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Meuse River Eco-Vessel: A Case Study on the Comprehensive Energy-Efficient Design of an Inland Passenger Vessel

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Abstract:

This paper outlines the systematic preliminary design of an inland passenger vessel for river Meuse, emphasizing energy efficiency and compliance with regulations. Beginning with the requirements, an electrical propulsion system was chosen to create a green vessel, aligning with the market trend toward zero-emission solutions. Using regression analysis, vessel dimensions were determined, and the general arrangements were optimized to meet requirements while maximizing passenger comfort. The design process involved a single iteration of the spiral, acknowledging the potential for further refinement. Scantlings were calculated per BV Rules, allowing for weight estimation and subsequent cost assessment, covering material, labor, and outfit costs. The hull form was shaped using Maxsurf™ for minimized resistance, and CFD calculations via FineMarine™ determined the required brake power, leading to engine selection. Detailed design steps included propeller design based on the Wageningen B series, rudder design according to regulatory calculations, and selection of a suitable bow thruster. An electrical balance assessment estimated overall consumption, guiding the selection of batteries, including emergency backups. Stability calculations, compliant with ES-TRIN Rules, were performed using Maxsurf's Stability module, presenting key parameters for each load case. This study offers insights into the preliminary design process for inland passenger vessels, introducing industry-standard tools and methodologies. The presented approach focuses on energy-efficient solutions and regulatory compliance, providing a foundation for further iterations and detailed design phases.

Keywords — **Advance Ship Design Eco-Passenger Vessel, Energy Efficiency, Meuse River, Preliminary Design**

1. INTRODUCTION

All the steps taken to propose an affordable, ergonomic, aesthetic, and energy-efficient vessel in this case study will be presented in the next sections. All the calculations have been carried out based on the Bureau Veritas rules of February 2019 - Rules for the Classification of Inland Navigation Vessels [1, 2] and the ES-TRIN regulations [3], to ensure a safe design that can be certified by the Class.

First, the main requirements are considered in the design, and the operational characteristics of the vessel are presented. Then, the ship's dimensions are addressed, based on the analysis of vessels designed for comparable purposes, thus having similar requirements. Next, the General Arrangement (GA) is detailed to propose an ergonomic ship and determine the location of the equipment required to operate the vessel. Then, the scantlings are selected according to the rules [1] to propose a sufficiently stiff and safe structure. After that, a powering analysis is performed based on CFD resistance calculations (made using the software FineMarine™), to determine the required brake power to propel the ship. This enables the selection of a suitable engine for the ship. Furthermore, the selected propeller and rudder designs according to the class rules are presented. An electrical load estimation is done to determine the power usage of all electrical systems on board and to select the batteries. Then, the weight estimation of the ship is performed to determine the position of its gravity centre and total displacement in lightweight and loaded conditions. Different load cases are taken into consideration. A cost estimation of the design is then realized. Stability calculations are made with Maxsurf to fulfill the rules' requirements. Four loading cases are considered to assess the ship's stability and three different passenger crowding situations are evaluated. Finally, conclusions will be raised from the presented design and analysis to emphasize the fact that the vessel is doable for a minimized cost and that it suits all requirements.

1.1. Requirements

It is essential to base the preliminary design on the basic requirements. As per requirements, the powering of the vessel should be as "green" as possible, meaning that the engine must be fully electrical or hybrid to meet the current trend of eco-friendly and energy-efficient vessels. The ship needs to carry 100 passengers and 2 crew members, including the captain and a sailor. Each person should have a seat. 80 seats are required on the main deck, and 20 on the upper deck terrace for the tour during the day. The 80 seats of the main deck should be removable to allow rearranging the main deck for dinner at night. In this configuration, tables need to be installed to accommodate 60 passengers. The dinner is prepared on shore, meaning that no kitchen is required. Only a pantry is necessary on the main deck to heat the meals and wash dishes. The ship should be accessible to handicapped people.

Due to the limited depth of the Meuse River and its numerous bridges, the maximum draft is 1.2 meters and the maximum air draft is 3.7 meters. Also, the mooring system should allow fast mooring operations to avoid losing time during boarding. Finally, considering cost efficiency, the overall cost should be minimized as much as possible to propose an affordable vessel.

1.2. Characteristics of Operation

The proposed route starts from the Yacht port of Liège near "Albert 1er"bridge, until Robinson's island in "Visé" and returns. This represents about 40 kilometers that are done at an operating speed of 10 km/h. Hence, the tour lasts about 4 hours. The tour is realized twice during the day: once in the morning from 8:00 to 12:00, and once in the afternoon from 14:00 to 18:00. The batteries are recharged in between. Moreover, at night, the ship welcomes passengers to have dinner on board from 19:00. In that case, the ship is docked in the Yacht port of Liège, as depicted in the figure below.

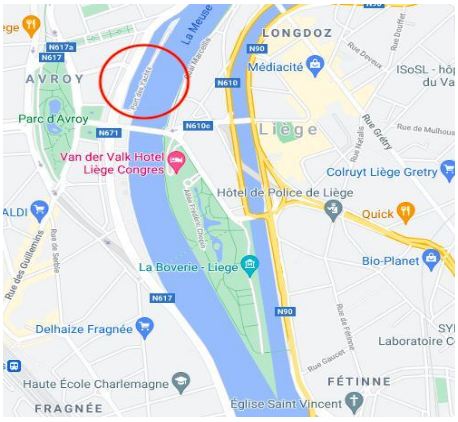

Figure 1. Starting point of the sail

2. DESIGN METHODOLOGY & RESULTS

2.1. Main Dimensions

In this step, the main dimensions for the first design are selected based on a regression analysis. During later design steps, these values are adapted to the exact requirements specified in the introduction.

2.1.1. Similar Ship Analysis

To select the preliminary dimensions of the vessel, an analysis of ships with a similar purpose and passenger capacity was done. For this, the main data of reference ships is listed first. Then, the ratios of the length of the ship to its breadth L_{WL}/B and its draft L_{WL}/T can be determined. These characteristic ratios and the average values can then be used to determine the main dimensions of the vessel.

In Figure 2, the breadth values of the reference ships are plotted against their lengths. Each blue dot in the diagram represents one parent vessel. The average length-to-breadth ratio is determined to be $L_{WL}/B = 3.4$ which is shown in red. Similarly, the draft is plotted against the length in Figure 2. The computed average length to draft ratio is $L_{WL}/T = 18.4$ ranging from 10 to 32.

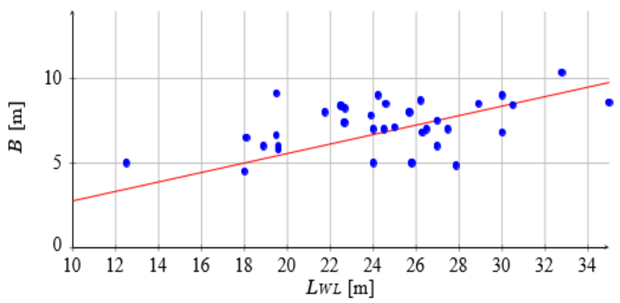

Figure 2. Regression Analysis - Breadth B Plotted against Length L_{WL}

2.1.2. Selection of Dimensions

Based on the analysis of the reference ship data, a first set of main dimensions is specified as shown in Table 1. These dimensions satisfy the limitations on the draft of T_{max} = 1.2 m given in the requirements. A length $L_{WL} \leq 24$ m is chosen to avoid stricter class regulations.

During the design process of the ship, these dimensions are adapted. As shown in Table 2., the preliminary length is kept to fulfill the previously mentioned restrictions, and the depth is not changed, either. During the preparation of the general arrangement, the breadth is slightly decreased as less space on the deck is needed to fit the dining and sitting arrangements, respectively. The final draft is determined after the weight estimation and the final hull modeling is done. It is found to be slightly less than the originally estimated value.

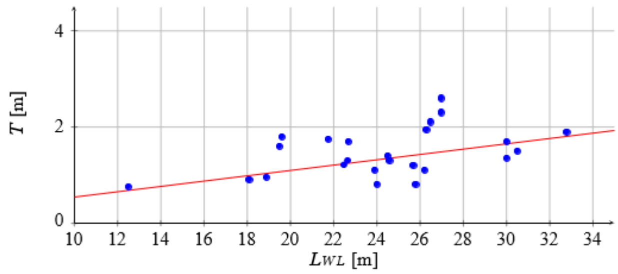

Figure 3. Regression Analysis - Draft T Plotted against Length L_{WL}

TABLE 1. PRELIMINARY DIMENSIONS OF THE SHIP

Parameter	Value	Unit
Length L_{OA}	24	m
Beam B	6	m
Depth D	1.7	m
Draft T	1	m

TABLE 2. FINAL DIMENSIONS OF THE SHIP

Parameter	Value	Unit
Length L_{OA}	24	m
Beam B	5.8	m
Depth D	1.7	m
Draft T	0.87	m

2.2. General Arrangement (GA)

The key point when realizing the GA is to carefully use each available space smartly. This is essential in order to propose a practical vessel to enhance the passengers' journey and ease the work of the crew members when operating the ship.

As mentioned in the ship's requirements presented in Section 1.1, two different arrangements must be designed. The first one allows 80 passengers to sit on the main deck and 20 on the upper deck to enjoy the tour. The second one lets 60 passengers have dinner on the main deck.

The profile view of the vessel and the two general arrangements proposed are presented in Figures 4,5 and 6. All the drawings have been made with Autocad™. Each drawing is represented with a scale of 0.5-meter frame spacing, and the reference 0 is taken at the rudder stock centre.

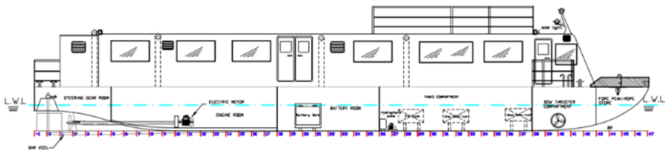

Figure 4. Profile View

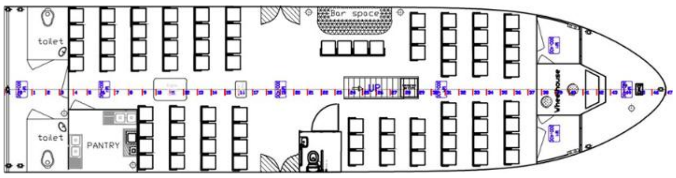

Figure 5. GA Sitting

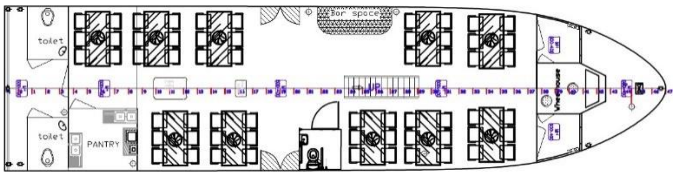

Figure 6. GA Dinning

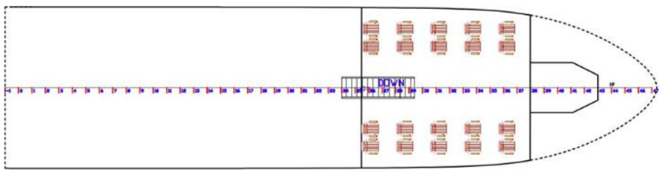

Figure 7. GA Upper Deck

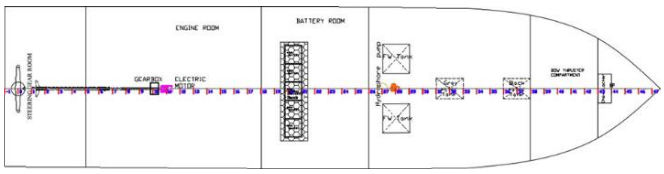

Figure 8. GA Bottom

As can be seen in Figure 4., wide windows are placed on the side walls of the super-structure to allow the passengers to appreciate the view. The ship's profile is symmetrical about the centre line so that only one side is depicted in Figure 4. On each side, a double door is located around the middle of the vessel, to allow an efficient boarding of the 100 passengers when the ship is docked. That way, passengers directly enter the ship close to their seats and time is saved. A small metallic bridge is used for boarding to fill the gap between the dock and the ship.

At the ship's bow, a single door is set up on each side of the wheelhouse to allow the crew members to quickly reach any side of the ship. For aesthetic reasons and to reduce overall air drag, the front part of the wheelhouse is inclined at 30 degrees from the vertical. A windshield equipped with 2 wipers is located on it, together with 2 square windows on the side walls, to give maximal visibility to the captain. On top of the wheelhouse, the front side lights are installed. 2 more lights are installed aft, also on top of the superstructure to make them more visible.

An open deck is provided at the aft and bow of the main deck, to perform mooring operations and also let the passengers enjoy some fresh air. It is also seen in Figure 4 that guard rails are provided on the terrace and the open deck for passengers and crew's safety. Additionally, 10 mooring fixations are installed on the open deck: 5 aft, and 3 plus 2 mooring bollards at the bow. Their symmetrical disposition results in an efficient, stable, and strong mooring. The anchor's winch is also represented at the bow of the open deck. This system allows to dive and lift the anchor without too much effort.

In total, 6 watertight compartments are designed below the main deck: the steering room, the engine room, the battery room, the tanks compartment, a bow thruster compartment, and a compartment at the bow to store the anchor's chain. Aeration pipes are installed to enable the air from each of these closed compartments to circulate. Aeration grids are also provided on the walls of each toilet, main deck, and wheelhouse.

Now, when looking at Figures 5 and 6, it can be seen that 2 toilet rooms are placed on the open deck at the aft of the vessel. They are both equipped with a small sink so that passengers can wash their hands. An additional toilet for eventual handicapped passengers is located right in the middle of the main deck to be easily accessible. It is equipped with special ramps. The pantry is placed aft on the starboard side. It is equipped with 2 large sinks to wash dishes and an oven and microwave to heat the meals.

As the ship is made for recreational tours, a bar is proposed to serve drinks to travelers. The second crew member mainly works there when no sailing operation is required. Drinks are not included in the price of the ticket. Moreover, Man Hatches (MH600x400), represented in blue in Figures 5 and 6, are present on the main deck to allow access to each compartment. For the engine room, an emergency access and engine casing hatch are also designed. In the wheelhouse, 2 seats allow the crew to sit and the control console is also represented.

Regarding the seating arrangement, the 80 removable seats are disposed of in rows as represented in Figure 5. 60 centimeters are kept between each row so that passengers can sit comfortably and even stretch their legs. There are 43 seats on the port side and 37 on the starboard side. This allows for an even distribution of the weight resulting from the 80 passengers on the main deck. This is crucial to avoid stability issues.

The upper deck plan is presented in Figure 7. Stairs are located in the centre of the main deck's room to allow passengers to go on the terrace. The opening that allows access to the terrace is a waterproof hatch that can be closed in case of rain. Again, to avoid stability issues, a symmetrical disposition of the 20 seats is taken, so that 10 seats are placed on each side of the terrace. The 20 seats on the terrace are fixed and waterproof.

Concerning the dining arrangement depicted in Figure 6, the 60 guests are disposed of in 10 tables of 6. The tables are chosen rectangular to gain space in the room. Once again, 5 tables are located on each side of the room to have a homogeneous weight distribution and avoid stability problems.

Finally, the bottom plan is presented in Figure 8. This view allows us to visualize the position of the necessary equipment in each of the 6 aforementioned compartments. As can be seen, the steering room contains the rudder control system. In the engine room, the electric motor and gearbox are present. The battery room contains all the batteries in a battery bank that is supported by small pillars to fix it properly to the bottom. The tanks' compartment is where all necessary liquids are stored, in tanks supported by pillars (c.f Figure 4). It contains 2 fresh water tanks of 0.5 m^3 each so that 1 m3 of fresh water is available. A hydrophore pump is used to inject the water into the plumbing arrangement. A grey water tank is used to store used fresh water, and a black water tank to store the feces from the toilets. These tanks can be emptied and cleaned at the port. A chain locker is also installed in the anchor's chain compartment.

2.3. Scantlings

To find the scantlings of the ship's structure, chapter 5 - section 6 - of the BV rules [1] concerning vessels of less than 40 meters is used. Formulas are present in these rules to compute the minimum scantlings required for the ship to be safe, i.e. resist operating loads with some defined margins.

To ease the calculations, it is first important to organize the structural arrangement of the vessel as follows: bottom shell, side shell, main deck, and superstructure. It will be seen that for each part of the structure, formulas are provided by the rules with defined parameters, to enable the naval architect to compute the section modulus w associated with each member. Tables are given in the rules to then select the dimensions of the profile according to the required value of w found.

The stiffening system of the vessel has been chosen as a combination of both longitudinal and transverse systems along the major part of its length. At the bow, only transverse frame reinforcements are selected because longitudinals (or stiffeners) are harder to weld on bent plates, and space is limited. 5 transverse watertight bulkheads are required by the rules [1]. They separate the 6 compartments located under the main deck. Moreover, one central girder and 2 side girders are designed to stiffen the ship and ensure that the space between them does not exceed 1.5 m, as required by the rules. At the level of the engine, frames are placed at each frame spacing - i.e. each 50 centimeters - to create additional support and dampen the vibrations due to the engine, to avoid their propagation in the rest of the structure. The central girder is separated to form a continuous reinforcement around the engine, as depicted in Figure 18. Also, a transverse frame is added at the level of the rudder to support its weight. The structural drawings can further be found in section 2.3.6.

To proceed with the preliminary scantlings' calculations, a stiffener spacing of 500 mm is selected for the bottom, side, main deck, and superstructure. For the transverse girders (or frames), which are the main supports of the longitudinals, a spacing of 2000 mm is chosen for all the parts of the structure. Finally, the girders' spacing is taken as 1500 mm as required by the rules, in the bottom, main deck, and superstructure. The side shells are not reinforced by longitudinal girders, because it would be too complicated to weld them on inclined shells, and transverse frames are sufficient to stiffen them.

The stiffeners are chosen as flat bars because of their low price and high availability on the market. Longitudinal girders and transverse frames are chosen as T profiles because the required values of their sectional modulus w are high. The material chosen for the vessel is mild steel.

2.3.1. Design Pressure Calculations

In order to calculate the scantlings for the bottom and side regions, the design pressure must first be computed according to the rules [1]. It is defined as the maximum pressure that can act on the structure due to the water column, considering different load cases due to different sea states. The pressure acting on the main deck and upper deck are also defined to consider the weight due to passengers and eventually other loads acting in these areas.

The procedure proposed by the BV rules [1] to compute the design pressure is as follows: First, a wave height of 0,6 m is selected according to the range of navigation IN (0,6), as shown in Table 3 presented below.

Range of navigation	Wave height, H
IN(0)	0
IN(0,6)	0,6
IN(0,6 < x ≤ 2)	0,6 < H ≤ 2,0

Figure 9. Wave Height (Rules)

For the bottom and side shells, the design external pressure p_E is taken as the sum of the still water pressure p_{SE} and added pressure due to waves p_{WE} at locations under the waterline, and as the wave pressure over the waterline, as shown below. where γ_{W2} is a partial safety factor taken equal to 1.

$$\text{for } z \le T_1: \quad p_E = p_{SE} + \gamma_{W2}\, p_{WE} \tag{1}$$

$$\text{for } z > T_1: \quad p_E = \gamma_{W2}\, p_{WE} \tag{2}$$

The wave pressure p_{WE} can be calculated according to Figure 10 below. T_1 is the scantling draft taken as 1.1 m, z is the vertical position where the pressure is calculated (taken as 0 for the bottom and 0,8 for the side), ρ and g are the seawater density and gravity acceleration, respectively taken as 1025 kg/m3 and 9,81 N/kg, and h_1 and h_2 are respectively the reference values of relative motion in upright and inclined conditions, calculated using: where B_W is the molded breadth taken as 6 m, and A_R the roll amplitude defined as: where

$$h_1 = h_2 - A_R \frac{B_W}{2} \tag{3}$$

$$A_R = \frac{n}{1,7}\left(\sqrt{\frac{GM}{\delta}} + 0,9\right)\frac{T_1}{B}\frac{6,3}{\sqrt[3]{\Delta}} \tag{4}$$

Δ is the ship's mass, GM the metacentric height, δ the roll radius of gyration taken as 0, 35B
(full load), and n is the navigation coefficient computed by: H being the wave height of 0,6

$$n = 0,85\ H \tag{5}$$

GM is given by: where C_{GM} = 0, 95 (full load), and C_B is the block coefficient. And h_2

$$GM = \frac{C_{GM} B^2}{12 T_1 C_B} + 0,5 T_1 - KG \qquad (6)$$

And h_2 is given by: where L is the ship's length between perpendiculars.

$$\frac{n}{1,7}\left[\left(0,63 - \frac{2,5L}{1000}\right) + (BT_1)^{0,14}\right] \qquad (7)$$

Furthermore, the still water pressure p_{SE} is given by:

$$p_{SE} = \rho g\,(T_1 - z) \qquad (8)$$

The results obtained for the design of external pressure p_E are presented in Table 3 below.

TABLE 3. DESIGN EXTERNAL PRESSURE FOR SCANTLINGS'

Location	t_1 [mm]	t_2 [mm]	t_3 [mm]	Selected t [mm]
Bottom	3,56	1,95	2,11	6
Side	3,49	1,10	-	5
Main deck	3,05	1,27	3,04	5
Upper deck (not exposed)	3,72	0,83	3,72	5
Upper deck (exposed)	4,22	1,13	4,22	5
Collision bulkheads	2,37	1,61	-	6
Watertight bulkheads	2,37	1,61	-	6

Note that the values given for the main deck and upper deck come from passenger crowding and weather margins, as shown in Figure 10 below.

Exposed deck location		p_E, in kN/m²
Weather deck, trunk		3,75 (n + 0,8)
Exposed deck of superstructure or deckhouse	First tier (non public)	2,0
	Upper tiers (non public)	1,5
	Public	4,0

Figure 10. p_E on Exposed Decks

2.3.2. Plating

The minimum required plate thickness can be determined according to Chapter 5, section 6 of the rules [1], for each part of the structure. For instance, the 3 following equations can be used for the bottom, and the bottom plate should not be less than the maximum value between t1, t2, and t3.

$$t_1 = 1{,}1 + 0{,}03\ L\ k^{0,5} + 3{,}6\ s \qquad (9)$$

$$t_2 = 16,4 C_a C_r s \sqrt{\frac{\gamma_R \gamma_m p}{R_y}} \qquad (10)$$

$$t_3 = 25,5 s K_{MZ} \sqrt{\frac{R_{eH} L}{E}} \qquad (11)$$

All the parameters present in these relations can be computed according to the rules. The results obtained and the choices made from them are presented in Table 4 below.

TABLE 4. REQUIRED THICKNESS FOR BOTTOM PLATE

Location	Design Pressure [kN/m²]
Bottom	11,59
Side	3,68
Main Deck	4,91
Upper Deck	4

2.3.3. Stiffeners

Scantlings of the stiffeners - and of the other stiffening members - can be determined by computing the required net section modulus w and shear area A_{sh}. A profile corresponding to a section modulus higher than the required computed value must be selected. The required net section modulus and shear area for the stiffeners can be computed using Figure 11 below.

Item	w (cm³)	A_{sh} (cm²)
Bottom, inner bottom, deck and hatch coaming longitudinals	$w = \frac{\gamma_R \gamma_m \beta_b p}{m R_y (1 - 0,18 \gamma_R \gamma_m K_{MZ})} s \ell^2 10^3$	$A_{sh} = 10 \gamma_R \gamma_m \beta_s \frac{p}{R_y} \eta s \ell$
Side and inner side longitudinals Longitudinal bulkhead longitudinals	$w = \beta_b \frac{\gamma_R \gamma_m p}{m R_y} s \ell^2 10^3$	

Figure 11. Required Net Section Modulus w and Shear Area A_{sh} for Stiffeners

Side stringers and bottom girders **(1)**	$w = \frac{\gamma_R \gamma_m \beta_b p}{m R_y} S \ell^2 10^3$	$A_{sh} = 10 \gamma_R \gamma_m \beta_s \frac{p}{R_y} S \ell$
Deck girders **(1)**	$w = \frac{\gamma_R \gamma_m \beta_b p}{m R_y} S \ell^2 10^3$	$A_{sh} = 10 \gamma_R \gamma_m \beta_s \frac{p}{R_y} S \ell$

Figure 12. Required Net Section Modulus w and Shear Area A_{sh} for Girders

One can see that 2 different formulas for w must be used for stiffeners on bottom, decks, and side, bulkheads. It is also important to remark that the external design pressure computed in 2.3.1 is used. The parameters involved in these relations are computed according to the rules [1]. The results of the scantlings' calculations are presented below in Table 5.

TABLE 5. RESULTS OF THE SCANTLINGS' CALCULATIONS FOR THE STIFFENERS

Structural member	Spacing	Span	p	Required *w*	Required A_{sh}	Selected *w*
Bottom longitudinal	0,5	2	11,59	10,62	0,45	13,43
Side longitudinal	0,5	2	3,68	2,72	0,14	4,5
Main Deck longitudinal	0,5	2	4,91	4,5	0,19	4,5
Upper Deck longitudinal	0,5	2	4	2,95	0,15	5
Bulkhead longitudinal	0,5	1,5	15,72	8,1	0,43	13,5

Units for spacing and span are given in m, p is the external design pressure in kN/m^2, [w]=cm^3, and [A_{sh}]=cm^2. Units are the same in Table 6.

2.3.4. Girders and Transverse Frames

The procedure is similar to determining the scantlings of the girders and the transverse frames, but using different formulas, shown in Figure 12 below. The results are presented below in Table 6.

TABLE 6. RESULTS OF THE SCANTLINGS' CALCULATIONS FOR THE GIRDERS/FRAMES

Structural member	Spacing	Span	p	Required *w*	Required A_{sh}	Selected *w*
Bottom girder	1,5	6	11,59	346,34	4,62	350
Bottom transverse	2	1,5	11,59	28,86	4,62	66
Side transverse	2	1	3,68	4,07	0,33	31
Main Deck girder	1,5	6	4,91	146,8	1,96	167
Main Deck transverse	2	1,5	4,91	12,23	0,65	31
Upper Deck girder	1,5	6	4	119,54	1,59	120
Upper Deck transverse	2	2	4	17,71	0,71	31

2.3.5. Profile Selection

The selection of the profiles based on the values of the previously computed required net section modulus w is presented in Table 7 below.

TABLE 7. PROFILES' SELECTION BASED (REQUIRED W)

Ti	Required w [cm^3]	Selected w [cm^3]	Selected profile
Bottom longitudinal	10,62	13,43	FB 70x8
Bottom girder	346,34	350	200x8 + 130x10
Bottom transverse	28,86	69	140x5 + 40x6
Side longitudinal	2,72	4,5	FB 50x5
Side Transverse	4,07	31	100x5 + 40x4
Main Deck Longitudinal	10,62	13,43	FB 50x5
Main Deck Girder	346,34	350	180x5 + 90x8
Main Deck Transverse	28,86	69	100x5 + 40x4
Upper Deck Longitudinal	2,95	4	FB 50x4
Upper Deck Girder	119,54	120	170x5 + 60x8
Upper Deck Transverse	9,96	120	170x5 + 60x8

These profiles are used to construct a safe structure, according to the computed design external pressure. Due to the structural arrangement, the loads are transferred from the stiffeners to the transverse frames, then to the girders, and finally to the bulkheads. This allows a smooth load transfer and enables the hull girder to sustain considerable loads. In the following section, the structural drawings are presented. All the scantlings and spacings are defined to allow the vessel to be produced in a shipyard.

2.3.6. Structural Drawings

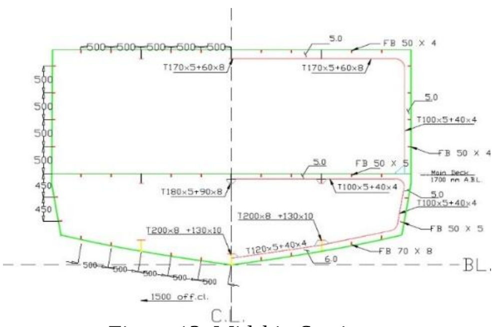

Figure 13. Midship Section

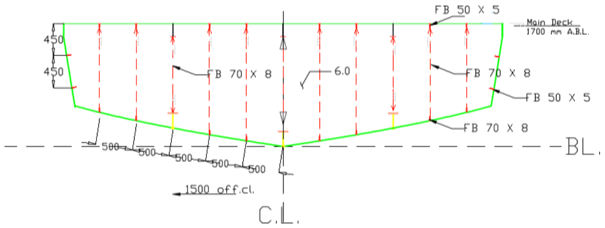

Figure 14. Bulkhead Section

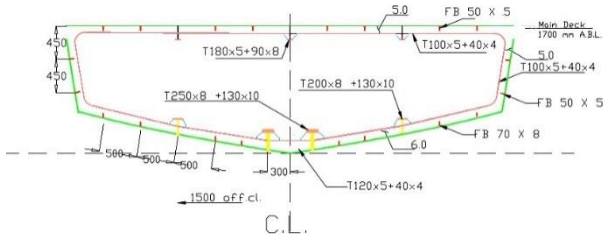

Figure 16. Engine Section

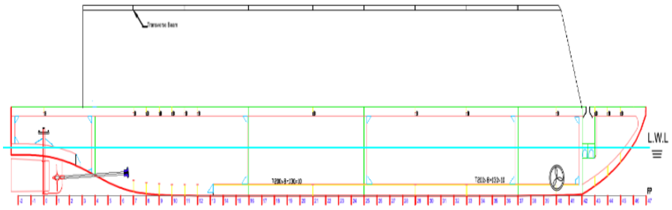

Figure 15. Profile

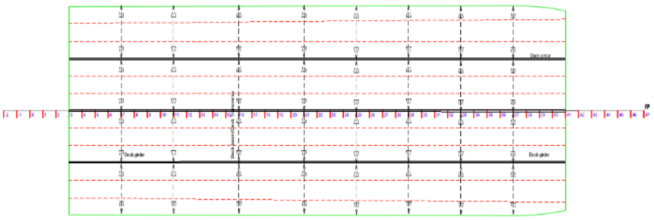

Figure 17. Upper Deck

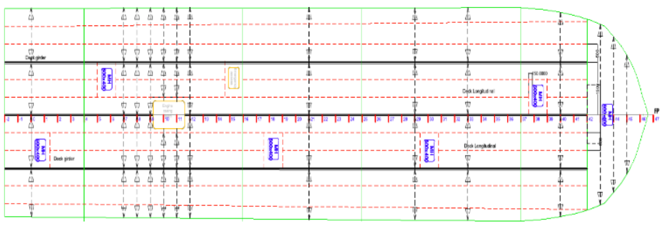

Figure 18. Main Deck

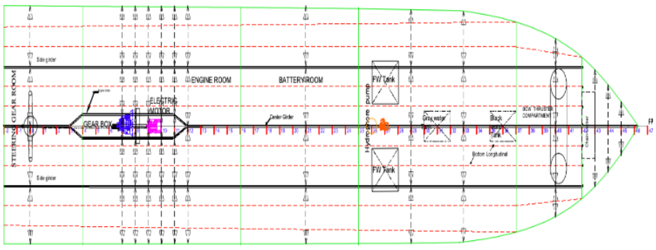

Figure 19. Bottom

2.4. Weight Estimation

The weight estimation is one of the most important steps during the design of the vessel because its results are essential for the stability calculations and, therefore, its safety during operation. In this section, the displacement and the location of the centre of gravity are determined for the preliminary design. The origin of the considered coordinate system is located at the most aft point on the centre line of the vessel and the x-axis on the axis of transverse symmetry.

In the first step, the lightship weight, which is composed of the outfit weight and the weight of the structure, is calculated. The different categories considered in the outfitting weight are listed in Table 8 with their mass and centre of gravity. In total, the weight of the outfitting is ΔOutfit = 20028.42 kg.

TABLE 8. WEIGHT ESTIMATION OF THE OUTFITTING

Category	Weight [kg]	LCG [m]	TCG [m]	VCG [m]
Main Deck Items	1202.00	9.41	-0.11	2.41
Upper Deck Items	550.00	20.11	-0.39	5.07
Life-saving equipment	850.00	12.42	-0.32	3.20
Fire fighting	158.00	75.60	-1.37	19.37
Floors	1980.00	7.76	-0.07	2.09
Painting	292.00	60.33	-1.04	15.40
Insulation	1560.00	10.64	-0.27	2.80
Mooring	660.00	24.48	-0.46	6.42
Tanks	239.00	71.48	-0.55	18.29
Navigation	239.00	73.68	-0.55	18.67
Piping	400.00	60.98	-0.33	16.77
Cables	500.00	49.70	-0.26	13.65
Aux Machinery	550.00	45.10	-0.24	12.26
Machinery & Propulsion	10077.3	2.46	-0.01	0.67
Other Hull Outfitting	742.13	33.58	-0.14	9.09
Total	20028.42	10.35	-0.07	1.26

To estimate the weight of the hull structure, all scantlings and plates are listed, and their mass and centre of gravity are individually considered. In Table 9, the results are shown based on categorizing the items into the main deck, the upper deck, the bottom, and the sides. Then, a welding allowance of 3% and an allowance for brackets of 5% is added to the weight of the structure. Finally, a total weight of ΔStructure = 31553 kg is determined. The LCG is located at 10.19 m measured from the aft and the VCG is at 1.29 m from the bottom line. As the hull structure is symmetric around the x-axis, a transverse centre of gravity of TCG = 0.00 m is found.

TABLE 9. WEIGHT ESTIMATION OF THE HULL STRUCTURE

Category	Weight [kg]	LCG [m]	TCG [m]	VCG [m]
Outfitting	20028.42	10.35	-0.07	1.26
Hull structure	31553.02	11.26	0.00	1.78
Light Ship	51581.44	10.71	-0.03	1.55

The total light ship weight Δ_{LS} is calculated by adding the weight of the outfitting and the weight of the structure: $\Delta_{LS} = \Delta_{Outfit} + \Delta_{Structure}$. In Table 10, the results are given.

TABLE 10. WEIGHT ESTIMATION OF THE LIGHTSHIP

Category	Weight [kg]	LCG [m]	TCG [m]	VCG [m]
Main Deck	6980.41	11.51	0.00	1.63
Upper Deck	5831.28	12.05	0.00	3.98
Bottom	11016.67	10.84	0.00	0.40
Sides	6805.65	11.01	0.00	2.27
Total structure	30634.00	11.26	0.00	1.78
Welding allowance	919.02	0.00	0.00	0.00
Brackets allowance	1531.70	0.00	0.00	0.00
Total	31553.02	11.26	0.00	1.78

The second part of the weight estimation is focused on the cargo weight. For this, passengers and consumables are considered. In total, a maximum of 102 people are aboard the vessel, and for each of them, a mass of 75 kg is considered. For the consumables, only water has to be accounted for. The needed amount of $1 m^3$ of water is divided into two tanks: the fresh water tank and the grey/black water (no water treatment) tank.

To estimate the weight and the centre of gravity of the cargo, three different load cases are considered. In the first one, 100% of the water is in the freshwater tank (see Table 11). In the second case, the freshwater tank is filled 50% (see Table 12), and in the third load case 10% (see Table 13). Additionally, 0.2 m^3 of water is considered to be permanently in the grey/black water tank. Lastly, the ES-TRIN rules require the consideration of a load case with no passengers and 10% freshwater Table 14.

TABLE 11. WEIGHT ESTIMATION OF THE CARGO - LOAD CASE 1

Category	Quantity	Weight [kg]	LCG [m]	TCG [m]	VCG [m]
Freshwater	1 m^3	1000	14.525	0	0.575
Grey + black water	0.2 m^3	200	16.507	0	0.575
Passengers main deck	80	6000	11.25	0	2.47
Passengers upper deck	20	1500	16.15	0	4.47
Crew	2	150	20	0	2.47
Total		8850	12.72	0.00	2.55

TABLE 12. WEIGHT ESTIMATION OF THE CARGO - LOAD CASE 2

Category	Quantity	Weight [kg]	LCG [m]	TCG [m]	VCG [m]
Freshwater	0.5 m^3	500	14.525	0	0.575
Grey + black water	0.7 m^3	700	16.507	0	0.575
Passengers main deck	80	6000	11.25	0	2.47
Passengers upper deck	20	1500	16.15	0	4.47
Crew	2	150	20	0	2.47
Total		8850	12.92	0.00	2.55

TABLE 13. WEIGHT ESTIMATION OF THE CARGO - LOAD CASE 3

Category	Quantity	Weight [kg]	LCG [m]	TCG [m]	VCG [m]
Freshwater	0.1 m^3	100	14.525	0	0.575
Grey + black water	1.1 m^3	1100	16.507	0	0.575
Passengers main deck	80	6000	11.25	0	2.47
Passengers upper deck	20	1500	16.15	0	4.47
Crew	2	150	20	0	2.47
Total		8850	12.83	0.00	2.55

TABLE 14. WEIGHT ESTIMATION OF THE CARGO - LOAD CASE 4

Category	Quantity	Weight [kg]	LCG [m]	TCG [m]	VCG [m]
Freshwater	0.1 m^3	100	14.525	0	0.575
Grey + black water	0 m^3	0	0	0	0
Passengers main deck	0	0	0	0	0
Passengers upper deck	0	0	0	0	0
Crew	0	0	0	0	0
Total		100	14.525	0	0.575

A summary of the weight estimation is given in Table 15. First, the characteristics of the lightship condition are reminded again. Then, the displacement of the full load condition is given which is calculated by adding the lightweight and the deadweight. The previously defined load cases are differentiated to show the difference in the LCG value. The total displacement of the passenger vessel is Δ = 60.6 t.

TABLE 15. WEIGHT ESTIMATION SUMMARY

Category	Weight [kg]	LCG [m]	TCG [m]	VCG [m]
Light Ship	51781.15	10.72	-0.03	1.54
Load Case 1	60631.15	10.99	-0.02	1.67
Load Case 2	60631.15	11.01	-0.02	1.67
Load Case 3	60631.15	11.02	-0.02	1.67
Load Case	51881.15	10.73	-0.03	1.54

2.5. Cost Estimation

In the ship design, estimating the cost of production is an important step. Common methods of estimating it are the top-down (Macro) and the bottom-up (Micro) methods. Based on available information Bottom-Up approach is adopted to find a cost estimate.

2.5.1. Material Cost

In the first step, the needed material needs to be estimated to then calculate the material costs. For this, the plating area needs to be determined first and suitable plates need to be selected. The results are shown in Table 16.

TABLE 16. ESTIMATION OF PLATES

Position	Area	Plates (L, W, T)	No. of plates
Area of Main Deck	139 m^2	8m,3m,5mm	6
Area of Upper Deck	114 m^2	8m,3m,5mm	5
Area of Bottom	63.58	8m,3m,6mm	3
Area of Side L-Plates (L, W, T)	L:25.3,U:50.6	6m,1.5m,5mm	3
U-Plates (L, W, T)		6m,1.5m,5mm	9
Transom Plate Area-6	6.45 m^2	6m,1.5m, 6mm	2
Bulkheads 6mm	33.16 m^2	6m,1.5m, 6mm	10
Approx. weld length	432 m^2		38 plates 372+122= 494

Next, the needed profiles have to be computed as shown in Table 17. From this, the costs for the profiles can be calculated by multiplying the cost per unit by the length. The section's price is estimated to be 6-18 euros per ft.

- Total length stiffeners (Main, Upper, Side) = 508m = 1667ft = 61667 = 10002 eur
- Total length stiffeners (Bottom) = 239.65m = 786ft = 8786 = 6288 eur
- Total length Girders (Main, Upper) = 123m = 404ft = 40412 = 4840 eur
- Total length Girder (Bottom, Keel) = 68.39m = 225ft = 22516 = 3600 eur
- Total length Frames (Main, bottom, Side, bottom) = 210m = 689ft = 68914 = 9646 eur

TABLE 17. ESTIMATION OF PROFILES

Position, No, L	**Stiffeners**	**Girders**	**Transverses**	**Weight/L**
Main Deck	50 × 8	180 × 5 + 90 × 8	100× 5+ 40 × 4	1532.51kg
No.	8	3	14	
Total Length	88m	64.5m	70.87m	223.37m
Upper Deck	50 × 4	170 × 5 + 60 × 8	170 × 5 + 60 × 8	1356.78kg
No.	8	3	8	
Total Length	156m	58.5m	48m	262.5m
Bottom	70 × 8	200 × 8 + 130 × 10	140 × 5 + 40 × 6	3161.81kg
No.	63	4	27	
Total Length	239.65m	68.39m	67.65m	375.69m
Side	50 × 5	-	100 × 5 + 40 × 4	847.5 kg
No.	12		43	
Total Length	264m		63.72m	327.72m

TABLE 18. ESTIMATION OF WELDING

Units	**Thickness**	**Approx. Weld Length [m]**	**Consumables [€]**
Plates	5mm (FB)	372	111.6
Plates	6mm (FB)	122	50
Transom Plate	6mm	13	48.8
Stiffeners (Main Deck)	8mm (FB)	88	66
Stiffeners (Upper Deck)	4mm (FB)	156	39
Stiffeners (Bottom Deck)	8mm (FB)	239	180
Stiffeners (Side Deck)	5mm (FB)	264	80
Girders (Main Deck)	5mm	64.5	19.35
Girders (Upper Deck)	5mm	58.5	17.55
Girders (Bottom Deck)	8mm	68.39	51.29
Frames (Main Deck)	5mm	70.87	21.26
Frames (Upper Deck)	5mm	48	14.4
Frames (Bottom Deck)	5mm	67.65	20.295
Frames (Side Deck)	5mm	63.72	19.12
Bulkhead-4 (Plates)	6mm	15	6
Bulkhead-16 (Plates)	6mm	15	6
Bulkhead-25 (Plates)	6mm	15	6
Bulkhead-37 (Plates)	6mm	13	5.2
Bulkhead-42(Plates)	6mm	10	4
Total Cost			767

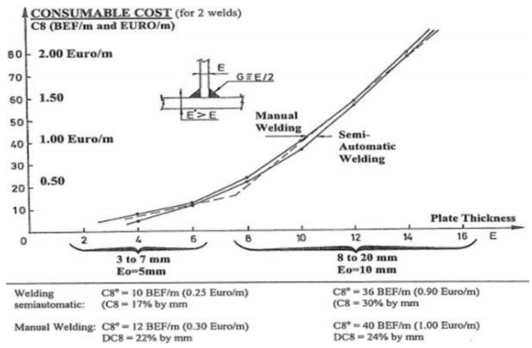

Figure 20. Cost of Consumable [8]

2.5.2. Labor Cost

The labor costs mainly consist of the man-hours for the welding and bending. For the estimation of the labor needed for welding, Figure 21 is used to approximate the workload. The results are shown in Table 19. A total of 356 hours of welding was found. As per J.C. Mandal [10], usually not more than 15% of plate stiffeners, and frames require bending. Therefore, the amount of plates to be bent can be estimated as follows: Bending (tons)= .15 × 34= approx. 5 tonnes.

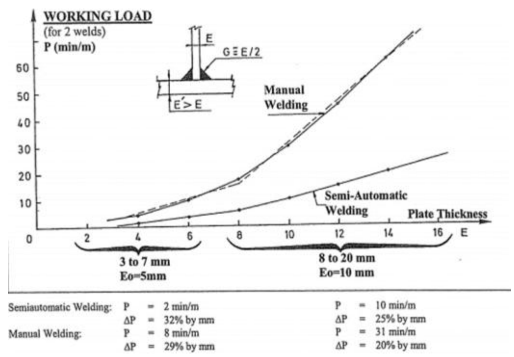

Figure 21. Working Load Diagram [8]

TABLE 19. ESTIMATION OF MAN-HOURS

Units	Thickness	Approx. Weld Length	Weld Hours
Plates	5mm (FB)	372m	62
Plates	6mm (FB)	122m	25
Transom Plate	6mm	13m	3
Stiffeners (Main Deck)-	8mm (FB)	88	20
Stiffeners (Upper Deck)	4mm (FB)	156	21
Stiffeners (Bottom Deck)	8mm (FB)	239	80
Stiffeners (Side Deck)	5mm (FB)	264	44
Girders (Main Deck)-	5mm	64.5	11
Girders (Upper Deck)	5mm	58.5	10
Girders (Bottom Deck)	8mm	68.39	23
Frames (Main Deck)-	5mm	70.87	12
Frames (Upper Deck)	5mm	48	8
Frames (Bottom Deck)	5mm	67.65	11
Frames (Side Deck)	5mm	63.72	11
Bulkhead-4 (Plates)	6mm	15	3
Bulkhead-16 (Plates)	6mm	15	3
Bulkhead-25 (Plates)	6mm	15	3
Bulkhead-37 (Plates)	6mm	13	3
Bulkhead-42(Plates)	6mm	10	3
Total Man Hours			356

The total labor cost can be calculated with the following formula [11]: where MH is Man- Hours, Ws is Net Steel Weight = 34 tonnes, L= Lpp = 22, Cb = 0.6, and C is the Shipyard Condition.

$$MH_S = C\frac{W_S^{2/3}L^{1/3}}{C_b}, \qquad (12)$$

For total labor costs:

- Man-Hours for Welding= 356 mh
- Man-Hours= Steel preparation + Outfitting Installation + Block Erection+ Plates Cut- ting+ Plates+ I beam cutting+ Bending to require size+ stiffener bending as per plate/hull design=1700-356=1344mh
- Total Man hours= 51*34=1700mh
- Labor Cost= 1700 * 15eur/mh= 25500 eur

Ship type	MH/Ton of St. wt	MH/CGT
VLCC	16	32
SUEZMAX	19	22
Product carrier	27	20
Chemical carrier	46	36
Bulk carrier	19	20
Container ship (4,400)	19	22
Container ship (1,880)	28	22
Reefer	43	34
Ferry	51	39
General cargo	56	29
Ocean tug	105	31

Figure 23. Estimated Man Hours Depending on Steel Weight [8]

2.5.3. Outfitting Cost

TABLE 20. OUTFITTING COST

No	Name	Cost (Euro)
1	Main Deck Items	32445
2	Upper Deck Items	3875
3	Life-Saving Equipment	14500
4	Fire Fighting	1100
5	Floors	20650
6	Painting	66600
7	Installation of Fire Protection	3600
8	Mooring	5700
9	Tanks	290
10	Navigation	3100
11	Piping	700
12	Cables	3000
13	Aux. Machinery	3880
14	Propulsion & Machinery	21680
15	Hull Outfitting	1250
Total		182370

The total cost of the vessel is estimated to be: Total Cost = (Design + Resistance Tests + Propeller Tests + Seakeeping Test) + Structural Cost + Outfits = 100,000 + 76339 +182370 = 358709 Eur.

2.6. Hull Form (Lines Plan)

The Hull Form lines plan is given in Figure 22.

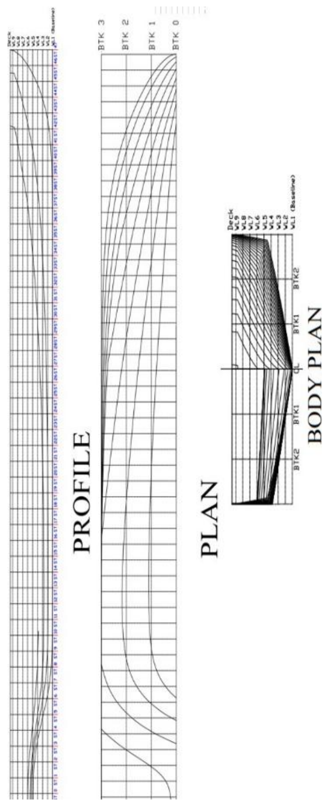

Figure 22. Lines Plan

2.7. Powering

This section is devoted to the determination of the required brake power needed to propel the ship. It is key to determine it to be able to select an appropriate engine. The first thing to do is to determine the ship's resistance for a given range of speeds, and it is done in section 2.7.1. Indeed, knowing the ship's speed and resistance, one gets the effective power EHP = Rs × vs, where Rs is the ship's resistance in N, and vs its speed in m/s. One can then obtain the required brake power. This procedure is further explained.

2.7.1. Resistance Estimation

To perform the resistance calculations, the CFD (Computational Fluid Dynamics) software FineMarine™ is used. This software allows naval architects to perform numerical CFD simulations on a 3D model for different purposes:
determination of the ship's resistance, initial stability, seakeeping, etc.

The first step is to model the hull form. This is done on MaxSurf™ as described in section 2.6, and the model is then exported to FineMarine to start the resistance calculations. Because CFD simulations are numerically costly, only half of the hull is modeled. This implies that the obtained resistance values must be multiplied by 2 to represent the total ship's resistance. Notice that it is important to have a closed hull form model to perform the CFD simulations.

Each simulation stops when the results converge, i.e. the residuals tend to zero. Such a convergence graph can be seen in the monitor window of FineMarine and is depicted below in Figure 23, for a speed of 12 km/h.

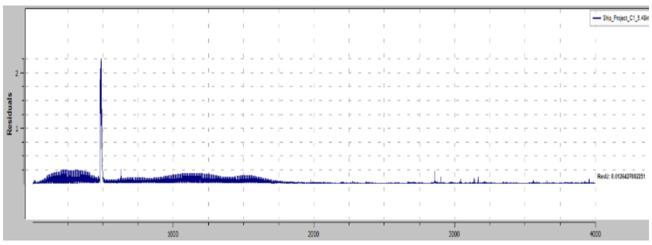

Figure 24. Residuals tend to zero, meaning that the results converge after a given number of iterations (vs = 12km/h)

It is seen that at least 2000 iterations are required for the residuals to be approximately zero. The monitor of FineMarine can also be used, for instance, to display the evolution with time of the forces and moments acting on the hull. It is seen that they converge as the residuals tend to zero.

Considering that the service speed of the vessel is 10 km/h, a first resistance simulation is performed for this speed. Other simulations are also done for 6, 8, and 12 km/h. 12 km/h is considered the maximum speed that the ship can reach. The following Table 21 presents the values obtained for different speeds.

TABLE 21. RESISTANCE VALUES FOR THE DIFFERENT CONSIDERED SPEEDS

Speed [km/h]	Speed [m/s]	Bare hull resistance [kN]
12	3,33	2,069
10	2,78	1,302
8	2,22	0,8
6	1,67	0,81

For each speed, FineMarine™ gives us the resistance of the bare hull, that is the resistance of the hull without appendages, as the model is a canoe body. To consider appendages, 20% of the bare hull resistance is taken as the added resistance due to appendages. The total ship's resistance is the sum of these 2 resistances. The effective power EHP can then be computed using EHP = $R_s \times v_s$ as previously mentioned. Then, a service allowance of 10% of the EHP is considered. From the EHP, one can obtain the delivered power to the propeller P_D and the Brake horsepower BHP by multiplying by efficiency factors. The hull efficiency is considered as $\eta_H = 1, 02$, the relative rotative efficiency is $\eta_r = 0, 98$, and the open water hull efficiency is taken as $\eta_o = 0, 505$. The product of these 3 efficiencies gives rise to the propulsive efficiency $\eta_{prop} = \eta_H \times \eta_r \times \eta_o$. This last efficiency is used to determine the delivered power P_D from the EHP_c including service allowance correction, $P_D = \frac{\mathrm{EHP_c}}{\eta_{prop} \times \eta_0}$. Then, one can consider the shaft efficiency as $\eta s = 0, 96$ to get the actual Brake Horse Power required at the engine level:, $BHP = \frac{P_D}{\eta_s}$. The results of these calculations are summarized in Tables 22 and 23 below.

TABLE 22. POWERS' ESTIMATION 1

Speed [km/h]	Bare hull resistance	*Rapp*	Total Resistance	*EHP*	*EHPc*
12	2,07	0,41	2,48	8,28	9,10
10	1,30	0,26	1,56	4,34	4,77
8	0,8	0,16	0,96	2,13	2,35
6	0,81	0,16	0,97	1,62	1,78

TABLE 23. POWERS' ESTIMATION 2

Speed [km/h]	EHP_c	η_{prop}	P_D	η_s	BHP	85% MCR
12	9,10	0,50	35,71	0,96	37,20	43,76
10	4,77	0,50	18,73	0,96	19,51	22,95
8	2,35	0,50	9,21	0,96	9,59	11,28
6	1,78	0,50	7,00	0,96	7,29	8,58

Units for the resistances are [R]=kW, Rapp stands for the resistance due to appendages, and EHP_c is the effective horsepower considering the 10% service allowance, such that $[EHP_c]$=kW. The efficiencies are non-dimensional quantities.

The value of 85% of the MCR (Maximum Continuous Rating) is obtained by the following operation: 85%MCR = $\frac{BHP}{0.85}$. The MCR is the maximum RPM (Rotation Per Minute) at which the engine can run during 1 year without being damaged. In that way, the engine will never be used at its maximum rating, but only at a maximum of 85% of it. One can see in Table 23 that the maximum required engine power is 43,76 kW.

2.7.2. Results with FineMarine™

FineMarine™ allows to display of the CFD flow around the hull's model. An example of a ship's speed of vs = 12km/h is depicted in Figures 24, 25, and 26.

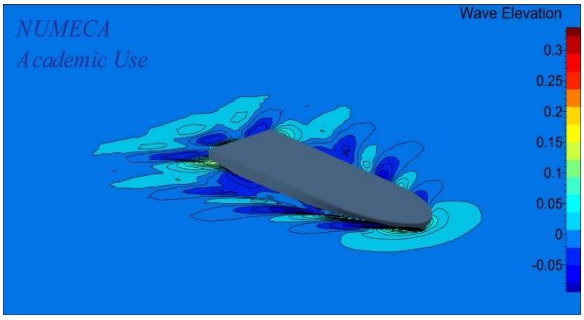

Figure 25. Wave Elevation around the Hull, Isometric View (vs = 12km/h)

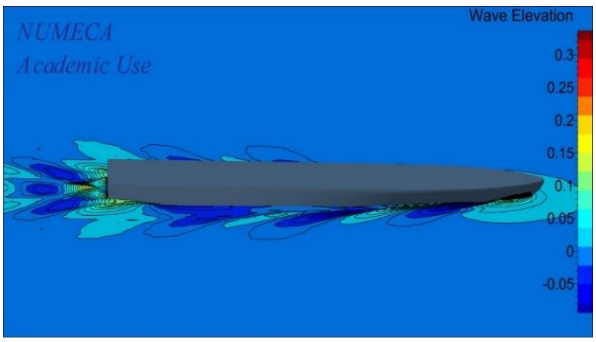

Figure 276. Wave Elevation around the Hull, Side View (vs = 12km/h)

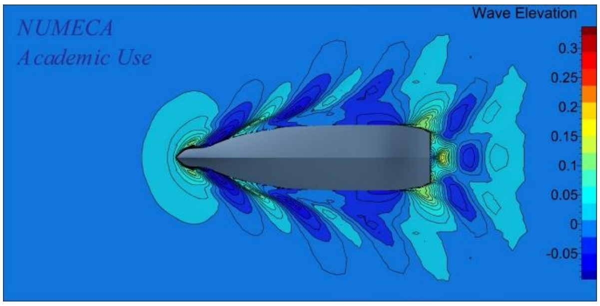

Figure 26. Wave Elevation around the Hull, Bottom View (vs = 12km/h)

2.7.3. Propeller Design

- Initial propeller data:

For estimating the propulsive power for engine selection, an investigation of the propeller characteristics was carried out using existing statistical charts sufficient enough to generate the thrust required to overcome the resistance at the design speed.

- Statistical Analysis:

The Wageningen B series was selected for the design of the propeller. This series was developed from the open-water analysis of 120 Troost (air-foil) form, open-wheel propellers in the Netherlands, Ship Model Basin (NSMB) at Wageningen. Given below are the ranges of the parameters of propellers in this series.

  - Configuration: Open-water
  - Number of blades: 2 to 7
  - Blade area ratio: 0.3 to 1.05
  - Pitch-Diameter ratio: 0.5 to 1.4
  - Advance coefficient: 0.1 to 1.5

- Propeller hull interaction:

The flow to the propeller is modified due to the interaction between the hull and the propeller.Hence while studying the propeller characteristics, factors like wake and thrust deduction have to be taken into consideration.

Wake fraction (W): Due to wake, the propeller advancement relative to the water is no longer at the same speed as the ship, but at a lower speed called velocity of advance (V_a). The wake fraction is defined as follows.

$$\boldsymbol{W} = \frac{\mathbf{V} - \mathbf{V_A}}{\boldsymbol{V}} \qquad (13)$$

Taylor's empirical formulation was used for the estimation of the wake. It is given by:

$$W = 0.5 \times C_B - 0.05 = 0.5 \times 0.42 - 0.05 = 0.16 \quad (14)$$

Thrust deduction fraction (t):

$$t = 1 - \frac{R_t}{T} \quad (15)$$

Thrust deduction factor's estimation using Taylor's empirical relation for a single screw propeller is given by:

$$t = 0.23 \times CB + 0.05 = 0.23 \times 0.42 + 0.05 = 0.15 \quad (16)$$

- Hull efficiency:

The work done in moving a ship at a speed V against a resistance R_t, is proportional to the product $R_t \times V$, or the work done by the propeller in delivering a thrust T at a speed of advance V_a, that is proportional to the product $T \times V_a$.

$$W = \frac{1-t}{1-w} = \frac{1-0.15}{1-0.16} = 1.02 \quad (17)$$

- Relative Rotative efficiency:

The relative rotative efficiency η_r ranges from 0.9 to 1. For our analysis, the value of 0.98 is taken.

The required thrust is given by:

$$T = \frac{R_T}{1-t} = \frac{2.73}{1-0.15} = 3.2\ kN \quad (18)$$

The advanced velocity V_A is given by:

$$V_A = V \times (1 - w) = 3.33 \times (1 - 0.16) = 2.8\ m/s \quad (19)$$

The maximum diameter of the propeller should not be bigger than 2/3 of the draft, and the minimum considered was 1/3 of the draft.

$$T/3 \leq diameter \leq 2T/3 \quad (20)$$

Where: T = 0.92 m, D_{max} = 2T/3 = 0.61 m, and D_{min} = T/3 = 0.306 m

To calculate the propeller immersion, 0.10 m of clearance from the hull is considered.

$$H_{Shaft} = T\left(\frac{D}{2} + 0.1\right) = 0.513 \quad (21)$$

Where T = 0.92 m, clearance = 0.10 m, and D = 0.6 m is the selected diameter.

- Procedure for propeller selection:

Propeller design begins with the initial approximation of the propeller's diameter, wake, and thrust deduction factor using empirical relations. Using the wake and thrust deduction fractions, the velocity of advance and required thrust can be estimated from the ship design's velocity and resistance. The following conditions are considered.

$$3 \leq Number\ of\ blades \leq 7 \quad (22)$$

$$0.3 \leq \frac{A_e}{A_o} \leq 1.05 \quad (23)$$

$$0.5 \leq \frac{P}{D} \leq 1.4 \quad (24)$$

$$D_{min} \leq D \leq D_{max} \quad (25)$$

The input parameters for the Hydrocomp Propexpert program were provided. Here the diameter is fixed due to hull clearance allowance and draft restriction. Hence Pitch, Blade Area Ratio, and Propeller efficiency were optimised. For the selection of the most efficient propeller, the parameters BAR, and P/D were iterated for the different constraints placed on them. The gear ratio was selected from the catalog of the chosen engine.

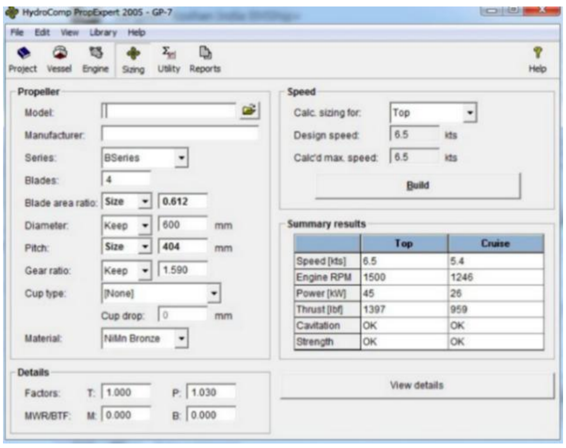

Figure 28. Output (Hydrocomp's software)

The most efficient propeller was found to have the characteristics listed in Figure 29 shown below. The number of blades chosen was 4.

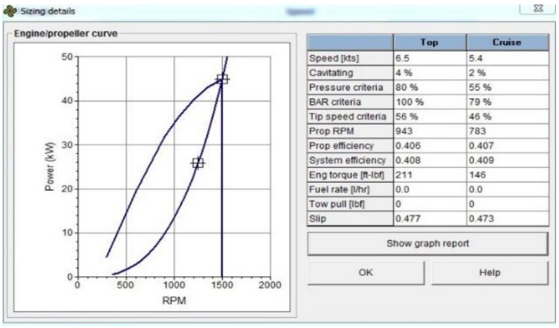

Figure 29. Output Window - Engine/propeller curve

Parameters	values
Pitch diameter ratio	0.673
Expanded area ratio	0.612
N (RPM)	943
Open water efficiency	0.406
Propeller diameter (m)	0.6

Figure 30. Propeller characteristics

2.7.4. Selection of Electric Motor

Based on the previous calculations, the electric motor can be chosen. For this, Transfluid S.p.A. is selected as the provider, and, therefore, their catalogs are searched for an electric propulsion system providing a power of at least 40 kW.

From the available electric propulsion systems, the BV101580W-DriveMaster 55W was selected. This motor provides a nominal power of 45 kW. A liquid-cooled system is chosen, as the given application is considered" medium duty" (500 hours of operation) in the Transfluid catalog which is not suitable for air cooling. Further specifications are given in Table 24 [6].

TABLE 24. SPECIFICATIONS OF ELECTRIC MOTOR DRIVEMASTER 55W

Parameter	Value
Motor Size	300-75
Nominal Power	45 kW
Intermittent Power	55 kW
Rotational Speed	1500 rpm
Battery Voltage	144 Vdc

2.8. Maneuvering System

The main maneuvering equipment needed for the ship is the rudder and the bow thruster. The rudder enables the vessel to navigate and the bow thruster provides better maneuverability. In the following sections, both are further specified.

2.8.1. Rudder Design

Rudders are one of the main maneuvering equipment used to control the path of a ship. To do so, it provides turning moments. The rudder is positioned in the aft right behind the propeller which was discussed in section 2.7.3. For the inland navigation vessel, a balanced (20-40% of its rudder area forward of the stock) single-plate rudder [5] is chosen to reduce the torque needed to turn the rudder [4]. Based on the BV rules4, it is designed in this section. A steel with a yield strength of σ_y = 235 N/mm^2 is considered.

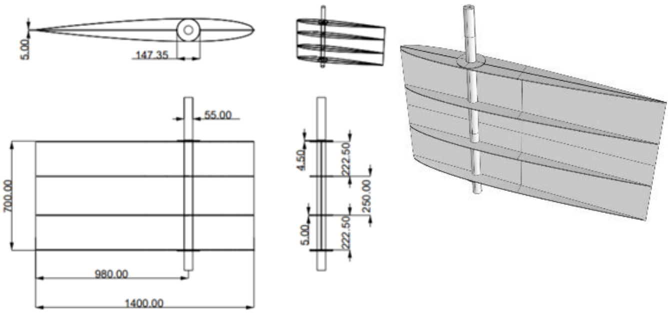

Figure 31. Rudder Design

In the first step, the rudder area A_r is calculated: $Ar = 0.0371 \cdot L_{WL} \cdot T = 0.0371 \cdot 24m \cdot 1.1m = 0.98\ m^2$. Based on the calculated area and the previously defined aft arrangement, the selected geometry of the rudder is 0.7 m x 1.4 m. Then, the rudder force C_R, rudder torque M_{TR}, and the maximum bending moment M_B acting on the rudder stock are determined. The results are given in Table 25.

TABLE 25. FORCES AND MOMENTS ON THE RUDDER

Parameter	Value	Unit
Rudder force C_R	3558.54	N
Rudder torque M_{TR}	931.93	N.m
Bending moment M_B	1423.41	N.m

Next, the diameter of the rudder stock, the plate thickness of the rudder, and the dimensions of its stiffeners are calculated. The minimum rudder stock diameter obtained following the rules is $d_{t,\ min}$ = 51.92 mm. To consider only commonly available sizes, a diameter of dt = 55 mm is chosen. For the calculation of the rudder's plate thickness, the spacing of the stiffening arms has to be defined first. A distance of 0.25 m is chosen which leads to several four stiffeners in total. Based on this, a rule thickness of tb = 4.75 mm is computed and a final plate thickness of t_b = 5 is defined. The same thickness is chosen for the stiffening arms. For these, also a minimum section modulus z_A is given in the rules which has a value of 4.45 cm3 for the given rudder. Keeping this in mind, a NACA 0015 profile (http://airfoiltools.com) with a thickness of 70% is chosen as the stiffener's geometry.

After the rudder's final design is defined, its weight can be calculated considering a material density of ρ = 7850 kg/m3. For the main rudder plate, a mass of m_{rp} = 38.5 kg is determined. The rudder arms have a combined mass of m_{ra} = 44.8 kg and the rudder stock of about m_{rs} = 22 kg. In total, the rudder has a mass of m_{tot} = 105.3 kg.

2.8.2. Bow Thruster Selection

To ensure good maneuverability of the vessel, a suitable bow thruster needs to be selected. The most important factors for this are the wind pressure and the lateral area of the ship. For the selection, a wind speed of v = 5 m/s is considered as it is the average wind speed over the year for the area of operation6. Therefore, the wind pressure p acting on the ship is:

$$\mathbf{p} = \frac{\mathbf{1}}{\mathbf{2}}\ \mathbf{p_{air}}.\boldsymbol{v}^{\mathbf{2}} = \mathbf{15.3}\ \boldsymbol{N/m^3} \qquad (26)$$

The lateral area can be determined from the general arrangement and is taken as A = 60 m^2. A correction factor of f = 0.75 is taken as the wind angle usually is not equal to 90 degrees which is the most demanding situation. The pivot point of the ship is taken as $l_p = 0.5L_{WL}$ =12 m and the distance between the pivot and the bow thruster is estimated to be l_b = 8 m. Therefore, the turning moment M and the thrust force F can be calculated as follows:

$$\mathbf{M} = \mathbf{pAfl_p} = \mathbf{8270\ N.m} \qquad (27)$$

$$\mathbf{p} = \frac{\boldsymbol{M}}{\boldsymbol{l_b}} = \mathbf{1040}\ \boldsymbol{N} \qquad (28)$$

Based on these calculations, a suitable bow thruster is selected. For this, the catalog of the company TWIN DISC SRL is searched for equipment that provides the necessary thrust. The selected model is BT 120N.

2.9. Electrical System

In this section, the consumed power of all appliances on board the vessel is estimated with an electrical load balance. Also, the batteries for the electrical engine and the emergency batteries are selected.

2.9.1. Electric Load Estimation

To estimate the electrical power needed for the passenger vessel, an electrical load balance is performed in two parts. First, all appliances except the main engine are considered. Then, the power needed for the engine, which is given in section 2.7.4, is added in order to select the batteries.

As the consumed power is dependent on the mode of operation, the following four operating conditions are considered:

- Port: power condition of the vessel in the harbour while docked or loading people
- Maneuvering: power condition during maneuvering where all maneuvering systems and most propulsion systems are active
- Sailing: power condition during navigation of the vessel
- Emergency: power condition during an emergency where power is mainly consumed by emergency systems, fire pumps, and communications systems

To consider the different values of power consumption in the operating modes, a utility factor UF is introduced, which gives the percentage of usage during each condition. Also, a load factor LF for each electrical component is used in the calculation to consider that the appliances do not run at their maximum capacity at all times. Therefore, the used load Pused can be calculated from the maximum load P_{max} of each component as follows:

$$\mathbf{P_{used}} = \mathbf{UF} \cdot \mathbf{LF} \cdot \mathbf{P}_{max} \qquad (29)$$

As shown in Fig. 31, the mode of operation that uses the most power is the maneuvering mode. In this mode, 44.6 kW is required.

2.9.2. Battery Selection

Based on the electrical power estimation of the previous section, the main battery set and the emergency batteries can be selected.

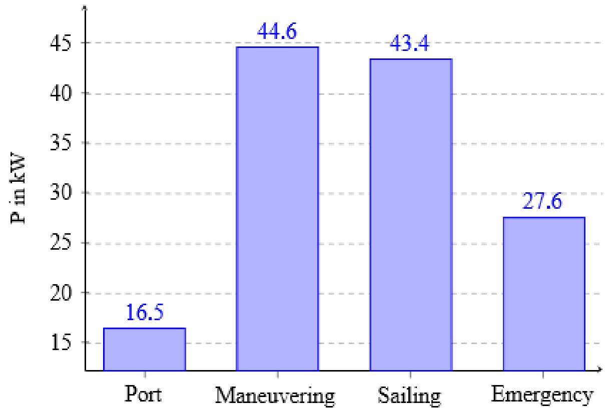

Figure 32. Used electrical power for different modes of operation

The main batteries need to provide power for six hours of operational time per day. After that, they will be recharged in the harbor. For the battery units, the total power to be provided is determined from the electrical load estimation and the specifications of the selected electrical motor.

The most demanding mode of operation in terms of electricity usage is the maneuvering condition. In this case, the electrical load is 44.6 kW. For the electrical motor, an intermittent power of 55 kW is specified. To find the total energy that the batteries need to provide, the total electrical load P_{total} needs to be multiplied by the time of operation:

$$\boldsymbol{Energy = P_{total} \cdot t_{operation} = (44.6 + 55) \cdot 6 = 597.6\ kWh} \quad (30)$$

To match the electric motor, the batteries are selected from the Transfluid catalog. As the motor requires a battery of 144 V and a total energy of about 600 kWh is needed, five LiFePO4 batteries of 122.9 kWh each are selected providing a total energy of 614.5 kWh. The detailed specification for each battery is given in Table 26.

TABLE 26. SPECIFICATIONS (MAIN BATTERIES)

Parameter	Value
Voltage	144 V
Energy	122.9 kWh
Dimensions	620x677x352 mm
Weight	1560 kg
Lifespan	4000 Cycles

Transfluid's LiFePO4 batteries are composed of lithium iron phosphate cells and one of their main advantages is the fast charging option where the batteries can be fully charged in only 2 hours. This way, the vessel's operation is more flexible and it is possible to operate the ship for more than six hours a day with a short charging break. The batteries' long lifespan of 4000 cycles and the no-emission operation contribute to green powering. Also, there are no mandatory maintenance services due to the integrated diagnosis system [7].

2.9.3. Emergency Batteries

The emergency batteries are utilized in case of emergency mode. In the electrical load estimation, an emergency power of $P_{emergency}$ = 27.6 kW is obtained. Adding a safety margin of 20%, a battery with at least 34 kW should be selected. Considering the BV rules7 and the ES- TRIN regulations8, which both require the batteries to provide a minimum of 30 minutes of power and the time needed to return to the shore safely, a minimum of one hour of emergency supply is chosen. Therefore, the batteries need to provide at least 34 kWh of energy.

As for the main batteries, Transfluid's LiFePO4 batteries are selected. They provide 61.4 kWh of energy which is enough to operate the ship for almost two hours in emergency mode and therefore fulfill the given requirements. More detailed information is presented in Table 27 [7].

TABLE 27. SPECIFICATIONS (EMERGENCIES BATTERIES)

Parameter	Value
Voltage	144 V
Energy	61.4 kWh
Dimensions	620x677x352 mm
Weight	780 kg

2.10. Stability

The stability of the passenger vessel is checked using European Standard laying down Technical Requirements for Inland Navigation vessels (ES-TRIN), 2019 [3]. The loading conditions as per the rule are defined and the large-angle stability for each of these loading conditions are assessed. The hydrostatics particulars for each condition are calculated, the position of floating equilibrium is found, the righting moment curve (GZ curve) is plotted for different angles of heel, and then the various criteria regarding these GZ curves are analyzed as per the rule requirement. These calculations are carried out using the software Maxsurf Stability module.

2.10.1. Loading Condition

Each of the loading conditions refers to a configuration of distribution of the deadweight items onboard. These items typically refer to the fixed deadweight items such as the weight of the passengers, and crew. In line with the operating profile of the ship and as per the rule, four loading conditions are defined:

1. At the start of the voyage: 100 % passengers, 98 % fuel and fresh water, and 10 % wastewater (Load Case 1).
2. During the voyage: 100 % passengers, 50 % fuel and fresh water, and 50 % wastewater (Load Case 2).
3. At the end of the voyage: 100 % passengers, 10 % fuel and fresh water, and 98 % wastewater (Load Case 3).
4. Unladen vessel: no passengers, 10 % fuel and fresh water, no wastewater (Load Case 4).

2.10.2. Stability Criteria

The stability of the vessel is assessed as per the rule ES-TRIN, chapter 19, “special provision for passenger vessel” – Article 19.03 (stability) [3]. The intact stability of the vessel for all loading conditions explained in the previous section with passenger crowding, wind pressure, and turning of the vessel has been checked as per the rule criteria.

The stability criteria as per the rule are summarized below:

1. The maximum righting lever h_{max} shall occur at a heeling angle of Φmax > Φmom +3° and shall not be less than 0.20 m. However, in the case of Φf < Φmax the righting lever at the down-flooding angle Φf shall not be less than 0.20 m.
2. The down-flooding angle Φf shall not be less than (Φmom +3°).
3. The area A under the curve of the righting levers shall, depending on the position of Φf and Φmax, reach at least the following values:

Case			A
1	$\varphi_{max} \leq 15°$ or $\varphi_f \leq 15°$		0,05 $m \cdot rad$ up to the smaller of the angles φ_{max} or φ_f
2	$15° < \varphi_{max} < 30°$	$\varphi_{max} \leq \varphi_f$	$0{,}035 + 0{,}001 \cdot (30 - \varphi_{max})\ m \cdot rad$ up to the angle φ_{max}
3	$15° < \varphi_f < 30°$	$\varphi_{max} > \varphi_f$	$0{,}035 + 0{,}001 \cdot (30 - \varphi_f)\ m \cdot rad$ up to the angle φ_f
4	$\varphi_{max} \geq 30°$ and $\varphi_f \geq 30°$		0,035 $m \cdot rad$ up to the angle $\varphi = 30°$

Figure 33. Area requirement of the GZ curve as per ES-TRIN

Where:

- h_{max} is the maximum lever arm
- Φ is the heeling angle
- Φf is the down-flooding angle
- Φ_{mom} is the maximum heeling angle (that should not exceed 12°) due to the loading condition “passenger crowding + wind” and “passenger crowding + turning”.

4. The initial metacentric height, GM0, corrected by the free surface effect in liquid tanks, shall not be less than 0.15 m.
5. The maximum heeling angle Φmom should not exceed 12° due to the loading condition “passenger crowding + wind” and “passenger crowding + turning”.
6. For a heeling moment resulting from moments due to persons, wind and turning, the residual freeboard shall be not less than 0.20 m.

2.10.3. Heeling Moment (Passenger Crowding)

As per the rule, the heeling moment due to one-sided accumulation of persons M_p shall be calculated according to the following formula:

- P is the total mass of persons on board in tones (assuming average mass per person as 0.075 ton).
- y lateral distance of centre of gravity of total mass of persons P from centerline in [m].
- g acceleration of gravity, g = 9.81m/s2.
- Pi in [tons] is the mass of persons accumulated on area Ai, s.t:

$$\mathbf{Mp} = \mathbf{g.P.y} = \boldsymbol{g} \times \boldsymbol{\Sigma_i}\, \boldsymbol{Pi.yi} \qquad (31)$$

- Ai is the area occupied by persons in [m^2].
- ni number of persons per square meter.Also, ni = 3.75 for free deck areas and deck areas with movable furniture. For deck areas with fixed seating furniture

such as benches, Ai shall be calculated by assuming an area of 0.50 m in width and 0.75 m in seat depth per person.

- yi is the lateral distance of geometrical centre of area Ai from centerline in [m].

For the calculation of the loading cases, the centre of gravity of a person shall be taken as 1 m above the lowest point of the deck at 0.5×Lwl, ignoring any deck curvature and assuming a mass of 0.075 t per person.

As per the rule, 1m^2 area is required for 3.75 passengers. We have, 80 passengers in main deck and 20 passengers in Upper Deck. As per the requirement, 21.33 m^2 (with 2.03 m centroid from center line) for main deck and 5.33 m^2 (with 2.57 m centroid from center line) for Upper Deck are needed.

- Heeling moment by Main deck passenger:

$$\mathbf{Mp = 9.81 \times 80 \times 0.075 \times 2.03 = 119.38\ kN.m} \tag{32}$$

- Heeling moment by upper Deck passenger:

$$\mathbf{Mp = 9.81 \times 20 \times 0.075 \times 2.57 = 37.828\ kN.m} \tag{33}$$

The distribution of the area has been considered to get maximum heeling moment as shown in the figures below.

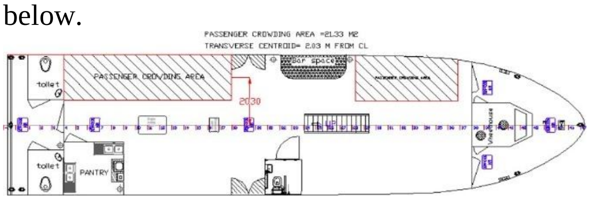

Figure 34. Passenger crowded area and centroid - Upper deck

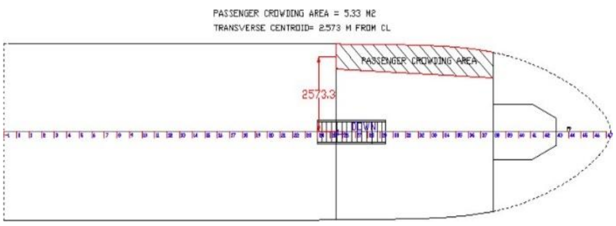

Figure 35. Passenger crowded area and centroid - Main deck

2.10.4. Heeling Moment due to Wind Pressure

As per ES-TRIN, chapter 19.5 3, heeling moment due to wind pressure:

$$\mathbf{Mw = Q_w . A_w . (l_w + \frac{T}{2})} \tag{34}$$

Where:

- ρ_w is the specific wind pressure of 0.25 kN/m^2.
- A_w lateral area of profile above plane of draft for considered loading condition in m^2.
- I_w centroid of the A_w from waterline.

We have lateral wind area of 54.33 m^2 with the centroid of 1.45 m above the design water line.

So, the heeling moment by wind pressure:

$$\mathbf{Mw = 0.25 \times 54.33 \times (1.45 + \frac{0.877}{2}) = 25.71\ kN.m} \tag{35}$$

2.10.5. Heeling Moment by Turning of the Vessel

As per ES-TRIN, chapter 19.6 [3], the moment in kN.m due to centrifugal force generated by the turning of the vessel is:

Where:

- C_{dr} = 0.45.
- C_B is the ship's block coefficient.
- v is the maximum speed of the vessel.
- KG is the distance from the centre of gravity and the keel.

2.10.6. Down-Flooding Points

The stability analysis of the vessel is limited by the down-flooding point, i.e. the point through which water enters the hull. For this vessel, the down-flooding points considered are the Engine Room ventilation openings, battery room ventilation and all air pipes locations. The co- ordinates of these points are shown in Figure 35.

	Name	Long. Pos. m	Offset m	Height m	Type
1	DF point 1	2.000	3.000	3.650	Downflooding p
2	DF point 2	4.500	3.000	3.650	Downflooding p
3	Engine room ventilation	10.500	3.000	3.650	Downflooding p
4	DF point 4	14.000	3.000	3.650	Downflooding p
5	DF point 5	20.500	3.000	2.700	Downflooding p
6	DF point 6	22.500	3.000	2.700	Downflooding p
7	Main deck Ventilation 1	5.000	3.000	3.300	Downflooding p
8	Main deck Ventilation 2	10.750	3.000	3.300	Downflooding p
9	Main deck Ventilation 3	14.000	3.000	3.300	Downflooding p

Figure 36. Down-flooding point - Coordinates

2.10.7. Tanks Definition

The various tanks in the vessel are modeled in the Maxsurf Stability model so that the various loading conditions may be defined. Figure 36 shows the definition parameters for the various tanks. The reference origin is the intersection of the baseline, centreline and FR0.

The hydrostatic curves and cross curves obtained with Maxsurf are depicted in figures 37 and 38.

Name	Type	Aft(m)	Fore(m)	F.Port(m)	F.Stbd(m)	Ftop(m)	Fbottom(m)
Fresh water 1	Tank	13.5	14.5	0.6	1.65	0.9	0.4
Fresh water 2	Tank	13.5	14.5	-1.65	-0.6	0.9	0.4
Grey water	Tank	15.5	16.5	-0.6	0.6	0.9	0.2
Black water	Tank	18	18.5	-0.75	0.75	0.9	0.2

Figure 37. Tanks definition

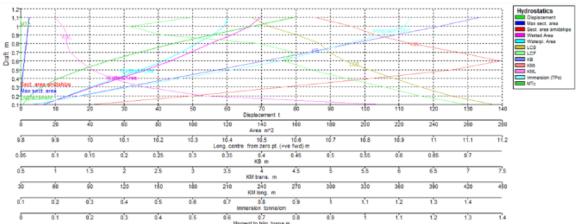

Figure 38. Hydrostatic Curves

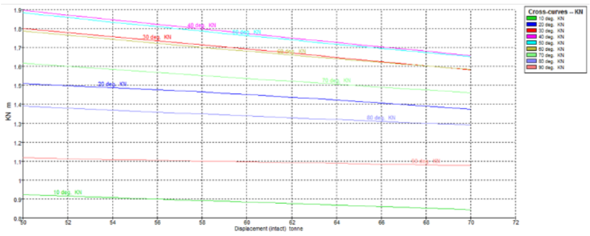

Figure 39. Cross Curves

2.10.8. Stability calculations

- Load case 1 (100% Pass., 98% FW, 10% Waste water)

Load case 1 represents the loaded condition. The specific gravity is taken as 1.000 (Density = 1t/m3).

	Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Total FSM tonne.m	FSM Type
1	Lightship	1	51.781	51.781			10.720	-0.030	1.540	0.000	User Specifi
2	Passengers on	80	0.075	6.000			11.250	0.000	2.470	0.000	User Specifi
3	Passengers on	20	0.075	1.500			16.150	0.000	4.470	0.000	User Specifi
4	Crew	2	0.075	0.150			20.000	0.000	2.470	0.000	User Specifi
5	Fresh water 1	98%	0.512	0.502	0.512	0.502	14.000	1.113	0.647	0.000	Maximum
6	Fresh water 2	98%	0.512	0.502	0.512	0.502	14.000	-1.132	0.647	0.000	Maximum
7	Grey water	10%	0.752	0.075	0.823	0.082	16.011	-0.420	0.304	0.131	Maximum
8	Black water	10%	0.449	0.045	0.491	0.049	18.249	-0.505	0.344	0.128	Maximum
9	Total Loadcas			60.555	2.338	1.136	10.997	-0.027	1.690	0.260	
10	FS correction								0.004		
11	VCG fluid								1.694		

Figure 40. Weight distribution – Load case 1

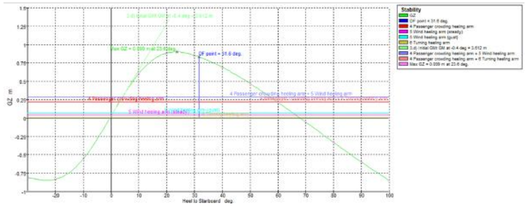

Figure 41. GZ curve – Load case 1

Heel to Starboard deg	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100
GZ m	-0.808	-0.835	-0.556	0.026	0.607	0.884	0.853	0.69	0.468	0.214	-0.057	-0.331	-0.599	-0.851
Area under GZ curve from zero h	18.4353	10.0641	2.8034	0	3.3153	11.0634	19.9278	27.7056	33.5301	36.9559	37.7494	35.811	31.1483	23.8869
Displacement t	60.55	60.55	60.55	60.55	60.55	60.55	60.55	60.55	60.55	60.55	60.55	60.55	60.55	60.55
Draft at FP m	0.426	0.64	0.816	0.877	0.816	0.64	0.426	0.179	-0.148	-0.65	-1.606	-4.381	n/a	-6.354
Draft at AP m	0.426	0.64	0.816	0.877	0.816	0.64	0.426	0.179	-0.148	-0.65	-1.606	-4.381	n/a	-6.354
WL Length m	23.384	23.469	23.568	23.581	23.568	23.469	23.384	23.464	23.687	23.83	23.926	23.986	24.019	24.022
Beam max extents on WL m	3.135	4.264	5.505	6	5.505	4.264	3.136	2.545	2.2	1.96	1.808	1.662	1.592	1.585
Wetted Area m^2	123.02	117.294	119.058	125.977	119.058	117.294	123.02	125.874	127.429	128.168	128.429	128.336	128.305	128.47
Waterpl. Area m^2	63.088	84.259	104.136	113.781	104.136	84.259	63.088	51.85	45.154	40.763	37.773	35.451	33.906	33.544
Prismatic coeff. (Cp)	0.743	0.718	0.681	0.645	0.681	0.718	0.743	0.754	0.757	0.761	0.764	0.767	0.77	0.774
Block coeff. (Cb)	0.539	0.501	0.475	0.42	0.475	0.501	0.539	0.555	0.561	0.573	0.587	0.61	0.597	0.581
LCB from zero pt. (+ve fwd) m	11.02	11.011	11.006	11.003	11.006	11.012	11.02	11.029	11.038	11.046	11.053	11.056	11.055	11.05
LCF from zero pt. (+ve fwd) m	11.475	11.167	10.857	10.508	10.857	11.167	11.475	11.681	11.842	12.015	12.192	12.216	12.117	12.038
Max deck inclination deg	30.0139	20.0114	10.0116	0.3693	10.0116	20.0114	30.0139	40.0153	50.0154	60.014	70.011	80.0062	90	99.9936
Trim angle (+ve by stern) deg	0	0	0	0	0	0	0	0	0	0	0	0	n/a	0

Figure 42.Stability parameters table – Load case 1

Rule	Criteria	Limit value	Actual value	Status
19.03.3 (a)	Value of Max.GZ	0.2	0.899	Pass
19.03.3 (a)	Angle at max. GZ requirement	ϕmax>= ϕmom+3	ϕmax = 23.6 deg; ϕmom(crowd+turn) = 3.85 deg; ϕmom(crowd+wind) = 4.48 deg	Pass
19.03.3 (b)	Angle at max. GZ requirement	φf >= φmom+3	ϕf = 31.6 deg; ϕmom(crowd+turn) = 3.85 deg; ϕmom(crowd+wind) = 4.48 deg	Pass
19.03.3 (c)	Angle at max. GZ requirement btw 15 deg and φmax	0.035+0.001(30-φmax)=0.0414	6.95	Pass
19.03.3 (d)	Initial GM	0.15	3.612	Pass
19.03.3 (e)	Heeling angle due to crowd+turn and crowd+wind	12	ϕmom(crowd+turn) = 3.85 deg; ϕmom(crowd+wind) = 4.48 deg	Pass
19.03.3 (f)	Residual freeboard	0.2 m	0.823	Pass

Figure 43. Stability criteria status – Load Case 1

- Load case 2 (100% Pass., 50% FW, 50% Waste water)

Load case 2 – During voyage. Specific gravity: 1.000 (Density = 1 t/m3).

	Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Total FSM tonne.m	FSM Type
1	Lightship	1	51.781	51.781			10.720	-0.030	1.540	0.000	User Specifi
2	Passengers on	80	0.075	6.000			11.250	0.000	2.470	0.000	User Specifi
3	Passengers on	20	0.075	1.500			16.150	0.000	4.470	0.000	User Specifi
4	Crew	2	0.075	0.150			20.000	0.000	2.470	0.000	User Specifi
5	Fresh water 1	50%	0.512	0.256	0.512	0.256	14.001	1.120	0.527	0.096	Maximum
6	Fresh water 2	50%	0.512	0.256	0.512	0.256	14.001	-1.120	0.527	0.096	Maximum
7	Grey water	50%	0.752	0.376	0.823	0.412	16.002	0.000	0.375	0.131	Maximum
8	Black water	50%	0.449	0.224	0.491	0.246	18.249	0.000	0.396	0.128	Maximum
9	Total Loadcas			60.543	2.338	1.169	11.018	-0.026	1.687	0.453	
10	FS correction								0.007		
11	VCG fluid								1.695		

Figure 44. Weight distribution – Load case 2

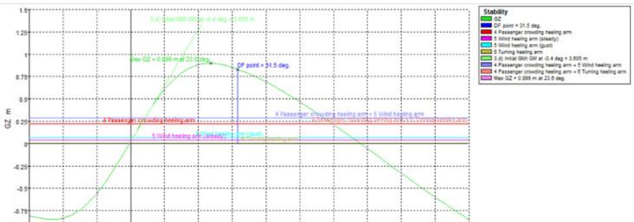

Figure 45. GZ curve – Load case 2

Heel to Starboard deg	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100
GZ m	-0.808	-0.835	-0.556	0.026	0.606	0.883	0.852	0.689	0.467	0.213	-0.057	-0.332	-0.6	-0.851
Area under GZ curve from zero heel m.deg	18.4199	10.0563	2.8014	0	3.3135	11.0558	19.9127	27.6831	33.4997	36.9173	37.7023	35.7559	31.0863	23.8196
Displacement t	60.54	60.54	60.54	60.54	60.54	60.54	60.54	60.54	60.54	60.54	60.54	60.54	60.54	60.54
Draft at FP m	0.419	0.635	0.812	0.874	0.812	0.635	0.418	0.168	-0.163	-0.671	-1.64	-4.452	n/a	-6.427
Draft at AP m	0.419	0.635	0.812	0.874	0.812	0.635	0.418	0.168	-0.163	-0.671	-1.64	-4.452	n/a	-6.427
WL Length m	23.395	23.476	23.573	23.586	23.573	23.476	23.395	23.479	23.699	23.839	23.933	23.991	24.021	24.021
Beam max extents on WL m	3.137	4.266	5.501	6	5.501	4.266	3.137	2.546	2.201	1.96	1.808	1.665	1.592	1.585
Wetted Area m^2	122.999	117.262	119.052	125.85	119.052	117.262	122.999	125.839	127.397	128.148	128.402	128.332	128.291	128.449
Waterpl. Area m^2	63.089	84.269	104.147	113.668	104.147	84.269	63.089	51.829	45.129	40.749	37.749	35.502	33.943	33.574
Prismatic coeff. (Cp)	0.743	0.719	0.682	0.646	0.682	0.719	0.743	0.755	0.758	0.762	0.765	0.768	0.771	0.775
Block coeff. (Cb)	0.539	0.501	0.474	0.419	0.474	0.501	0.539	0.556	0.561	0.574	0.588	0.607	0.596	0.58
LCB from zero pt. (+ve fwd) m	11.042	11.034	11.028	11.026	11.028	11.034	11.043	11.052	11.062	11.07	11.076	11.08	11.078	11.073
LCF from zero pt. (+ve fwd) m	11.475	11.168	10.87	10.53	10.87	11.168	11.476	11.677	11.839	12.02	12.192	12.234	12.132	12.052
Max deck inclination deg	30.0148	20.0122	10.0126	0.3884	10.0126	20.0122	30.0148	40.0163	50.0164	60.0148	70.0116	80.0066	90	99.9932
Trim angle (+ve by stern) deg	0	0	0	0	0	0	0	0	0	0	0	0	n/a	0

Figure 46. Stability parameters table – Load case 2

Rule	Criteria	Limit value	Actual value	Status
19.03.3 (a)	Value of MaxGZ	0.2	0.899	Pass
19.03.3 (a)	Angle at max GZ requirement	ϕmax>= ϕmom+3	ϕmax = 23.6 deg; ϕmom(crowd+turn) = 3.86 deg; ϕmom(crowd+wind) = 4.5 deg	Pass
19.03.3 (b)	Angle at max GZ requirement	φf >= φmom+3	ϕf = 31.5 deg;ϕmom(crowd+turn) = 3.86 deg; ϕmom(crowd+wind) = 4.5 deg	Pass
19.03.3 (c)	Angle at max GZ requirement btw 15 deg and φmax	0.035+0.001(30-φmax)=0.0414	6.95	Pass
19.03.3 (d)	Initial GM	0.15	3.605	Pass
19.03.3 (e)	Heeling angle due to crowd+turn and crowd+wind	12	ϕmom(crowd+turn) = 3.86 deg; ϕmom(crowd+wind) = 4.5 deg	Pass
19.03.3 (f)	Residual freeboard	0.2 m	0.826	Pass

Figure 47. Stability criteria status – Load Case 2

- Load case 3 (100% Pass., 10% FW, 98% Waste water)

Load case 3 – At the end of the voyage. Specific gravity: 1.000 (Density = 1 t/m3).

	Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Total FSM tonne.m	FSM Type
1	Lightship	1	51.781	51.781			10.720	-0.030	1.540	0.000	User Specifi
2	Passengers on	80	0.075	6.000			11.250	0.000	2.470	0.000	User Specifi
3	Passengers on	20	0.075	1.500			16.150	0.000	4.470	0.000	User Specifi
4	Crew	2	0.075	0.150			20.000	0.000	2.470	0.000	User Specifi
5	Fresh water 1	10%	0.512	0.051	0.512	0.051	14.003	1.102	0.427	0.096	Maximum
6	Fresh water 2	10%	0.512	0.051	0.512	0.051	14.003	-1.102	0.427	0.096	Maximum
7	Grey water	98%	0.752	0.737	0.823	0.807	16.001	0.000	0.543	0.000	Maximum
8	Black water	98%	0.449	0.440	0.491	0.481	18.250	0.000	0.558	0.000	Maximum
9	Total Loadcas			60.709	2.338	1.391	11.054	-0.026	1.686	0.193	
10	FS correction								0.003		
11	VCG fluid								1.689		

Figure 48. Weight distribution – Load case 3

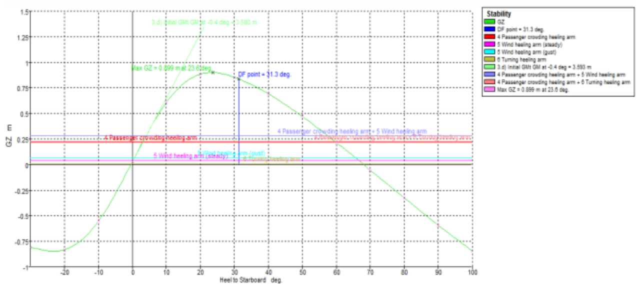

Figure 49. GZ curve – Load case 3

Heel to Starboard deg	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100
GZ m	-0.807	-0.834	-0.555	0.026	0.607	0.883	0.853	0.691	0.469	0.216	-0.054	-0.327	-0.595	-0.846
Area under GZ curve from zero heel m.deg	18.3943	10.0382	2.7927	0	3.3206	11.0688	19.9326	27.7141	33.5491	36.9926	37.811	35.9054	31.2844	24.0731
Displacement t	60.71	60.71	60.71	60.71	60.71	60.71	60.71	60.71	60.71	60.71	60.71	60.71	60.71	60.71
Draft at FP m	0.41	0.629	0.807	0.869	0.807	0.629	0.41	0.157	-0.179	-0.694	-1.675	-4.524	n/a	-6.504
Draft at AP m	0.41	0.629	0.807	0.869	0.807	0.629	0.41	0.157	-0.179	-0.694	-1.675	-4.524	n/a	-6.504
WL Length m	23.416	23.491	23.585	23.597	23.585	23.491	23.417	23.506	23.72	23.856	23.945	23.999	24.025	24.02
Beam max extents on WL m	3.138	4.268	5.499	6	5.499	4.268	3.138	2.547	2.202	1.961	1.804	1.674	1.594	1.586
Wetted Area m^2	123.25	117.459	119.204	125.815	119.205	117.459	123.251	126.027	127.59	128.363	128.624	128.603	128.538	128.685
Waterpl. Area m^2	63.099	84.249	104.287	113.603	104.287	84.249	63.1	51.768	45.07	40.705	37.723	35.632	34.042	33.658
Prismatic coeff. (Cp)	0.744	0.72	0.683	0.648	0.683	0.72	0.744	0.755	0.759	0.763	0.766	0.769	0.772	0.776
Block coeff. (Cb)	0.541	0.502	0.472	0.417	0.472	0.502	0.541	0.556	0.562	0.575	0.59	0.603	0.595	0.578
LCB from zero pt. (+ve fwd) m	11.079	11.07	11.064	11.061	11.064	11.07	11.079	11.089	11.099	11.107	11.113	11.117	11.116	11.11
LCF from zero pt. (+ve fwd) m	11.483	11.17	10.892	10.562	10.892	11.17	11.483	11.671	11.833	12.018	12.19	12.27	12.162	12.077
Max deck inclination deg	30.0163	20.0135	10.0143	0.4204	10.0143	20.0135	30.0163	40.0179	50.0179	60.0161	70.0126	80.0071	90	99.9926
Trim angle (+ve by stern) deg	0	0	0	0	0	0	0	0	0	0	0	0	n/a	0

Figure 50. Stability parameters table – Load case 3

Rule	Criteria	Limit value	Actual value	Status
19.03.3 (a)	Value of MaxGZ	0.2	0.899	Pass
19.03.3 (a)	Angle at max GZ requirement	ϕmax>= ϕmom+3	ϕmax = 23.6 deg; ϕmom(crowd+turn) = 3.83 deg; ϕmom(crowd+wind) = 4.47 deg	Pass
19.03.3 (b)	Angle at max GZ requirement	φf >= φmom+3	ϕf = 31.3 deg; ϕmom(crowd+turn) = 3.37 deg; ϕmom(crowd+wind) = 4.47 deg	Pass
19.03.3 (c)	Angle at max GZ requirement btw 15 deg and φmax	0.035+0.001(30-φmax)=0.0414	6.95	Pass
19.03.3 (d)	Initial GM	0.15	3.593	Pass
19.03.3 (e)	Heeling angle due to crowd+turn and crowd+wind	12	ϕmom(crowd+turn) = 3.83 deg; ϕmom(crowd+wind) = 4.47 deg	Pass
19.03.3 (f)	Residual freeboard	0.2 m	0.831	Pass

Figure 51. Stability criteria status – Load Case 3

- Load case 4 (0% Pass., 10% FW, 10% Waste water)

Load case 4 – Unladen condition Specific gravity: 1.000 (Density = 1 t/m^3).

	Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Total FSM tonne.m	FSM Type
1	Lightship	1	51.781	51.781			10.720	-0.030	1.540	0.000	User Specifi
2	Fresh water 1	10%	0.512	0.051	0.512	0.051	14.003	1.102	0.427	0.096	Maximum
3	Fresh water 2	10%	0.512	0.051	0.512	0.051	14.003	-1.102	0.427	0.096	Maximum
4	Grey water	0%	0.752	0.000	0.823	0.000	16.494	0.000	0.200	0.000	Maximum
5	Black water	0%	0.449	0.000	0.491	0.000	18.490	0.000	0.200	0.000	Maximum
6	Total Loadcas			51.883	2.338	0.102	10.726	-0.030	1.538	0.193	
7	FS correction								0.004		
8	VCG fluid								1.542		

Figure 52. Weight distribution – Load case 4

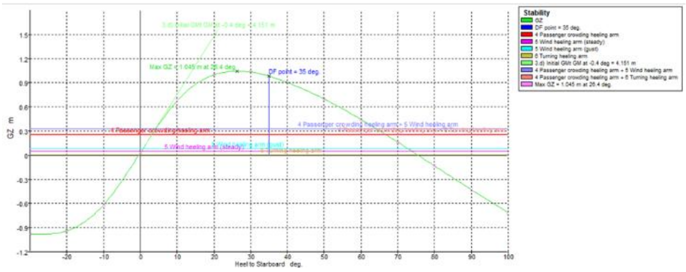

Figure 53. GZ curve – Load case 4

Heel to Starboard deg	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100
GZ m	-0.979	-0.941	-0.616	0.031	0.676	0.998	1.033	0.903	0.696	0.443	0.162	-0.134	-0.428	-0.712
Area under GZ curve from zero heel m.deg	20.9138	11.1768	3.0923	0	3.7054	12.3696	22.7092	32.4784	40.519	46.2471	49.2886	49.4342	46.6173	40.9081
Displacement t	51.88	51.88	51.88	51.88	51.88	51.88	51.88	51.88	51.88	51.88	51.88	51.88	51.88	51.88
Draft at FP m	0.328	0.583	0.781	0.854	0.781	0.583	0.328	0.031	-0.365	-0.984	-2.152	-5.506	n/a	-7.483
Draft at AP m	0.328	0.583	0.781	0.854	0.781	0.583	0.328	0.031	-0.365	-0.984	-2.152	-5.506	n/a	-7.483
WL Length m	23.045	23.233	23.374	23.394	23.374	23.233	23.045	23.035	23.355	23.569	23.711	23.808	23.883	23.948
Beam max extents on WL m	3.197	4.348	5.319	6	5.319	4.348	3.197	2.595	2.218	1.948	1.71	1.595	1.541	1.536
Wetted Area m^2	111.818	106.032	111.162	118.617	111.162	106.032	111.818	114.377	115.624	115.724	115.188	115.096	115.214	115.468
Waterpl. Area m^2	64.449	85.136	98.011	108.688	98.011	85.136	64.448	52.786	45.582	40.116	35.567	32.966	31.677	31.433
Prismatic coeff. (Cp)	0.728	0.698	0.656	0.615	0.656	0.698	0.728	0.744	0.746	0.747	0.749	0.751	0.754	0.757
Block coeff. (Cb)	0.498	0.457	0.486	0.41	0.486	0.457	0.498	0.517	0.528	0.549	0.593	0.615	0.597	0.577
LCB from zero pt. (+ve fwd) m	10.743	10.736	10.73	10.728	10.73	10.736	10.744	10.753	10.762	10.772	10.779	10.783	10.782	10.777
LCF from zero pt. (+ve fwd) m	11.491	11.084	10.651	10.381	10.651	11.084	11.491	11.682	11.881	12.024	11.895	11.818	11.764	11.713
Max deck inclination deg	30.0078	20.0049	10.0024	0.0829	10.0024	20.0049	30.0079	40.0099	50.011	60.0109	70.0087	80.0048	90	99.9954
Trim angle (+ve by stern) deg	0	0	0	0	0	0	0	0	0	0	0	0	n/a	0

Figure 54.Stability parameters table – Load case 4

The stability criteria for the vessel are within the limits for all load cases considered.

Rule	Criteria	Limit value	Actual value	Status
19.03.3 (a)	Value of Max.GZ	0.2	0.919	Pass
19.03.3 (a)	Angle at max. GZ requirement	ϕmax>= ϕmom+3	ϕmax = 26.4 deg; ϕ(wind) = 0.191 deg	Pass
19.03.3 (b)	Angle at max. GZ requirement	ϕf >= ϕmom+3	ϕf = 35 deg;ϕ(wind) = 0.191 deg	Pass
19.03.3 (c)	Angle at max. GZ requirement btw 15 deg and ϕmax	0.035+0.001(30-ϕmax)=0.0386	7.1	Pass
19.03.3 (d)	Initial GM	0.15	3.664	Pass
19.03.3 (e)	Heeling angle due to crowd+turn and crowd+wind	12	ϕ(wind) = 0.191 deg	Pass
19.03.3 (f)	Residual freeboard	0.2 m	0.847	Pass

Figure 55. Stability criteria status – Load Case 4

3. 3D Modelling

The 3D model has been realized using Blender™ 2.92. Different views are presented below.

Figure 56. 3D exterior view of the Ship (Day)

Figure 57. 3D exterior view of the Ship (Night)

Figure 58. 3D view of the upper deck

Figure 59. 3D interior view in sitting arrangement-1

Figure 60. 3D interior view in sitting arrangement-2

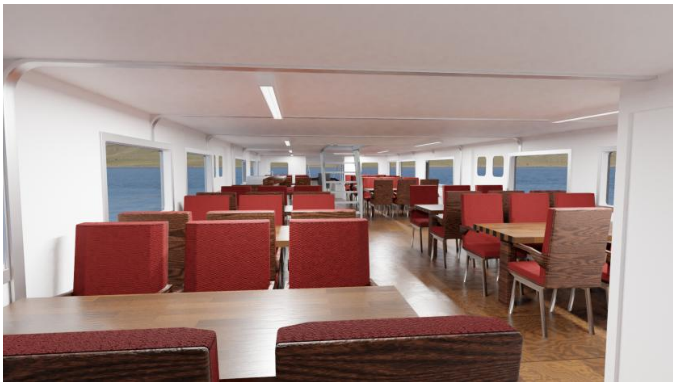

Figure 61. 3D interior view in dining arrangement

4. SUMMARY

Throughout this case study, the preliminary design of an inland passenger vessel has been presented in details. All the necessary steps taken to design a ship that fits the rules' & requirements. A complete analysis is conducted, going through numerous inter-related design stages, the a to propose a preliminary assessment that can further be developed into a more detailed design used for production. Only one iteration of the design spiral was made, and additional iterations can be performed to improve the proposed preliminary design.

First, the requirements have been defined as a basis for the design. One important requirement led to select an electrical propulsion system to design an energy-efficient and “green” vessel. The use of electrical batteries enables to obtain a zero-emission vessel, which is more and more desired in this market. Next, the ship’s main dimensions were found based on a regression analysis of existing data. Then, the general arrangements of the vessel have been exposed. The major challenge in the conception of the GA has been to find a specific location for each required element, while satisfying the requirements, and maximizing spaces for circulation and increase passengers’ comfort onboard. Every required element has been defined and exposed on the drawings. Then, the scantlings have been calculated based on the BV Rules [1], and once defined, the weight estimation could be done. Additionally, a cost estimation has been performed based on the material cost, labor costs, and cost of the outfit. A final cost is thus proposed. Next, the hull form was defined using Maxsurf™ to minimize the ship’s resistance at the operational speed. The required brake power was estimated based on CFD calculations done with FineMarine™. Therefore, the engine was selected. After that, the propeller design was made based on Wageningen B series and optimized using Hydrocomp Propexpert program. Then, the rudder was designed based on rules’ calculations. A suitable bow thruster was selected. Moreover, the vessel’s electrical balance was performed in order to know the overall electrical consumption of the ship, and thus estimate the electrical power required. This step is required for the battery selection. Emergency batteries are also selected to provide additional power in case of emergency. Finally, stability calculations are performed using Maxsurf’s Stability module considering 4 loading conditions. The vessel’s intact stability should fulfill the requirements defined in the ES-TRIN Rules [3]. All the results obtained from Maxsurf are exposed for each load case, including weight distribution, GZ-curves, stability parameters and criteria.

This case study involves usual steps required to perform the preliminary design of an inland Eco-passenger vessel, in which many common tools used in industry were introduced with a focus on energy efficiency & economical product development.

In conclusion, the design and analysis process culminated in a well-balanced and efficient passenger vessel. The integration of advanced technologies, careful consideration of stability criteria, and the use of industry-standard tools contributed to a vessel that not only meets regulatory requirements but also prioritizes safety, performance, and passenger comfort. The detailed design parameters, stability calculations, and 3D modeling collectively reflect a comprehensive approach to maritime engineering, showcasing the potential for a successful and sustainable passenger vessel in inland navigation.

This study serves as a valuable blueprint for future vessel design projects/case studies, emphasizing the importance of incorporating energy efficient system in design to achieve an optimal balance between functionality, safety, and environmental considerations in the maritime domain.

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