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Design analysis of an innovative concept of a displacement motor yacht with eco-drive

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Abstract

In response to the challenges of environmental protection and the need to be close to nature and to reconnect with it, an unusual motor yacht design is developed with an abstract architectural form modeled on an armadillo. Due to the innovative form of the hull, a specific approach to pre-design is used, with the research objective of verifying that for the organic form of the hull, it would be possible to meet all the design criteria and regulations required for the design of a yacht. This article first characterizes the initial assumptions and then presents the process of determining the main dimensions with simultaneous modification of the hull shape. In order to maintain the basic dimensional proportions, based on the classic motor yacht, the recommended values of design factors are controlled. Moreover, the hydrostatic parameters of the unconventional hull shape are calculated. As a result of preliminary resistance and propulsion analyses, a propulsion system in the form of electric motors is selected, and, to meet emission requirements, the use of photovoltaic panels is additionally proposed. A stability and equilibrium analysis is carried out for one of the load cases and checked with the requirements of the Polish Register of Shipping (PRS) rules. The design of the hull of the yacht, covered in an interesting form of scales, together with the layout of the yacht's interior, is presented in three-dimensional form, bringing the conceptual idea to life. The result of the design work and analysis is an inspiring hull shape based on nature, complying with the design guidelines and regulations that apply to yacht design.

Introduction

The degradation of the natural environment, as well as human isolation during the difficult time of the pandemic, have caused people to increasingly seek to return to nature and reconnect with it. One of these ways of spending leisure time is recreation in water areas – in silence, peace, and closeness to nature. It is not surprising that the development of the yachting industry worldwide, including in Poland, is performing very well, and yacht rentals are breaking records (PAP, 2022). Therefore, yacht designers, in order to increase the attractiveness, competitiveness, and utility values of the constructed vessels, are outdoing themselves in creating unusual and unique concepts, standing out from others, attracting the attention of any observer and, additionally, combining proximity to nature and ecology.

One exemplary architectural design based on the strong correlation of solid construction with its counterpart in nature is the Lotus Temple in New Delhi, India (Government of Delhi, 2023), reminiscent of the lotus flower – which is an important symbol in Hindu tradition. In the yachting industry, on the other hand, one of the few examples is the 137-meter superyacht *Avanguardia* (Tindale, 2020), designed by Italian Lazzarini Design and modelled on a swan. The unconventionality of the design focuses on the swan's head element, which is a 16 m motorboat that acts as a detachable element from the whole. However, the idea did not go beyond conceptual design.

At the same time, the originality of the ideas triggers an innovative approach to the design process. In this case, the classic model of the watercraft design process (presented by, among others, Schneekluth and Bertram (Schneekluth & Bertram, 1998), Watson (Watson, 1998), Larsson and Eliasson (Larsson & Eliasson, 2000), and Papanikolaou (Papanikolaou, 2014)), in the form of an iterative process based on knowledge gained from a population of vessels already built that enables the use of empirical or statistical mathematical relationships, will not be applicable. The reason for this is the lack of data and the need to use a customized design approach.

Creating a novel and unusual yacht design is always a major challenge to see if futuristic imagination and reality can be combined into a practical, safe, comfortable, and aesthetically pleasing architectural body that meets basic design criteria and regulations. The atypicality of the design stems from the shape of the hull, modeled on a terrestrial animal called a pangolin, which is covered with armor in the form of distinctive scales. The chosen animal is of broader interest to one of the co-authors of the work, so it was the main inspiration. The architectural originality of the hull means that the design process is based on individual assumptions. It starts with the development of the shape of the body and then the determination of the main dimensions, accounting for the functional qualities. This form of design is now possible thanks to appropriate computer programs that support and facilitate this phase of the project. When creating a non-standard design, the basic task is to check whether the developed hull shape will meet the basic design criteria, such as buoyancy, stability, and balance.

Research aim

The aim of this study is to check whether, for an unusual conceptual design of a yacht with a futuristic shape based on nature with ecological propulsion and safe for the environment and recreational cruising, all the design criteria required by regulations for yacht design will be achieved. In order to realize the main objective of this work, it is necessary to:

1. Formulate the initial assumptions for the project.
2. Develop a hull shape that replicates the body of an armadillo animal and, at the same time, maintains the dimensional proportions of the innovative body so that it meets the regulations and design criteria, including the buoyancy condition.
3. Determine the main dimensions, parameters, and design coefficients, keeping the analyses iterative to confirm the buoyancy capability.
4. Develop a three-dimensional hull body with a functional layout of all decks, facilitating modifications with simultaneous visualization.
5. Carry out resistance-propulsion calculations to select an eco-friendly propulsion system to ensure the assumed speed (additionally using renewable sources).
6. Pre-estimate the mass of the yacht with equipment and the coordinates of its center.
7. Check that the design of a yacht with a specific shape meets the design regulations, including stability criteria and equilibrium.

Design assumptions and design methodology for the yacht concept

The basis for determining the main dimensions of the yacht is the definition of the design assumptions, i.e.:

1. Yacht type and purpose: displacement, double-deck motor yacht for recreational sailing.
2. Design category: B/C, for waters with good sunlight due to the fitting of photovoltaic panels.
3. Maximum speed: $v = 10$ knots.
4. Overall length limit: $L_c = 21.0$ m.
5. 4 crew (accommodated) and 4 additional persons (occasional).
6. Propulsion system: electric motor.
7. Autonomy A: 4 days.
8. High level of comfort – large cabins over 12 m^2 with separate bathrooms and 1.5×2 m berths. Spacious living area of about 40 m^2 inside the yacht and about 70 m^2 outside. Minimum standing height indoors: 2 m.
9. Hull and deckhouse material: polyester-glass laminate.
10. Classification regulations: in accordance with PRS guidelines and JAC regulations.

Using a trial-and-error method to estimate the main dimensions of the yacht, the shape of the solid is first developed by mapping the characteristic elements of the animal's silhouette (Figure 1).

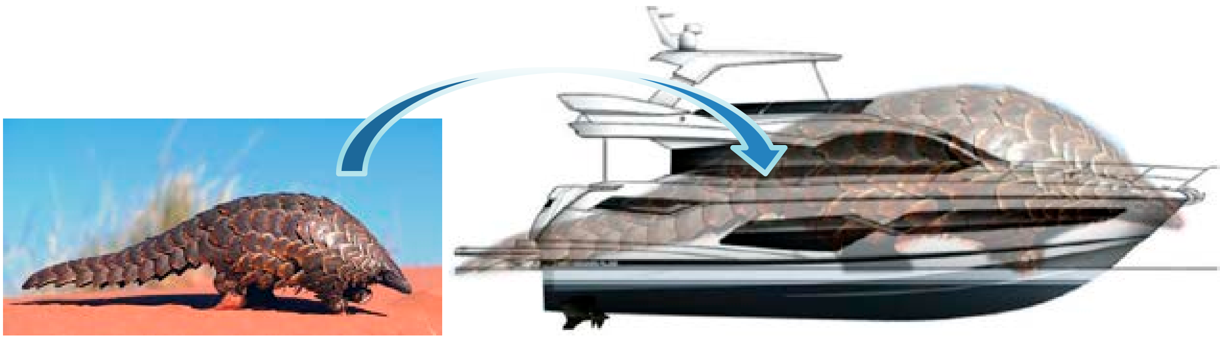

Figure 1. Comparison of a classic yacht hull with a pangolin silhouette (program used is Corel PhotoPaint)

In order to maintain the dimensional proportions of the new body, a comparative method is used based on the classic Greenline 68 with a similar-sized, displacement-powered yacht.

The dimensional analysis started with an assumed overall length of L_c = 21.0 m to then determine the length at the waterline L_{wl}, width B, and draft T – as shown in Figure 2. The remaining parameters, i.e., breadth at the waterline B_{wl}, breadth at the transom B_p, and the angle of subdivision, were obtained by creating the hull shape while verifying the most important design coefficients, i.e., speed-to-length ratio *SLR*, Froude number *Fn*, displacement-to-length ratio *DLR*, or prismatic coefficient C_p. The range of variation of these coefficients, confirming the buoyancy character of the yacht hull, is shown in Table 1.

Basic design factors – as criteria factors for a displacement yacht:

- Froude number *Fn*:

$$Fn = \frac{v}{\sqrt{(g \cdot L_{wl})}} = 0.377 \tag{1}$$

- According to the Froude number, the limiting displacement speed (in the imperial system) is:

$$v_{\max} = 1.34\sqrt{L_{wl}\,[\text{ft}]} = 10.4\ [\text{kn}] \tag{2}$$

Above this speed, it is estimated that an unfavorable range of speeds is obtained.

- Speed to length ratio *SLR*:

$$SLR = \frac{v}{\sqrt{L_{wl}}} = 1.27 \tag{3}$$

- Displacement ratio to length *DLR*:

$$DLR = \frac{D\,[\text{lt}]}{(0.01 \cdot L_{wl}[\text{ft}])^3} = 234 \tag{4}$$

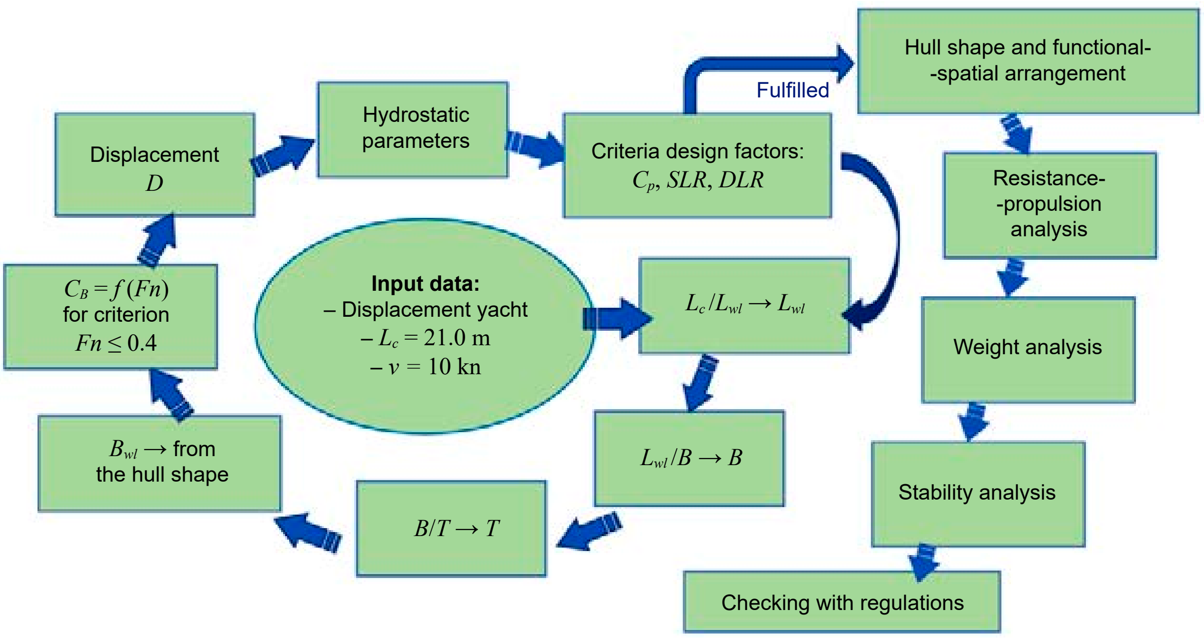

Figure 2. Iterative process of the main design stages applied to the innovative yacht

- Limiting displacement velocity in relation to displacement-length relationship SLR_{max}:

$$SLR_{max} = \frac{8.26}{DLR^{0.311}} = 1.514 \quad (5)$$

According to the literature (Larsson & Eliasson, 2000; Sponberg, 2010), the design coefficients confirm that the criteria for buoyancy flotation are met, among others: the range of the *Fn* number corresponds to the hypothetical wave resistance curve for this speed range (Table 1).

At this preliminary stage, the basic dimensions of the yacht are determined, which are necessary to carry out further design stages, i.e., checking the resistance-propulsion characteristics, stability characteristics with equilibrium, unsinkability, performance, utility values, and comfort of the yacht's cruising.

Table 1. Estimated main dimensions of the yacht and design factors

No.	Design factor	Range of values displacement yachts	Calculated value	First estimated dimensions
1.	C_B	0.35–0.55	0.45	
2.	C_p	0.52–0.66	0.59	
3.	*SLR*	1.0–1.5	1.27	L_c = 21.0 m
4.	*DLR*	180–270 moderately heavy	234	L_{wl} = 18.9 B = 5.5 m T = 1.1 m H = 5.3 m
5.	C_m	0.55–0.89	0.78	
6.	C_{wp}	0.59–0.81	0.74	
7.	*Fn*	0.2–0.42	0.377	

Hull shape concept and hydrostatic parameters

At the same time, the yacht's external design process began with the sketching and development of the hull concept, which is mostly a representation of the body silhouette of the pangolin. Figure 1 illustrates the differences and similarities of the proposed hull shape in relation to the traditional yacht silhouette. The overall arrangement of the interior layout meets the technical requirements.

Table 2. Hydrostatic parameters – from the Maxsurf Modeler

No.	Parameter	Value	Unit
1.	Displacement	50 080	kg
2.	Volume (displaced)	48.858	m^3
3.	Draft amidships	1.1	m
4.	Immersed depth	1.1	m
5.	WL length	18.424	m
6.	Beam max extents on WL	5.29	m
7.	Wetted area	84.305	m^2
8.	Max section area	4.478	m^2
9.	Waterplane area	72.154	m^2
10.	Prismatic coefficient (Cp)	0.592	–
11.	Block coefficient (Cb)	0.456	–
12.	Max Section area coefficient (Cm)	0.776	–
13.	Waterplane area coefficient (Cwp)	0.74	–
14.	Longitudinal center of buoyancy (LCB length)	−0.527	from zero pt. (+ve fwd) m
15.	Longitudinal center of flotation (LCF length)	−0.854	from zero pt.
16.	Longitudinal center of buoyancy (LCB %)	−2.86	from zero pt.
17.	Longitudinal center of flotation (LCF %)	−4.635	from zero pt.
18.	Centre of buoyancy above keel (KB)	0.698	m
19.	Transverse metacentric Radius (BMt)	2.529	m
20.	Longitudinal metacentric Radius (BML)	28.778	m
21.	Transverse metacentric Height (GMt) corrected	3.227	m
22.	Longitudinal metacentric Height (GML)	29.475	m
23.	Transverse metacentre above keel (KMt)	3.227	m
24.	Longitudinal metacentre above keel (KML)	29.475	m
25.	Length: beam ratio	3.483	–
26.	Beam: draft ratio	4.812	–
27.	Length: vol^0.333 ratio	5.04	–

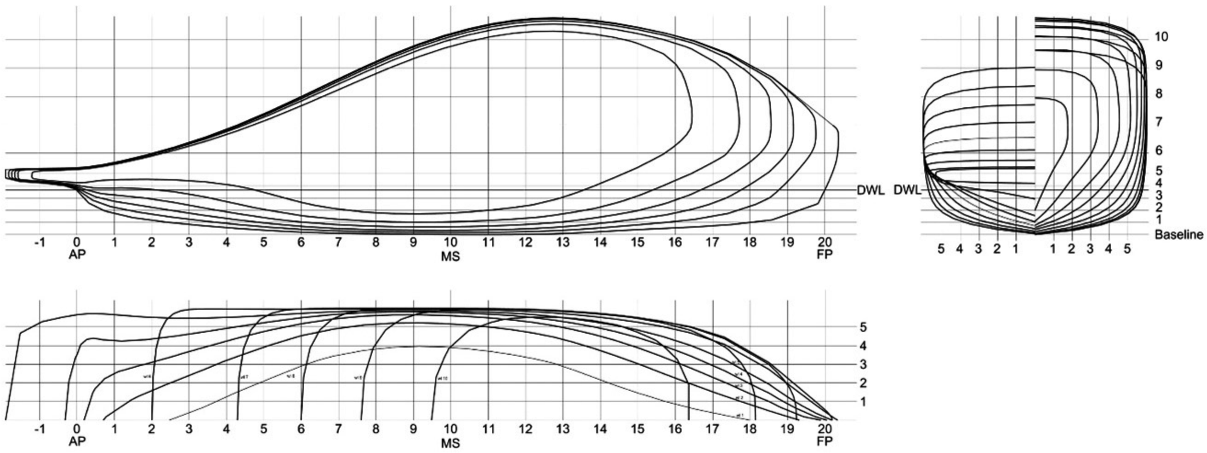

Figure 3. Concept of theoretical lines of the Pangolin yacht (using Rhinoceros)

The shape of the hull under development has a characteristic deckhouse concentrated in the extreme bow section, gently transitioning in the midship area to a pronounced flattening towards the stern. The deckhouse is located in front of the geometric center of the underwater section (when viewed from the bow). The body becomes slightly more organic, with fewer sharp angles and edges – without losing any of its dynamism. A distinctive feature is the long, aft sun platform, which is an open deck that reproduces the characteristic "tail" of the animal. After repeated refinements to the form of the hull shape, resulting from the management of the internal volume of the lump and decks and the fulfillment of the design criteria, an innovative hull shape is created, and the hydrostatic parameters are determined using the Maxsurf Modeler program. The final form of these parameters is shown in Table 2.

Figure 3 shows the developed shape of the yacht's hull in the form of theoretical lines.

Interior design concept

The conceptual body of the yacht includes three decks (Figure 4):

1. The swim/day deck, which includes a galley, a mess room with a sofa and table, as well as a recreation and lounging area at the far end of the stern (for spending time outdoors). Lifting hatches are provided on the floor to allow access to the engine room compartment with the electric motor and other propulsion system components.
2. The upper (main) deck is above the sundeck and is used as a mess, office, and stateroom. On this level in the forward section is the steering room, which is separated by a half bulkhead from the rest of the deck.
3. The lower deck, which includes a sleeping area with a large corridor and two cabins with a high standard of equipment, has double beds and private bathrooms with bath and shower. The forward cabin is the largest space – with a central double bed (2×1.6 m).

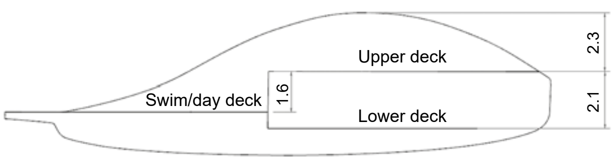

Figure 4. Conceptual division of decks in a yacht body (using Rhinoceros 7)

Figure 5 shows a 3D vision of the yacht's interior layout, which captures the realistic appearance of the yacht with its interior components and is important from the point of view of a weight and stability analysis.

Large scale-shaped windows – Figure 6 (modeled on a pangolin) – are modeled in the yacht's hull, with movable covers to regulate the entering light. Photovoltaic panels are provided on the outside of the covers.

The engines with batteries have been placed aft under the swim deck, which has the desirable effect of moving the center of gravity towards the stern. Given the shape of the hull, this offers an advantage in terms of balance but also makes it easier to install, repair, or replace propulsion components.

Propulsion analysis – resistance criterion

The resistance-propulsion analysis of the yacht's hull is carried out for a maximum speed of up to v = 10 kn, using Wyman's formula (Gerr, 2001; 2008) as a universal calculation method, designed

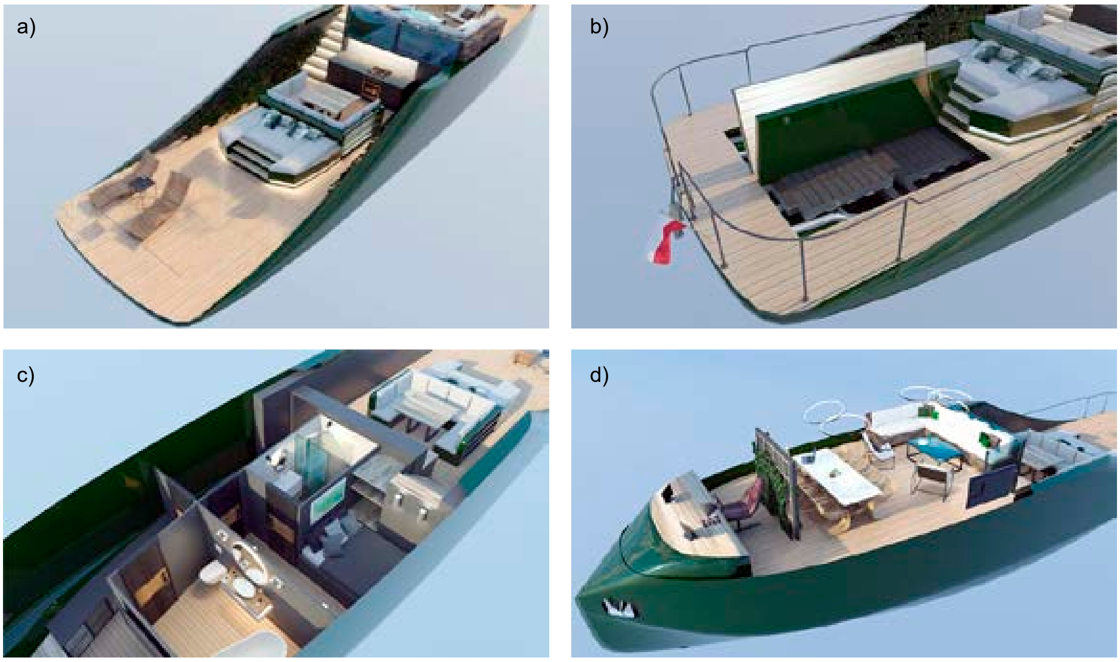

Figure 5. Visualization of deck layout concept: a) view of the swim deck, b) open hatches to the engine room, c) view of the lower deck, and d) view of the upper deck (using Blender)

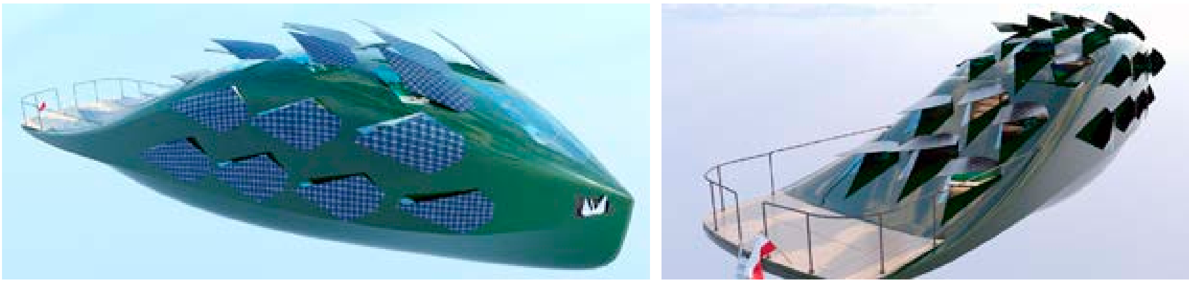

Figure 6. Conceptual view of windows with photovoltaic covers (using Blender)

for displacement yachts as well as sliding yachts. Wyman's speed formula allows good calculational results for *SLR* < 2 (Gerr, 2008). The calculations are carried out using the Maxsurf Resistance program for a hull with input parameters, i.e., wetted area $S = 83.359$ m^2, 1/2 angle of entrance $\varepsilon = 25.8^{\circ}$, deadrise at 50 % L_{wl} $\alpha = 11.3^{\circ}$, and displaced volume $V = 48.896$ m^3. The method considered an overall efficiency of $\eta = 58$ % – according to Torqeedo electric motor catalog data (Torqeedo, 2023). The results of the analysis are presented in tabular form (Table 3) and graphically in Figure 7. The Wyman method is used to calculate the power at the shaft of the *SHP* propeller. The characteristics of the method relate to the C_w factor, which considers and depends on the value of the *SLR* factor, so that:

Table 3. Resistance results using Wyman's method

No.	Speed [knots]	*Fn* [–]	Wyman resistance [kN]	Wyman power [HP]
1.	0.500	0.019	0.1	0.031
2.	1.000	0.038	0.2	0.248
3.	2.000	0.077	0.8	1.982
4.	3.000	0.115	1.9	6.688
5.	4.000	0.153	3.3	15.852
6.	5.000	0.191	5.2	30.962
7.	6.000	0.230	7.5	53.502
8.	7.000	0.268	10.2	84.959
9.	8.000	0.306	13.3	126.820
10.	9.000	0.344	16.9	180.569
11.	10.00	0.383	20.8	247.695

$$SHP = \left(\frac{D\,[\text{ft}]}{1000}\right)\cdot\left(\frac{v\,[\text{knots}]}{C_w\cdot\sqrt{L_{wl}}}\right)^3 \ [\text{HP}] \tag{6}$$

$$C_w = 0.8 + 0.7\cdot SLR \tag{7}$$

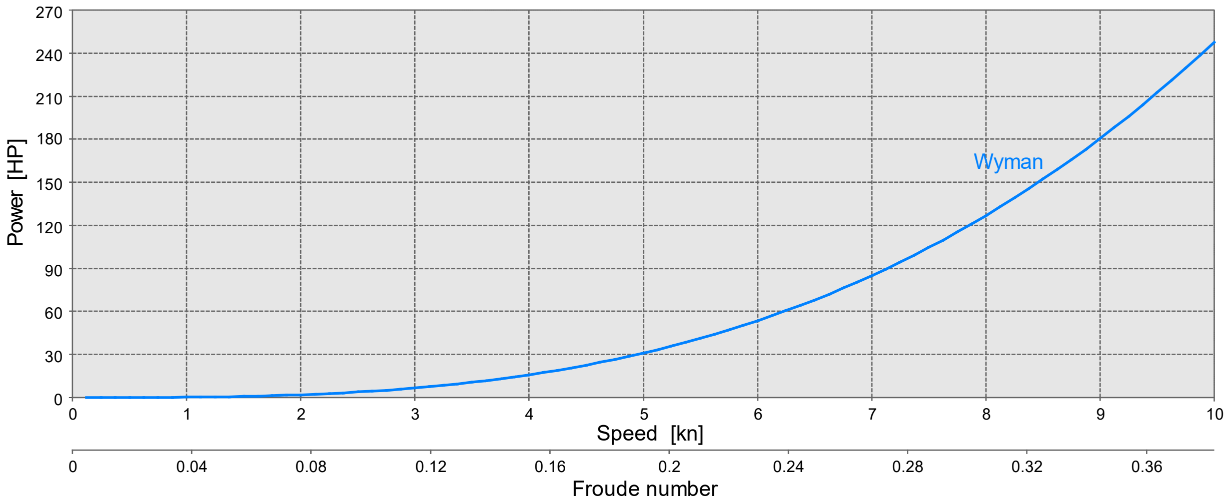

Figure 7. Power as a function of speed (Maxsurf Resistance)

The calculation (Figure 7) for the assumed maximum speed $v = 10$ kn results in a power requirement of 248 HP (185 kW). Two stationary motors of the Deep Blue 100i 900 model (Torqeedo, 2023), with a power of 136 HP (100 kW) each and a weight with full electronics (465 kg) and a Deep Blue Batterie 40 battery pack (Torqeedo, 2023), are chosen. This engine is the most powerful electric motor model offered on the market today. It provides continuous power and a high torque of 1060 Nm. For the recreational yacht being designed, the use of an electric motor has a number of advantages: quiet operation to help the crew carry on conversations or relax, greater comfort when cruising as a result of fewer vibrations, achieving zero emissions, and providing a pleasant experience for the user while also being good for the environment.

For the electric motor set, 12 batteries are provided (weight of a single 284 kg) with a total battery capacity of 524 kWh. The range is closely related to the speed, so their relationship is summarized as two characteristics (Figure 8). The batteries are charged by solar panels located on the window covers with a total capacity of 10.8 kW or by port chargers.

Stability analysis – stability criterion

The stability analysis is performed for the operational states required by the regulations. Table 4 summarizes the components of the masses for a yacht equipped with full reserves and the coordinates of their centers. The yacht exhibits minimal heeling to the side, with the center of mass displaced from the amidships towards the bow at 1.256 m relative to the base plane.

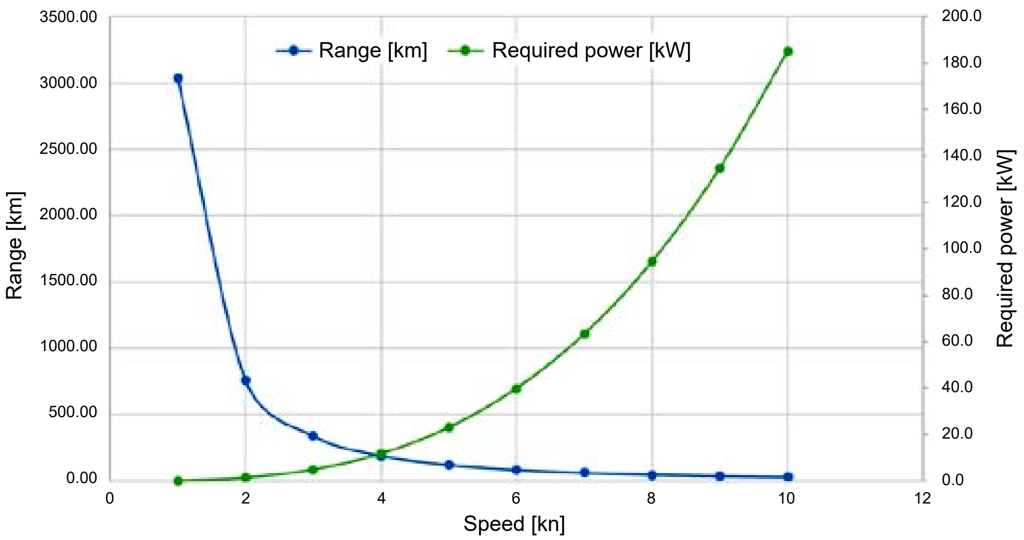

Figure 8. Range and power required for various speeds

Table 4. Summary of the components of the yacht masses and the coordinates of their center

No.	Name	Mass [t]	Position of center of mass *x* [m]	Position of center of mass *y* [m]	Position of center of mass *z* [m]
1.	Hull with deckhouse	12.96	10.988	0.009	2.479
2.	Interior equipment	2.26	12.328	−0.021	1.904
3.	Deck equipment	0.935	19.956	0.005	2.012
4.	Electric motors and batteries	5.0	3.967	0	1.185
5.	Electrical equipment and automation	1.0	14	0	1.1
6.	Crew with luggage (permanent and occasional)	1.0	15.4	0.2	1.6
7.	Provisions	0.048	9.8	0.1	2.2
8.	Water tanks (100 %)	3.118	11.002	0.0	0.548
9.	Permanent ballast	23.72	9.75	0.0	0.595
	Total weight of yacht with equipment	**50.04**	**10.07**	**0.006**	**1.256**

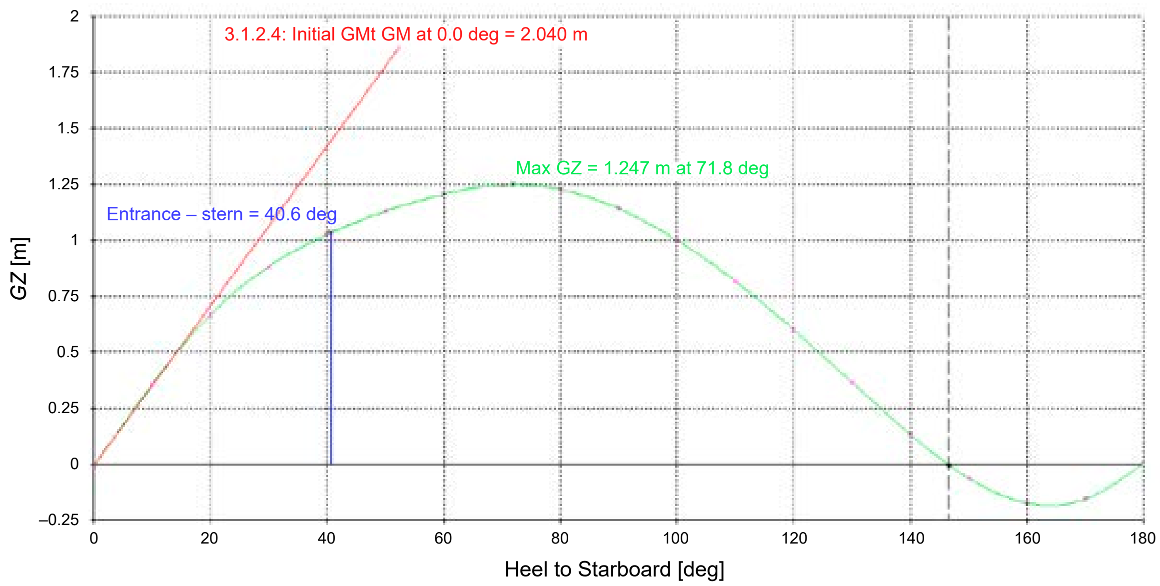

Figure 9. Righting arm curve *GZ* as a function of the heel angle (*ϕ*) (Maxsurf Stability)

For the maximum displacement condition, the yacht has been balanced, and it floats with a minimum trim aft of $t = 0.21$ m, with an average draft of $T = 1.087$ m. The results of the stability analysis are shown in Figure 9. The stability criteria required have also been achieved (Table 5).

Table 5. Basic stability criteria for a motor yacht (Polish Register of Shipping, 1996)

No.	GZ stability requirements (*f*)	Value	Unit
1.	Initial metacentric height not less than 0.5 m	2.040	m
2.	Righting lever at an angle of heel of 30° not less than 0.2 m	1.247	m
3.	Maximum righting lever values at an angle of heel greater than 30°	71.8	deg
4.	Range of positive values of static stability arms not less than 70°	146	deg
5.	Angle of flooding not less than 40° (entrance stern)	40.6	deg

Conclusions

The preliminary design analyses are clearly innovative due to the unusual shape of the hull of the yacht inspired by nature, which required an individual approach and the specificity of the analyses carried out, while meeting the required regulations. Based on design assumptions and restrictions (and, in this case, wide-ranging creativity), the main dimensional parameters were determined, and an unconventional architectural body of the yacht with a functional layout was developed, keeping the full-size height of the rooms to satisfy ergonomic criteria. The hull shape is very interesting and eye-catching, as well as the form of the husks covering the hull. The unusual shape of the hull fulfilled all the design objectives required, including the basic buoyancy equation.

The dimensional proportions and design parameters describing the geometric shape of the hull confirmed the buoyancy characteristics of its floatation. Crucially for the futuristic shape, the hydrostatic properties of the hull were calculated. The use of electric propulsion and photovoltaic panels places the yacht in the fully ecological group, which means it fulfills environmental standards. To achieve the assumed maximum speed of 10 kn, two electric motors with a total power of 200 kW and a set of 12 batteries were installed in the hull. The cruising range at this speed is approximately 52 km (a short distance), but, for an average speed of about 5 kn, it is more than 210 km. In this way, autonomous energy has been successfully combined (by using photovoltaic panels and electric propulsion) with an unconventional hull body of high, hotel-level standard. The project fits perfectly in terms of green energy, which is very important for the environment and the EU's zero-emission requirements. A preliminary analysis of transverse and longitudinal stability showed that the unusual shape fulfills the basic requirements for motor yachts. Due to the displacement reserve, a permanent ballast was used in the hull in the form of lead tanks at the bottom (this lowered the yacht's center of mass, which had a positive effect on stability).

In the next iteration, an increase in the number of batteries may be considered, which will increase the cruising range. The created design concept of the yacht is a tremendous object that could be a showpiece of any port city, including Szczecin. Its original and modern character could bring many benefits in terms of increasing the city's tourist attractiveness.

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