying to optimise their performance.

Once the forms are generated, an analysis of the resistance is carried out in order to define the propulsive system. Next, the general arrangement is made: the decks and spaces are distributed to make a functional design of the technical and accommodation spaces.

As the propulsive system is defined, the engine area and auxiliary systems are established. The electrical consumers that have not yet been taken into account are calculated and an electrical balance is made for the different load situations in which the yacht will be. With its result, the necessary electrical battery is defined.

The next step is the structural calculation of the yacht, which in addition to the structure's design, results in a more accurate weight estimation.

With all the elements studied in the project, the weight estimation is calculated and the sailing performance of the vessel is obtained for a more precise position of the centre of gravity.

For the development of this project, Maxsurf Software will be used for the hull design, calculations of naval architecture data, and stability. Rhinoceros will be used for the generation of planes, diagrams, 3D geometries and renders. Wolfson Unit software will be used for the VPP and structure design.

All the distances in this report refer to a Cartesian coordinate axis, the centre of which is located at the lowest point of the hull, and aligned with the farthest aft end.

2 PRELIMINARY ANALYSIS

The objective of this chapter is to determine the main dimensions of the yacht. Fast boats are configured from the same idea: to increase their speed in calm waters, the friction resistance and/or wave resistance of their underbody must be reduced as much as possible. In addition, and should not be considered less important, behaviour at sea should be optimized.

There is no single method for sizing a vessel, but different approaches to the problem depend on the type of vessel to be designed. These methods could be classified as empirical or parametric. The parametric method is based on a comparison with an existing vessel, also called a base vessel, or a population of similar vessels. For this, it is assumed that the reference ships all have optimal designs for the mission for which they were created. The interpolation of data in the database of similar vessels is a reliable method if their quality is good, whereas the extrapolation of data carried out in comparison with an existing vessel carries many risks.

The empiric method is based on a mathematical optimization model for selected merit criteria, which is mainly used for ships with innovative designs for which no valid references are found. Generates a database of alternatives characterized by the value of the different criteria of merit employed and alternately, produces a mathematical model in which merit criteria are assembled into a multidimensional function and which can be solved by advanced optimization techniques. Ideally, the two methods should be used, i.e., starting from a base vessel on which to rely and which can be compared with other similar existing methods to verify that it is not a “strange” vessel, from which alternatives characterized by criteria of merit would be generated and the most convenient solution would be chosen.

2.1 Parametric study

To begin the parametric study, a database with similar ships to the desired one is created. The vessels selected have similar dimensions to the required ($L_{WL} = 9 \pm 1[m]$), are recent (all within the last 6 years), high-performance racing yachts and comply with the World Sailing Offshore Special Regulations. Table 2.1 is a database with the collection of boats found in the market research. In this table, the airdraft is referred to as the height from the waterline to the top of the mast and SA is the sailing area upwind.

Company	Name	L_{OA} $[m]$	L_{hull} $[m]$	L_{WL} $[m]$	B_{OA} $[m]$	Airdraft $[m]$	Δ $[kg]$	Ballast $[kg]$	SA $[m^2]$	Main $[m^2]$	Head $[m^2]$	Spinnaker $[m^2]$	Propulsion $[HP]$
Jeanneau	Sun fast 30 OD	10.4	8.99	8.4	2.99	14.1	2700	1000	59				10
J boats	J/99	9.94		8.72	3.4		3800	1520	53				20
Jeanneau	Sun fast 3300	10.11	9.99	8.9	3.4		2650	1400	61.9				15
Dehler	30 One Design	10.3	9.14	8.97	3.28	14.3	2800	940		33.5	28.2	100	10
JPK	1030	10.34		9.06	3.24		3700	1500		35	26	105	20
Bénéteau	Figaro 3	10.89	9.75	9.46	3.48	15.22	3175	1111		39.5		121	21

Table 2.1: Database of similar boats to the project

2.1.1 Regressions

In order to follow the parametric study, regressions between the different parameters are found to derive the range and average dimensions of this type of boat. From the dimensions described in the previous database, the volumetric displacement is obtained (∇) and from it the slenderness ratio ($SR = L_{WL}/\nabla^{1/3}$), as well at the remaining Sailing Areas upwind (SA= sum of main and head sails), and the ballast ratio (BR= $ballast/\Delta$). Lastly, the B_{WL} is assumed to be 85% of B_{OA} based on the supervisor's experience, and the relation L_{WL}/B_{WL} is obtained. The value of all these parameters for the boats in the database is presented in Table 2.2.

Name	L_{WL} $[m]$	B_{WL} $[m]$	L_{WL}/B_{WL}	Δ $[kg]$	∇ $[m^3]$	$L_{WL}/\nabla^{1/3}$	Ballast $[kg]$	BR	SA $[m^2]$	$SA/\nabla^{2/3}$
Sun fast 30 OD	8.4	2.54	3.31	2700	2.6	6.08	1000	37	59	30.9
J/99	8.72	2.89	3.02	3800	3.7	5.63	1520	40	53	22.1
Sun fast 3300	8.9	2.89	3.08	2650	2.6	6.48	1400	53	61.9	32.9
30 One Design	8.97	2.79	3.22	2800	2.7	6.42	940	34	63.7	32.6
1030	9.06	2.75	3.29	3700	3.6	5.91	1500	41	61	25.9
Figaro 3	9.46	2.96	3.20	3175	3.1	6.49	1111	35	72.8	34.3

Table 2.2: Parameters of the database vessels studied in the parametric study

The representation of the obtained regressions is presented in Appendix B.

Analyzing the relations between the dimensions, it can be seen how the narrower the boat (higher L_{WL}/B_{WL}), the more slender and light it is, as well as the bigger sail area it has. The Ballast Ratio does not change much, being around 40% for all the vessels. Among the studied boats, two of them do not follow this trend. One of them is narrower, but also heavier and with smaller sail area; and another is wider, as well as lighter and bigger sails. The first one could have been designed to be more stable in rough conditions, since a narrower boat can cut through waves more efficiently, providing a smoother ride in rough seas. The additional weight may be to enhance this stability too, ensuring the boat remains steady and less prone to capsizing. The second one is more extreme since a wider boat with a larger sail area can harness more wind power, making it faster and more agile while the reduced weight means it can accelerate quickly and perform better in racing conditions.

2.2 Study of the main dimensions

2.2.1 Beam analysis

Once the regressions are obtained based on similar boats, the dimensions of the project have to be determined. The L_{WL} is fixed, but an analysis of B_{WL} is performed. The objective is to determine the influence of this parameter on the overall resistance and stability of the hull. The wider the boat, the more displacement the hull has, and thus the less weight the ballast will have to carry, making it easier to define its shape and material; and being normally more stable. On the other hand, the narrower it is, the more weight the ballast should carry, normally resulting in bigger and weirdly shaped bulbs; with less stability. The general idea is that the wider the hull, the higher the resistance and stability, but this analysis aims to quantify this relation.

In order to carry out this study, three different beams are considered. One of them is within the regression average relation, and the others are higher and lower than this average, all within reasonable values compared to the database. All the other dimensions will be the same in the three boats, to have the most homogeneous results possible, setting them to be in the average obtained before in the regressions. The assigned dimensions for the three studied boats are presented in Table 2.3.

Name	L_{WL} $[m]$	B_{OA} $[m]$	B_{WL} $[m]$	L_{WL}/B_{WL}	Δ $[kg]$	∇ $[m^3]$	$L_{WL}/\nabla^{1/3}$	Ballast $[kg]$	BR	SA $[m^2]$	$SA/\nabla^{2/3}$
Boat 1		3.2	2.72	3.31							
Boat 2	9	3.3	2.805	3.21	3135	3.1	6.2	1254	40	63.2	30
Boat 3		3.4	2.89	3.11							

Table 2.3: Dimensions of the study boats

The draught is set equal to the only value obtained in the study of similar vessels, 0.5 m. The centres of buoyancy and flotation are situated at the aft of the centre line, simulating the normal area and volume distribution along the hull. The prismatic coefficient is around 0.55-0.56 in this type of boat, and 0.56 is selected for the study since it is representative of the fullness of the underwater sections of the yacht. Additionally, the fuller this is, the greater the resistance. The midship coefficient also defines the fullness of the underbody, more in particular of the largest section. A reasonable value of this coefficient for this type of boat is 0.7, which is the value set for the study. These parameters are summarized in Table 2.4.

T $[m]$	LCB $[m]$	LCF $[m]$	C_P	C_M
0.5	4.9	5.1	0.56	0.7

Table 2.4: Parameters of the study boats

Additionally, the same keel and bulb are set for the study. This is an approximation, since, as said before, the wider the boat, the smaller the bulb and keel normally are. The dimensions that define these appendices are defined in Table 2.5.

Span	[m]	1.8
Root Chord	[m]	1
Tip Chord	[m]	0.8
t/c	[-]	0.12

(a) Study keel particulars

Chord	[m]	1.4
Average t/c	[m]	0.15
WSA	[m^2]	1.8

(b) Study bulb particulars

Table 2.5: Study appendices dimensions

Resistance analysis

The first part of the study to compare and determine the best beam disposition is determining the generated resistance of each model. The *Delft Systematic Yacht Hull Series* is used to calculate the resistance since it is specific for Sailing yacht resistance prediction. To confirm the applicability of this method, it is checked that the requirements of hull dimensions are fulfilled, which is shown in Table 2.6.

Dimension/Parameter	Requirement	Value	Valid
Fn	0-0.75	0.2-0.45	✓
L_{WL}/B_{WL}	2.76-5	3.2-3.4	✓
B_{WL}/T	2.46-19.32	5.4-5.8	✓
$L_{WL}/\nabla^{1/3}$	4.34-8.5	6.2	✓
LCB/L_{WL}	-6-0	-4.44	✓
C_P	0.52-0.6	0.56	✓

Table 2.6: Verification of dimension and speed requirements for *Delft Systematic Yacht Hull Series* use

The resistance is calculated by using an Excel spreadsheet provided by the supervisor, in which the systematic series is programmed.

By entering the main dimensions and parameters of the hull and appendages, the Excel spreadsheet provides the total induced resistance (of hull and appendages) for the range of 0.1 to 0.6 Froude number for a heeling angle from 0 to 30 degrees. The resistance results for the three boats are obtained and compared between them for the Froude range of 0.2 to 0.45 since is in this range where this type of vessel normally sails, and it is crucial as the wave-making resistance starts to become more significant, and the hull begins to interact more with its own wave system. This comparison can be found in Appendix C.

From the obtained results, it can be seen that generally, the resistance decreases when raising the beam, even if this is minimal, with a maximum of 3% from the narrower to the wider boat. On the contrary, when the boat is slightly heeled, it has been found that the wider boat generates more resistance, but this difference is also slight. This increase in resistance could be due to an increase in wetted surface area when heeled, which means more skin friction resistance.

Stability analysis

The second part of the study is focused on the influence of the beam change on the overall stability of the boat. The stability analysis will be assessed by comparing the curve of righting arms (GZ). These curves depend on several actual unknowns, like the position of the centre of gravity or buoyancy, so several assumptions and approximations will be made.

Firstly, the metacentric height (GM) is obtained as $GM = KB + BM - KG$. The centre of gravity is assumed to be in the waterline, thus $KG = 0.5$ $[m]$; and the centre of buoyancy at a 70% of the draught based on the underbody shape of this type of boat, so $KB = 0.7 \cdot T = 0.35$ $[m]$. Then, the metacentric radius (BM) is estimated as

$$BM = \frac{I}{\nabla} \qquad I = \frac{L_{WL} \times B_{WL}^3}{12} \cdot C_{WP}^2 \tag{2.1}$$

Where C_{WP} is the waterplane coefficient, obtained as $C_{WP} = \frac{A_{WP}}{L_{WL} \cdot B_{WL}}$ and A_{WP} is the waterplane area obtained in the Delft series spreadsheet. The summary of all these values for each of the study boats is presented in Table 2.7.

Name	B_{WL}[m]	A_{WP} $[m^2]$	C_{WP}	∇ $[m^3]$	BM $[m]$	KB $[m]$	KG $[m]$	GM $[m]$
Boat 1	2.72	16.3			2.20			2.05
Boat 2	2.805	16.8	0.67	3.1	2.41	0.35	0.5	2.26
Boat 3	2.89	17.4			2.63			2.48

Table 2.7: Metacentric height obtention for the stability analysis of the study of the dimensions

Next, the GZ curves can be obtained for a range of heeling angles following the study, set from 0 to 40 degrees. The formula used is $GZ = GM \cdot \sin\theta \cdot \cos\theta$. The three GZ curves are plotted, which can be found in Appendix C.

From the obtained results, it can be seen that the increase of stability when raising the beam is noticeable, more than a 20% from the narrower to the wider boat.

By comparing both the resistance and stability of the three studied boats it is concluded that an increase on the beam (within reasonable values compared to the database) leads to a significant stability increase without much variation in the generated resistance.

2.2.2 Displacement and draft analysis

Next, a second iteration of the study is performed, with the aim to determine the influence of the variation of displacement and draft; since when varying the breadth, these parameters will change too. The same three boats are studied, combining two other drafts and displacements: the same displacement as before is kept changing the draft $\pm 0.1\ m$, and the same draft as before is kept changing the displacement $\pm 0.3\ m^3$. All the other parameters are kept the same as before.

Using the same Excel spreadsheet where the *Delft Systematic Yacht Hull Series* is programmed to calculate the resistance, the results show that increasing the displacement leads to a small decrease in resistance (at low heel angles, as will be applied). The most significant differences are when changing the draft, where at small heel angles, increasing it the resistance will rise too, with up to a 20% difference between the smaller and bigger draft.

For the stability study in this second iteration, the same process as before is followed, using the same formulas and results of the Excel spreadsheet as explained in Section 2.2.1. First, having a look at the formula used to obtain the metacentric height: $GM = KB + BM - KG$, it can be deduced that the change of displacement will affect the BM term, both by the explicit expression to calculate it and the waterplane area (which will be bigger when increasing the displacement) that is used to calculate the inertia. On the other hand, the change in the draft will influence the other two terms of the expression, since the centre of gravity is situated in the waterplane, and the centre of buoyancy is supposed to be a percentage of this. The final results are analysed, and it results that when increasing the displacement, the stability is reduced, up to a 20% difference between the smaller and bigger displacements. The difference in results when changing the draft is minimal.

In summary, while increasing displacement tends to reduce resistance slightly and significantly affects stability negatively, variations in draft primarily influence negatively the resistance without markedly impacting stability.

2.2.3 Midship and prismatic coefficients analysis

At the beginning of the study, in section 2.2, both the midship and prismatic coefficients were fixed in order to obtain comparable results. In this iteration, the influence of these parameters is studied. The same process as the previous iteration is repeated, changing this time both the C_P and C_M too. The prismatic coefficient is changed within the valid range to use the *Delft Systematic Yacht Hull Series*, $C_P = [0.52 - 0.6]$, to obtain the resistance as before. It is studied for values of 0.52, 0.56 and 0.6 to perform the study in a broad interval. For the midship coefficient, it is changed ± 0.5 from the initial value (0.7).

A similar process as before is followed. In this case, the displacement, the beam and one of the coefficients are changed, studying a total of fifty-four boats, half of which corresponds to the study of each of the coefficients. The draft is defined for each case after creating the boat that matches the parameters. The same processes as before are followed to obtain the resistance and stability parameters.

The results of this study are extensive and not so conclusive. For the stability, increasing the C_P, the GM rises too, meaning more stability. The resistance is a more complex analysis since the results depend on the Froude number and the heel angle. For low and high Froude numbers (<0.25;>0.35) the resistance is slightly reduced when increasing the C_P; while in the range in between, it depends on the heel angle: at higher heel angles (≥ 20) the resistance generally increases with C_P, and the opposite occurs for lower heel angles. Regarding the draft, by increasing the C_P it is almost proportionately reduced.

For the midship coefficient, the changes are considered almost insignificant: less than a 3% variation in resistance between the higher and the lower C_M. For the stability, when increasing the C_M, the GM increases proportionally (thus better stability), but the variation is considerably smaller than when changing the C_P.

To sum up, the stability changes proportionally to C_M and increases even more when C_P rises. Regarding the resistance, its changes with C_M are insignificant; and for C_P depends on the heel angle and Froude number.

2.2.4 Conclusions of the study

After this thoughtful study, it is concluded that the parameters that would generate a smaller resistance and higher stability are a wide beam, and smaller draft and displacement. Regarding the coefficients, a high C_P would be better regarding the stability but its influence on the resistance for this case is uncertain; the C_M influence is not much.

In order to determine the final dimensions of the vessel, it is going to be modelled taking into account the conclusions of this study.

2.3 Navigation areas

It has not been specified any particular area where the yacht would compete, but the endurance of the vessel is essential for some calculations. To obtain it, out of all ORC regattas, the ones where boats from the database have participated in recent editions are selected, a total of seventeen different tournaments. Except for one specific race, between all the others the maximum distance traversed by a vessel is 700 nautical miles; and along all the races the maximum time limit to complete one is 3 days. These two limits will set the endurance of the design yacht. The names and details of the regattas in which the boats from the database participate are listed in Appendix D.

3 HULL DESIGN

The objective of this chapter is to design the hull based on the parameters obtained in the previous chapter. The previous analysis was merely based on numbers, whereas now the visual shape and geometry of the boats will be analysed and taken into account.

The current trend of hull shapes, based on the database, is to have a flat bottom and a marked stem. This aligns with the fact that the racing vessels have a small cabin with the bare minimum necessary, to reduce the hull's weight as much as possible, thus making it faster. The flat bottom has an advantage compared to more "V" shaped hulls: with the same displacement, the wetted area is smaller, which results in less resistance. The marked and vertical stem elongates the length, which is decisive in reducing the wave resistance. The transom present in most of the database boats allows the flat forms to continue until the aft of the vessel, which generates extra dynamic lift when it is sailing at higher speeds. This property together with the low weight of the vessel causes it to come out slightly out of the water, and be able to stand on the wave formed by the hull, pass it and thus enter the semi-planning range.

The previously defined hull shape is very advantageous regarding the transversal and longitudinal static stability, but its RAOs (Response Amplitude Operators) produce large accelerations which would cause fatigue in the crew, and since the accommodation lacks comfort, the crew's fatigue would accumulate day by day.

3.1 Design process

The forms are designed using the Naval Architecture software Maxsurf starting from half a cylinder. This surface is modified creating several sections horizontally and transversely. One of the extremes is closed moving its points to the centre-line, and all the other points are moved to obtain a shape that complies with the characteristics described before. Since the intended bow has a lot of curvature, another surface is done to more precisely model this part by having more control points (the points that determine the shape and behaviour of the surface). It is done by copying the hull surface, so it has the same number of rows of control points, and moving its points to create the correct shape of the bow.

After converging to a solution close to the design parameters defined in the previous chapter, the resulting shape does not visually match the database boats. At this point, the previous work is analysed and it is encountered that the relation between B_{WL} and B_{OA} assumed in the Dimension's study does not correspond to this type of boat.

3.2 Second dimensions study

The previous dimensions study is not valid anymore so a new one is made. Since this time around a hull is already modelled, it is used to make the study more complete and exhaustive.

In the first place, a more accurate relation between B_{WL} and B_{OA} is found. To do so, the front images of the boats contained in the database are imported into Rhino. After, they are scaled according to their overall beam and their water length beam is measured. Later, the ratio between these two is obtained and corresponds to around 0.65 for all the cases. Then, it is established that the B_{WL} is 65% of B_{OA}, considering it a value accurate enough. Next, the relation L_{WL}/B_{WL} is again obtained for all the boats. The new database vessel's parameters are presented in Table 3.1, which only differs from Table 2.2 in the third and fourth columns.

multicolumn1c|Name	L_{WL} $[m]$	B_{WL} $[m]$	L_{WL}/B_{WL}	Δ $[kg]$	∇ $[m^3]$	$L_{WL}/\nabla^{1/3}$	Ballast $[kg]$	BR	SA $[m^2]$	$SA/\nabla^{2/3}$
Sun fast 30 OD	8.4	1.94	4.32	2700	2.6	6.08	1000	37	59	30.9
J/99	8.72	2.21	3.95	3800	3.7	5.63	1520	40	53	22.1
Sun fast 3300	8.9	2.21	4.03	2650	2.6	6.48	1400	53	61.9	32.9
30 One Design	8.97	2.13	4.21	2800	2.7	6.42	940	34	63.7	32.6
1030	9.06	2.11	4.3	3700	3.6	5.91	1500	41	61	25.9
Figaro 3	9.46	2.26	4.18	3175	3.1	6.49	1111	35	72.8	34.3

Table 3.1: Parameters of the database vessels studied in the parametric study with B_{WL} corrected

The representation of the new L_{WL}/B_{WL} regression with respect to L_{WL} is presented in Appendix B.

All the considerations described in the previous chapter regarding the relation between the different parameters still apply.

Next, the process follows the third iteration of the previous study (described in section 2.2.3): the beam, displacement and C_P are analysed at the same time in order to determine the best combination of these in the overall resistance and stability of the hull.

The three different beams to compare have to be determined. As before, one is within the regression or average relation, and the others are higher and lower than this average, all within reasonable values compared to the database. The other changing dimensions are as stated in the previous study. The draft and C_M will change so the other values meet the stated ones. It has already been concluded that the draft changes with C_P, and that the midship coefficient barely influences the results, so this decision should not have a great impact on the conclusions.

In total, twenty-seven different hulls are modelled in Maxsurf based on the one created in the previous section. The main dimensions that they have to comply with from the study, by making all the possible combinations are presented in Table 3.2.

The same keel and bulb as before are set for the study.

L_{WL} [m]	B_{OA} [m]	B_{WL} [m]	L_{WL}/B_{WL}	∇ [m^3]	$L_{WL}/\nabla^{1/3}$	C_P
9	3.2 - 3.3 - 3.4	2.1 - 2.15 - 2.2	4.3 - 4.2 - 4.1	2.8 - 3.1 - 3.4	6.4 - 6.2 - 6.0	0.52 - 0.56 - 0.6

Table 3.2: Dimensions of the second study boats

The resistance analysis is performed as in the first study, using the *Delft Systematic Yacht Hull Series* Excel spreadsheet. It was already verified that all the dimensions and speeds are within the requirements to use this method, and the new parameter C_P was selected accordingly. The new length-beam ratio is checked in Table 3.3.

Dimension/Parameter	Requirement	Value	Valid
L_{WL}/B_{WL}	2.76-5	4.1-4.3	✓

Table 3.3: Verification of the new length-beam ratio requirement for *Delft Systematic Yacht Hull Series* use

The other values inputted in the spreadsheet correspond in this case to the values obtained from the modelled hulls in Maxsurf.

For the second part of the study, the stability analysis, the software Maxsurf Stability is used importing each of the hulls obtaining much more accurate results. The GM is calculated for three heel angles besides the upright condition: 15, 20 and 25 degrees; angles which a vessel of these characteristics normally experiences.

3.2.1 Results of the second dimensions study

The number of results analysed in this second study is much higher. Stability results (GM) are relatively easy to compare, but resistance is somewhat more complex. It is therefore decided to create a criterion for disseminating the best cases.

For the resistance, the analysis is focused on the conditions at which the boat will sail: upright up until $Fr = 0.2$ and heeled from there. In the considered important conditions, the resistance varies in a range from 2 to 25 %. The chosen criterion to identify the best cases is to single out by colour the best 10 (orange) and 5 (green) per cent resistance results of each case. By applying this criterion, two cases have all their analysed resistance results within these margins with a similar number of same coloured values: $B_{WL} = 2.15; \nabla = 3.1; C_P = 0.56$ & $B_{WL} = 2.2; \nabla = 3.1; C_P = 0.56$. Another two cases have just one resistance result out of the margins: $B_{WL} = 2.15; \nabla = 3.1; C_P = 0.6$ & $B_{WL} = 2.2; \nabla = 3.1; C_P = 0.52$.

For the stability, all the heel angles are compared. For each of them, the variation along the results is from 25 to 85 per cent. In this case, the criterion set is to single out by colour the best 10 (orange) and 5 (green) percent GM results for the heeled cases, and the best 15 (orange) and 10 (green) for the upright condition. By applying this criterion, five cases have all their analysed stability results within these margins: $B_{WL} = 2.15; \nabla = 3.1; C_P = 0.56$, $B_{WL} = 2.15; \nabla = 3.1; C_P = 0.6$, $B_{WL} = 2.2; \nabla = 3.1; C_P = 0.52$, $B_{WL} = 2.2; \nabla = 3.1; C_P = 0.56$ & $B_{WL} = 2.2; \nabla = 3.1; C_P = 0.6$. The last two cases have all their results in green.

Combining both the stability and resistance results, it is concluded that the best hull parameters are $B_{WL} = 2.2; \nabla = 3.1; C_P = 0.56$. The rest of the hull design is based on these dimensions.

3.3 Chine study

After having a look at other similar boats, it is noticed that most of them have a hard chine built in. The objective when introducing this feature is to reduce the water-plane area in the upright position to bring down the resistance, while increasing it when heeled to increase the stability. This idea assumes that when heeled the boat already has high speed so the increase in resistance is not as important as the stability.

The height at which the hard chine should be designed is uncertain, and no bibliography is found in this respect. For this reason, it is decided to analyse different heights of the chine to gain a better understanding of the advantages of this feature and determine its best position.

The chine is modelled by compacting several rows of control points. This way the sharp transition is created, while ensuring continuity between the upper and lower parts of the hull. The number of compacted points depends on the transversal stiffness of the surface (how much influence the control points have): the higher the stiffness, the more points are needed. In this case, the transversal stiffness is level five, and four control points need to be compacted to create the feature.

A total of seven designs are modelled with different hard chines heights. Two of these heights are extreme (at the waterline and half a meter above it), and the others are in between. In order to identify the best one several parameters will be analysed and compared:

- The water-plane area changes when heeling
- The GM change when heeling
- The upright GM change with different hard chine heights

The stability data for each design is obtained using Maxsurf Stability and presented in Appendix E. Several conclusions are gathered:

- For the model with the hard chine in the waterline, the waterplane area is highly reduced when heeling as well as the GM, as expected.
- On the contrary, in the model with the hard chine 0.5 m above the waterline, the waterplane area is reduced only a 3% when heeled 25^o and the GM does not decrease as much, even if it is

not the most optimal solution.

- Some solutions achieve an almost unchanged water-plane area and an increase in the GM when heeled
- The best solution found is when the hard chine is 0.3 m above the waterline, the waterplane area is increased a bit when heeled. The GM is also increased when heeling, up to a 15% at 15^o and only decreases a 3% when heeled 25^o

3.4 Shape refinement

After the chine is added, the surfaces are refined using Gaussian curvature analysis. This is an iterative process, where the modifications made to correct certain parameters divert others again, in which it is relied at all times on one's intuition until finally the forms of the ship that fit all the previous parameters as well as having a nice curvature are obtained.

3.5 Design completion

In the design of the dead works (the part of the hull that is above the waterline) prevails the objective of reaching a balance between maximizing crew efficiency and safety while maximizing structural integrity and aerodynamic efficiency. With this in mind, the hull is changed a bit: the freeboard is increased to have more height below deck, and the top part of the transom is widened so the crew can be seated farther away from the centre line, having more space, and better stability: helping reduce the rolling motion of the boat and provide a more stable platform for the crew.

Regarding the coachroof, it is designed so the crew can stand in the accommodation area while trying to maintain an aerodynamic and functional shape. The longitudinal shape is thought so the Genoa can change sides easily on the turns, and its position is chosen so all the crew fits seated in the cockpit. Transversely, it is wide enough so the crew can sit behind and shelter from water, waves and wind. At the same time, there is enough space on both sides so the crew can easily walk and handle the sails or make any other required operation. This deck area, mainly destined so people can walk on it during sailing, is not parallel to the baseline but inclined so when the boat is heeled at the most common heel angle (later explained in Section 4.1.4), it is parallel to the waterline. The access to the interior is set to height from the cockpit deck, according to regulation [29], to avoid water embarking into the interior of the yacht.

The final lines plan of the vessel can be found in the Lines plan drawing.

3.6 Calculations of Naval Architecture

In this section, from the designed forms, the different characteristic parameters of Naval Architecture will be exposed and analysed.

Hydrostatics

The hydrostatic data resulting from the final forms of the vessel can be found in the Lines plan drawing.

The height of the centre of gravity (KG) depends on the loading condition of the vessel. As the weight distribution has not yet been determined, it cannot be included in the table . The value of the metacentric height (GM) is a function of KB and BM, but also of KG, so it is not included in the table either.

Curve of areas

The curve of areas resulting from the final forms of the vessel can be found in the lower part of the Lines plan drawing, representing the area of each section along the length of the vessel. To see it easier between all the lines, it is scaled, being four times wider in the drawing.

By analyzing the resulting curve, it can be seen how the underwater volume is distributed along the length, with a more-or-less constant increase and decrease. No noticeable convexity or concavity can be perceived in the graph, which aligns with the vessel's shape.

4 APPENDICES AND SAIL DESIGN

The objective of this chapter is to size and design the sails and appendices that will complement the already-designed hull, ensuring optimal performance and manoeuvrability of the sailing vessel.

Sails are responsible for generating the propulsive force, while the appendices are crucial for stabilizing the vessel and facilitating precise steering. The sizing and design of both sails and appendices are strongly connected, as the lateral forces exerted by the sails must be effectively countered by the appendices to prevent excessive yawing moments. Poor interaction between these components could lead to increased drift and obstruct the vessel's ability to maintain a steady course, particularly under varying wind and sea conditions.

This chapter will explore the detailed process of sizing and designing sails and appendices, taking into account aspects such as hydrodynamic profiling, and the use of advanced simulation tools to achieve an optimal balance between performance, stability, and manoeuvrability on the racecourse.

4.1 Appendices design

The design of appendices plays a fundamental role in determining the performance and handling characteristics of a sailing racing yacht, being critical not only for providing stability and steering control but also for minimizing drag and optimizing hydrodynamic efficiency. Depending on the type of boat to be designed different types of appendages could be installed. In this project, two appendices will be defined: the rudder and the keel. In this section, the complex process of designing these appendices is explained.

4.1.1 Foil theory

The keel and rudder work as wing sections. This section, also called foil, is defined by some parameters:

- Chord Length (c): The straight-line distance between the leading edge (also called nose) and the trailing edge (called tail) of the foil, which can vary along its depth.
- Draft (D), also called span (s): The height of the foil, the distance between the chords.
- Camber: The curvature of the mean line of the foil.
- Thickness (t): The maximum distance between both sides of the foil, usually expressed as a percentage of the chord length.
- Angle of Attack (α): The angle between the chord line of the foil and the oncoming flow of water.

- Aspect Ratio (AR): The ratio of the draft to the mean chord length (obtained as the sum of upper and lower chord divided by two).
- Taper Ratio: The ratio between the lengths of the lower chord and the upper one.
- Planform: The outline shape of the foil when viewed from the side. It essentially describes the two-dimensional shape of the foil's surface in the plane of its draft and chord.

In 2D, when the angle of attack of the section with respect to the flow is zero, the distribution of flow and speed on both sides is equal: the pressure is the same. The pressure in the nose and tail is high (no flow here), and low in between. When the angle of attack is different to zero, the distribution of flow is not the same on both sides, thus the speed and pressure either. The resultant of the sum of forces on both sides is a force almost perpendicular to the undisturbed flow. Actually, one of the objectives is to make this angle between the force and the undisturbed flow 90^o. The centre of effort of this resulting force is located in the forward part, at one quarter from the nose approximately. [11]

In 3D, the flow tends to move around the tip from the leeward to the windward side and thus the pressure is higher on the leeward. This creates a downward motion on the leeward side, gradually increasing from zero at the root to a maximum on the tip. A corresponding motion upwards is created on the windward. The streamlines on the two sides of the foil have different directions, and when they meet on the trailing edge, vortices are created. All these vortices created at the trailing edge tend to roll up into a single one left behind, which contains rotational energy that increases the induced resistance (the drag). At the tip, the generated side force must go to zero since no pressure jump between the two sides can exist here. On the contrary, near the root the flow is uninfluenced by the tip and a large force may be generated (the lift), since the bottom of the hull acts as a wall, preventing the overflow. The variation between root and tip depends on the shape of the foil, and the best distribution of the force is an elliptical one, where the minimum amount of vertical energy is left behind, which means that the induced resistance is minimized. The simplest way to obtain an elliptical distribution of the side force is to make the foil planform elliptic. This means that the chord length must vary elliptically from tip to root. The elliptical planform has certain disadvantages, not least from a practical point of view, so trapezoidal keels are much more common and it is, in fact, possible to obtain a force distribution which is very nearly elliptic for this kind of keel too. If the force distribution on the wing is not elliptic, the drag is increased while the lift is decreased.

If the bottom of the hull may be considered as a flat plate of infinite extension, the flow around the foil would be the same as if the plate had been replaced by the mirror image of the foil in the plate. A flat wall parallel to the flow thus acts as a symmetry plane.

The shape of the tip also influences the velocity distribution, and thus the forces. Depending on this shape the trailing, free vortices, which are aligned with the local flow, may be positioned slightly differently. The best design is the simplest one with a square cut-off in both views, while the worst is a tip that is rounded in both directions. This is because the flow along the tip is guided backwards by the flat ending. If the tip is round, it tends to move more upwards, so the vortex stays further down with the square configuration. Following this reasoning, the important part to keep straight is the aft. The square shape in the front view is also better than the rounded one since the downward flow on the leeward side separates at the edge and the vortex is moved below the tip. A rounded shape permits the flow to move around to the windward side before it separates, so the vortex may be found on the windward side, not at maximum depth.

4.1.2 Foil section

The sectional shape of the keel does not have such a significant effect on its characteristics as the planform, but on the other hand, the most important planform parameter, the aspect ratio, is fixed in most class rules and heavily penalized in rating rules. A study of the influence of the sectional characteristics may therefore be worthwhile.

The NACA sections are a set of standardized airfoil shapes normally use in the industry to define the section of hydrofoils. Two different series are used in this industry: four-digit series and six-series. The six-series are thinner sections than the four-digit, which tend to be thicker.

In the condition explained before, there is a laminar boundary layer developing backwards from the leading edge. After a certain distance, the flow becomes unstable, and shortly thereafter the boundary layer undergoes a transition to a turbulent state. Under certain conditions, the flow may separate and recirculation may occur. As explained before, at an angle of attack the flow is not the same on the two sides, and the boundary layer development is determined from the pressure distribution, which in turn depends on the shape. A favourable pressure distribution with diminishing pressure stabilizes the flow, which is then sucked backwards. An increasing pressure works in the opposite direction and destabilizes the flow in such a way that transition moves upstream and separation occurs more easily.

Comparing both NACA series in these conditions:

- The four-digit has its pressure minimum very far forward. This means that a favourable pressure distribution exists on only a small front part of the chord, and that transition is likely to occur far forward. Consequently, it has a small region of laminar flow.
- On the six-series series section the maximum thickness, and hence the pressure minimum, occurs further back, and a much larger laminar zone can be anticipated, resulting in a considerable drag reduction.
- The thin section works well only in a small range of angles of attack, while the thick section accepts larger angles. The thin sections have the smallest drag at small angles of attack, while the so-called “drag bucket” (range of angles of attack where the drag on the foil is minimized) is much wider for the thick ones.

- At small angles of attack the difference between lifts is small. However, at high angles of attack, the thin sections tend to stall abruptly, with a large loss in lift as a consequence, while the thick sections exhibit a much more gradual stall, with an almost constant lift. When a thick section stalls, separation occurs on the suction side near the trailing edge. The larger the angle, the larger the separated zone, but the changes are smooth. In the opposite case, in a very thin section, the flow cannot follow the sharp bend around the nose even for small angles of attack, so a separation bubble develops at this part. When the angle is increased the bubble grows smoothly until it reaches the trailing edge and the maximum lift is developed. No jump in lift occurs, but the drag is large for all angles.

4.1.3 Keel design

The objective of the keel is to balance the given side force from the sails at the expense of the smallest possible drag.

After looking at the keels of the database boats, a bulbous keel is selected in all the cases. It lowers the centre of gravity of the keel, which makes a more stable and faster vessel since less driven power from the sails is spilt if the boat remains upright. Regarding the flow analysis, The bulb promotes separation of the vortex, helping the flow to pass the tip and move up on the other side. The main disadvantages of the bulb are that the wetted area increases greatly and that some interference drag is created in the corners between the bulb and the keel. These negative aspects may, however, be well compensated by the large increase in stability, so it is decided to also select this type of keel.

The difference in stability between the fin and bulbous keel is great. Between the bulbous keels, the T-keel is slightly better than the others in terms of performance metrics such as hydrodynamic efficiency (reduced drag and improved flow around the keel), lift-to-drag ratio, or overall sailing performance. [31].

To select its section, it is important to notice that it normally operates at small angles of attack and the speed of the yacht depends on the drag produced at these small angles. Since the lift and angle of attack for the keel are small, from what has been explained before, sections of the six-series are preferable.

According to Larsson [11], the size of the keel is related to the sail area as:

$$\frac{A_k}{SA} \sim [2.2, 3.1]$$

where A_k is the keel area and SA is the sail area. The best area in this range is assessed in the VPP by comparing different keel areas with the same draft and Taper ratio, which should be around 0.8 by looking at images of the database boats. Regarding the section and thickness, Larsson agrees that since the lift and angle of attack for the keel are small, sections of the six-series are preferable for this application as long as the thickness ratio is not too small to keep the drag bucket wide enough for upwind sailing. He recommends a minimum 12% of thickness/chord ratio, a thick section is favourable from a ballast point of view, but the drag at zero angle of attack increases with thickness and a thick keel at the root produces unnecessary waves when heeling. Thus, the 64-series is selected, trying to keep a 12% thickness/chord ratio.

The position of the keel is close to the center of the boat, almost aligned to the mast so the moment produced by the sail and keel forces is not great. It is estimated the draft of the keel based on other boats is approximately 1.5 m.

In the keel assessment, the bulb should also be considered. According to Vacanti [31], the NACA foils 00 would be suitable for a bulb, it should not exceed 15% of thickness/chord ratio to keep drag low and should have a very high length/thickness ratio to minimise wave drag caused by the underwater displacement of the bulb. As mentioned before, the T-keel is selected, thus the bulb must be longer than the chord of the keel at the tip, around double. The thickness/chord ratio is set to 12% to reduce the drag but still be suitable in upwind sailing, and the length/thickness is set to 25%.

A combination of keel fin and bulb will be designed for each studied Sail Area (which will be explained later). Lastly, the ballast mentioned in the first dimensions study, in section 2.2 has to be taken into account. The combined weight of the keel and rudder has to be 1254 kg. To achieve it, the smaller keel is fully made of lead, the intermediate one is made of stainless steel and the bigger of iron. This includes both the fin and bulb.

4.1.4 Rudder design

The main task of the rudder is to provide enough moment to manoeuvre the yacht under all conditions. Therefore, the rudder has to be designed with emphasis on the maximum side force required. It operates most of the time at higher angles of attack than the keel, particularly if the yacht is sailing in a seaway and corrections to the course have to be made continuously. Since the design boat is fast, a relatively small rudder is required. From what has been explained before, sections of the four-digit series are preferable.

The vessel will have two rudders symmetric with respect to the centerline, just like all the boats from the database. This is a common aspect in racing yachts, which tend to heel, since the double rudders allow one of them to be completely submerged and functional in this condition, ensuring effective control. This configuration helps prevent cavitation, where air bubbles form around the rudder due to low pressure, and reduces drag by also pulling one of the rudders out of the water, enhancing the overall performance of the yacht. Double rudders also help balance the loads, improve the directional stability of the vessel, and allow beamier boats for sharper turns and better handling, particularly at lower speeds or tight spaces.

From the reference vessels it can be seen that while some of them have the rudders at the aft, stern-mounted, others have them positioned below the hull. Positioning the rudders at the aft gives a longer arm for steering, so small movements of the tiller can produce significant changes in direction, providing good maneuverability; and are easier to integrate, install and maintain. Additionally, an advantage of the stern-mounted rudders is that when heeled, one of them can be lifted completely out of the water, decreasing the drag and imbalances. On the contrary, the structure is more complex and the connection to the hull is less stiff, making it easier to break. The rudders located below the hull are easier to be placed wider apart which provides better maneuverability and performance. Another advantage of this placing is the reduction in cavitation. Finally, it is decided to position the rudders below the hull, since the connection to the hull is stiffer, have better performance, and cavitation is reduced. The main advantages of the stern-mounted relied on the possibility of lifting one of the blades, but since the regattas in which this vessel would compete have frequent turns and raising the blade takes time, it would not be done as frequently and the possibility of a blade breaking would be higher.

The design of the rudder will not be such, but a selection of the best rudder between the ones given by a supplier as rudders are rarely built in, but bought. This selection is based on the lift force the rudder has to generate in order to maintain the force equilibrium. To obtain this force, a yaw moment on the longitudinal balance is considered, which can have a huge effect causing the vessel to either point up into the wind, (weather helm) or bear off (lee helm). To maintain a straight course, a rudder angle is required, thus the force it generates. The total aerodynamic and hydrodynamic forces from the sails, keel and hull are equal and opposite, but not aligned, creating a yaw moment. To maintain the yaw moment equilibrium the tiller is pulled to the side of the yacht, creating a rudder moment that equals the rig moment. When the yaw moment turns the yacht head to wind, the rudder side force is additive to the hull and keel side force reducing the required side force from these, whilst the rudder drag increases overall drag. The lift the rudder requires to keep the yacht sailing in a straight line is calculated from this equilibrium of forces, assuming the hydrodynamic drag angle is half the apparent wind angle, and in a range of wind speed and angles. Then, the required rudder area is obtained assuming the rudder angle is 10 degrees, and obtaining the lift coefficient at this angle for the profile of the supplied rudders. Finally, the rudder blade is selected bearing in mind that the rudders are inclined with respect to the hull so they are upright, and thus optimum, at the most common heel angle (from the ones obtained in the VPP); so when the boat is sailing at low speeds, slightly heeled, both rudders will generate lift while being inclined; and at high speeds, the vessel will be more heeled, with one of the rudders almost upright and at least half of the other out of the water.

Another important consideration with twin rudders is their distance from the centerline. They are positioned so that, when the boat is heeled at the most common heel angle, each rudder can turn up to 30 degrees while the blade remains below the hull. Longitudinally, the rudders are placed as far aft as possible to maximize the steering arm, which enhances control and manoeuvrability. However, they must also be positioned such that the entire blade length stays within the hull's length even when the vessel trims. Ensuring the hull-rudder stock connection is robust is essential, so adequate space must be left at the stern for this reason too.

4.2 Sail design

Designing sails for a racing yacht is a rather meticulous and complex process. The sails are always tailor-made for each vessel since they have such a great impact on its performance, speed, and manoeuvrability. This section explores the multifaceted aspects involved in sail design, understanding the different parts, types and their utilization with the purpose of optimising their functionality. Sails are the primary propulsion system of a sailing yacht, converting wind energy into forward motion. An explanation of the different types of sails that can be found in this type of boat and the different techniques to modify them when sailing are explained in Appendix A.

The yachts have different sail sets for different wind conditions, and in this project, a set optimized for upwind sailing will be designed. While downwind sailing also requires specialized sails designed to capture wind from behind the boat (such as spinnakers), upwind conditions are often the focus due to their tactical importance (success in the upwind legs of the regattas often determines overall race performance) and the technical challenges they present (sailing against the wind requires sails that can efficiently generate lift and drive the boat forward). To sum up, this sail set is designed for upwind sailing since its effective design and performance can significantly impact a boat's overall competitiveness and success in regattas. Then, the sail set will be composed of a mainsail and genoa, since it is more versatile and is what most of the boats from the database have in their upwind set.

4.2.1 Physical theory

The Sails generate propulsive force similarly to foils, as explained in section 4.1.1. In this case, the negative pressures on the suction side are much larger than the positive pressures on the pressure side, resulting in the primary force contribution from the suction on the leeward side of the sail.

Additionally, when two sails are positioned next to each other, their interaction with airflow changes significantly. Larsson compares the difference in flow between the complete sail set and just one sail [11]. Compared to a single sail, in the complete set, the air approaches the mainsail at a smaller angle, while the opposite happens in the headsails. This results in decreased suction over the forward half of the main sail, significantly reducing total force. On the other hand, the suction on the leeward side of the headsail increases towards the trailing edge, generating a greater force. This interaction between sails contrasts with the Venturi effect, where the pressure decreases and speed increases as the flow passes through a constriction. In contrast, the air between the sails is not constrained and tends to flow freely, often diverting to the leeward side of the headsail and the windward side of the mainsail.

The mast generates three flow separation zones that affect sail performance: two behind the mast on each side and one on the aft part of the leeward side. Proper mast shaping and turbulence control can minimize the first two separation zones. The third one is influenced by these because significant separation at the front creates a thick boundary layer in the attached flow area. By proper sheeting and a good mast design, this zone can be very small or even eliminated. It is essential to avoid separation in order to maintain the pressure difference between sail sides as high as possible, to have optimal sail performance and reduced drag (which is increased due to the separation itself).

Mast shape influences flow disturbances. If the boundary layer becomes turbulent before separation, separation is more pronounced compared to when the Reynolds number is low and the boundary layer remains laminar until separation. Turbulence delays separation due to its stirring effect on the flow: high-speed fluid from outside the boundary layer is drawn inward, energizing the flow that is at the verge of separating from the surface. When the Reynolds number is in the subcritical region and laminar separation occurs, introducing roughness causes the boundary layer to turn turbulent earlier, possibly before separation. This is delay, as explained, and reduces drag. During sail operation, the stagnation point on the mast is always on the windward side. Therefore, the flow entering the leeward side of the sail must pass over any riblets present, even if they are aligned with the mast's symmetry plane. There is no effect on the flow on the windward side, so to improve the mast shape, a better solution is to put one riblet on each side.

Regarding sail planform, vortex shedding occurs at the top and boom, inducing an induced resistance. To mitigate this, sails benefit from a high aspect ratio, and sealing the gap between sails and the deck is advantageous (except for the boom gap, where the crew must be). Since the sail is a wing of practically zero thickness, the camber of the sail section significantly influences forces, increasing the forces when it is longer. Maximum camber position is also important: mid-chord camber is ideal for upwind sailing, while broad reaches benefit from aft camber. Overlapping genoas and mainsails require forward maximum camber positions, optimizing sail performance.

4.2.2 Sail selection

In section 2.1.1, the Sail Area upwind regression was obtained from similar boats. This will be used to study which sail set allows the boat to go faster. Three sail sets are designed that correspond to a $SA/\nabla^{2/3}$ ratio of 25, 30 (the one obtained in the regression) and 35 ($SA = 50,\ 60\ \&\ 70\ m^2$). It is important to remark that upwind and downing conditions must be studied separately since due to their apparent wind angle, the sail behaves differently in each scenario, and when sailing downwind the sail is not acting like a foil anymore.

According to Larsson [11], the area of the main sail should be approximately 54% of the total sail area, which matches the database boats sails. He also recommends the Aspect Ratio of the mainsail to be 5.8, and of the fore 7.1. These numbers do not fully match the database boats, which have the Aspect Ratio of the mainsail between 5.8 and 6.2 and of the fore between 5.5 and 6.9. To relate the total area with the dimensions of the main, the roach factor is assumed to be 1.45, obtained after doing some simple calculations of the database boats. With all this info, several sail sets are obtained, with the three different Sail Area-Displacement ratios and with six different Aspect Ratio combinations, testing the Aspect Ratio of the mainsail being 5.8 and 6.2 and of the fore 5.5,6 and 7.

4.3 Velocity Prediction Program (VPP)

In order to find the best combination of keel, rudder and sails that generate the most power and create the least resistance, thus the yacht goes faster, a VPP (Velocity Prediction Program) is used. A VPP is a mathematical model which determines the conditions at which the aerodynamic forces and hydrodynamic forces are in equilibrium. The aerodynamic includes the heeling moment, the sail force and the aerodynamic drive force. The hydrodynamic ones cover the righting moment, the drag of the hull and the keel side force. The results are represented on a polar plot, where the velocity of the wind, the boat and the wind angle are illustrated for a given sail set. It is important to emphasize that the position of the centre of gravity is yet to be determined, thus it is assumed to be in the waterline as was made in the preliminary analysis (Chapter2).

First, VPPs combining the different keels and sail sets are run. The program is set to a true wind speed between 4 and 25 kts. As mentioned before, the upwind position is the one to be optimised, thus the wind heading angle of study is set between 32 degrees (since it is impossible to sail into the wind, this is the estimated limit) and 110 degrees (in theory after 90 degrees the reach is passed and the sail set should change). The sail sets are studied changing the keel area, maintaining the draft and Taper ratio mentioned in previous sections. From this, it is concluded that when reducing the area of the keel the vessel acquires greater speeds, but when the area is the lowest, at high speed and wind angles the speed starts decreasing, thus there is a limit. Regarding the sails, it is also noticed that the sail sets with the lower Sail area-displacement ratio reach higher speeds overall. Finally, the best combination of keel and sail set is selected, mainly comparing boat speeds but making sure the heel angles are not disproportionate.

The VPP obtained from this combination is shown as a polar plot in Figure 4.1.

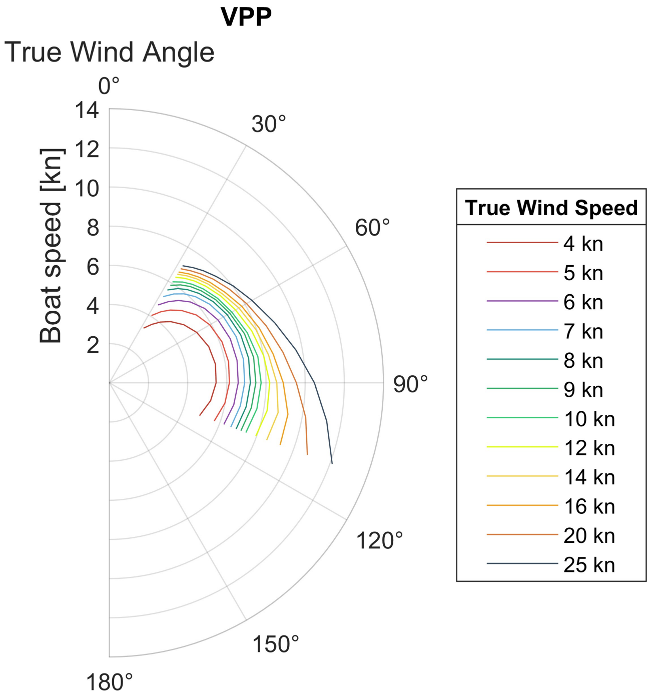

Figure 4.1: Polar plot of the obtained VPP

Once these two are set, the lift that the rudder must generate is determined. The VPP provides the heel angle, leeway, apparent wind speed and angle, total resistance, heel force, and boat speed for the studied range. Based on these results, the hydrodynamic drag angle (relative to the direction of the side force and the hydrodynamic force) is assumed to be half the apparent wind angle so the resistance can be decomposed into side force. At this point an approximation is made: it is considered that the rudder's drag is minimal and that the side resistance is equal to the side force generated by the sails. The total aerodynamic force is then obtained, and by ensuring that the rudder moment is equal to the rig yaw moment, the rudder force is calculated. Using simple trigonometry, the lift of the rudder is then obtained. With the lift coefficient formula, the necessary area of the rudder is calculated. Finally, a suitable rudder blade is selected from the range offered by the supplier, Jefa [21].

In order to position the rudders, the most common heel angle is obtained: 14^o. The rudders are inclined accordingly, and transversely and longitudinally positioned.

The final sail set, keel and rudder can be visualised in the Sail plan & Rig design drawing.

4.4 Comparison with database boats

In order to verify that the performance of the chosen sails is adequate, the obtained polar plots of the VPP are compared to polar plots of existing boats which are models of the database. Visually comparing polar plots of several similar boats is complex, thus three different speeds that represent low, intermediate and high wind speeds are selected to ease the analysis. These can be found in Appendix F.1.

It can be seen that the chosen sails are within the values of speeds of the existing boats up to a wind angle of 90^o. As mentioned before, sail sets normally change around this angle, so this discrepancy is explained by it. It is noticed that the chosen sails generate higher speeds both in low and high wind speeds, which, although good news, suggests that the approximate position of the centre of gravity differs from reality, or that some restrictions of the rating system are being overlooked. The rest of the thesis will be dedicated to determining as exactly as possible the position of the centre of gravity in order to obtain a VPP as accurate to reality as feasible.

4.5 Rig

In order to exploit and control the sails, the rig is a critical component. The combination of mast, boom, cables and winches helps support and adjust the position, shape and angle of the sails. The rig is a direct influence in the capacity to exploit the sails, and thus the boat's speed. In this section, the rig will be dimensioned following the Nordic Boat Standard (NBS), which is an accepted standard engineering practice.

The starting point is to determine the type of rig that conforms the boat. All the boats from the database have the same rig type, thus the same will be used in this case: F-2, fractional rig with 2 spreaders. The location of the spreaders is again based on the boats from the database. The length of these is determined by the angle of the vertical shrouds with respect to the mast.

The calculations of the Standard are based on the righting moment at 30^o heel angle, which is obtained from Maxsurf Stability. Then, it is checked that the NBS is valid for the obtained sails: the area of the foretriangle is not greater than 1.6 times the area of the mainsail ($I \cdot J/(E \cdot P) < 1.6$), and secondly that the sail area is greater than the righting moment divided by 128 times the heeling arm.

The shrouds

The shrouds are fixed cables that support the mast and keep it upright transversely together with the spreaders. They are dimensioned by obtaining the force they must withstand, which comes from the wind pressure on the sails and dynamic additions from wind and sea. These forces are calculated considering two different load cases: one in which the rig is loaded by only a foresail, and another in which the rig is loaded by a deep reefed mainsail. The forces are distributed along the shrouds, so their tension and load are obtained.

The shrouds are made of stainless steel cables in a 1x19 Dyform formation, which makes them very rigid and stretch low when high loads are applied. From a supplier, the minimum diameter they should have to withstand the calculated loads is obtained. The cable that goes from the top of the mast is continuous until the bottom spreader, thus its diameter is determined by the most demanding part from the ones it composes.

The disposition and specifications of the shrouds can be found in the Sail plan & Rig design drawing.

The stays

The stays are fixed cables that support the mast longitudinally. The boats from the database only have aft and fore stays, without any other longitudinal support. Their dimensioning force is derived from the righting moment at 30° of heel, and with the obtained breaking strength, and being made of the same material as the shrouds, the minimum diameter of the stays is determined. It is recommended that the diameter of the forestay is at least 6 mm to limit its stretch. Regarding the backstay, due to the geometry of the mainsail, placing it on the centerline is not feasible as it would obstruct the sail from changing sides during turns. Therefore, two backstays are used, each connecting the mast to one side of the transom.

The disposition and specifications of the stays can be found in the Sail plan & Rig design drawing.

The mast

The tension in the shrouds and stays induces compression in the mast, and in order not to bend or break it has to have sufficient stiffness, and enough moment of inertia transversely (Ix) and longitudinally (Iy). The mast is divided into panels, delimited by the spreaders. The required stiffness is different for each panel and depends on the load as well as on the length of the panel in question. The required moments of inertia will be obtained as suggested by NBS, but only the highest of the three panels will be used to select the mast.

The mast will be made of carbon to reduce the weight and increase performance since carbon composite combines stiffness and strength with low weight. The Young's modulus of this lamination is unknown, so instead of calculating the required moments of inertia, the flexural rigidity are obtained (EI). Then, from the masts given by the supplier the one that has the required flexural rigidity is selected. Its size is detailed in the Sail plan & Rig design drawing.

The boom

The boom helps control the shape and angle of the mainsail. It is subjected to bending forces coming from the wind pressure on the mainsail, which is counteracted by the sheet and kicking strap. According to the NBS, the required vertical section modulus should be calculated and the boom selected accordingly. However, the supplier has a table in which by entering the Righting moment and the foot length of the mainsail (E), the appropriate boom model is obtained. As in the case of the mast, it will be made of carbon. Its size is detailed in the Sail plan & Rig design drawing.

The spreaders

The spreaders are horizontal or slightly angled spars attached to the mast and support the shrouds. By pushing the shrouds outwards, spreaders increase the angle at which the shrouds meet the mast, which improves the lateral stability and overall rigidity of the mast, preventing it from bending or flexing under the load of the sails. They also help distribute the loads more evenly across the mast and the rigging, reducing stress concentrations that could lead to failures. The location and dimensions of these spreaders are shown in the Sail plan & Rig design drawing.

The winches

The winches are mechanical devices used to increase the sailor's leverage when hauling in or adjusting running rigging (ropes used to control the sails). One pair of winches at each side of the cockpit are included in these types of boats (all the boats from the database follow this pattern), of which each corresponds to a sail. The NBS does not include a way to size the winches, so the guide given by a supplier will be used instead. The genoa winches, positioned in the cockpit, need to be size 46 to handle the larger loads from the headsail. In contrast, the winches for the mainsail, located on top of the coach roof, should be size 40 to manage the mainsail control lines effectively. Their position with respect to the sails and rig can be seen in the Sail plan & Rig design drawing.

Additionally, the required guardrails to prevent man-overboard are also designed, with their position, height, openings and required lines as established in ISO 15085 [25]. They are also represented in the sail plan.

5 RESISTANCE ANALYSIS AND POWER PREDICTION

The objective of this chapter is to estimate the required driving power for the yacht to achieve the desired speed, overcoming the resistance created by it, and to select an appropriate engine based on this estimation. In addition, the most appropriate propeller configuration will be determined. Since the engine is typically one of the heaviest components on a vessel, its weight significantly impacts the position of the centre of gravity, essential for obtaining an accurate VPP.

Since the project yacht is designed purely for racing, the use of mechanical propulsion will be limited to two main scenarios: moving the vessel to the starting port or regatta area; and emergency situations when a critical part of the rigging, such as the mast, breaks and the vessel can no longer sail. The design will be focused on the latter scenario, where the conditions are extreme since the first one can be planned and prepared for well in advance.

5.1 Resistance

Obtaining the resistance cannot be conducted from the test of a scale model in a towing tank and then scaling the results. On the contrary, it will be predicted based on a systematic series generated from ships already built and tested, the already mentioned *Delft Systematic Yacht Hull Series*, which as has been shown before, can be applied to the design yacht.

The Froude's hypothesis will be the starting point to explain the different components of resistance:

$$C_T = C_V + C_R \tag{5.1}$$

With C_V being the viscous resistance coefficient and C_R being the residual one.

On this basis, the ITTC'57 (57^{th} *International Towing Tank Conference*) recommends obtaining the resistance as

$$C_T = (1 + k)\ C_F + C_W \tag{5.2}$$

Where C_F is the coefficient of friction resistance, C_W is the coefficient of wave formation resistance and $r = (1 + k)$ is the form factor.

From it, the recommendation made by the ITTC'78 is applied [19]:

$$C_T = C_{TM} + r \times (C_{fppB} - C_{fppM}) + \Delta C_F + C_A + C_{AAS} \tag{5.3}$$

Where C_{fpp} is the flat plate friction coefficient of the ship (B) and model (M), C_{TM} the total model resistance coefficient, ΔC_F an additive roughness correction, C_A an additive correlation correction, and

C_{AAS} the coefficient of air resistance. Then, $C_{TM} - r \times C_{fppM}$ is the wave-forming resistance coefficient (same in the model and the boat) and $r \times C_{fppB}$ is the viscous resistance coefficient of the boat. It is then observed that to the viscous and residual resistance proposed by Froude, an additive correction of roughness, the air resistance and a correlation correction are added. The *Delft Systematic Yacht Hull Series* is based on a large number of towing tank experiments conducted on various yacht hull models, where the total resistance was obtained using the above formula. The C_{TM} was obtained in the towing tank experiments, the C_F was calculated using the linear correlation ITTC'57 $C_F = \frac{0.067}{(\log_{10} Re)^2}$, and the form factor obtained from Holtrop and Mennen studies [7]. The other terms of the equation were solved using the formulas suggested by the ITTC.

The results obtained from the systematic series could be used to represent the yacht in calm water. It is important to clarify that the term C_W of the formula suggested by the ITTC'57 represents the waves formed by the vessel's movement, not the ones it encounters. The scenario under consideration is when an important part of the rigging breaks, likely to occur under very bad weather conditions. Therefore, the waves encountered by the yacht must be taken into account when calculating the resistance generated by the yacht.

The added resistance due to a seaway is computed by the approximation that Prof Gerritsma presented in the 11^{th} Chesapeake sailing Yacht Symposium [6]. The systematic series analysis of the results showed that for a constant wave direction, height, and period, the added resistance for all the yachts depends on their length, displacement, and pith gy-radius. These results were used to develop a non-dimensional approximation for yachts that fall into the Delft series range (as is the case of the design vessel).

The wave direction, height, and period are taken from standard data for offshore and coastal locations related to the Beaufort scale. From the needed vessel data, the length and displacement were presented before, and the gy-radius is calculated as $\sqrt{\frac{I}{\Delta}}$, numbers obtained from Maxsurf.

Next, the conditions under which the engine will be used must be determined. Given that the vessel's class requires it to withstand winds greater than force 8 on the Beaufort scale, it is reasonable to consider that the vessel could encounter an emergency in force 6 conditions. Regarding the vessel's speed, it is sensible to set it at a Froude number of 0.4 in the displacement region, which is approximately equivalent to 7 knots.

Once all the conditions are determined, both parts of the resistance can be calculated. The *Delft Systematic Yacht Hull Series* resistance is obtained using the given Excel spreadsheet for the desired speed. Since the resistance simulates an emergency scenario, it is calculated with the vessel upright, without heel, since when the rigging is damaged and the vessel cannot sail, the vessel is generally brought upright to stabilize and facilitate safe handling, so it is likely to be in this position rather than heeled. Next, the added resistance is calculated for the weather conditions and vessel speed. Finally, these two terms are summed up, resulting in a generated resistance of 1700 N. The different resistance components with respect to the Froude calculated as explained before are presented in Figure 5.1.

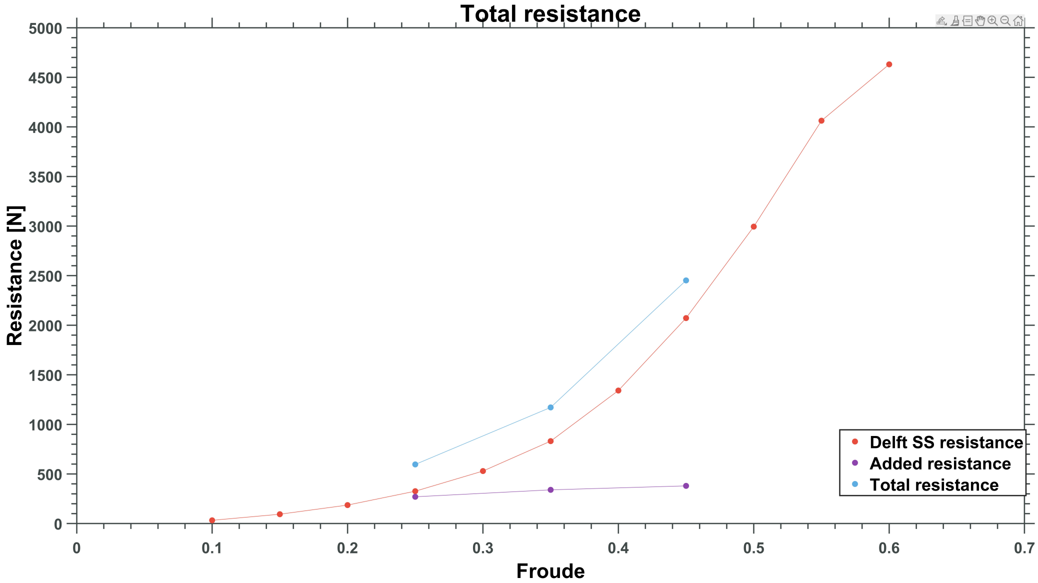

Figure 5.1: Resistance components with respect to Froude

5.2 Required propulsive power

Next is to estimate the propulsive power, that is, the power on the shaft at the exit of the engine, from the effective power, necessary to tow the boat in calm waters. The required power is going to determine the engine to be installed.

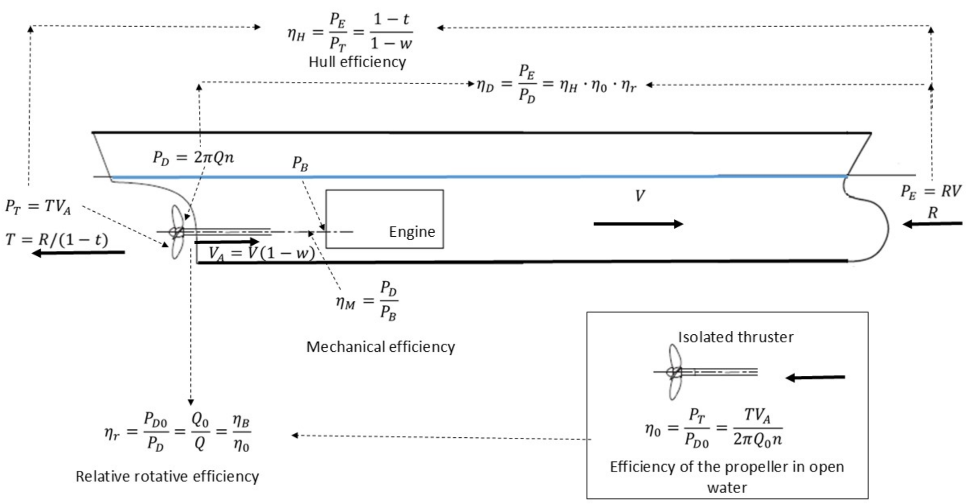

Figure 5.2: Image that represents the different efficiencies and power to be considered from the propeller-hull interaction [32]

Figure 5.2 represents the different efficiencies and power to be considered for the engine power estimation.

At $7kn$, a resistance of 1700 N is generated. The effective power then is $P_E = R \times V = 1700 \times (7 \times 0.5144) = 5247\ W$.

To calculate the wake fraction and the thrust deduction, Taylor formulas [14] for ships with one propeller are used. The coefficients are as follows:

$$w = 0.5 \times C_B - 0.05 = 0.5 \times 0.36 - 0.05 = 0.213 \tag{5.4}$$

$$t = 0.6 \times w = 0.6 \times 0.21 = 0.149 \tag{5.5}$$

With the obtained values, it is possible to determine the hull efficiency, the propeller inflow velocity, the propeller thrust and the power delivered by the propellers.

$$\eta_H = \frac{1-t}{1-w} = \frac{1-0.21}{1-0.15} = 1.11 \tag{5.6}$$

$$V_A = V(1-w) = 7 \times 0.5144(1-0.21) = 2.43\ m/s \tag{5.7}$$

$$T = \frac{R}{1-t} = \frac{1700}{1-0.149} = 1951\ N \tag{5.8}$$

$$P_T = T \times V_A = 1951 \times 2.43 = 4734.59\ W \tag{5.9}$$

To calculate the relative rotative efficiency, the formula proposed by Holtrop and Mennen [8] and Holtrop [9] is used:

$$\eta_r = 0.9922 - 0.05908\left(\frac{A_E}{A_O}\right) + 0.07424\left(C_P - 0.0225 \times B\right) = 0.9922 - 0.05908 \times 0.45 + 0.07424\left(0.56 - 0.0225 \times 2.21\right) = 1.00 \tag{5.10}$$

The calculation of the expanded blade area ratio (A_E/A_O) is found in the following section.

The indicative mechanical efficiency for ships with transmission via gearbox is 0.95 [14]. The efficiency of the propeller in open water is calculated in the following section and results in 0.48.

Finally, the ratio between the effective power and the power delivered by the engine is obtained:

$$\frac{P_E}{P_B} = \eta_D \times \eta_M = \eta_H \times \eta_0 \times \eta_r \times \eta_M = 1.11 \times 0.48 \times 1.00 \times 0.95 = 0.50 \tag{5.11}$$

Therefore, the power delivered by each engine must be the effective power divided by the previous ratio, that is:

$$P_B = \frac{P_E}{0.50} = \frac{5247}{0.50} = 10423\ W \tag{5.12}$$

The Volvo Penta D1-20 inboard diesel engine is installed, with 13.8 kW of crankshaft power, which is similar to the engines installed in the vessels of the database.

5.3 Sizing of the propeller

For the sizing of the propeller, the first step is to determine its diameter. In other types of boats, this distance is determined by the needed clearances between the propeller, rudder and hull according to regulation. For sailing boats, this is not the case, and only the clearance between the propeller and the hull must be adequate to prevent cavitation and ensure smooth operation. The sizing then will be based on a visual estimation from other boats. It is estimated that the diameter varies from 30 to 40 cm between the boats. To perform a more thorough analysis, three different diameters are studied: 30, 35 and 40 cm.

Keller proposes a formula to determine the minimum expanded blade area ratio necessary to prevent cavitation [10]:

$$\frac{(1.3 + 0.3 \cdot Z) \cdot T}{(10,100 + 1,026 \cdot h_a) \cdot D_P^2} + K \tag{5.13}$$

Where Z is the number of blades of the propeller, T is the thrust calculated in the previous section, h_a is the height of the water column above the shaft line, and K is a constant depending on the number of propellers.

Having a look at the other boats, the number of blades varies between 2 and 3, so both cases will be studied to find the most optimal combination. The height of the water column above the shaft will be calculated as a function of the diameter as $0.35 + D \cdot 1.2\ m$, the sum of the draft at the approximate position of the propeller and its diameter, taking into account a clearance of 20% this measurement. The constant K is 0.2 as the vessel only has one propeller. The expanded blade area ratio for each combination then results as presented in Table 5.1.

D (cm)	30		35		40	
z	2	3	2	3	2	3
BAR	0.59	0.65	0.20	0.20	0.42	0.45

Table 5.1: Minimum Blade-Area ratio for each studied propeller according to Keller

To find the optimal RPM for the calculated diameters, the parabolas relating the dimensionless thrust coefficient and the advance ratio in the systematic series are represented. For this, the value of both terms as a function of n is calculated:

$$K_T = \frac{T}{\rho \cdot n^2 \cdot D_P^4} = \frac{1951}{1025 \cdot n^2 \cdot D_P^4} = \frac{1.90}{n^2 \cdot D_P^4} \tag{5.14}$$

$$J = \frac{V_A}{n \cdot D_P} = \frac{2.43}{n \cdot D_P} \tag{5.15}$$

To eliminate the dependence on angular velocity, the equation of the parabola is calculated as a function of the diameter:

$$\frac{K_T}{J^2} = \frac{1.90}{2.43^2 \cdot D_P^2} = \frac{0.32}{D_P^2} \rightarrow K_T = \left(0.32 \cdot D_P^2\right) \cdot J^2 \tag{5.16}$$

To represent the parabola, the value of K_T is determined for different values of J for each diameter.

Different Wageningen b-series propellers are used, selecting the most appropriate for each combination of diameter and number of blades. These b-series begin with a BAR of 0.3. Therefore, for the propellers with a 35 cm diameter, which have a minimum BAR of 0.2, the BAR is set to 0.3 for the analysis. For the others, the BAR is approximated to the nearest available value in the series, which increments in intervals of 0.05. The corresponding $K_T - J$ curves are plotted in each series, and the results are analysed.

In Appendix G, the aforementioned series are represented, with the parabola relating K_T and J drawn in red. Additionally, for each intersection of the Pitch/Diameter ratio lines with the parabola (blue lines), the propeller efficiency was found and a curve with all these points, coloured green, was drawn.

For each case, both the maximum efficiency of the propeller and the alignment of its angular velocity with the engine's are analysed. According to the supplier, three different gearboxes can be connected to the engine, thus, for each propeller, it will be ensured that the required angular speed can be achieved using one of these gearboxes.

From the studied propellers, only those with a diameter of 40 cm and the one with a diameter of diameter 35 cm and 3 blades require an angular speed that matches the generated by the engine through a gearbox. Among these, the propeller with a diameter of 40 cm and 3 blades is selected. This choice is based on the fact that, along the three, it has a higher efficiency in open water at lower angular speed, which translates into lower fuel consumption and allows the engine to have a higher operative range to increase its speed, and for example, avoid obstacles.

The previous study is entirely theoretical and in these types of boats, the propellers are not custom-made but selected from existing options. In the end, it is selected a Volvo Penta 3-blade folding propeller with a diameter of 41 cm and with a pitch-diameter very close to the one that allows the maximum propeller efficiency, within a 2% margin.

6 ANALYSIS OF THE SYSTEMS AND GA

The objective of this chapter is to dimension and place on board all equipment, systems and furniture. This division does not make up the majority of the ship's weight, but the sum of all of them, together with their position, contribute to changing the centre of gravity. The centre of gravity of all equipment on board must be on the centre line to avoid unwanted trimming and heeling. Another reason to analyse and arrange these elements is to make a distribution oriented to favour greater inertia in the three turning axes of the ship, within the realistic possible distributions on board. In this chapter, the systems related to the engine and water supply are dimensioned, along with all the essential systems for the vessel's proper operation. Next, a hotel load will be calculated by analysing the onboard energy-consuming elements, to seize the necessary batteries to dispose of onboard. Lastly, all these systems and equipment will be organised so the general arrangement (GA) is designed and the structure, one of the parts that weights the most, can be planned and sized accordingly.

6.1 Water system

The water system in the design boat is a critical component that ensures the crew remains hydrated, healthy, and capable of performing at their best throughout the race. Given the constraints of space, weight, and efficiency, the design and management of the water system on a racing sailboat are meticulously planned. It normally consists of tanks for water storage, filters that remove particulates and contaminants from the water supply, and a distribution system consisting of pipes, pumps, and fixtures.

Calculating the water tank capacity onboard involves determining the total amount of water needed to sustain the crew for the duration of their journey, since these boats normally do not have a desalination system nor means to generate drinking water in the middle of the sea. Racing yachts, like the one being designed in this project, often have limited space and weight considerations, so the water tank capacity is typically optimized to balance the crew's essential water needs with the boat's performance requirements.

To calculate the capacity of the tanks, it is necessary to obtain the autonomy in time of the boat. Autonomy will be studied so that the yacht can sail a complete regatta as mentioned in Section 2.3, so it is set to 3 days.

According to Gerr [5], surveys seem to agree on the usage of 7.2 litres per person per day for personal use. Since the crew is composed of 4 persons and the regattas should not last more than 3 days, a water tank capacity of at least 86.4 litres is needed. This aligns with the water capacity of the database's boats, ranging between 80 and 100 l.

Waste water treatment is regulated by MARPOL [2]. Grey water (the relatively clean waste water from the sink and kitchen appliances) can only be discharged directly into the sea without treatment when the vessel is sailing at a speed higher than 4 knots and is farther than 12 miles form the coast. In any other case, including when it is in port, the waste water must be stored in a grey water tank for subsequent discharge to land or sea. Since the vessel does not have a predefined route or speed, it is sensible to install a grey water tank with the same capacity as the fresh water one, so the waste water can be stored if it cannot be discharged directly into the sea during the whole regatta. These tanks have to be strategically placed to maintain the boat's balance and performance. It would be ideal to place them low in the hull to help lower the centre of gravity, and in a centerline position so the transfer of water form one another does not generate any unwanted heel. Additionally, they both should be accessible for refilling or pumping-out. In reality, the space is very limited, so even if all this will be taken into account their final disposition is constricted by the location of the furniture, structure and all other systems. A dedicated grey water discharge system is designed, so when the regulation allows it the water can be set out, allowing the vessel to reduce weight to maximize speed. The flow rate of the grey water pump to be sucked from the tank and discharged to port is regulated by MARPOl.

Additionally, a toilet is installed and connected to a small black water tank. Black waste water must always be treated before discharged. Given the yacht's autonomy of only three days, a tank is installed to hold the waste for the entire duration of the regatta, eliminating the need for a discharge system. For typical racing yachts, it is advisable to estimate black water generation at 2-3 litres per person per day. To ensure sufficient capacity without a discharge system, a conservative estimate of 3 litres per person per day is used for tank sizing.

The location and specification of all the elements that compose the system are presented in the Systems plan drawing.

6.2 Fuel system

The fuel system in a pure sailing yacht, while often less important than in powerboats, plays a crucial role in ensuring the engine operates efficiently and reliably in case of emergency. It normally consists of tanks for fuel storage, filters that provide finer filtration to protect the engine from contaminants, and a distribution system consisting of fuel lines, pumps and fixtures.

To calculate the fuel tank capacity, the engine's fuel consumption rate, the total distance to be covered, and the speed of the vessel need to be considered. The same hypothetical emergency case used to size the engine is used to determine the necessary fuel: an essential part of the rig is broken and it is necessary to go back to port safely. In order to exaggerate the emergency condition, it is going to be assumed that it occurs in the middle of a regatta, as far as possible from port. From the endurance established for the vessel, this would be at 350 nautical miles from the staring/ending port. At the designed speed of 7 knots, it would take approximately 50 hours. Consulting the fuel consumption chart of the engine in its technical sheet, it is found that at the design speed, the fuel consumption is approximately 2 litre per hour. Then, the total fuel volume needed would be 100 litres. The tank should be cushioned and correctly fixed to the structure, mainly made of polyethylene. Its optimum location would be over the boat's centre of buoyancy so there is no change in trim with varying tank levels and the weight is kept far off the ends to reduce pitching. Again, its final location is limited by the location of the furniture, structure and all other systems.

The standard ISO-10088 specifies requirements for permanently installed fuel systems and fixed fuel tanks in small crafts [27], specifying the size of the different hoses. By following it, the fuel system is designed. The location and specification of all the elements that compose the system are presented in the Systems plan drawing.

6.3 Bilge system

The bilge system is a critical component designed to manage and remove unwanted water from the boat's bilge areas (lowest parts of the hull). Efficient bilge systems are essential for maintaining buoyancy, stability, and overall performance, especially in the demanding conditions of a racing environment. Normally, the water accumulates in the bilge due to various reasons: leakage through the hull or deck fittings, condensation, water entering the boat during sailing, or rainwater that seeps in through hatches or other openings. The bilge system consists of the bilge pump, and discharge hoses that direct water from the bilge pumps overboard through through-hull fittings. It also has non-return valves which prevent seawater from flowing back into the bilge through the discharge hoses.

The standard ISO-15083 specifies requirements for bilge pumping systems for small crafts [23]. Following it, two pumps must be installed onboard: a primary one which is permanently attached to the boat structure and its activation accessible from the main steering position; and a secondary one which should be capable of removing water from all bilge compartments. These pumps can be manual, mechanical or electric, and their combined capacity should be 900 l/h (15 l/min). A combination of manual and electric pumps is installed: the manual pump (secondary) ensures a backup in case of electrical failure, while the electric one (primary) offers efficient and quick water removal abilities.

The location and specification of all the elements that compose the system are presented in the Systems plan drawing.

6.4 Steering system

The rudder system in a racing vessel is a crucial component for steering and manoeuvrability, directly impacting the vessel's performance and safety. An efficient rudder system ensures precise control and responsiveness, essential for competitive sailing. The rudder system consists of the rudder blade (already selected in Chapter 4), the rudder stock which connects the blade to the steering mechanism, the tiller used by the helmsman to control the rudder, and the steering mechanism that transmits the movement of the tiller to the rudder stock.

The rudder stock is critical for the strength and reliability of the rudder system since it must be robust enough to withstand the forces exerted by the water while the boat is in motion. The standard ISO 12215-8 [24] specifies the requirements for the design, construction, and testing of rudders and their supporting structures, and will be used to size the rudder stock. This calculation is based on the bending moment at the hull bearing, the design torque of the rudder, and the material properties. The forces acting on the rudder are determined based on the length, displacement, and class of the vessel, and the rudder area. The supplier provides rudder stocks made of aluminium and stainless steel, and a stock made of Stainless Steel AISI 630 is chosen for its superior mechanical properties, including higher tensile strength, hardness, and excellent wear resistance. Including this material's properties, the minimum diameter stock according to the standard is 37 mm. A Stainless Steel AISI 630 rudder stock of 38 mm is installed to be a bit conservative. The diagram of the system as well as the specification of all its parts can be seen in the Systems plan drawing.

6.5 Cooling system

The cooling system ensures that the engine operates within its specified temperature range, enhancing reliability and efficiency. Typically, two types of cooling systems are used: seawater cooling and freshwater cooling. The seawater system takes water from the ocean, circulates it through the engine's cooling pipes and then discharges it overboard. The fresh water (or closed-loop) one uses this type of water to cool down the engine, passing it through a heat exchanger later to be recirculated. A combination of both systems also exists, where the fresh water directly cools the engine, but this water is cooled down by a circulation of seawater in a heater exchanger.

The engine selected to be installed onboard already has the cooling system built in. It uses a hybrid cooling system, employing both fresh and seawater. The fresh water system utilizes a mixture of water with antifreeze, which exchanges its temperature with seawater pumped into the system. After exiting the heat exchanger, the seawater passes to the exhaust system. The through-hull fitting which allows the seawater to enter the system is integrated with the saildrive, facilitating the installation of the engine.

6.6 Exhaust system

The exhaust system ensures the safe and efficient operation of the engine by directing exhaust gases away from the vessel's interior. The exhaust system consists of the manifold that collects exhaust gases from the engine cylinders and directs them into the pipe, the exhaust pipe which carries exhaust gases to the through-hull fitting, a muffler to cool and silence the exhaust gases and that prevents water from backflowing into the engine, and the through-hull fitting that allows exhaust gases to exit the vessel, normally situated in the transom.

The selected engine has installed the exhaust manifold and exhaust elbow, in which the gases are cooled by the included cooling systems. The manifold is fresh-water cooled with the same system as the engine to reduce the temperature of the exhaust gases, which are mixed with the seawater used in the cooling system. The rest of the system is designed and presented in the Systems plan drawing.

6.7 Electrical system

The electrical system ensures the operation of various onboard systems, including navigation, communication, lighting, and safety equipment. Due to the demanding nature of racing, the electrical system must be robust, reliable, and efficient. The system consists of batteries, a charging system, distribution panels and wiring. The sizing of the batteries is the most relevant part of this system as it is the limiting factor for the operation of the equipment that requires electricity since the boat will not have any other means to carry or recharge electricity during a regatta. At the same time, it is the part which takes the most space and weight. Due to all this, the current section will be focused on determining which equipment requires electricity on board and to size the batteries required for their correct operation.

Pumps of the systems

The vessel is equipped with various types of pumps, each serving distinct yet crucial functions to facilitate smooth sailing operations, and all of them, except the manual bilge pump, require electricity to function.

In the sanitation and freshwater system, the pumps that distribute the water from the fresh water tank, as well as the ones that impulse the water to the grey or black water tanks need to be taken into account. Similar is the case of the fuel system, where the pumps needed to transfer and purify the diesel require electricity to function. However, fuel pumps mounted on the engine will not be considered part of the hotel load. Additionally, the electrical bilge pump installed on board as per regulation, as explained before, requires electricity to operate.

The pumps that are part of the cooling system are integrated with the engine and therefore do not need to be assessed in this part either.

Light Services

Lighting services are critical for ensuring safety, operational efficiency, and compliance with maritime regulations, especially during nighttime sailing and low visibility conditions like fog. The interior and deck lights are required to ensure visibility and safety in living spaces or outside during night time operations. Additionally, navigation lights are required by ISO 16180 for safe operation during low visibility conditions [26]: two all-around lights in a vertical line, two separate sidelights and stern lights. They are essential for indicating the vessel's position and direction to other boats.

Navigation and communication equipment

These equipment are essential for ensuring competitive performance and safety during races, having tools to optimize navigation, communication, and tactical decision-making on the water. They are designed to provide real-time data, continuously consuming electrical energy.

The design vessel will be provided with all the advanced technological tools the boats from the database have:

- Autopilot. Automates steering, allowing the crew to focus on sail handling and navigation
- GPS Chartplotter. Provides real-time navigation data and electronic charts for precise navigation
- VHF Radio. Essential for communication with other vessels and shore stations
- Compas. Provides real-time information about the vessel's magnetic heading, crucial for maintaining course direction and serving as a backup in case of electronic navigation system failures
- AIS (Automatic Identification System). Transmits and receives vessel identification and position data to enhance situational awareness and collision avoidance

In addition, the screens and graphic displays needed to display this information are also essential and consume electricity continuously. Another essential instrument is a wind sensor positioned aft of the vessel, which measures the speed and direction of the wind, crucial for sail trimming and navigation. This instrument is very light and barely consumes any power, so it is not taken into account in the analysis

6.7.1 Hotel load

The *Hotel load* refers to the total electrical power demand of onboard systems. Calculating and managing this load is crucial to ensure the vessel's electrical system can reliably supply power, this is the capacity of the batteries is adequate.

The whole electrical power required for two different conditions is computed. The number of units of each machine or element that draws electrical energy is calculated, together with its unitary power. Analyzing the navigation and emergency scenarios, a coefficient will be computed for every machine: the K_{sr} factor, which is the percentage at which the machine is running with respect to the total power. The necessary power is given by the multiplication between the total power of each component and the K_{sr} factor.

By adding up all the electrical utility power and considering a 15% margin, the total electrical power for every scenario is calculated. The most severe scenario between navigation and emergency will be used to size the service battery. The complete electrical balance is presented in 6.1.

				Navigation		Emergency	
Equipment	N	Unitary power [W]	Total power [W]	ksr	P[W]	ksr	P[W]
Sanitary water services							
Fresh water pump	1	1.5	1.5	0.2	0.3	0	0
Grey water pump	1	1.5	1.5	0.2	0.3	0	0
Sewage pump	1	1.5	1.5	0.1	0.15	0	0
Lighting services							
Interior lighting	10	0.5	5	0.5	2.5	0.5	2.5
Navigation lights	4	2.5	10	0.5	5	0.8	8
Navigation and communications equipment							
Autopilot	1	0.6	0.6	0.2	0.12	0.2	0.12
Electrical actuator	1	3.6	3.6	0.8	2.88	0.8	2.88
Compas	1	0.4	0.4	1	0.4	1	0.4
Graphic Display	1	1.9	1.9	0.5	0.95	0	0
AIS	1	1.2	1.2	0.5	0.6	0	0
GPS Chartplotter	1	2	2	0.8	1.6	0.8	1.6
VHF	1	13	13	0.2	2.6	0.2	2.6
Others							
Bilge pump	1	1.5	1.5	0.2	0.3	0.2	0.3
				Total [W]	17.7	Total [W]	18.4

Table 6.1: Hotel load

The most severe condition is the emergency scenario, in which the resulting power is multiplied by the 72 hours of endurance of the vessel and divided by the voltage of the circuit (12 V) to obtain the required capacity of the battery, with a 15% margin as mentioned before. Its location and details can be seen in the Systems plan drawing.

It seems relevant to note that another battery is necessary to start the engine, which provides electrical energy to initiate the engine's combustion process, but it is already included within the selected engine.

6.8 General arrangement

As a short-handed (4-person) ocean racing vessel, the space distribution is optimised for sailing while having a functional interior where the crew can rest and take shelter from harsh weather conditions.

The interior is accessed from the cockpit through a top-opening hatch, which prevents water ingress, and via stairs, located mid-aft. The interior height allows for standing, which is not taken for granted in such racing boats. The sleeping spaces are distributed throughout the hull: two beds in the fore, benches in the dining area, and two beds in separate cabins in the aft. The number of resting spaces triples the necessary capacity, as only two crew members are expected to be sleeping simultaneously. This ensures that when the vessel is heeled, trimmed, or in very bad weather conditions, the crew can find a stable place to rest. The fore beds have storage space underneath and can be elevated for additional storage so even the mainsail folded fits along the interior. In the dining area, a table with elevating wings provides a place to eat while seated on the benches.

The kitchen is located in the port midsection, equipped with a sink, stove, and cabinets below the counter and on the wall. In front are a toilet and a navigation station. The toilet, positioned towards the aft, features folding doors for privacy and the WC is positioned on a platform. The navigation station doubles as a small office or work area, providing a strategic position for monitoring navigation and communication systems, which are installed on the surrounding walls. It also has a built-in chair and ample storage space.

The central cockpit, protected by the coach roof sides, offers a sheltered location. All control equipment is placed beside the entrance in this protected area. The 'one step' cockpit design minimizes hazards when accessing the deck. Additionally, the mainsail boom is placed high above the deck to minimise the risk of head injury. To provide support when the vessel is heeled, a raised area along the cockpit's centerline allows for secure footing. Safety equipment, including the guard-rails to prevent man-overboard incidents, surround the deck. Lastly, multiple storage lockers on the aft deck, foredeck and under the cockpit seats provide ample stowage space. The coachroof has windows at both sides and in the ceiling, allowing natural light to illuminate the interior. The starboard window is interrupted in the toilet area to ensure full privacy.

The final disposition can be found in the General Arrangement and General Arrangement profile and transverse sections drawings.

7 STRUCTURE: DESIGN AND SCANTLING

The structure is, except for the keel, the part that has the most contribution to the overall weight and position of the centre of gravity, essential for a correct estimation of the VPP as stated previously.

In order to determine the dimensions, design pressures and scantling the structure of the vessel, the ISO-12215 rule will be followed. Within this, mainly Part 5 will be used (Design pressures for monohulls, design stresses, scantling determination). The procedure to be pursued to determine the scantling is listed in Table 2 of this part of the standard.

Structural design and previous considerations

The objective of following this standard is to achieve a structural resistance that ensures its integrity. To follow the regulation, the structural arrangement of the vessel must be first designed. To do so, the structure of the database boats, also manufactured in FRP, is studied. It is observed that several bulkheads or frames support the structure transversely, aligned with the general arrangement disposition. Longitudinally, the number of girders varies from one to another, ranging between 3 to 4 in the hull. The material used in the plates (both hull and deck) is sandwich.

First, 6 transversal divisions are established, five of them which are bulkheads: the three farther aft provide more strength in the engine and systems area, the fore one acts as a collision bulkhead, and the one aft of it provides strength and separation between zones. The frame is located in the midships area, coinciding with the line of subdivision between the dining room and the kitchen/toilet area.

Regarding the girders, the hull has two running longitudinally below the chain plate (which will act as a natural stiffener): one in line with the supports of the engine and the other in between this one and the hard chine. On the deck, including the cockpit area, a longitudinal is placed along the centerline.

The 3D created in Rhinoceros with the hull, coachroof and cockpit, is cut according to the subdivisions just described, conforming the panels of the vessel. The girders are also created as lines and cut in their intersection with frames or bulkheads. All these parts are then imported into the software *HullScat*. In this program, the different laminates and reinforcements for each part are designed, and their compliance with the ISO rule is checked. The final report given by the software can be found in Appendix H.

Design Pressures

To determine the design pressure of any element of the structure, different formulas are used depending on the area in which it is located, which also depends on various adjustment factors. The vessel is divided into different areas in the rule: bottom, side, deck and closed cockpit. Depending on the area at which an element is located, the design pressure will be determined by different forces and pressures. In cases where the same element is in two zones, “The method of the averaged constant pressure”, as explained in section A.7. This method “determines a constant pressure throughout the area, calculated as an average weighted between pressures”. The pressure of the element shall be calculated independently as if it was completely in one area and in the other, and both will be averaged according to the percentage of element that is in each zone.

Hard chine

Before progressing any longer, the possibility of the hard chine acting as a natural stiffener needs to be verified. Section 5 of Annex A “Case where round bilged and hard chined panels act as "natural" stiffeners” is related to this, and stipulates that the chine is considered as acting like a longitudinal when the spacing of the nearby elements is multiplied by a correction factor that depends on the chine average angle. In this case, the correction factor is 1.06.

Materials and lamination considerations

The vessel will be constructed using fibreglass, as it is standard for boats of this type. Each part will be laminated with various layers of material and infused at the end to ensure optimal resin distribution, which enhances the structural integrity and overall strength of the laminate while minimizing excess weight. It also reduces the risk of air pockets and other defects that can compromise the integrity of the material, ensuring a higher quality and more reliable hull, essential for its intended use.

Four different fibre orientations will be used in the lamination to provide strength in different directions and to withstand various loads:

- Chopped Strand Mat (CSM). The fibres are randomly oriented, offering no specific directional support but aiding in adhesion between different layers and paint applications. Its main drawbacks are its high resin content and weight.
- Unidirectional (UD). All fibres are aligned in one direction, providing significant strength along that axis. This type of fibre distribution is mainly used in the crowns of stiffeners, which are subject to axial loads.
- Biaxial. These act like unidirectional layers positioned 90 degrees offset from each other, providing strength in two perpendicular directions.
- Double Bias (DB). The fibres are oriented at +/- 45 degrees from the reference direction, offering shear strength.

The core of the sandwich laminates will be made of cross-linked PVC, which facilitates resin flow between the fibres during infusion.

All panels with a surface facing the exterior will include a CSM in the outer layer to improve impermeability, appearance and paint adhesion. Bulkheads will be symmetrical, to ensure uniform strength and stiffness on both sides, providing balanced structural support and preventing warping or twisting under load. They will include CSM on both exterior layers since they both will be exposed in the interior accommodation area.

According to ISO 12215, two methods can be used for structural assessment: simplified and enhanced. The simplified method is less detailed and generally sufficient for panels due to their predictable and uniform load-carrying behaviour. In contrast, the enhanced method is more detailed and requires precise load calculations and accurate material properties. This method is necessary for stiffeners due to their critical role in maintaining structural integrity, allowing for a more detailed evaluation of stress and strain, and accounting for interactions with other structural elements and localised effects.

Forces distribution

The loads encountered by the vessel are transmitted through the hull panels to the structural elements. The distribution of forces among these elements depends on their flexural rigidity (EI): the structural elements with higher EI will support and constrain those with lower EI. For stiffeners and frames, their EI can be assessed by examining their size and lamination. However, determining the EI of bulkheads is not as straightforward. Therefore, it is generally assumed that bulkheads support the stiffeners.

7.1 Scantling of the plating and bulkheads

The panels are assessed with the simplified method. The step before obtaining the laminate of the panels is to determine the design pressure for each of them. To do this, different pressures are used depending on the area in which the panel is located. The pressure of a panel is studied at its centre.

To calculate design pressures, the first step is to separate the structure into panels, done in the 3D model in Rhino. Each panel is located between two longitudinal and two transverse reinforcements. This panel shall be geometrically characterized by s (spacing between stiffeners) and l (span). In addition, the curvature factor f (curvature of a curved panel on side s) should be considered.

After obtaining the design pressure according to what has been explained before, a reduction factor is calculated. It depends on the ratio between l and s and the curvature factor. Next, the analysis is started with an initial composition of the sandwich laminates, from which its mechanical and geometric properties are obtained.

The required core shear and section modulus of both skins are obtained. Then, it is checked that these are lower than the ones offered by the lamination. The process is iterative, changing the laminate so it complies with the core shear and section modulus.

The opening in the bottom for the rudder stock to pass will be surrounded by single-skin laminate. An initial composition will be set and its weight per unit area of reinforcement will be compared with the required one. This process will again be iterated until a solution is found.

In the areas of deck openings (for windows, tiller lever and mast) and stress concentration (below the winches) the sandwich laminate is reinforced by adding DB and Biaxial layers to outer and inner skins.

During the iterative process of calculating the panels' lamination, it is encountered that one specific panel in the fore part is very big and has a relatively high design pressure compared to the others. This is solved by inclining the bottom stiffener so the size of this panel is reduced, without increasing the design pressure of the one beside it.

The final composition and distribution of the laminates are presented in the Structural layout and Structure: Details F-I & Lamination table drawings.

7.2 Scantling of the stiffeners and frame

The reinforcements are assessed with the enhanced method. The step before obtaining the size and lamination of the stiffeners is to determine the design pressure for each of them. To do this, different pressures are used depending on the area in which the reinforcement is located. The pressure of a stiffener is studied at its centre.

To calculate the design pressures, the first step is to separate the reinforcements at their intersections with others or bulkheads, done in the 3D model in Rhino. The stiffeners are geometrically characterized by s (spacing) and l (span). In addition, the curvature factor f (curvature of the stiffener) should be considered.

After obtaining the design pressure according to what has been explained before, the collaborative width is obtained, which depends on the relation between l and s. Then, the conditions of fixation of the stiffener are taken into account with a coefficient (ϵ), based on the force distribution explained before. Next, the analysis is started with an initial sizing of the stiffener and design of the laminate, from which its mechanical and geometrical properties are obtained.

The bending moment is obtained, which depends on the design pressure, s, l, the distance from the stiffener neutral axis to the flange, the inertia of the stiffener and affected by the coefficient ϵ. The shear stress is calculated too, which depends on the design pressure, s, l and the total web cross-sectional area. Then, the required web height-thickness and flange width-thickness are obtained. Finally, it is checked that the required stresses and geometrical properties are lower that the breaking strengths reduced by a safety factor that depends on the material, the design category, and the geometry of the designed reinforcement. Once again, the process is iterative, changing the size and lamination of the stiffener so it complies with all verifications of bending and shear stress, and geometrical properties.

The core of the stiffeners is made of PVC of 60 kg/m^3, which is not taken into account to assess their mechanical properties.

The final size, composition and distribution of the reinforcements are presented in the Structural layout and Structure: Details A-E drawings.

7.3 Keel structure

The keel is supported and attached to the hull with bolts. At the same time, these bolts distribute the pressure to their backing plates and structural floors. The keel is made by casting, and since it is made of lead, the material is too soft to drill and tap the keel bolts into the top of the keel, so a stainless steel keel bolt armature is securely clamped into the mould before casting (stainless steel floats in melted lead, so they do not mix). This way the keel can be securely attached to the hull.

Part 9 of ISO 12215 focuses specifically on the structural requirements for small craft keels and keel attachments. It provides guidelines for the design, construction, and testing of keel structures to ensure their strength, durability, and safety. The floors, bolts and backing plates are dimensioned using this standard by creating an Excel spreadsheet.

Keel floors are transverse structural elements within the hull that support the keel and distribute the loads it generates throughout the hull structure. They are critical for maintaining the integrity and performance of the keel-hull connection. In this vessel, they are placed in between the central girders. The structure consists of four floors at equal intervals along the length of the keel, without positioning one at either of the extremes.

The analysis starts with an initial sizing of the floor and design of the laminate, from which its mechanical and geometric properties are obtained. To define the design stress of each floor, three different cases are analysed: 90° knockdown case (heeled at 90°), which is usually the most severe transverse bending load; vertical impact load in relation to the events of dry-docking or purely vertical and upwards grounding; and longitudinal impact exerted at the bottom of the leading edge of the keel. The forces are distributed along the keel and the shear force and bending moment are computed, considering if the floors are simply supported or fully-fixed to the girder, using the same method as for the stiffeners previously. Then, for each floor, the most severe shear stress and bending moment condition are selected from the three cases and it is checked that these stresses are lower than the shear-breaking and the breaking bending strengths of the stiffener reduced by a safety factor that depends on the material and the design category. Once again, the process is iterative, changing the size and lamination of the floors so they comply with both verifications of the bending and shear stresses.

The standard also outlines the specifications for keel bolts, including their material, size, and installation to ensure secure attachment and load distribution. In order to asses their size, their number and location have to be decided first. Eleven bolts are placed on top of the floors' lapping. The minimum bolt diameter is then obtained, based on their material and location, for the first and last loadcase from the mentioned before. The most demanding one is then selected to size the bolts. All the bolts are assumed to be of the same size to ease the calculations. It is also worth saying that by using the formulas, the diameter of the neck is obtained, so Table D.1 of the norm was used to determine the corresponding standard normal diameter (with a bigger neck than the calculated). Regarding the material, stainless steel 316 was selected for the bolts since it offers excellent corrosion resistance and has good mechanical properties.

Lastly, the backing plate dimensions, hull thickness and details of connection to the structure are also assessed by the standard. The backing plates are plates situated on top of the hull bottom, that provide a secure and stable surface for the nuts that tighten onto the keel bolts, distributing the load over a larger area to prevent damage to the hull. In this part the size of the area with raised bottom pressure with respect to the ballast keel, which should be constructed in single-skin laminate is detailed. Then, following Table D.2 of the standard, the backing plates dimensions and hull thickness of this area are determined.

The final keel structure, including the details of all the elements that form it, is presented in the Structure: Details A-E drawing.

7.4 Mast structure

The mast is a critical component of the rigging system, supporting the sails and withstanding various forces from the wind and the motion of the vessel. Moreover, it is a very slender component, which increases the risk of buckling under axial loads, so the assessment of its support is essential for the correct load distribution. Masts can be classified into two main types based on their installation: keel-stepped and deck-stepped. The keel-stepped masts extend from the deck, through the hull, and are set at the bottom of the boat. On the contrary, the deck-stepped masts are set on the deck and do not extend down to the keel, so the support comes from the deck and structures below it. It is decided to position the mast keel-stepped, since this way, it is easier to control its bending and the reef and position of the sail.

Part 10 of ISO 12215 focuses on the rig loads and the structures needed to support them. This standard addresses the structure calculation for a keel-stepped mast, thus this will be followed to size it. The calculation will be carried out by creating an Excel spreadsheet.

In this type of configuration, the mast is supported by a transversal floor which at the same time is supported by longitudinal girders. The first thing to do is design this construction: the floor will be supported by the girders in the middle of the bottom area, below the hard chine, to avoid increasing the loads of the keel girders. The analysis starts with an initial sizing of the floor and design of the laminate, from which its mechanical and geometric properties are obtained. Next, the design compression force on it is calculated, which depends on the design righting moment (note is based on the same principles as the rig calculation), the geometry of the floor, and a dynamic overloading factor which depends on the length of the vessel. Later, the short span design bending moment and shear stress in the mast step are obtained. Finally, it is checked that these stresses are lower than the shear-breaking and the breaking bending strengths of the stiffener are reduced by a safety factor that depends on the material and the design category. Once again, the process is iterative, changing the size and lamination of the floor so it complies with both verifications of the bending and shear stress. The final floor dimension and details are presented in the Structure: Details F-I & Lamination table drawing.

8 WEIGHT ESTIMATION

To obtain a more accurate VPP all the weights that compose the vessel must be rigorously studied. First, the lightweight of the vessel will be obtained. Subsequently, the other weights will be considered to determine the displacement and position of the centre of gravity in different conditions.

8.1 Lightweight

The lightweight includes all the groups that make up the boat when it is delivered. It is finished, but it is empty of consumables and crew. First, the weight and position of the centre of gravity of each group are calculated.

Structure

Hullscant gives the weight per square meter or meter of each laminate and reinforcements. By calculating the area and length of each structure element, the total weight can be determined. As mentioned before, the core of the stiffener was not assessed before, so it will be added to the weight of each stiffener based on its dimensions.

Additionally, the weight of the gelcoat applied to the material and the accommodation floor is computed.

The detailed weight estimation is presented in Appendix I.1.

Engine and systems

This group includes the engine and battery, the heaviest elements by far from the studied in the System's section. The detailed weight estimation is presented in Appendix I.2.

Furniture and accommodation

This group includes all the furniture of the accommodation. The weight of the tables, cabinets and beds are computed by taking into consideration their size. The detailed weight estimation is presented in Appendix I.3.

Appendices

In this group not only the heaviest component of the vessel, the keel, is assessed, but also the steering and rig system. The detailed weight estimation is presented in Appendix I.4.

Other

This includes the equipment that is very light or has yet to be decided, like the navigation and communication equipment, the safety equipment, illumination, small systems' components, shrouds, stays, spreaders, and winches. Due to the estimated location of all these components, it is set at the deck's height and towards the aft.

The total weight of each group is summarised in Table 8.1, obtaining the final values of the lightweight.

	Weight [kg]	L_{CG} [m]	T_{CG}[m]	V_{CG} [m]
Structure	617.65	4.87	0.00	0.93
Appendices	1243.29	4.32	0.00	-0.53
Accommodation	220.47	4.50	0.06	0.77
Stystems	165.20	2.52	0.00	0.45
Extra	150.00	4.30	0.00	1.30
Total lightweight	2396.62	4.35	0.01	0.15

Table 8.1: Lightweight estimation

8.2 Deadweight

The deadweight is calculated by the sum of equipment not fixed to the vessel, including consumables and crew. In this case, this group is composed of fuel, fresh water and crew. Several conditions are analysed where the crew is in different points of the vessel to later analyse their impact in the VPP. The conditions are: all the crew at one side of the cockpit, 2 of them inside the boat, and one in the fore deck and another in the mast area. In all the cases the fuel and water tanks are full, to try getting a better understanding of how the boat will perform when fully loaded, ensuring that the VPP results are applicable to real-world sailing conditions. The deadweight will be directly obtained in the final calculation, since it is not considered relevant to obtain its value separately.

8.3 Final calculations

This section compiles all the weights for each condition.

All crew at one side of the cockpit

	Weight [kg]	L_{CG} [m]	T_{CG}[m]	V_{CG} [m]
Lightweight	2396.62	4.35	0.01	0.15
Fuel	93.50	1.09	0.00	0.44
Water	100.00	5.27	0.94	0.54
Crew	300.00	1.50	1.44	1.85
Total (Δ)	2890.12	3.98	0.19	0.35

Table 8.2: Total displacement estimation for the condition of all crew at one side of the cockpit

Two crew inside

	Weight [kg]	L_{CG} [m]	T_{CG}[m]	V_{CG} [m]
Lightweight	2396.62	4.35	0.01	0.15
Fuel	93.50	1.09	0.00	0.44
Water	100.00	5.27	0.94	0.54
Crew	300.00	3.60	0.72	1.55
Total (Δ)	2890.12	4.20	0.11	0.36

Table 8.3: Total displacement estimation for the condition of two crew inside

One crew in the fore deck and another in the mast area

	Weight [kg]	L_{CG} [m]	T_{CG}[m]	V_{CG} [m]
Lightweight	2396.62	4.35	0.01	0.15
Fuel	93.50	1.09	0.00	0.44
Water	100.00	5.27	0.94	0.54
Crew	300.00	4.05	0.72	2.05
Total (Δ)	2890.12	4.25	0.11	0.41

Table 8.4: Total displacement estimation for the condition of one crew in the fore deck and another in the mast area

9 VPP COMPARISION

The VPP is obtained for the combination of the loading conditions described before. This VPP is compared with the previous one and with the ones from the database as presented in Appendix F.2. It can be seen how the design yacht now is closer to the values of similar boats. The greatest difference is at a 12 kn of wind speed, with a significant reduction of boat speed in this condition. At 20 kn, the boat speed has also decreased while at 6 kn it has decreased at lower wind angles and increased at higher values. Comparing the results with preliminary VPP, the changes are in the range of 4%, with this more accurate VPP enlightening higher speeds at higher wind angles for lower wind speeds, but occurring the opposite at higher speeds.

Concerning other parameters, they are generally aligned with the change of boat speed: for example, the heel angle has increased at lower wind angles and increased at lower wind angles for low speed, and the opposite has happened at higher wind speeds.

The VPP for each separate condition is also obtained and presented in Figure 9.1

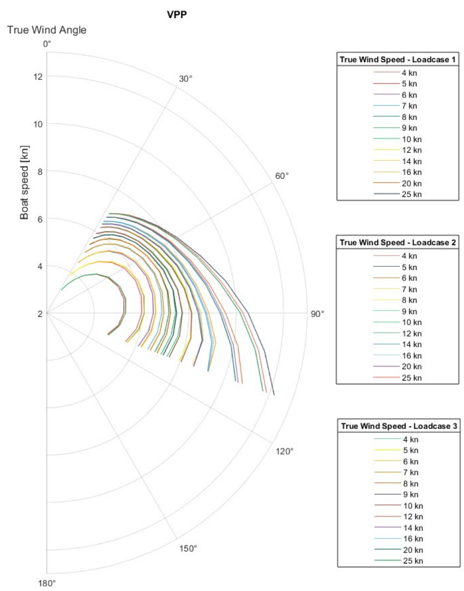

Figure 9.1: Comparison between the VPPs of the three loadcases represented in a polar plot

This comparison shows that the loadcases 2 and 3 achieve higher boat speeds at lower wind speeds and higher angles compared to the first loadcase. The third loadcase has higher boat speeds at high wind speeds. For the first scenario, concentrating the weight on one side increases the heeling moment, which can lead to increased heel. The boat speed might be lower because this excessive heel can lead to reduced hydrodynamic efficiency, increased leeway, and a decrease in the effective sail area presented to the wind. In the second case, the crew distributes the weight more evenly across the boat, which can improve its trim and reduce excessive heel. It can achieve higher speeds at lower wind speeds and higher angles of attack because it maintains better trim and a more efficient sail shape, leading to increased boat speed. The third case is an accentuation of the previous one since placing some crew forward helps keep the bow down, which can help to maintain a better hull form in the water.

10 OFFSHORE RACING CONGRESS RATING

The Offshore Racing Congress (ORC) is the standardized rating system that is decided to be used in this design as stated before. Their main objective is for boats with different sizes, designs, and capabilities to compete on an even playing field. This is achieved by assigning each boat a "handicap" which is translated in a time correction, thus the order in which vessels cross the finish line can differ from their final ranking. This severely affects the final classification of a vessel, with performance not being the sole determining factor, so to ensure a competitive design the rating needs to be considered carefully.

The All Purpose Handicap (APH) is used by the ORC to reflect the yacht's overall performance potential in various wind conditions and course types. It is calculated by considering several factors, including the vessel design's age, hull, rigging, sails and displacement. With this data, the ORC predicts the yacht's performance in various sailing conditions, and the handicap rating is obtained. The APH is used to adjust the yacht's elapsed time during a regatta to obtain the corrected time so that yachts are ranked based on their performance relative to their handicap. The corrected times determine the final standings. A yacht with a better performance relative to its APH will have a better-corrected time and thus a higher ranking.

Although the exact calculation of the APH is not openly described by the ORC, their Rating System [18] provides some general allowances and penalties that can serve as a guide. Additionally, the APH of all the boats under the ORC is published, along with their characteristics, enabling comparisons.

Twelve boats from the database already constructed and within the ORC rating are analysed. The results align with the general guidelines given in the Rating system: the combination of Sail Area-Volume ratio, Sail Area-Wetted Surface ratio, and Length-Volume ratio has a significant influence on the handicap. Vessels, even those of the same class, with a higher combination of these ratios tend to have a higher handicap and vice versa. A high APH translates into less time correction.

For the design boat, the combination of these ratios is higher than the studied boats, which would tend to a lower APH and thus more correcting time. This could explain why the sails and appendices of the database boats have not been more exploited: even if the VPP comparison shows they perform worse in the upwind condition, the rating is beneficial for them with a lower time correction.

11 STABILITY ANALYSIS

Finally, it is checked if the designed boat complies with the stability requirements since this could also be why the VPP differs from the database boats. The ISO 12217 [28] is used since it is the standard that specifies the stability and buoyancy requirements to ensure safety and performance under various conditions. Part 2 of this is the one indicated for sailing vessels with a length greater than 6 meters. By applying this standard it will be also verified if the boat meets the requirements of the design category that has been chosen, A.

Following the standard, different options define the tests to be applied according to the characteristics of the boat. Due to the design category, only option 1 can be followed, which requires the following tests (Table 2 of the Standard):

- Downflooding-height test
- Downflooding angle
- Minimum righting energy
- Angle of vanishing stability
- Stability Index

The detection and removal of water is also required, but no test needs to be performed since the vessel already complies with ISO 15083 regarding the bilge suction points and ISO 11812 regarding the drainage of the cockpit.

11.1 Loading conditions

According to the standard, three loading conditions should be studied along the different tests:

- Maximum load. The crew (considering 75 kg per person) is positioned in the cockpit area, and all the tanks are filled.
- Minimum operation. The boat is in lightweight condition with the addition of a mass to represent the crew of 150 kg (based on the vessel's length) positioned in the centerline of the cockpit
- Loaded arrival. To the crew that was positioned in the minimum operation condition, the remaining is added at the shearline at midlength of the hull. The fuel and fresh water tanks have 10 % of their maximum capacity remaining, while black and grey water tanks are filled to 95%. In this condition free surfaces occur in the tanks, thus their influence in the vertical position of the centre of gravity is taken into account.

The total weight and the position of its centre of gravity for each condition are summarized in Table 11.1.

Loadcase	weight [kg]	L_{CG} [m]	T_{CG}[m]	V_{CG} [m]
Maximum load	3041	4.003	-0.123	0.394
Minimum operation	2852.2	4.21	0.046	0.373
Loaded arrival	2852.2	4.21	0.046	0.373

Table 11.1: Summary of the loading conditions

The detailed calculation can be found in Appendix J.1.

11.2 Application of requirements set by the Standard

Next, each different test is explained and the results are analysed. The righting arm (GZ) curves are obtained in *Maxsurf Stability* for each of the loading conditions and the requirements are later checked by creating an Excel spreadsheet. The GZ curves and the detailed verification of the requirements are presented in Appendix J.2.

Downflooding height & angle

These requirements are to ensure that a level of watertight integrity appropriate to the design category is maintained. They are performed in the "Maximum load" condition. Only one downfloading point shall be considered, which is the entrance to the vessel's interior.

The downflooding height demonstrates sufficient margins of freeboard, setting a minimum value based on the hydrostatics of the vessel and the location of the downflooding point. The freeboard in the loading condition is calculated in Maxsurf from the datum of the waterline height. It is higher than the requirement for almost 50 cm.

The downflooding angle requirement ensures there is a sufficient margin of heel angle before significant quantities of water can enter the boat. The required angle depends on the design category (40 degrees in this case), and the design vessel surpasses it for more than 100 degrees.

11.2.1 Minimum righting energy

This requirement ensures that the required energy for the vessel to be heeled until the vanished angle (the angle at which GZ is zero other than the upright position) is larger than a value that depends on the design category. This requirement should be studied in the "Minimum operation" and "Loaded arrival" conditions, and after their GZ curve is obtained in Maxsurf, it is verified that for both cases the righting energy is greater than the set value.

11.2.2 Angle of vanishing stability

This requirement is intended to ensure an absolute minimum survival capability in severe conditions, by comparing the vanished angle of the "Minimum operation" and "Loaded arrival" conditions with a required minimum that depends on the displacement of the vessel in each condition. In this case, the requirement is barely fulfilled.

11.2.3 Stability index (STIX)

The stability index is a method of obtaining an assessment of the ability of the vessel to resist and recover from a knockdown or inversion. The index consists of a length factor which may be modified by seven factors which address separate aspects of the stability and buoyancy properties. Each factor is calculated for the "Minimum operation" and "Loaded arrival" conditions and depends on the geometrical properties of the vessel and characteristics of the GZ curve. Then, the stability index must be compared to a required value based on the loading condition of the vessel. Both loading conditions pass the stability index with more than a 10% margin.

In conclusion, the vessel meets all the stability criteria. In the case of the angle of vanishing stability, this is for less than 1 %. This minor range is not alarming, as it could easily be influenced in favour of the criteria by slight changes in onboard equipment or the precision of the boat's mould, thus should not affect the design for the VPP comparison with other boats.

12 CONCLUSIONS

This thesis presents a detailed exploration of the design and development process for a competitive racing yacht, culminating in a final design that meets the industry standards and optimizes performance.

The project began with a thorough market study, which provided the foundation for understanding current trends, and competitor designs. From this, a comprehensive dimensions study was carried out to determine the influence of the different parameters on the overall resistance and stability.

This initial phase led to the design process, where the most time-consuming and hard-to-face challenge appeared: the estimated beam on the waterline for the boats on the database was incorrect and not only new values for this dimension had to be obtained, but part of the dimension analysis needed to be repeated.

Regarding the VPP, a thorough process was followed to understand its base principles and obtain a keel-sail set combination which optimised performance. Comparing the obtained VPP with the ones of similar boats, it reached higher speeds both at low and high wind speeds. This, although good news, led to an investigation to find the reason behind it, obtaining a more accurate VPP based on a more precise weight estimation; and studying the rating system and the stability regulations to conclude if some restrictions were being overlooked.

The process of obtaining a more precise weight estimation and position of the centre of gravity went through hydrodynamical and aerodynamical analysis, regulations study, architectural and interior spaces design, systems parts and functionality research, and composites structure scantling. This highlights the complexity and detail that goes into the design of a boat, even of small dimensions and basic systems such as this one. Additionally, this process emphasises the important relation between all the parts that make up a boat, and more, in particular, the influence of correctly calculation the displacement of the boat and its centre of gravity.

One of the key achievements of this project is the significant improvement in performance compared to existing designs. The iterative design process led to a final design that offers a competitive advantage in racing scenarios. Notably, the design meets all regulatory requirements, ensuring that it is not only high-performing but also compliant with the required standards.

Along the process, the project faced several challenges, particularly in balancing the conflicting demands of speed and stability. These challenges highlighted the importance of an iterative approach, where continuous testing and refinement were crucial. In addition, the design of the boat in composite materials has been a great challenge due to my lack of knowledge and expertise in the subject. Luckily, I was backed by the supervisor and managed to successfully complete the structure design

In terms of future work, there are several aspects for further exploration. Firstly, the exact calculation of the handicap by the ORC is not accessible, thus the guide followed to estimate the influence of the geometrical parameters is not exact. By contacting the organization and certifying the vessel as a design, a more accurate estimation of the time penalty could be obtained. Secondly, the current design could benefit from additional real-world testing in a towing tank to validate the simulation results and refine the design further. Computational Fluid Dynamics (CFD) could also be used for this purpose. Lastly, exploring alternative materials and construction techniques could offer new opportunities for enhancing performance while reducing costs.

Being part of this project has allowed me to discover another point of view on shipbuilding, learning about the development of not-so-conventional ships, which in turn has been a challenge encountering several problems. Also, by doing the project within a recognised university in the yacht design industry, I was able to attend classes, learn, and meet professionals top-notch in this sector, always surrounded by people passionate about sailing and yacht design. In addition, I have been able to put into practice and expand much of the knowledge acquired during my master's. This project has also significant implications for my future career: the design principles and methodologies developed here can serve as a benchmark for future yacht designs. Additionally, the concepts, and principles encountered and learnt have broadened my understanding not only of VPPs but also concerning composite structures, rating systems, or competitive design, for example.

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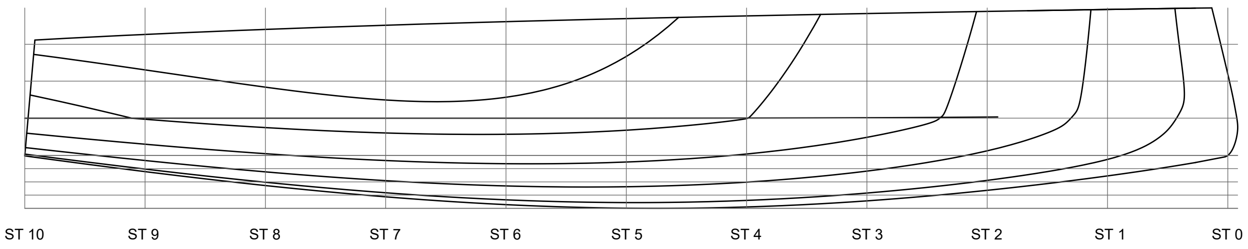
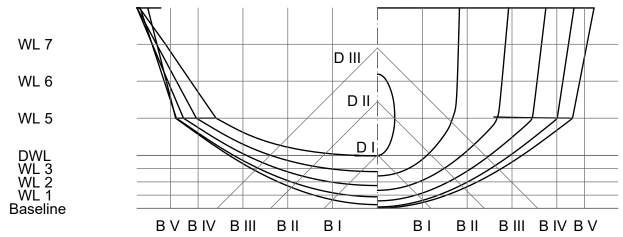
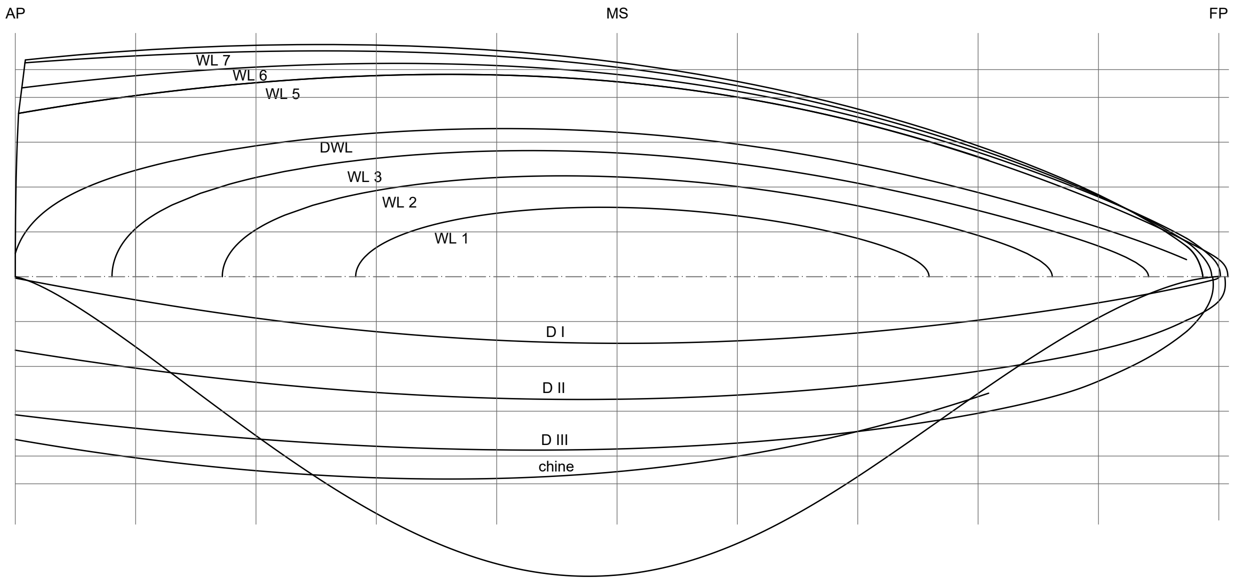
Drawings







Curve of sectional areas (scaled 1:4)

MAIN DIMENSIONS	
Displacement (Δ) [t]	2.91
Displaced volume () [m^3]	2.84
Length overall (LOA) [m]	9.08
Length at the waterline (LWL) [t]	8.96
Beam overall (BOA) [m]	3.46
Beam at the waterline (BWL) [m]	2.20
Draft Amidships (T) [m]	0.39
Wetted surface area (WSA) [m^2]	15.58
Prismatic coefficient (CP)	0.56
Block coefficient (CB)	0.36
Max Sect. area coefficient (CM)	0.66
Waterpl. area coefficient (CF)	0.73
LWL/BWL	4.07
LCB/LWL [%]	47.98
LCF/LWL [%]	44.98
Slenderness ratio	6.39

SPACINGS [mm]	
Sections	896
Buttocks I-IV	336
Buttocks IV-V	208
Waterlines 0-DWL	99
Waterlines DWL-7	279
Diagonals (at 45°)	400

EMship+ Advanced Design | SOLENT UNIVERSITY SOUTHAMPTON | CENTRALE NANTES

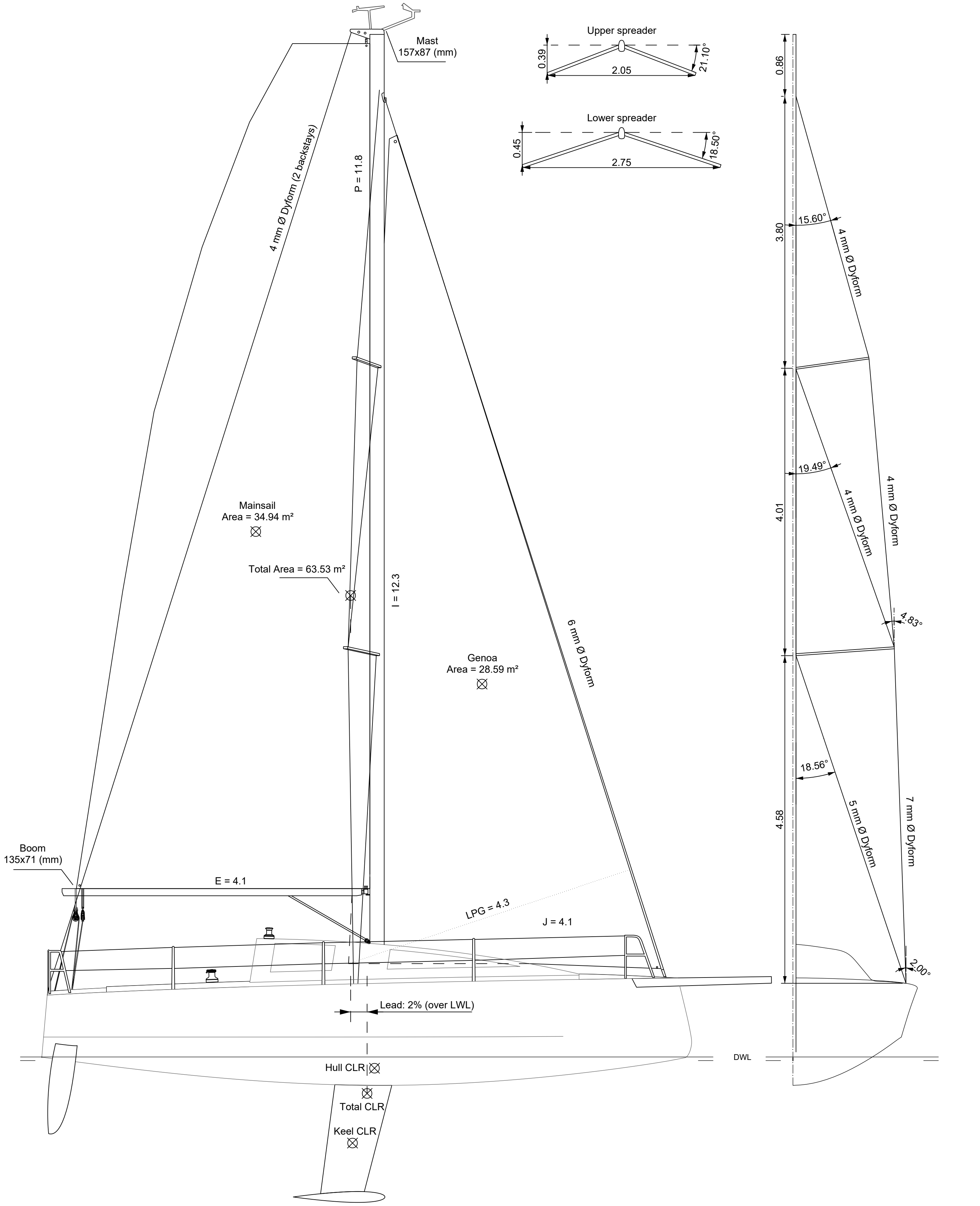
PROJECT
Design of a 30 ft high-performance racing yacht

DRAWN BY
Clara Monsalve Prieto

PLAN
Lines plan

SCALE
1:40

FORMAT
A3

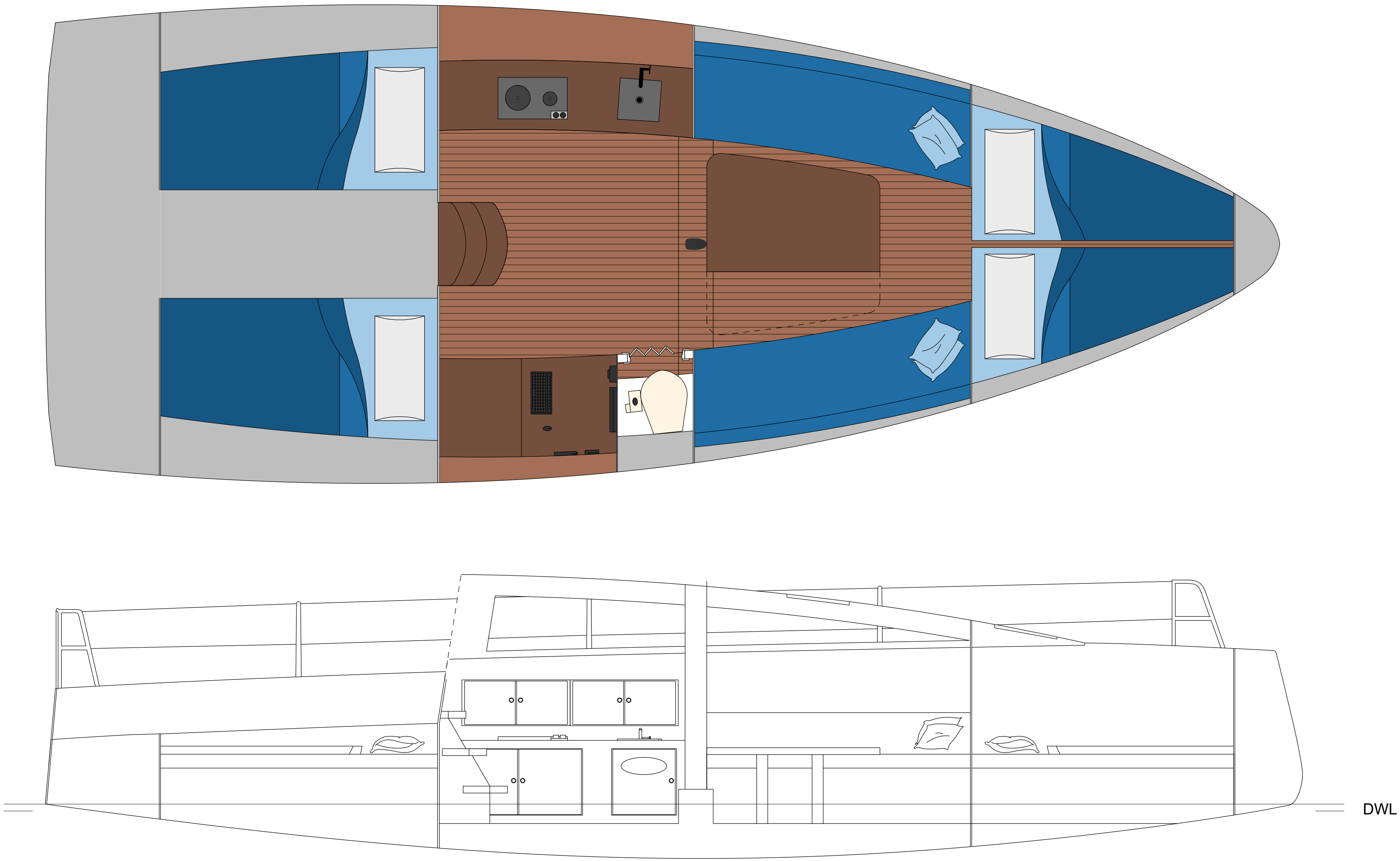


RUDDER DATA (JEFA 27R)	
Draft [m]	1.23
Lateral area [m²]	0.36
Inclined transversaly [°]	14
Offset from CL [m]	1.00

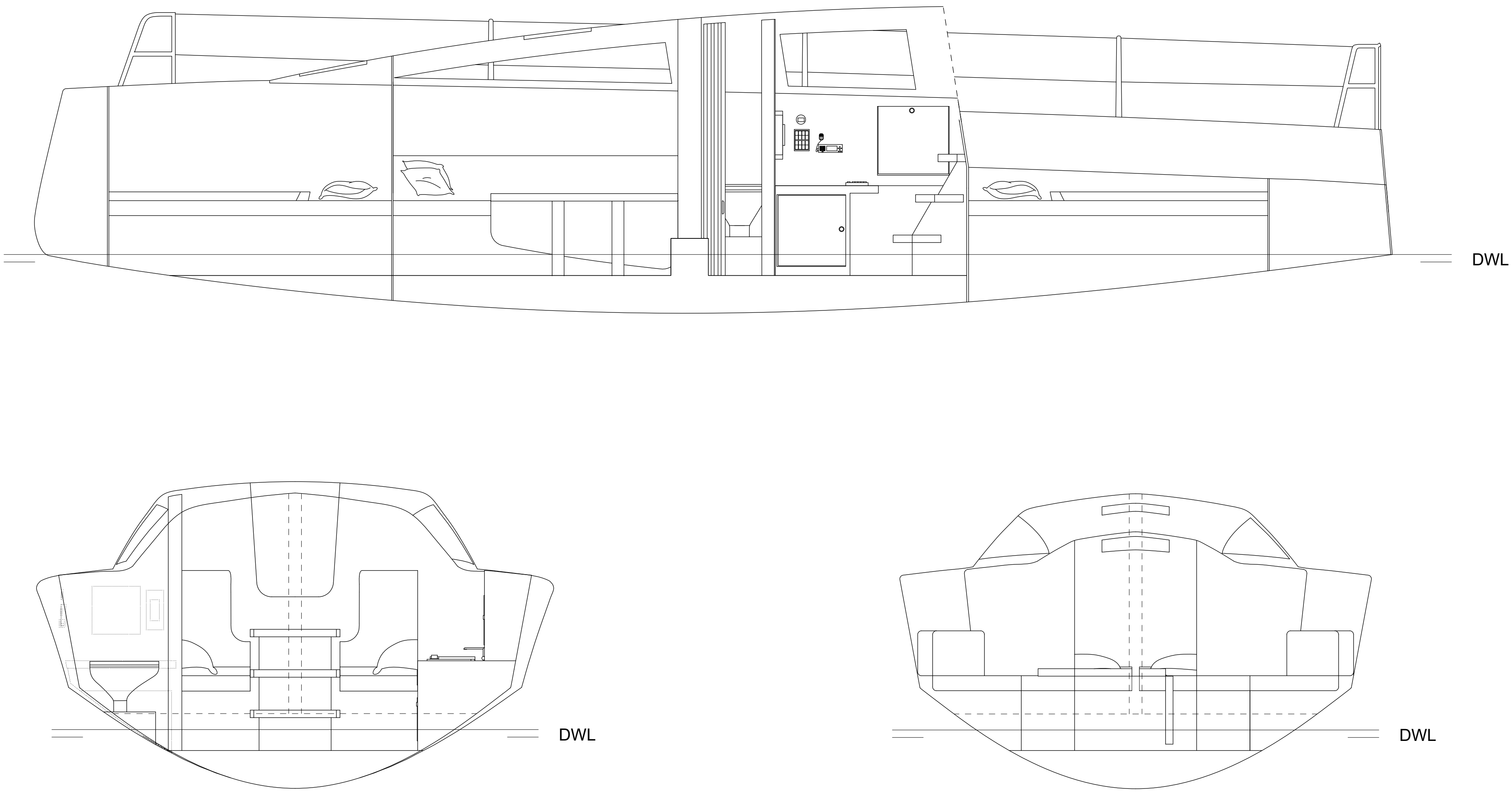
KEEL DATA			
Fin mass [kg]	843	Bulb mass [kg]	308
Root chord [m]	0.8	Bulb length [m]	1.28
Root thickness (t/c)	0.12	Horizontal t/c	0.25
Tip chord [m]	0.6	Vertical t/c	0.12
Tip thickness (t/c)	0.12	Total draft [m]	1.64

EMship+ Advanced Design | SOLENT UNIVERSITY SOUTHAMPTON | CENTRALE NANTES

PROJECT		
Design of a 30 ft high-performance racing yacht		
DRAWN BY: Clara Monsalve Prieto		PLAN: Sail plan & Rig design
UNITS: meters	SCALE: 1:50	FORMAT: A3

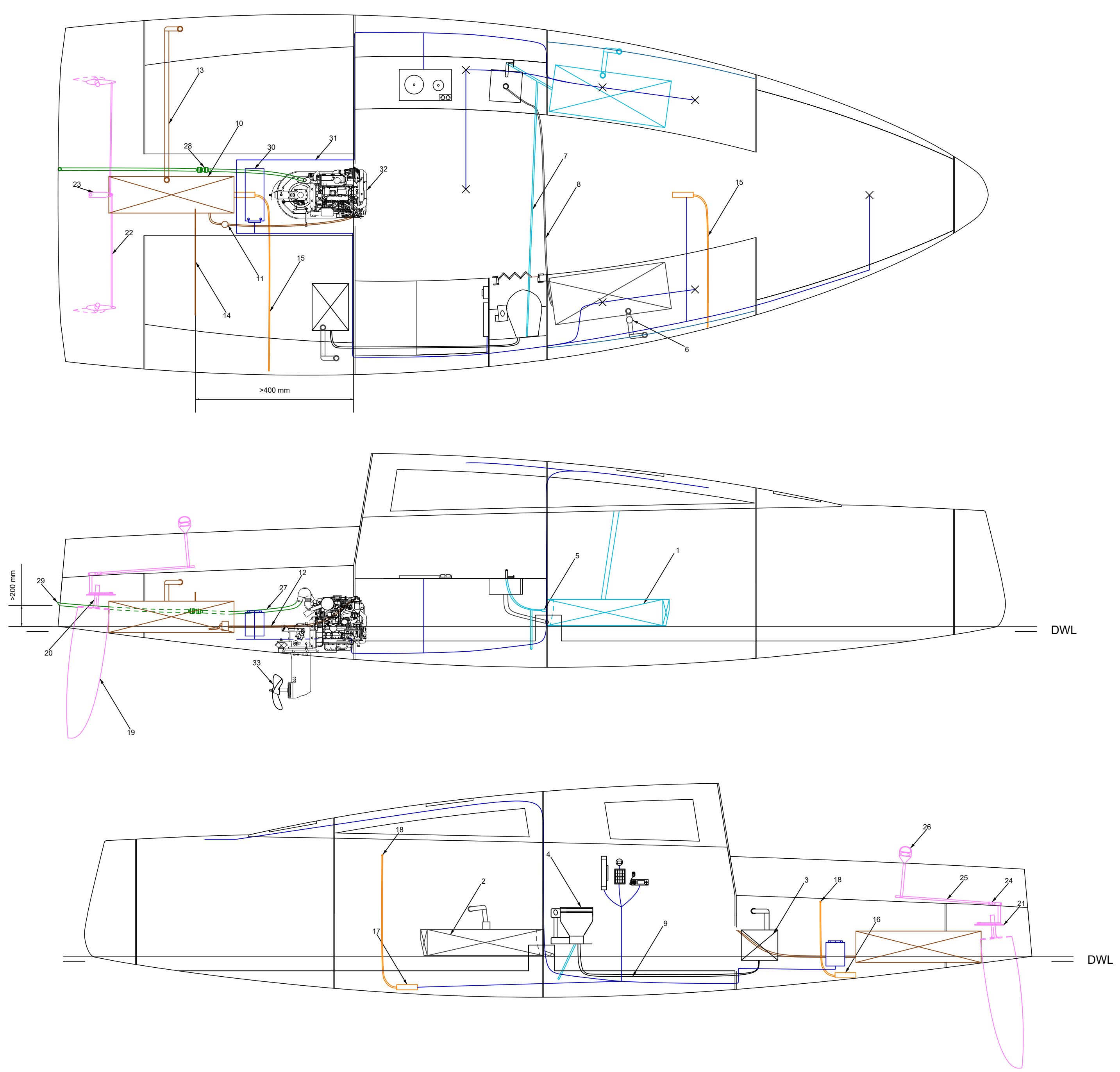


PROJECT Design of a 30 ft high-performance racing yacht	
DRAWN BY Clara Monsalve Prieto	PLAN General Arrangement
SCALE 1:20	FORMAT A2



PROJECT Design of a 30 ft high-performance racing yacht	
DRAWN BY Clara Monsalve Prieto	PLAN GA Profile and Transverse Sections
SCALE 1:20	FORMAT A2

EMship+ Advanced Design
SOLENT UNIVERSITY SOUTHAMPTON
CENTRALE NANTES

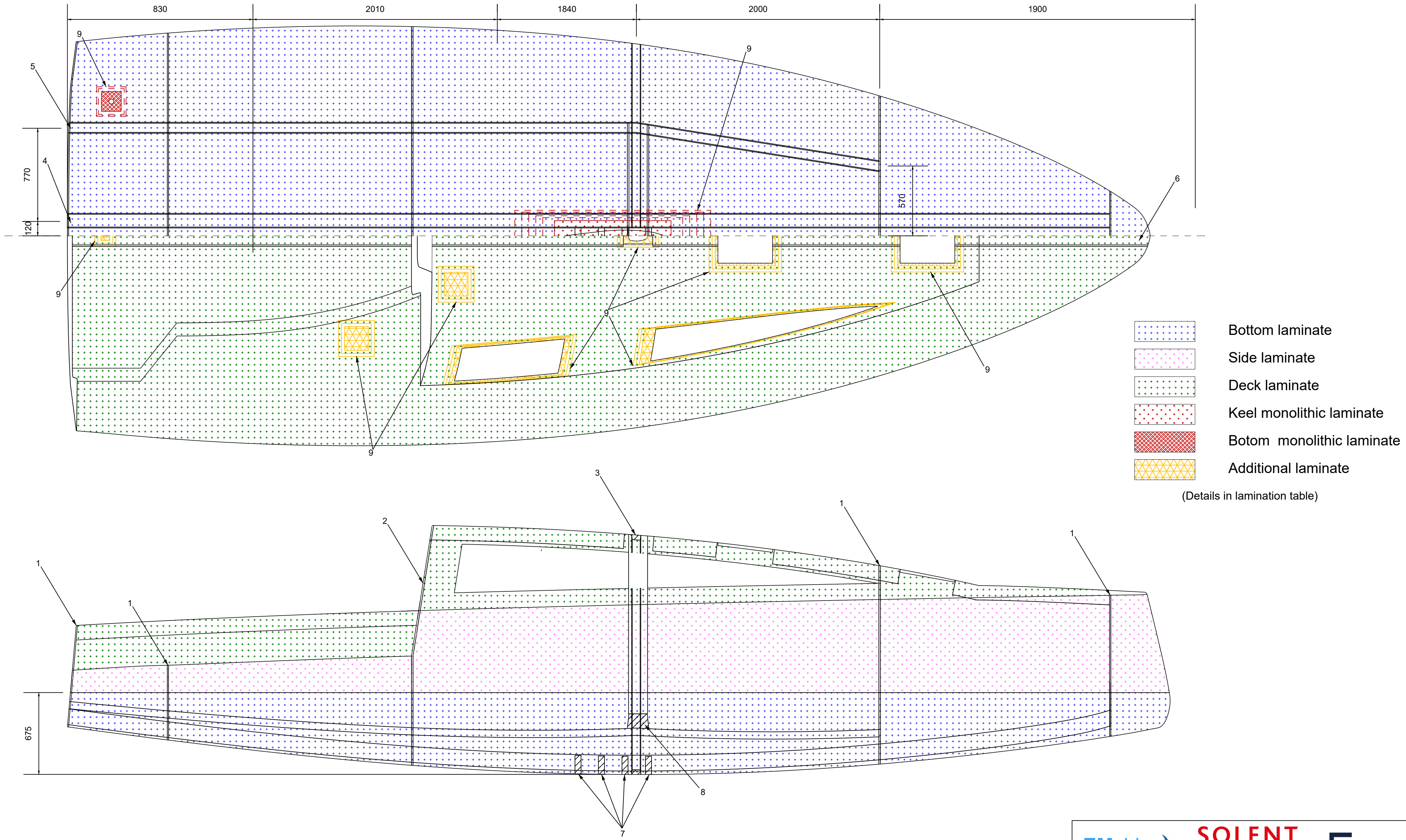


Fresh water	Black water	Bilge system	Exhaust system
Grey water	Fuel system	Steering system	Electric system

LEGEND					
1	Fesh water tank (100 l)	Vetus TANKW100	22	Draglink	Jefa DL100110-30
2	Grey water tank (100 l)	Vetus TANKW100	23	Tiller lever	Jefa TLJ050
3	Black water tank (42 l)	Vetus WWS4212B	24	Tiller head	Jefa 47035
4	Toilet	Jabsco Manual Toilet	25	Tiller	Jefa TIL-GRP1
5	Water pump (13.2 l/min)	Vetus WP1213B	26	Tiller Extension	Spinlock Asymmetric Tiller Extension
6	Grey water discharge pump (7.6 l/min)	Vetus WP1208B	27	Exhaust hose	Vetus SLANG40
7	Fresh water pipe	Vetus DWHOSE19B	28	Exhaust muffler	Vetus DEMPMP40
8	Grey water pipe	Vetus WWHOSE19B	29	Transom exhaust connection	Vetus TRC40R
9	Black water pipe	Vetus SAHOSE38	30	Battery	Vetus VESMF125
10	Fuel tank (110 l)	Vetus ATANK110	31	Wires	10 AWG cables
11	Fuel filter	Vetus NSF16DS	32	Engine	Volvo Penta D1-20
12	Fuel hose	Vetus FUHOSE16A	33	3-blade folding propeller	Volvo Penta LH - 3583386
13	Fuel filler hose	Vetus FFHOSE38			
14	Fuel breather hose	Vetus FUHOSE13A			
15	Bilge hoses	Vetus SAHOSE16			
16	Electric bilge pump	Vetus EMP140			
17	Manual bilge pump	Vetus BLPM020			
18	Non-return valves	Vetus SYNRE			
19	Rudder blade	Jefa RUD27R			
20	Rudder stock	Jefa AISI 630 38 mm			
21	Tiller lever	Jefa TLL040			

EMship+ Advanced Design — SOLENT UNIVERSITY SOUTHAMPTON — CENTRALE NANTES

PROJECT: Design of a 30 ft high-performance racing yacht	
DRAWN BY: Clara Monsalve Prieto	PLAN: Systems plan
SCALE: 1:40	FORMAT: A3

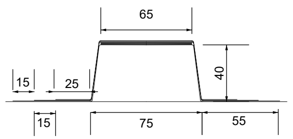


LEGEND			
1	Bulkheads (Lamination table)	6	Deck Stiffener (Detail D)
2	Entrance bulkhead (Lamination table)	7	Keel floor (Detail E)
3	Frame (Detail A)	8	Mast step (Detail F)
4	Keel stiffener (Detail B)	9	Tabbing (Details G, H & I)
5	Bottom stiffener (Detail C)		

EMship+ Advanced Design
SOLENT UNIVERSITY SOUTHAMPTON
CENTRALE NANTES

PROJECT Design of a 30 ft high-performance racing yacht		
DRAWN BY Clara Monsalve Prieto	PLAN Structural layout	
UNITS milimeters	SCALE 1:30	FORMAT A3

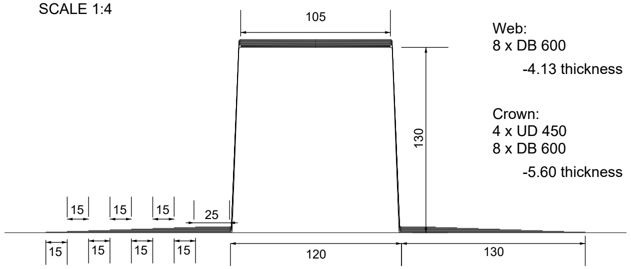
Detail A - Frame
SCALE 1:4



Web:
3 x DB 600
-1.55 thickness

Crown:
4 x UD 450
3 x DB 600
-3.02 thickness

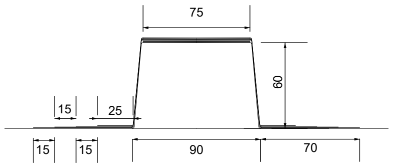
Detail B - Keel stiffener
SCALE 1:4



Web:
8 x DB 600
-4.13 thickness

Crown:
4 x UD 450
8 x DB 600
-5.60 thickness

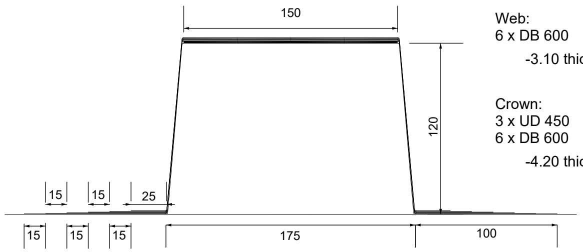
Detail C - Bottom stiffener
SCALE 1:4



Web:
4 x DB 600
-2.06 thickness

Crown:
4 x UD 450
4 x DB 600
-3.54 thickness

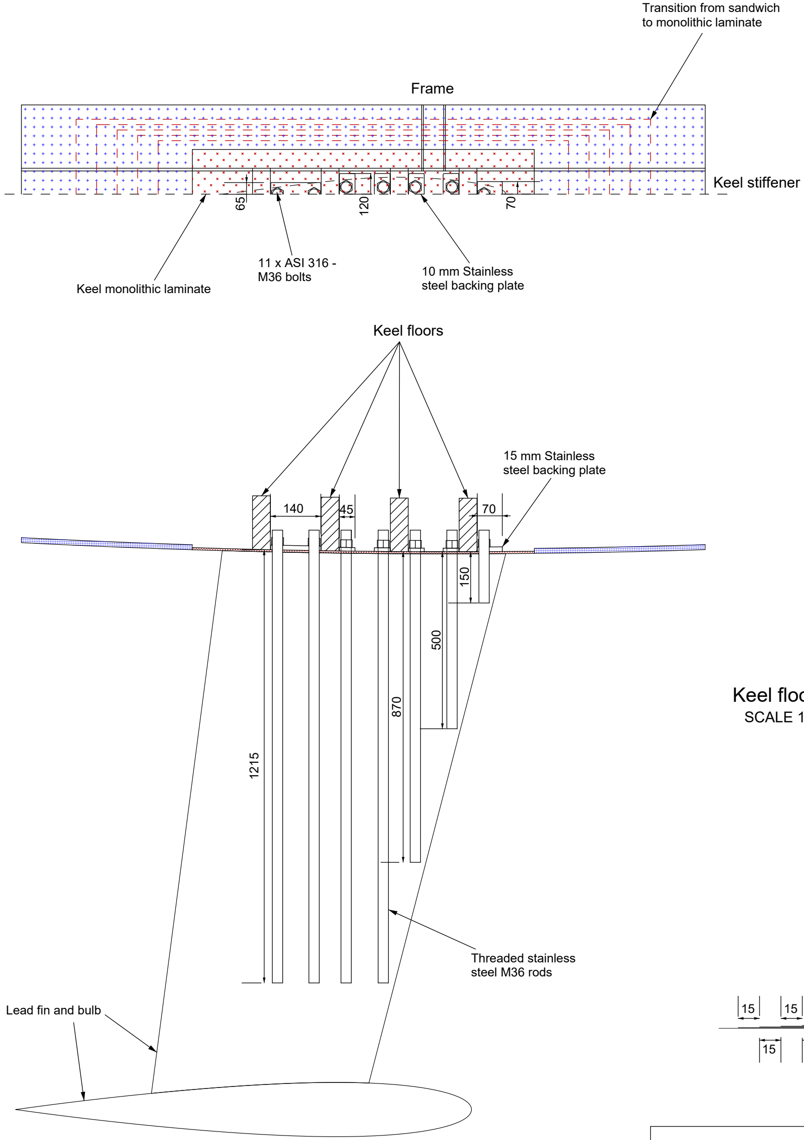
Detail D - Deck stiffener
SCALE 1:4



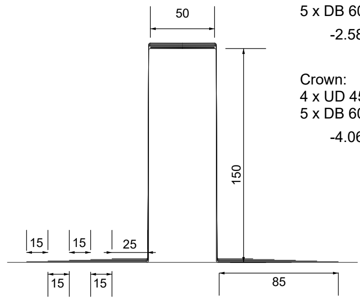
Web:
6 x DB 600
-3.10 thickness

Crown:
3 x UD 450
6 x DB 600
-4.20 thickness

Detail E - Keel structure
SCALE 1:15



Keel floors
SCALE 1:4



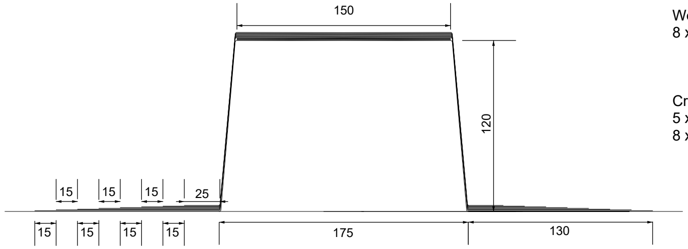
Web:
5 x DB 600
-2.58 thickness

Crown:
4 x UD 450
5 x DB 600
-4.06 thickness

EMship+ Advanced Design | SOLENT UNIVERSITY SOUTHAMPTON | CENTRALE NANTES

PROJECT: Design of a 30 ft high-performance racing yacht		
DRAWN BY: Clara Monsalve Prieto	PLAN: Structure: Details A-E	
UNITS: milimeters	SCALE: Various	FORMAT: A2

Detail F - Mast step
SCALE 1:4

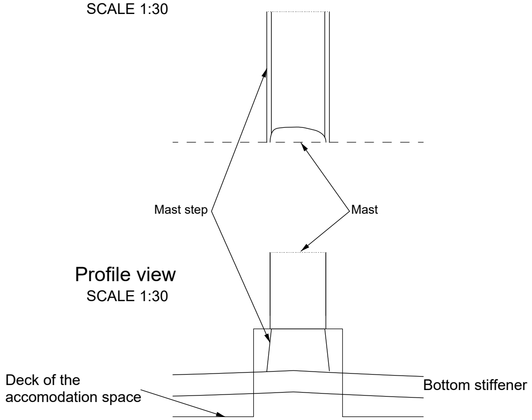


Web:
8 x DB 600
-4.13 thickness

Crown:
5 x UD 450
8 x DB 600
-5.97 thickness

Plan view
SCALE 1:30

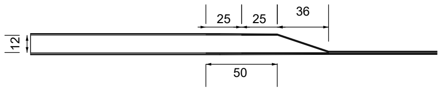
Profile view
SCALE 1:30



Detail G - Transition from Bottom sandwich laminate to Bottom monolithic laminate*
SCALE 1:4

Sandwich
Inner skin:
2 x Biaxial 300
1 x DB 300

Outer skin:
1 x DB 300
2 x Biaxial 300
1 x CSM 200

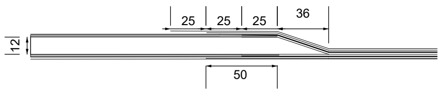


Monolothic
2 x Biaxial 300
4 x Biaxial 450
2 x Biaxial 300
1 x CSM 200

Detail H - Transition from Bottom sandwich laminate to Keel monolithic laminate*
SCALE 1:4

Sandwich
Inner skin:
2 x Biaxial 300
1 x DB 300

Outer skin:
1 x DB 300
2 x Biaxial 300
1 x CSM 200



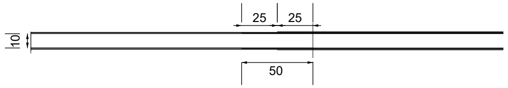
Monolothic
2 x CSM 600
2 x Biaxial 300
2 x CSM 600
2 x Biaxial 300
1 x CSM 600
1 x CSM 200

* Each additional layer is integrated in the sandwich gradually in 25 mm intervals. The Biaxial 300 and CSM 200 layers are continued, since they are part of both laminates

Detail I - Transition from Deck to Additional laminate
SCALE 1:4

Sandwich
Inner skin:
2 x Biaxial 300
1 x DB 200

Outer skin:
1 x DB 200
2 x Biaxial 300
1 x CSM 200



Additional laminate:
1 x DB 450
1 x Biaxial 450
(to each skin)

LAMINATION TABLE

Skin layer	Cloth type	Code	Thickness [mm]	Bottom laminate	Side laminate	Deck laminate	Bulkheads	Entrance bulkhead	Keel monolithic laminate	Bottom monolithic laminate	Additional laminate
Inner skin	Chopped Strand Mat 600 kg/m³	CSM 600	1.123								
	Chopped Strand Mat 200 kg/m³	CSM 200	0.374				1	1			
	Biaxial 0/90 450 kg/m³	Biaxial 450	0.387					2		2	1
	Biaxial 0/90 300 kg/m³	Biaxial 300	0.258	2	2	2	1		2	2	2
	Double Bias +/-45 450 kg/m³	DB 450	0.387					1			1
	Double Bias +/-45 300 kg/m³	DB 300	0.258	1							
	Double Bias +/-45 200 kg/m³	DB 200	0.172		1	1	1				1
	Chopped Strand Mat 600 kg/m³	CSM 600	1.123						1		
Core	Cross-linked PVC - Rigid PVC I 90kg/m³	PVC 90	12	1							
	Cross-linked PVC - Rigid PVC I 90kg/m³	PVC 90	10		1			1			
	Cross-linked PVC - Rigid PVC I 80 kg/m³	PVC 80	9				1				
	Cross-linked PVC - Rigid PVC I 60 kg/m³	PVC 60	10			1					1
Outer skin	Chopped Strand Mat 600 kg/m³	CSM 600	1.123						1		
	Double Bias +/-45 450 kg/m³	DB 450	0.387					1			1
	Double Bias +/-45 300 kg/m³	DB 300	0.258	1							
	Double Bias +/-45 200 kg/m³	DB 200	0.172		1	1	1				
	Biaxial 0/90 450 kg/m³	Biaxial 450	0.387					2			1
	Biaxial 0/90 300 kg/m³	Biaxial 300	0.258	2	2	2	1		2	2	2
	Chopped Strand Mat 600 kg/m³	CSM 600	1.123						2		
	Chopped Strand Mat 200 kg/m³	CSM 200	0.374	1	1	1	1	1		1	1

EMship+ Advanced Design
SOLENT UNIVERSITY SOUTHAMPTON
CENTRALE NANTES

PROJECT Design of a 30 ft high-performance racing yacht		
DRAWN BY Clara Monsalve Prieto	PLAN Structure: Details F-I & Lamination table	
UNITS milimeters	SCALE Various	FORMAT A2

Appendices

A SAILING VOCABULARY

Some vocabulary specific to sailing vessels includes:

- Leeway. Refers to the sideways drift of the yacht due to the combined effect of wind, hull resistance, and leeward forces.
- Leeward. The side of the yacht facing away from the wind direction.
- Windward. The side of the yacht facing into the wind.
- Upwind. Sailing in a direction that is against the wind or at an angle where the wind is coming from the fore of the boat.
- Downwind. Sailing in the same direction as the wind or at an angle where the wind is coming from astern the boat.
- Apparent wind angle. The angle between the boat's heading and the direction of the apparent wind, which is the wind experienced on a moving boat, resulting from the combination of the true wind (the wind felt when the boat is stationary) and the wind generated by the boat's own motion.

Three main types of sail can conform a sail set:

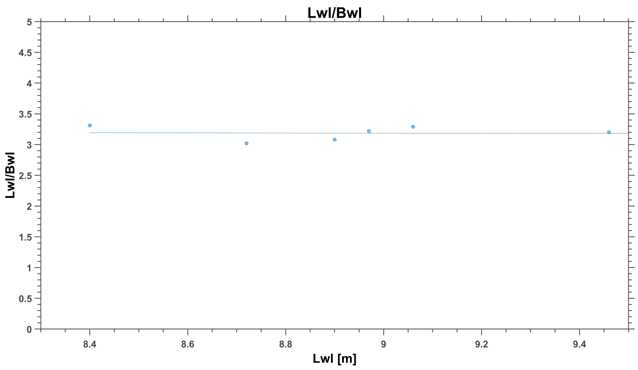
- Mainsail: Positioned on the mast and attached to the boom, it is the largest and most critical sail. It provides the primary driving force for the yacht by capturing wind energy and converting it into forward motion.
- Headsails (Jibs and Genoas): Located forward of the mast, they enhance manoeuvrability and are crucial for pointing closer to the wind, especially upwind. These can be of two types: Jibs and Genoas. The Jibs are smaller, and generally used for upwind; while the Genoas have a larger sail area by overlapping the mainsail, being more powerful in light to moderate wind conditions.
- Spinnaker: A specialized downwind sail used to maximize speed when sailing off the wind. Spinnakers come in various types, including asymmetrical and symmetrical, tailored for different wind angles and sailing conditions.

Once the sail areas are positioned on the boat, these are not static and can be adapted by using different techniques:

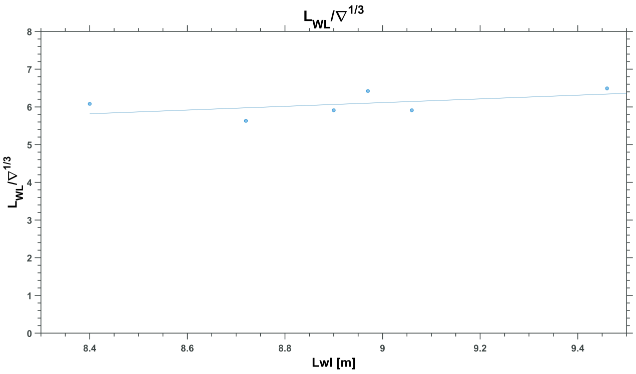
- Reefing: Reduce sail area to manage excessive wind conditions and maintain control, by lowering part of the sail and securing it to the boom.
- Flattening: Adjusting sail shape to reduce curvature (camber) and increase aerodynamic efficiency, crucial in high winds to reduce drag and maintain optimal sailing performance since

it does not reduce the sail area as much as reefing does.

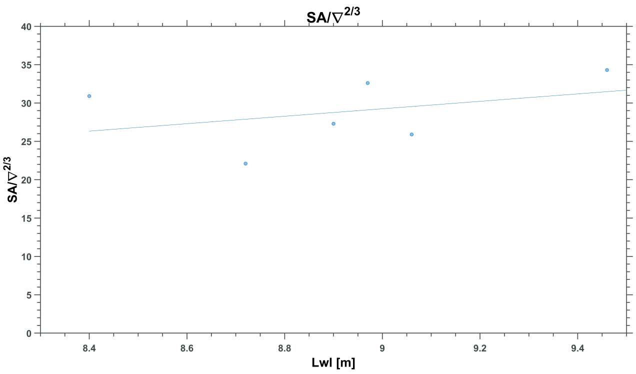
B REGRESSIONS FROM THE DATABASE



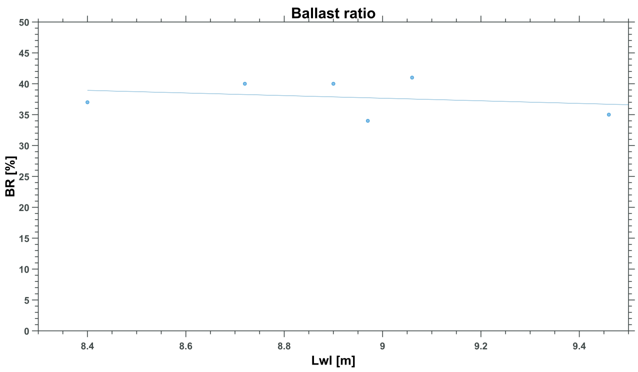
(a) Lwl/Bwl regression



(b) $L_{WL}/\nabla^{1/3}$ regression



(c) $SA/\nabla^{2/3}$ regression



(d) Ballast ratio regression

Figure B.1: Regressions of the first dimensions study

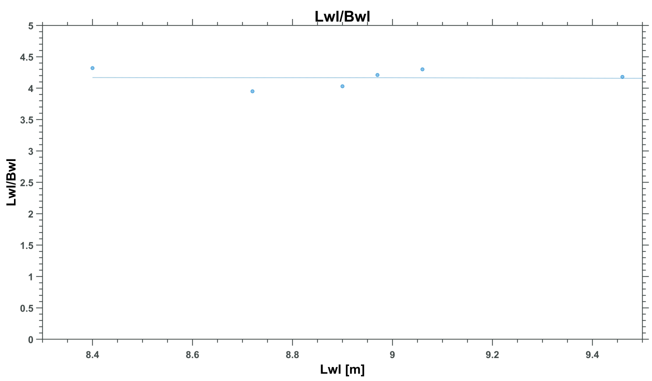
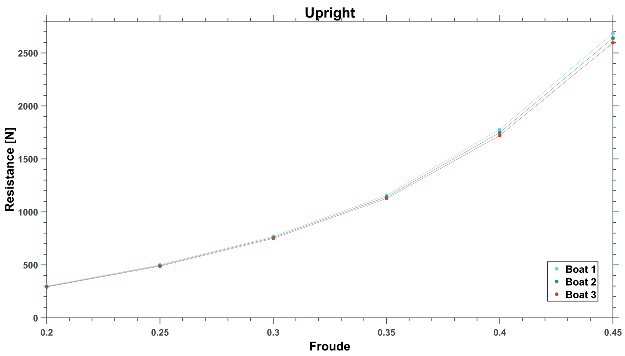
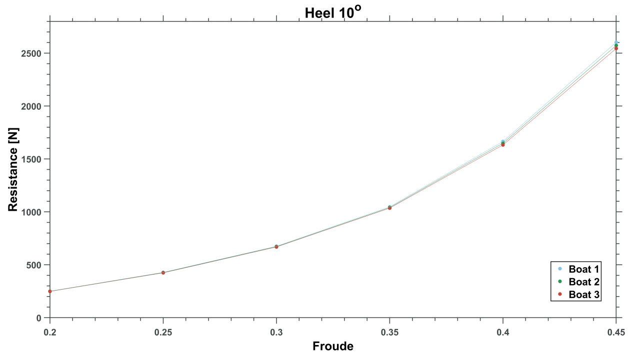


Figure B.2: Lwl/Bwl regression of the second dimensions study

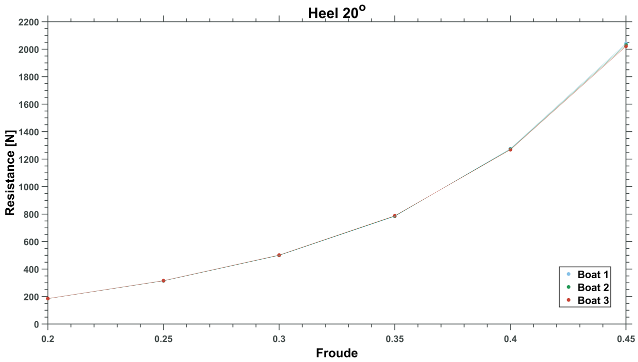
C BEAM ANALYSIS OF THE FIRST DIMENSIONS STUDY



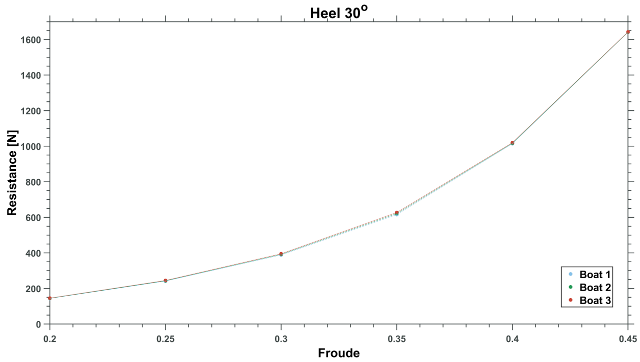
(a) Resistance comparison when upright



(b) Resistance comparison when heeled 10 degrees



(c) Resistance comparison when heeled 20 degrees



(d) Resistance comparison when heeled 30 degrees

Figure C.1: Resistance comparison of the beam analysis of the first dimensions study

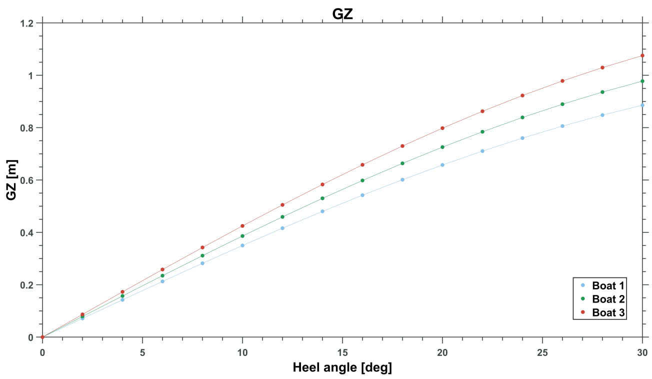


Figure C.2: Stability comparison of the beam analysis of the first dimensions study

D REGATTAS DATABASE

Championship	Distance [nm]	Average time taken to complete (h)	Time limit
ORC World Championship 2023	18.5	1.85	3 h
ORC DH World Championship	215	21.5	56 h
ORC DH European Championship 2023	175	17.5	3 days
Rolex Fastnet Race	695	69.5	
Rolex Middle sea	606	60	50 h
RORC Caribbean 600 Race	600	60	3 days
ROLEX CHINA SEA RACE	565	56.5	3 days
RORC Easter Challenge			150 min
Cervantes Trophy Race	160	16	
Myth of Malham Race	235	57	
Morgan Cup Race	150	15	30 min
Cowes Dinard St Malo Race	150	15	
Sevenstar Round Britain and Ireland Race	1800	180.2	
De Guingand Bowl Race	160	16	
Channel Race	160	16	
SSE Renewables Round Ireland Race	700	70.4	
La Trinité Cowes Race	350	35	

Table D.1: Regattas in which the database boats participate

E RESULTS FROM THE CHINE STUDY

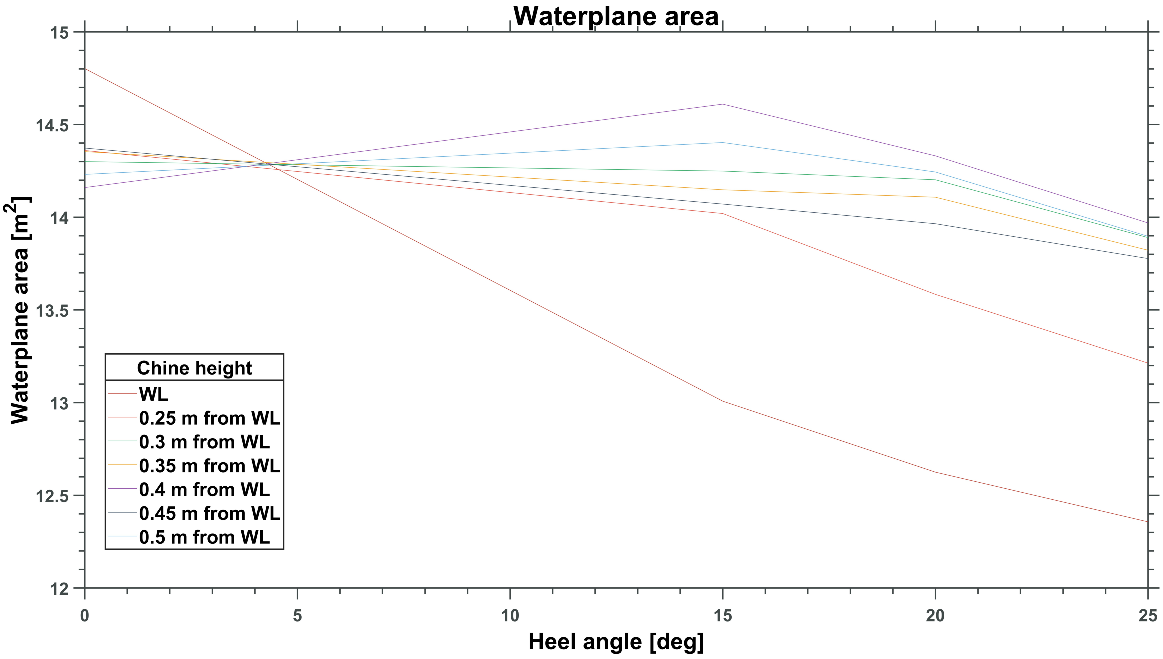


Figure E.1: Comparison of the Waterplane area between the different studied chine heights

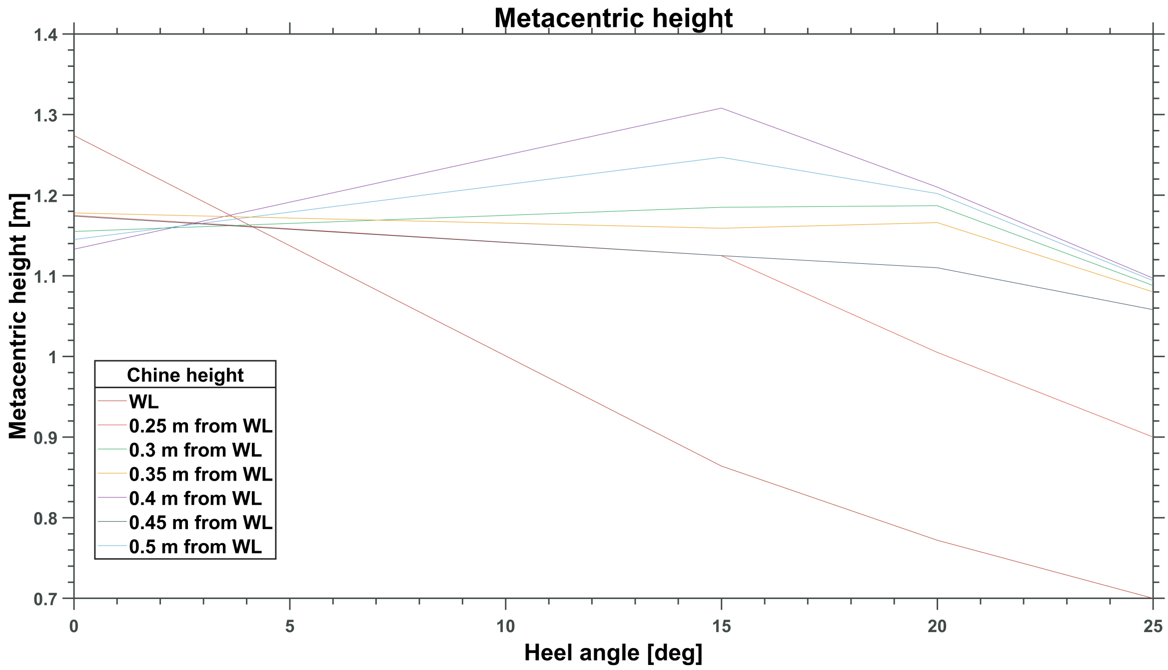
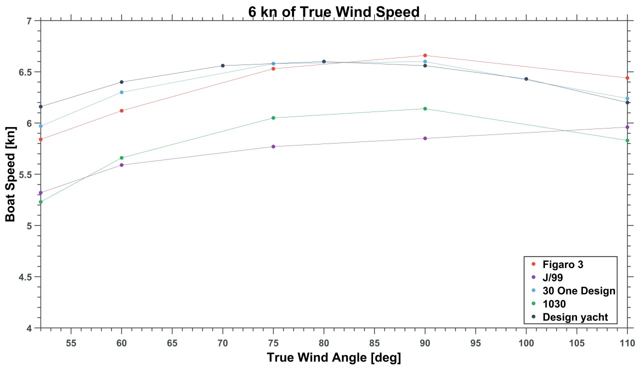


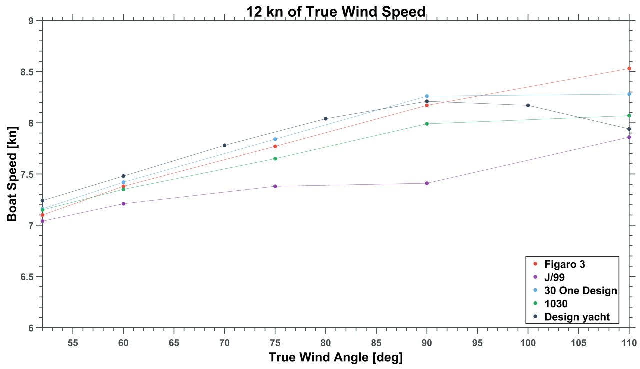
Figure E.2: Comparison of the Metacentric height between the different studied chine heights

F VPP COMPARISION

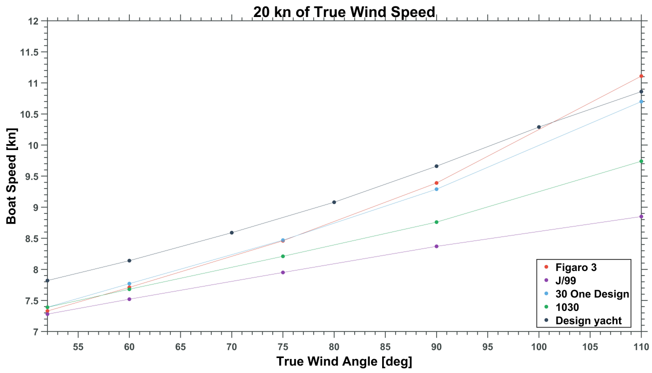
F.1 Comparison between the preliminary VPP of the design yacht and models from the database



(a) Comparison at 6 kn



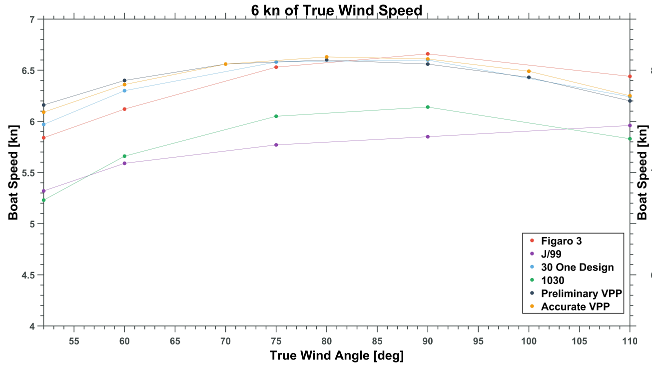
(b) Comparison at 12 kn



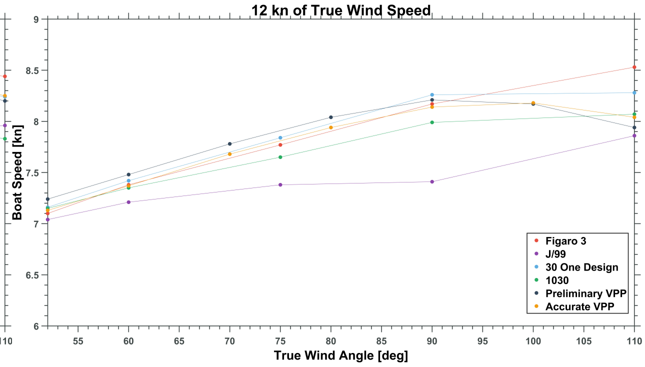
(c) Comparison at 20 kn

Figure F.1: Comparison between the preliminary VPP of the design yacht and models from the database

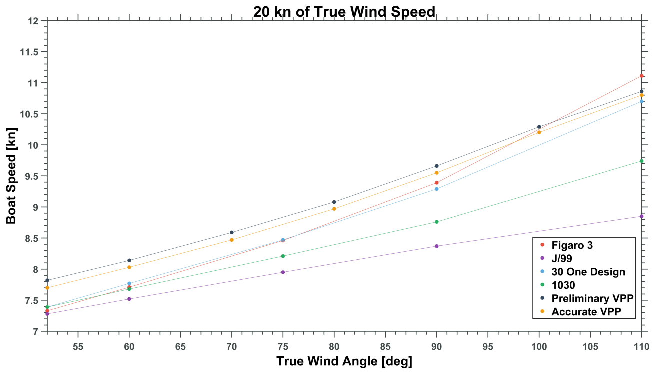
F.2 Comparison between the more accurate VPP, the preliminary VPP and models from the database



(a) Comparison at 6 kn



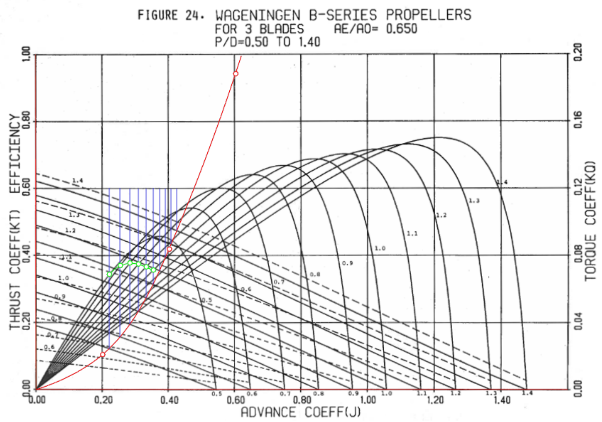
(b) Comparison at 12 kn



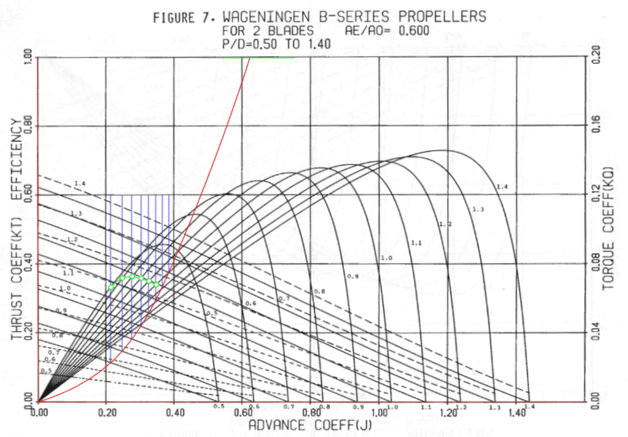
(c) Comparison at 20 kn

Figure F.2: Comparison between the more accurate VPP, the preliminary VPP and models from the database

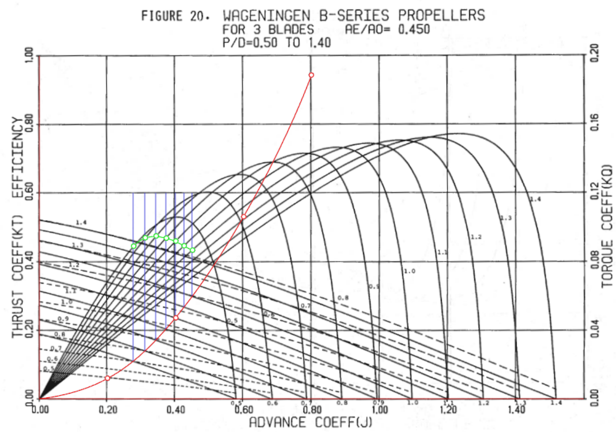
G WAGENINGEN B-SERIES PROPELLERS



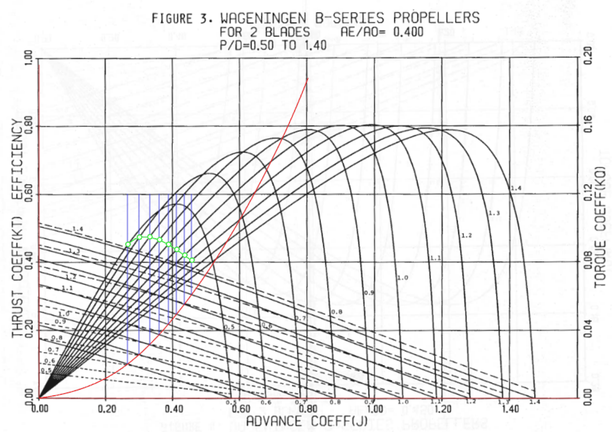
(a) B-series of Wageningen 3-blades and area/disc ratio of 0.65, which corresponds to the propeller of 30 cm of diameter



(b) B-series of Wageningen 2-blades and area/disc ratio of 0.6, which corresponds to the propeller of 30 cm of diameter

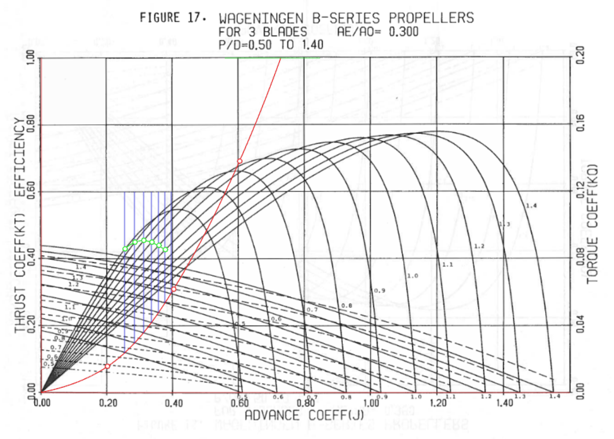


(c) B-series of Wageningen 3-blades and area/disc ratio of 0.45, which corresponds to the propeller of 40 cm of diameter

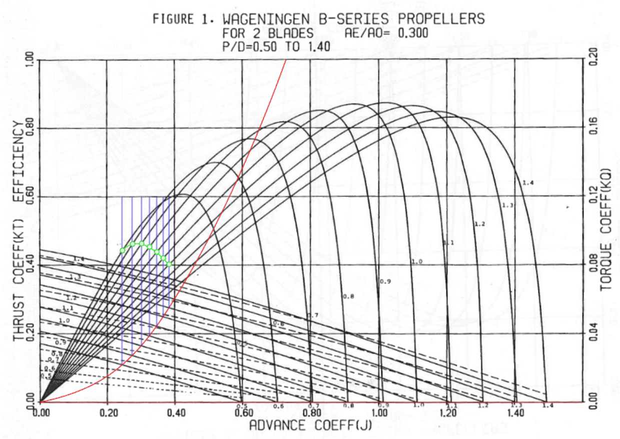


(d) B-series of Wageningen 2-blades and area/disc ratio of 0.4, which corresponds to the propeller of 40 cm of diameter

Figure G.1: Representation of the study carried out in the B-series of Wageningen propellers for each studied combination of propeller diameter and number of blades



(e) B-series of Wageningen 3-blades and area/disc ratio of 0.3, which corresponds to the propeller of 35 cm of diameter



(f) B-series of Wageningen 2-blades and area/disc ratio of 0.3, which corresponds to the propeller of 35 cm of diameter

Figure G.1: Representation of the study carried out in the B-series of Wageningen propellers for each studied combination of propeller diameter and number of blades [3]

H STUCTURE REPORT

Panel Geometry

ID	Length mm	Width mm	Aspect Ratio	Long. Position m	x/Lwl	Location	Z_Q m	Z_{Tx} m	Z_{SDA} m	Z_{SDT} m	Long. curvature mm	Trans. curvature mm
Side fore	835.6	356.2	2.346	8.871	0.990	Side	0.694	0.107	1.106	1.108	12.7	39.7
Side aft	910.0	705.1	1.291	0.451	0.050	Side	0.584	-0.059	0.887	0.759	4.1	6.9
Side 6	823.3	211.4	3.895	8.674	0.968	Side	0.693	-0.046	1.104	1.100	26.6	1.4
Side 5	2043.1	812.4	2.515	7.635	0.852	Side	0.685	-0.193	1.088	1.057	50.4	12.9
Side 4	2041.9	781.9	2.611	5.685	0.634	Side	0.667	-0.350	1.053	0.976	40.9	2.0
Side 3	1688.7	750.5	2.250	3.842	0.429	Side	0.645	-0.361	1.011	0.900	22.8	0.4
Side 2	2101.3	724.6	2.900	1.951	0.218	Side	0.615	-0.224	0.952	0.822	26.1	0.3
Fore 1	367.5	358.5	1.025	8.899	0.993	Bottom	0.128	0.129	1.106	1.109	31.5	29.4
Aft 3	909.6	378.1	2.406	0.451	0.050	Bottom	0.194	-0.059	0.887	0.759	1.8	5.9
Aft 2	908.2	784.1	1.158	0.451	0.050	Bottom	0.026	-0.059	0.887	0.759	1.3	33.9
Aft 1	910.1	190.1	4.787	0.451	0.050	Bottom	-0.057	-0.059	0.887	0.759	1.3	1.3
6.2	269.1	200.1	1.345	8.674	0.968	Bottom	0.161	-0.046	1.104	1.100	12.1	4.1
6.1	219.2	188.6	1.162	8.673	0.968	Bottom	-0.012	-0.046	1.104	1.100	24.7	2.5
5.2	1973.0	707.0	2.791	7.635	0.852	Bottom	0.067	-0.193	1.088	1.057	38.7	46.9
5.1	1917.0	199.2	9.623	7.635	0.852	Bottom	-0.170	-0.193	1.088	1.057	24.2	11.1
4.3	2031.0	606.5	3.349	5.685	0.634	Bottom	0.102	-0.350	1.053	0.976	23.4	12.7
4.2	2013.6	656.5	3.067	5.685	0.634	Bottom	-0.205	-0.350	1.053	0.976	21.8	32.9
4.1	2002.0	193.4	10.352	5.685	0.634	Bottom	-0.341	-0.350	1.053	0.976	22.0	4.3
3.3	1685.3	652.2	2.584	3.842	0.429	Bottom	0.104	-0.361	1.011	0.900	14.2	9.4
3.2	1685.1	815.4	2.067	3.842	0.429	Bottom	-0.211	-0.361	1.011	0.900	15.2	40.2
3.1	1685.7	191.5	8.803	3.842	0.429	Bottom	-0.355	-0.361	1.011	0.900	14.5	3.0
2.3	2102.7	580.9	3.620	1.951	0.218	Bottom	0.138	-0.224	0.952	0.822	13.6	9.6
2.2	2104.9	795.4	2.646	1.951	0.218	Bottom	-0.111	-0.224	0.952	0.822	13.9	36.2
2.1	2107.9	191.2	11.025	1.951	0.218	Bottom	-0.220	-0.224	0.952	0.822	14.0	2.0
Deckfore	372.5	190.1	1.959	8.734	0.975	Deck	1.110	0.001	1.105	1.103	2.1	2.5
Deck6	1138.2	601.2	1.893	8.045	0.898	Deck	1.118	-0.144	1.095	1.074	3.7	10.9
Coach4	2031.3	984.2	2.064	5.685	0.634	S/Structure. Closed cockpit side	1.283	-0.350	1.053	0.976	19.1	118.2
Coach5	852.0	525.1	1.623	7.095	0.792	S/Structure. Closed cockpit side	1.192	-0.258	1.079	1.035	3.6	29.1
Coach3	1687.1	1375.7	1.226	3.843	0.429	S/Structure. Closed cockpit side	1.344	-0.361	1.011	0.900	11.9	236.8
Deck4	2046.7	489.3	4.183	5.685	0.634	Deck	1.082	-0.350	1.053	0.976	6.0	5.8
Deck5	866.8	472.7	1.834	7.095	0.792	Deck	1.109	-0.258	1.079	1.035	1.2	4.0
Deck3	1688.8	498.0	3.391	3.844	0.429	Deck	1.039	-0.361	1.011	0.900	4.1	6.5
Banera 2.1	2099.1	803.7	2.612	1.951	0.218	Deck	0.562	-0.224	0.952	0.822	3.7	13.9

ID	Length mm	Width mm	Aspect Ratio	Long. Position m	x/Lwl	Location	Z_Q m	Z_{Tx} m	Z_{SDA} m	Z_{SDT} m	Long. curvature mm	Trans. curvature mm
Banera 2.2	2099.2	459.5	4.568	1.951	0.218	Deck	0.800	-0.224	0.952	0.822	20.5	5.0
Banera aft	1107.9	910.3	1.217	0.451	0.050	Deck	0.499	-0.059	0.887	0.759	13.8	1.3
Baneraaft2	907.1	442.7	2.049	0.451	0.050	Deck	0.729	-0.059	0.887	0.759	3.7	5.2
Deck2	2099.2	872.4	2.406	1.951	0.218	Deck	0.986	-0.224	0.952	0.822	6.3	16.8
Deckaft	907.1	497.3	1.824	0.451	0.050	Deck	0.916	-0.059	0.887	0.759	1.9	4.7
Bulkhead_aft	2733.3	469.7	5.820	0.000	0.000	Bottom & Side	0.893	0.000	1.107	0.741	0.0	0.0
Bulkhead2	2517.5	833.7	3.020	0.902	0.101	Side	0.947	-0.118	0.909	0.778	0.0	0.0
Bulkead fore	1215.3	659.0	1.844	8.585	0.958	W/tight Bulkhead	1.057	-0.077	1.103	1.096	0.0	0.0
Bulkhead entrance	2955.1	1658.8	1.781	3.002	0.335	Side	0.987	-0.323	0.987	0.865	0.0	0.0
Plate keel	2002.1	382.0	5.241	5.685	0.634	Bottom	-0.333	-0.350	1.053	0.976	22.4	17.6
Bulkhead saloon	1295.9	1097.3	1.181	6.685	0.746	Bottom & Side	0.601	-0.300	1.072	1.018	0.0	0.0
Aft 3 single skin	909.6	378.1	2.406	0.451	0.050	Bottom	0.194	-0.059	0.887	0.759	1.8	5.9
4.1 single skin keel	2002.0	193.4	10.352	5.685	0.634	Bottom	-0.341	-0.350	1.053	0.976	22.0	4.3
3.1 single skin keel	1685.7	191.5	8.803	3.842	0.429	Bottom	-0.355	-0.361	1.011	0.900	14.5	3.0

Panel Coefficients and calculations

ID	A_D m^2	K_{AR}	K_{SUP}	K_C	K_L	K_{2b}	K_{SHb}	K_{2l}	K_{SHl}	Design Pressure Kn/m^2
Side fore	0.298	0.663	-	0.672	1.000	0.500	0.484	0.337	0.460	19.217
Side aft	0.642	0.487	-	1.000	0.449	0.406	0.415	0.334	0.457	5.504
Side 6	0.112	0.917	-	1.000	1.000	0.500	0.504	0.337	0.460	26.496
Side 5	1.650	0.358	-	1.000	1.000	0.500	0.502	0.337	0.460	10.157
Side 4	1.528	0.369	-	1.000	1.000	0.500	0.503	0.337	0.460	10.121
Side 3	1.267	0.393	-	1.000	0.828	0.500	0.494	0.337	0.460	8.639
Side 2	1.313	0.391	-	1.000	0.617	0.500	0.507	0.337	0.460	6.201
Fore 1	0.132	0.846	-	0.577	1.000	0.315	0.344	0.310	0.439	38.757
Aft 3	0.344	0.632	-	1.000	0.449	0.500	0.484	0.337	0.460	13.005
Aft 2	0.712	0.463	-	0.925	0.449	0.366	0.384	0.326	0.451	9.536
Aft 1	0.090*	0.982	-	1.000	0.449	0.500	0.503	0.337	0.460	20.211
6.2	0.054	1.000	-	0.963	1.000	0.419	0.402	0.336	0.458	45.804
6.1	0.041	1.000	-	0.788	1.000	0.367	0.371	0.326	0.452	45.804
5.2	1.250	0.399	-	0.817	1.000	0.500	0.502	0.337	0.460	18.253
5.1	0.099*	0.953	-	0.863	1.000	0.500	0.509	0.337	0.460	43.649
4.3	0.920	0.447	-	1.000	1.000	0.500	0.508	0.337	0.460	20.481
4.2	1.077	0.422	-	0.890	1.000	0.500	0.506	0.337	0.460	19.308
4.1	0.094*	0.971	-	1.000	1.000	0.500	0.509	0.337	0.460	44.483
3.3	1.063	0.424	-	1.000	0.828	0.500	0.497	0.337	0.460	16.069
3.2	1.374	0.378	-	0.894	0.828	0.500	0.486	0.337	0.460	14.322
3.1	0.092*	0.977	-	1.000	0.828	0.500	0.508	0.337	0.460	37.073
2.3	0.844	0.462	-	1.000	0.617	0.500	0.509	0.337	0.460	13.042
2.2	1.582	0.364	-	0.913	0.617	0.500	0.501	0.337	0.460	10.277
2.1	0.091*	0.978	-	1.000	0.617	0.500	0.509	0.337	0.460	27.645
Deckfore	0.071	1.000	-	1.000	1.000	0.491	0.461	0.338	0.460	18.951
Deck6	0.684	0.489	-	1.000	1.000	0.488	0.471	0.339	0.460	9.270
Coach4	1.999	0.324	0.670	0.653	-	0.500	0.490	0.337	0.460	5.000
Coach5	0.447	0.565	0.670	0.864	-	0.467	0.445	0.340	0.458	7.178
Coach3	2.321	0.279	0.670	0.570	-	0.388	0.421	0.331	0.455	5.000
Deck4	0.599*	0.522	-	1.000	1.000	0.500	0.509	0.337	0.460	9.896
Deck5	0.410	0.587	-	1.000	1.000	0.485	0.461	0.339	0.459	11.128
Deck3	0.620	0.516	-	1.000	0.828	0.500	0.507	0.337	0.460	8.096
Banera 2.1	1.615	0.361	-	1.000	0.617	0.500	0.500	0.337	0.460	5.000

ID	A_D m^2	K_{AR}	K_{SUP}	K_C	K_L	K_{2b}	K_{SHb}	K_{2l}	K_{SHl}	Design Pressure Kn/m^2
Banera 2.2	0.528*	0.546	-	1.000	0.617	0.500	0.507	0.337	0.460	6.382
Banera aft	1.009	0.405	-	1.000	0.449	0.385	0.394	0.330	0.454	5.000
Baneraaft2	0.402	0.595	-	1.000	0.449	0.500	0.468	0.337	0.460	5.064
Deck2	1.831	0.342	-	1.000	0.617	0.500	0.494	0.337	0.460	5.000
Deckaft	0.451	0.567	-	1.000	0.449	0.485	0.457	0.339	0.459	5.000
Bulkhead_aft	0.551*	0.538	-	1.000	0.399	0.500	0.512	0.337	0.460	5.000
Bulkhead2	1.738	0.350	-	1.000	0.500	0.500	0.509	0.337	0.460	5.000
Bulkead fore	0.801	0.460	-	1.000	-	0.486	0.474	0.339	0.459	7.399
Bulkhead entrance	4.902	0.206	-	1.000	0.734	0.482	0.494	0.339	0.459	5.000
Plate keel	0.365*	0.620	-	0.910	1.000	0.500	0.509	0.337	0.460	28.408
Bulkhead saloon	1.422	0.348	-	1.000	1.000	0.374	0.409	0.328	0.453	10.876
Aft 3 single skin	0.344	0.632	-	1.000	0.449	0.500	0.478	0.337	0.460	13.005
4.1 single skin keel	0.094*	0.971	-	1.000	1.000	0.500	0.500	0.337	0.460	44.483
3.1 single skin keel	0.092*	0.977	-	1.000	0.828	0.500	0.500	0.337	0.460	37.073

NOTE- Some panels are high aspect ratio, and in accordance with ISO 12215-5 Errata 2023-12-31 the design area has been limited. Those panels where this has occured are marked with a * in the design area column

Panel Requirements and Offered

	Required				Offered				
ID	w_f g/m2	Core shear mm	SM_I cm^3	SM_O cm^3	Offered	w_f g/m2	Core Shear mm	SM_I cm^3	SM_O cm^3
Side fore		4.353	0.0	0.0	Sandwich side	-	1.0	0.1	0.1
Side aft		3.363	0.0	0.0	Sandwich side	-	1.0	0.1	0.1
Side 6		5.384	0.0	0.0	Sandwich side	-	1.0	0.1	0.1
Side 5		8.041	0.1	0.1	Sandwich side	-	1.0	0.1	0.1
Side 4		7.711	0.1	0.1	Sandwich side	-	1.0	0.1	0.1
Side 3		6.275	0.0	0.1	Sandwich side	-	1.0	0.1	0.1
Side 2		4.379	0.0	0.0	Sandwich side	-	1.0	0.1	0.1
Fore 1		5.577	0.0	0.0	Sandwich bottom	-	1.0	0.1	0.1
Aft 3		4.651	0.0	0.0	Sandwich bottom	-	1.0	0.1	0.1
Aft 2		5.654	0.0	0.0	Sandwich bottom	-	1.0	0.1	0.1
Aft 1		3.692	0.0	0.0	Sandwich bottom	-	1.0	0.1	0.1
6.2		6.902	0.0	0.0	Sandwich bottom	-	1.0	0.1	0.1
6.1		4.831	0.0	0.0	Sandwich bottom	-	1.0	0.1	0.1
5.2		10.232	0.1	0.1	Sandwich bottom	-	1.0	0.1	0.1
5.1		7.293	0.0	0.0	Sandwich bottom	-	1.0	0.1	0.1
4.3		12.081	0.1	0.1	Sandwich bottom	-	1.0	0.1	0.1
4.2		10.963	0.1	0.1	Sandwich bottom	-	1.0	0.1	0.1
4.1		8.367	0.0	0.0	Sandwich bottom	-	1.0	0.1	0.1
3.3		10.125	0.1	0.1	Sandwich bottom	-	1.0	0.1	0.1
3.2		10.040	0.1	0.1	Sandwich bottom	-	1.0	0.1	0.1
3.1		6.886	0.0	0.0	Sandwich bottom	-	1.0	0.1	0.1
2.3		7.373	0.0	0.1	Sandwich bottom	-	1.0	0.1	0.1
2.2		7.255	0.1	0.1	Sandwich bottom	-	1.0	0.1	0.1
2.1		5.144	0.0	0.0	Sandwich bottom	-	1.0	0.1	0.1
Deckfore		5.450	0.0	0.0	Sandwich deck	-	1.0	0.1	0.1
Deck6		8.840	0.0	0.0	Sandwich deck	-	1.0	0.1	0.1
Coach4		5.276	0.0	0.0	Sandwich deck	-	1.0	0.1	0.1
Coach5		4.998	0.0	0.0	Sandwich deck	-	1.0	0.1	0.1
Coach3		5.861	0.1	0.0	Sandwich deck	-	1.0	0.1	0.1
Deck4		8.003	0.0	0.0	Sandwich deck	-	1.0	0.1	0.1
Deck5		8.216	0.0	0.0	Sandwich deck	-	1.0	0.1	0.1
Deck3		6.641	0.0	0.0	Sandwich deck	-	1.0	0.1	0.1
Banera 2.1		6.627	0.0	0.0	Sandwich deck	-	1.0	0.1	0.1

	Required				Offered				
ID	w_f g/m2	Core shear mm	SM_I cm^3	SM_O cm^3	Offered	w_f g/m2	Core Shear mm	SM_I cm^3	SM_O cm^3
Banera 2.2		4.848	0.0	0.0	Sandwich deck	-	0.7	0.1	0.1
Banera aft		6.534	0.0	0.0	Sandwich deck	-	0.7	0.1	0.1
Baneraaft2		3.557	0.0	0.0	Sandwich deck	-	0.7	0.1	0.1
Deck2		7.186	0.1	0.0	Sandwich deck	-	0.7	0.1	0.1
Deckaft		3.891	0.0	0.0	Sandwich deck	-	0.7	0.1	0.1
Bulkhead_aft		2.675	0.0	0.0	Sandwich bulkheads	-	0.6	0.1	0.1
Bulkhead2		4.748	0.0	0.0	Sandwich bulkheads	-	0.6	0.1	0.1
Bulkead fore		5.413	0.0	0.0	Sandwich bulkheads	-	0.6	0.1	0.1
Bulkhead entrance		8.025	0.2	0.2	Sandwich bulkhead entrance	-	1.7	0.2	0.2
Plate keel		9.605	0.0	0.0	Sandwich bottom	-	1.0	0.1	0.1
Bulkhead saloon		10.021	0.1	0.1	Sandwich bulkhead entrance	-	1.7	0.2	0.2
Aft 3 single skin	2972.9	-	-	-	Single skin bottom	3200.0	-	-	-
4.1 single skin keel	2147.4	-	-	-	Single skin keel	4400.0	-	-	-
3.1 single skin keel	1941.1	-	-	-	Single skin keel	4400.0	-	-	-

Panel Results

	Material Properties				Results					
ID	EI N/mm^2	W_{FIBRE} g/m^2	Core Shear Stress N/mm^2	Core Comp. Stress N/mm^2	w_f ratio	$T_{core\ s}$ ratio	SM_I ratio	SM_O ratio	Plating Comply ?	Core Comply ?
Side fore	8.34E+5	1800	0.533	0.621	-	2.50	4.35	5.44	PASS	PASS
Side aft	8.34E+5	1800	0.533	0.621	-	3.23	3.21	4.02	PASS	PASS
Side 6	8.34E+5	1800	0.533	0.621	-	2.02	6.02	7.53	PASS	PASS
Side 5	8.34E+5	1800	0.533	0.621	-	1.35	1.06	1.33	PASS	PASS
Side 4	8.34E+5	1800	0.533	0.621	-	1.41	1.15	1.44	PASS	PASS
Side 3	8.34E+5	1800	0.533	0.621	-	1.73	1.47	1.83	PASS	PASS
Side 2	8.34E+5	1800	0.533	0.621	-	2.48	2.19	2.74	PASS	PASS
Fore 1	1.26E+6	2000	0.533	0.621	-	2.32	5.01	6.24	PASS	PASS
Aft 3	1.26E+6	2000	0.533	0.621	-	2.79	4.88	6.09	PASS	PASS
Aft 2	1.26E+6	2000	0.533	0.621	-	2.29	2.29	2.85	PASS	PASS
Aft 1	1.26E+6	2000	0.533	0.621	-	3.51	12.42	15.49	PASS	PASS
6.2	1.26E+6	2000	0.533	0.621	-	1.88	6.12	7.64	PASS	PASS
6.1	1.26E+6	2000	0.533	0.621	-	2.68	9.62	12.00	PASS	PASS
5.2	1.26E+6	2000	0.533	0.621	-	1.27	1.22	1.52	PASS	PASS
5.1	1.26E+6	2000	0.533	0.621	-	1.78	6.07	7.57	PASS	PASS
4.3	1.26E+6	2000	0.533	0.621	-	1.07	1.20	1.50	PASS	PASS
4.2	1.26E+6	2000	0.533	0.621	-	1.18	1.23	1.53	PASS	PASS
4.1	1.26E+6	2000	0.533	0.621	-	1.55	5.45	6.80	PASS	PASS
3.3	1.26E+6	2000	0.533	0.621	-	1.28	1.33	1.66	PASS	PASS
3.2	1.26E+6	2000	0.533	0.621	-	1.29	1.07	1.33	PASS	PASS
3.1	1.26E+6	2000	0.533	0.621	-	1.88	6.67	8.32	PASS	PASS
2.3	1.26E+6	2000	0.533	0.621	-	1.76	2.06	2.57	PASS	PASS
2.2	1.26E+6	2000	0.533	0.621	-	1.79	1.53	1.91	PASS	PASS
2.1	1.26E+6	2000	0.533	0.621	-	2.52	8.98	11.19	PASS	PASS
Deckfore	8.34E+5	1800	0.314	0.341	-	2.00	7.70	13.27	PASS	PASS
Deck6	8.34E+5	1800	0.314	0.341	-	1.23	1.58	2.73	PASS	PASS
Coach4	8.34E+5	1800	0.314	0.341	-	2.06	1.64	2.82	PASS	PASS
Coach5	8.34E+5	1800	0.314	0.341	-	2.18	3.24	5.58	PASS	PASS
Coach3	8.34E+5	1800	0.314	0.341	-	1.86	1.24	2.13	PASS	PASS
Deck4	8.34E+5	1800	0.314	0.341	-	1.36	2.19	3.77	PASS	PASS
Deck5	8.34E+5	1800	0.314	0.341	-	1.32	2.15	3.70	PASS	PASS
Deck3	8.34E+5	1800	0.314	0.341	-	1.64	2.58	4.44	PASS	PASS
Banera 2.1	8.34E+5	1800	0.314	0.341	-	1.64	1.60	2.76	PASS	PASS

	Material Properties				Results					
ID	EI N/mm^2	W_{FIBRE} g/m^2	Core Shear Stress N/mm^2	Core Comp. Stress N/mm^2	w_f ratio	$T_{core\ s}$ ratio	SM_I ratio	SM_O ratio	Plating Comply ?	Core Comply ?
Banera 2.2	8.34E+5	1800	0.314	0.341	-	2.24	3.84	6.62	PASS	PASS
Banera aft	8.34E+5	1800	0.314	0.341	-	1.66	1.62	2.80	PASS	PASS
Baneraaft2	8.34E+5	1800	0.314	0.341	-	3.06	5.22	8.99	PASS	PASS
Deck2	8.34E+5	1800	0.314	0.341	-	1.51	1.36	2.34	PASS	PASS
Deckaft	8.34E+5	1800	0.314	0.341	-	2.80	4.32	7.44	PASS	PASS
Bulkhead_aft	5.07E+5	1400	0.456	0.522	-	3.67	4.83	5.02	PASS	PASS
Bulkhead2	5.07E+5	1400	0.456	0.522	-	2.06	1.53	1.59	PASS	PASS
Bulkead fore	5.07E+5	1400	0.456	0.522	-	1.81	1.70	1.77	PASS	PASS
Bulkhead entrance	1.57E+6	3100	0.533	0.621	-	1.44	1.00	1.04	PASS	PASS
Plate keel	1.26E+6	2000	0.533	0.621	-	1.35	2.40	3.00	PASS	PASS
Bulkhead saloon	1.57E+6	3100	0.533	0.621	-	1.15	1.36	1.41	PASS	PASS
Aft 3 single skin	3.75E+4	3200	-	-	1.08	-	-	-	PASS	-
4.1 single skin keel	3.00E+5	4400	-	-	2.05	-	-	-	PASS	-
3.1 single skin keel	3.00E+5	4400	-	-	2.27	-	-	-	PASS	-

Stiffener Dimensions

	Dimensions										
ID	Length mm	Spacing mm	Curvature mm	Long. post m	x/Lwl	Location	Z_Q m	Z_{Tx} m	Z_{sda} m	Z_{sdt} m	Be+Bb (mm)
Bottom stff 4	2025.0	590.0	24.0	5.685	0.634	Bottom	-0.102	-0.350	1.053	0.976	570.320
Bottom stff aft	906.4	760.0	1.0	0.451	0.050	Bottom	0.105	-0.059	0.887	0.759	203.770
Bottom stff 2	2102.1	760.0	14.0	1.950	0.218	Bottom	-0.020	-0.224	0.952	0.821	459.640
Bottom stff 3	1684.6	760.0	17.0	3.842	0.429	Bottom	-0.090	-0.361	1.011	0.900	475.100
Engine stff 5	1920.4	560.0	35.0	7.640	0.853	Bottom	-0.181	-0.193	1.088	1.057	518.090
Engine stff 2	2107.7	760.0	14.0	1.950	0.218	Bottom	-0.230	-0.224	0.952	0.821	490.650
Engine stff aft	909.7	760.0	1.0	0.451	0.050	Bottom	-0.056	-0.059	0.887	0.759	234.470
Deckfore	299.8	350.0	0.0	8.734	0.975	Deck	1.115	0.001	1.105	1.103	210.000
Deck 5	1080.3	960.0	5.0	8.045	0.898	Deck	1.147	-0.144	1.095	1.074	454.000
Sup 5	837.1	1430.0	5.0	7.096	0.792	S/Structure. Front	1.250	-0.258	1.079	1.035	318.000
Sup 4	2015.9	1540.0	24.0	5.688	0.635	S/Structure. Front	1.478	-0.350	1.053	0.976	724.250
Sup 3	1683.8	1670.0	14.0	3.844	0.429	S/Structure. Front	1.633	-0.361	1.011	0.900	435.670
Deck2	2099.0	1740.0	4.0	1.951	0.218	Deck	0.552	-0.224	0.952	0.822	410.780
Deckaft	903.7	1246.6	1.0	0.451	0.050	Deck	0.487	-0.059	0.887	0.759	299.660
Frame 4 deck	498.8	1867.7	9.0	4.685	0.523	Deck	1.054	-0.385	1.032	0.935	261.770
Frame 4 sup	1190.7	1859.2	183.0	4.685	0.523	S/Structure. Top	1.499	-0.385	1.032	0.935	292.810
Frame 4 side	762.8	1865.3	1.0	4.685	0.523	W/tight Bulkhead	0.509	-0.385	1.032	0.935	261.530
Frame 4.3	601.6	1858.2	8.0	4.685	0.523	W/tight Bulkhead	0.401	-0.385	1.032	0.935	260.820
Frame 4.2	823.7	1849.3	43.0	4.685	0.523	Bottom	-0.264	-0.385	1.032	0.935	259.930
Frame 4	190.5	1843.9	4.0	4.685	0.523	Bottom	-0.389	-0.385	1.032	0.935	259.390
Deck sup 5	1911.1	1430.0	65.0	7.627	0.851	Deck	1.161	-0.194	1.088	1.057	525.720

Stiffener Calculations

	Calculations					
ID	K_{AR}	K_{SUP}	K_L	K_{SF}	K_{BM}	Design Pressure KN/m^2
Bottom stff 4	0.180	-	1.000	0.500	0.063	8.572
Bottom stff aft	0.303	-	0.449	0.500	0.083	7.000
Bottom stff 2	0.167	-	0.617	0.500	0.083	7.000
Bottom stff 3	0.204	-	0.828	0.625	0.125	7.727
Engine stff 5	0.192	-	1.000	0.625	0.125	8.799
Engine stff 2	0.166	-	0.617	0.500	0.083	7.000
Engine stff aft	0.302	-	0.449	0.500	0.083	7.000
Deckfore	0.612	-	1.000	0.500	0.083	11.590
Deck 5	0.257	-	1.000	0.500	0.063	4.861
Sup 5	0.261	0.686	-	0.625	0.125	5.000
Sup 4	0.141	0.670	-	0.500	0.063	5.000
Sup 3	0.161	0.670	-	0.625	0.125	5.000
Deck2	0.130	-	0.617	0.500	0.083	5.000
Deckaft	0.262	-	0.449	0.500	0.083	5.000
Frame 4 deck	0.304	-	0.922	0.500	0.063	5.317
Frame 4 sup	0.199	0.698	-	0.500	0.063	5.000
Frame 4 side	0.252	-	-	0.500	0.063	3.560
Frame 4.3	0.281	-	-	0.500	0.063	2.807
Frame 4.2	0.244	-	0.922	0.500	0.083	10.289
Frame 4	0.436	-	0.922	0.500	0.083	18.400
Deck sup 5	0.151	-	1.000	0.625	0.125	3.500

Stiffener Results

	Required				Offered					Results				
ID	BM_D N.m	F_D N	Web h/t	Flange w/t	Offered Stiffener	BM_D N.m	F_D N	Web h/t	Flange w/t	BM_D ratio	F_D ratio	Web H/T_W ratio	Flange D/T_F ratio	stiffener comply?
Bottom stff 4	1296.2	5120.8	44.4	31.5	Bottom stiff	2135.8	23210.0	29.070	21.186	1.65	4.53	1.53	1.49	PASS
Bottom stff aft	-364.2	2411.0	63.8	57.6	Bottom stiff	-2004.4	22574.0	29.070	21.186	5.50	9.36	2.20	2.72	PASS
Bottom stff 2	-1958.9	5591.6	42.4	25.5	Bottom stiff	-2109.5	23093.0	29.070	21.186	1.08	4.13	1.46	1.20	PASS
Bottom stff 3	-2083.1	6182.7	40.3	24.7	Bottom stiff	-2113.5	23111.0	29.070	21.186	1.01	3.74	1.39	1.17	PASS
Engine stff 5	-2271.5	5914.1	75.2	45.8	Engine stiff	-7909.5	76925.0	35.991	18.737	3.48	13.01	2.09	2.45	PASS
Engine stff 2	-1969.4	5606.5	77.2	49.1	Engine stiff	-7883.6	76886.0	35.991	18.737	4.00	13.71	2.15	2.62	PASS
Engine stff aft	-366.9	2419.8	116.9	111.3	Engine stiff	-7536.6	75983.0	35.991	18.737	20.54	31.40	3.25	5.94	PASS
Deckfore	-30.4	608.1	208.4	367.1	Deck stiff	-6786.3	60731.0	38.760	35.689	223.40	99.87	5.38	10.29	PASS
Deck 5	340.4	2520.8	103.2	114.1	Deck stiff	7345.3	61698.0	38.760	35.689	21.58	24.48	2.66	3.20	PASS
Sup 5	-626.3	3740.8	84.5	83.2	Deck stiff	-7188.7	61342.0	38.760	35.689	11.48	16.40	2.18	2.33	PASS
Sup 4	1955.7	7761.2	58.9	48.2	Deck stiff	7534.9	61888.0	38.760	35.689	3.85	7.97	1.52	1.35	PASS
Sup 3	-2959.2	8787.3	55.3	38.7	Deck stiff	-7327.6	61666.0	38.760	35.689	2.48	7.02	1.43	1.08	PASS
Deck2	-3194.1	9130.6	54.2	37.1	Deck stiff	-7302.0	61616.0	38.760	35.689	2.29	6.75	1.40	1.04	PASS
Deckaft	-424.2	2816.4	97.3	100.9	Deck stiff	-7162.1	61266.0	38.760	35.689	16.88	21.75	2.51	2.83	PASS
Frame 4 deck	154.4	2476.9	46.2	66.5	Frame	1131.6	12174.0	25.840	21.495	7.33	4.92	1.79	3.09	PASS
Frame 4 sup	494.2	3320.6	40.0	37.3	Frame	1138.9	12221.0	25.840	21.495	2.30	3.68	1.55	1.73	PASS
Frame 4 side	241.5	2532.5	45.7	53.2	Frame	1131.5	12173.0	25.840	21.495	4.69	4.81	1.77	2.47	PASS
Frame 4.3	118.0	1569.2	58.1	76.1	Frame	1131.3	12172.0	25.840	21.495	9.59	7.76	2.25	3.54	PASS
Frame 4.2	-1000.6	7288.5	27.0	26.1	Frame	-1131.1	12171.0	25.840	21.495	1.13	1.67	1.04	1.21	PASS
Frame 4	-102.6	3231.7	40.5	81.5	Frame	-1131.0	12170.0	25.840	21.495	11.02	3.77	1.57	3.79	PASS
Deck sup 5	-2257.9	5907.4	67.5	44.5	Deck stiff	-7407.4	61791.0	38.760	35.689	3.28	10.46	1.74	1.25	PASS

I DETAILED WEIGHT ESTIMATION

In this appendix, the weight estimation is developed for each of the groups considered.

I.1 Structure

For the panels, the weight is estimated based on the calculation given by Hullscant per square meter.

Panel position	Weight [kg/m^2]	Area [m^2]	m [kg]	x_g [m]	y_g [m]	z_g [m]
Bottom	4.45	24.57	109.27	4.06	0.00	0.32
Side	3.96	14.29	56.54	4.76	0	1.04
Deck	3.66	28.47	104.09	3.59	0	1.43
Bulkheads	3.396	5.63	19.12	2.09	0	0.83
Entrance bulk	6.23	4.49	27.99	3.00	0	1.01
Total			317.01	3.82	0.00	0.91

Table I.1: Calculation of the weight and centre of gravity of the panels

For the stiffeners, the weight estimation results using the weight per meter given by Hullscant and adding the weight of the core (60 kg/m^3). In the case of the symmetrical stiffeners, both of them are considered in the length calculation.

Stiffener	Weight [kg/m]	Length [m]	m [kg]	x_g [m]	y_g [m]	z_g [m]
Keel	5.70	17.26	98.43	4.30	0	0.14
Bottom	2.16	17.60	38.06	3.35	0	0.35
Deck	5.27	8.92	47.049	4.44	0	1.50
Frame	1.34	3.96	5.30	4.69	0	1.07
Total			188.83	4.15	0	0.55

Table I.2: Calculation of the weight and centre of gravity of the reinforcements

Additionally, the gelcoat of the exterior panels and the panels which create the interior floor are considered.

Element	Weight [kg/m^2]	Area [m^2]	m $[kg]$	x_g $[m]$	y_g $[m]$	z_g $[m]$
Gelcoat	0.60	74.64	44.78	15.96	0.00	3.75
Floor of the interior	3.66	9.04	49.56	4.36	0.00	0.25
Total			94.34	9.87	0.00	1.91

Table I.3: Calculation of the weight and centre of gravity of the additional structural elements

Then the total weight of the structure is obtained.

	Weight [kg]	L_{CG} [m]	T_{CG}[m]	V_{CG} [m]
Panels	317.01	3.82	0.00	0.91
Stiffeners	188.83	4.15	0	0.55
Others	94.34	9.87	0.00	1.91
Total	617.65	4.87	0.00	0.93

Table I.4: Calculation of the weight and centre of gravity of the structure

I.2 Engine and systems

The weight estimation includes the heaviest elements by far from the studied in the System's section, which are the engine and the battery.

	Weight [kg]	L_{CG} [m]	T_{CG}[m]	V_{CG} [m]
Engine	132	2.68	0	0.45
Battery	33.2	1.88	0	0.43
Total	165.2	2.52	0	0.45

Table I.5: Calculation of the weight and centre of gravity of the engine and systems

I.3 Furniture

The weight estimation of all the furniture and appliances of the accommodation area is presented next.

	Weight [kg/m^2]	Area [m^2]	m [kg]	L_{CG} [m]	T_{CG}[m]	V_{CG} [m]
Tables, counter and chair	10.00	3.31	33.10	4.42	-0.06	0.80
Bench	17.00	2.40	40.80	5.69	0.00	0.75
Cabinets	15.00	2.16	37.20	3.73	0.59	0.85
Beds	2.93	6.66	19.51	4.12	0.00	0.75
Matress/cushions	6.00	10.26	61.56	4.67	0.00	0.75
Stairs			12.00	3.19	0.00	0.60
Stove			4.50	3.56	1.17	0.85
Sink			1.00	4.31	1.07	0.87
Toilet			10.80	4.45	-1.18	0.72
Total			220.47	4.50	0.06	0.77

Table I.6: Calculation of the weight and centre of gravity of the furniture

I.4 Appendices

The weight estimation of the heaviest component of the vessel, the keel, is assessed, as well as the steering and rig system is presented in the following table.

	Weight [kg]	L_{CG} [m]	T_{CG}[m]	V_{CG} [m]
Keel	843.50	4.39	0.00	-0.79
Bulb	308.00	4.31	0.00	-1.66
Mast	25.79	4.69	0.00	7.49
Boom	7.20	2.25	0.00	2.65
Rudders	14.00	0.21	0.00	0.07
Sails	44.80	4.40		6.80
Total	1243.29	4.32	0.00	-0.53

Table I.7: Calculation of the weight and centre of gravity of the appendices

J STABILITY ANALYSIS IN DETAIL

In this appendix, the loadcases calculation and GZ curves are presented, as well as the detailed criteria verifications.

J.1 Loadcase calculation

The weight estimation and position of the centre of gravity of all three loading conditions are next presented. These include the tank capacity as described in Chapter 11, and the Free Surface Moments Correction when applied.

Maximum load

Item Name	Quantity	Unit Mass [kg]	Total Mass [kg]	L_{CG} [m]	T_{CG}[m]	V_{CG} [m]
Lightship	1	2396.6	2396.6	4.352	0.006	0.195
Crew	1	150	150	1.52	0	1.85
Fresh water	0%	101.1	0	5.284	-0.854	0.4
Grey water	0%	101.1	0	5.284	0.854	0.4
Black water	0%	41.5	0	2.609	0.915	0.35
Fuel	0%	100.8	0	1.104	0	0.33
Total Loadcase			2546.6	4.185	0.005	0.293

Table J.1: Calculation of the weight and centre of gravity of the Maximum load condition

Minimum operation

Item Name	Quantity	Unit Mass [kg]	Total Mass [kg]	L_{CG} [m]	T_{CG}[m]	V_{CG} [m]
Lightship	1	2396.6	2396.6	4.352	0.006	0.195
Crew	1	300	300	1.52	-1.44	1.85
Fresh water	100%	101.1	101.1	5.283	-0.885	0.527
Grey water	100%	101.1	101.1	5.283	0.885	0.527
Black water	100%	41.5	41.5	2.602	1.042	0.524
Fuel	100%	100.8	100.8	1.1	0	0.48
Total Loadcase			3041	4.003	-0.123	0.394

Table J.2: Calculation of the weight and centre of gravity of the Minimum operation condition

Loaded arrival

Item Name	Quantity	Unit Mass [kg]	Total Mass [kg]	L_{CG} [m]	T_{CG}[m]	V_{CG} [m]	FSM [kg.m]
Lightship	1	2396.6	2396.6	4.352	0.006	0.195	0
Crew	1	150	150	1.52	0	1.85	0
Crew LA	1	150	150	4.5	0	1.5	0
Fresh water	10%	101.1	10.1	5.284	-0.864	0.414	4.436
Grey water	95%	101.1	96	5.283	0.885	0.521	5.575
Black water	95%	41.5	39.4	2.602	1.04	0.518	3.037
Fuel	10%	100.8	10.1	1.1	0	0.345	3.302
Total			2852.2	4.21	0.046	0.367	16.35
FS correction						0.006	
Total Loadcase			2852.2	4.21	0.046	0.373	

Table J.3: Calculation of the weight and centre of gravity of the Loaded arrival condition

J.2 Stability graphs and criteria verification

The GZ curves of all three loading conditions are next presented. These include all the important parameters to verify the intact stability. The detailed numbers and verifications of the intact stability criteria for each loading condition are shown in the tables following each GZ curve.

Maximum load

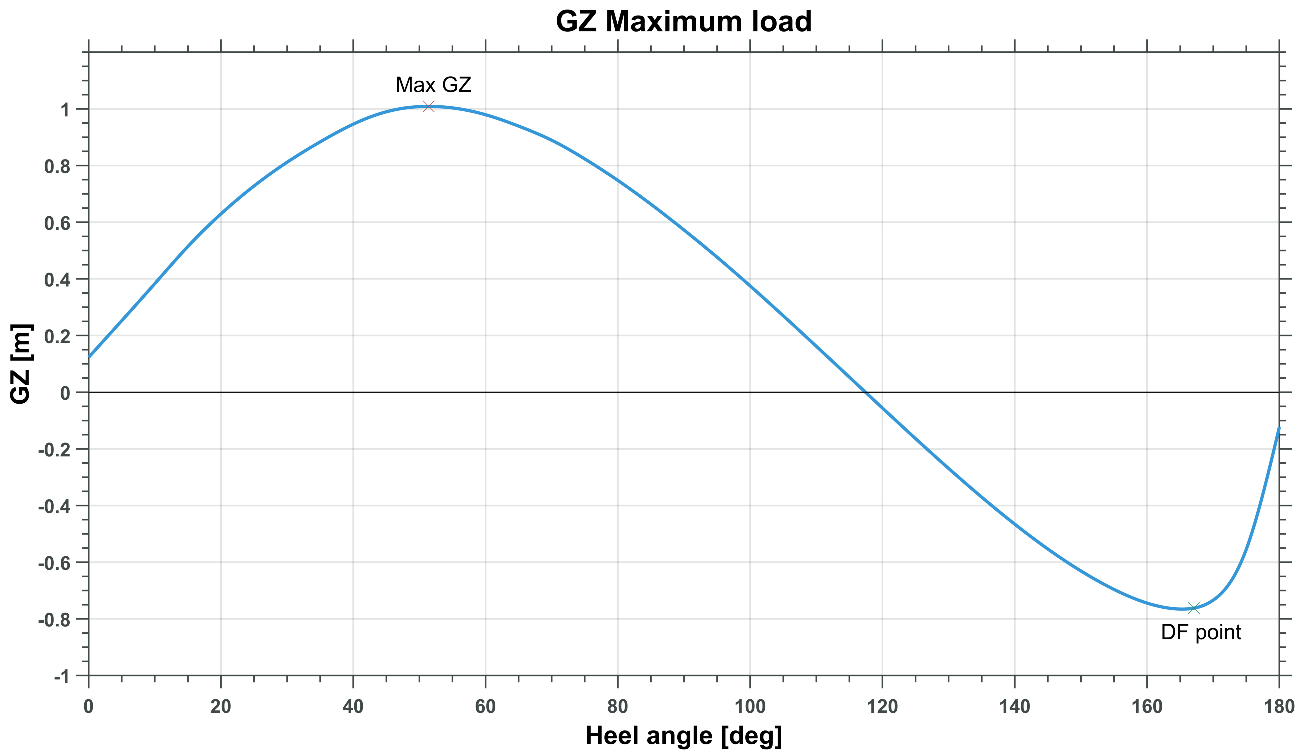


Figure J.1: GZ curve of the Maximum load condition

Criteria		(units)	Result	Pass/Fail	(%)
6.2.2 Downflooding height at equilibrium				**Pass**	
H1	0.61				
F1.1	0.67				
F1.2	0.59				
F1	0.67				
F2	0.73				
F3	1				
F4	0.64				
F5	1				
from the greater of					
hd	0.19	m			
hd min.	0.5	m			
the min. freeboard of the downflooding point					
shall be greater than (>)	0.5	m	0.874	Pass	174.8
6.2.3 Downflooding angle				**Pass**	

shall be greater than (>)	40	deg	167	Pass	417.5

Table J.4: Detailed criteria verification of the stability for the Maximum load condition

Minimum operation

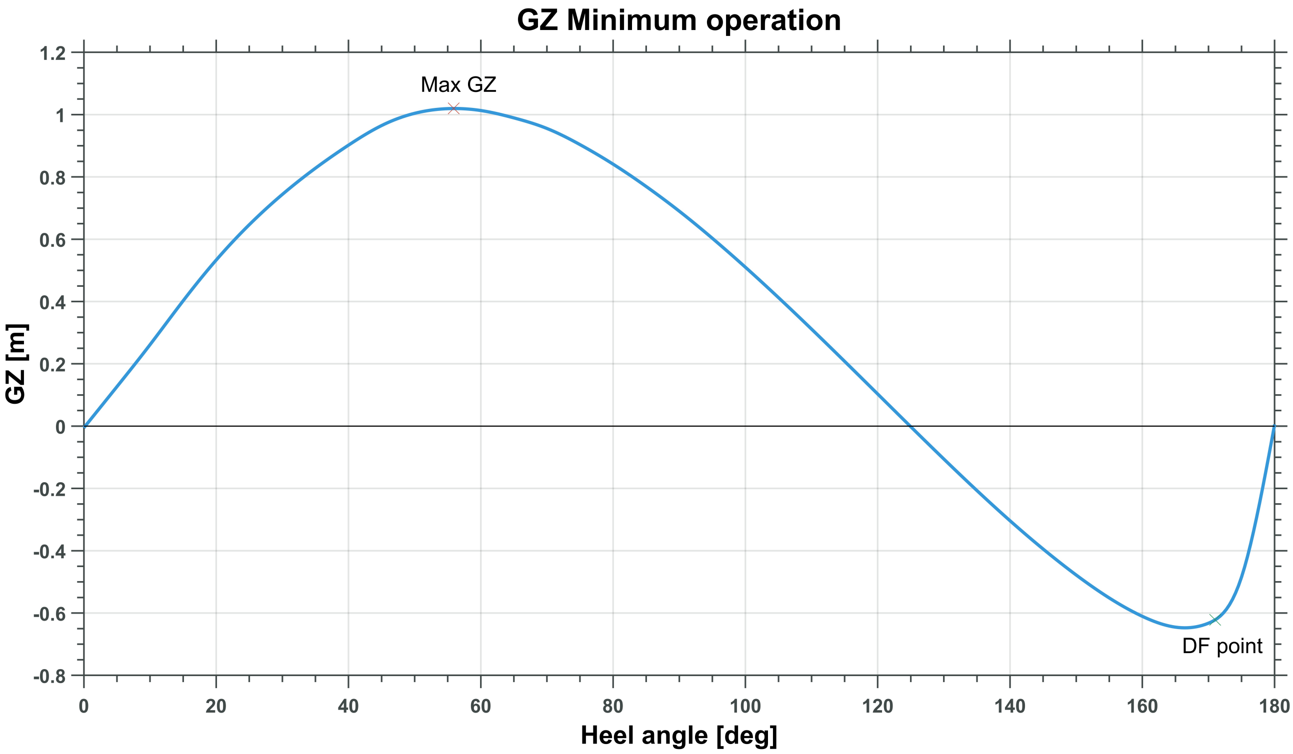


Figure J.2: GZ curve of the Minimum operation condition

Criteria		(units)	Result	Pass/Fail	(%)
6.4 Minimum righting energy				**Pass**	
shall be greater than (>)	172000	kg.m.deg	200644	Pass	165.5
6.5 Angle of vanishing stability				**Pass**	
shall be greater than (>)	121	deg	124.91	Pass	100.5
6.6 Stability index (STIX)				**Pass**	
FDS, dynamic stability factor	1.50				
FIR, inversion recovery factor	1.01				
FKR, knockdown recovery factor	1.41				
FDL, displacement-length factor	0.89				

FBD, beam-displacement factor	0.64				
FWM, wind moment factor	1.00				
FDF, downflooding factor	1.25				
STIX value shall be greater than (>)	32,0	m	36	Pass	127.9

Table J.5: Detailed criteria verification of the stability for the Minimum operation condition

Loaded arrival

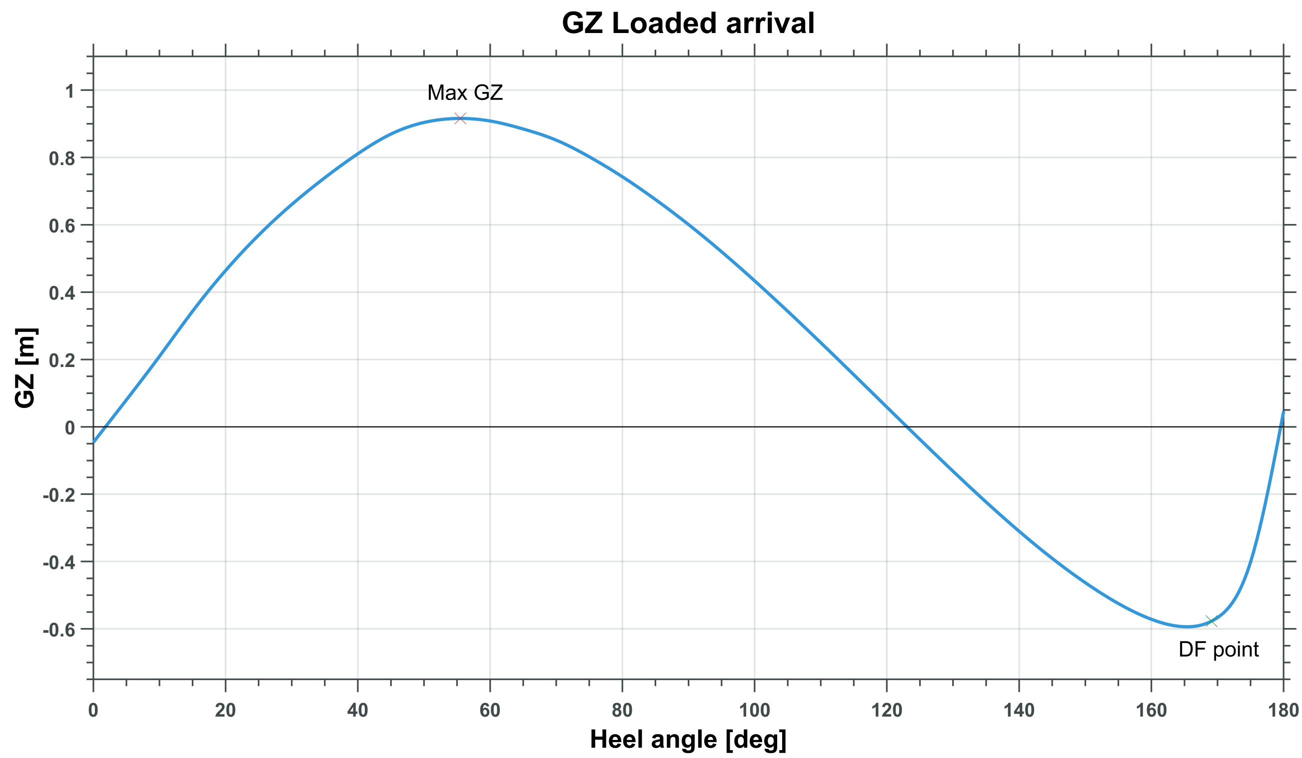


Figure J.3: GZ curve of the Loaded arrival condition

Criteria		(units)	Result	Pass/Fail	(%)
6.4 Minimum righting energy				**Pass**	
shall be greater than (>)	172000	kg.m.deg	356500	Pass	207.3
6.5 Angle of vanishing stability				**Pass**	
shall be greater than (>)	121	deg	124.30	Pass	100.1
6.6 Stability index (STIX)				**Pass**	
FDS, dynamic stability factor	1.44				

FIR, inversion recovery factor	1.00				
FKR, knockdown recovery factor	1.39				
FDL, displacement-length factor	0.90				
FBD, beam-displacement factor	0.75				
FWM, wind moment factor	1.00				
FDF, downflooding factor	1.25				
STIX value shall be greater than (>)	32,0	m	35	Pass	110.9

Table J.6: Detailed criteria verification of the stability for the Loaded arrival condition