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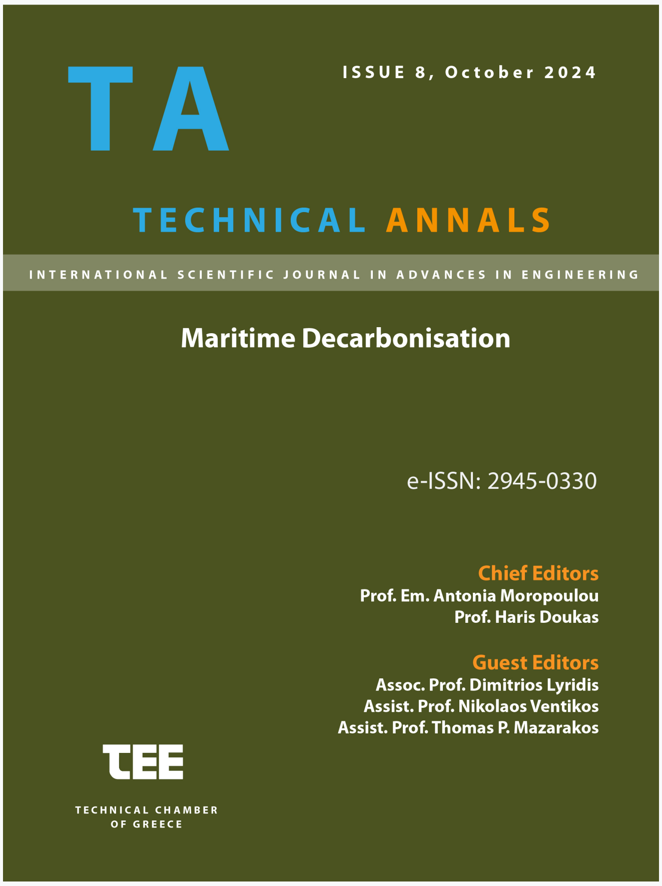

Hydrodynamic analysis and use of innovative materials for the design of a scale model traditional pleasure boat

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Hydrodynamic analysis and use of innovative materials for the design of a scale model traditional pleasure boat

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Abstract. This work presents a novel approach that integrates naval architecture and traditional shipbuilding. It is an innovative solution that bridges the two sectors, offering a novel perspective to the traditional shipbuilding industry and, concomitantly, underscoring methods to integrate novel technologies into traditional shipbuilding. This integration of novel technologies into traditional shipbuilding is a crucial step in the broader decarbonization process of shipping. The paper delineates the fundamental design parameters of a traditional yacht. The vessel is distinguished by a “karavoskaro” bow and a “barkalas” stern. Initially, the lines plan of the traditional vessel was mapped in 3D ship design software, followed by the calculation of the basic hydrostatic and hydrodynamic quantities. Subsequently, a three-dimensional model was designed to scale, and a physical prototype of the hull was constructed using three-dimensional printing technology. The latter was then used as a mold for the construction of the glass reinforced polyester hull of the traditional vessel using the hand lay-up technique. The objective of this study is to establish a methodology for integrating traditional shipbuilding expertise with contemporary naval architecture science and technology, with a focus on the blue economy and the decarbonization of shipping. The integration of traditional shipbuilding art, a cornerstone of the development of the Greek maritime state, which has evolved and persisted throughout the ages, with innovative technologies, holds the potential to serve as a crucial mechanism in the establishment of a lightweight fleet that aligns with the demands of sustainable maritime transportation within the Greek maritime domain.

Keywords: Traditional Shipbuilding, 3D Printing, Hydrodynamics

1 Introduction

Maritime decarbonization has emerged as a pivotal priority for the maritime industry, as ships represent a substantial contributor to greenhouse gas emissions, responsible for approximately 3% of global anthropogenic emissions. In response, the International Maritime Organization (IMO) has established targets to achieve net zero greenhouse gas emissions from ships by approximately 2050, with interim targets of reducing emissions by 20% to 30% by 2030 and by 70% to 80% by 2040 [1, 2].

According to the Global Marine Technology Trends 2030 report [3], Lloyd's Register, QinetiQ, and the University of Southampton examined 56 technologies and focused on 18 that were considered transformative for ship design, naval power, and the use of ocean space. Among the key technologies proposed are hydrodynamic analysis and ship design to improve propulsion and reduce energy consumption, the use of advanced materials to reduce weight and increase durability [4], the use of advanced manufacturing methods to reduce costs and increase efficiency, and the use of renewable energy sources to reduce emissions [5].

The decarbonization of ships represents a significant challenge for the shipping industry, and traditional shipbuilding is a sector that can contribute to this objective. However, achieving the strategic goals outlined by the International Maritime Organization (IMO) [1] is hampered by the constraint of not modifying the conventional design of traditional ships [6, 7]. This limitation imposes an approach that will not interfere excessively with the traditional character of the vessel. The central objective of this study was to highlight a methodology for the incorporation of novel technologies into the domain of traditional shipbuilding, while maintaining the integrity of the limitations imposed by the traditional nature of these vessels and the cultural significance they possess.

Additive manufacturing (AM), also known as 3D printing, is a rapidly evolving technology for product manufacturing, which has already been adopted in several industries such as automotive, aerospace, shipbuilding, construction and biomedical. One of the most popular 3D printing techniques is Fused Deposition Modelling (FDM) in which the material in form of a filament is deposited layer by layer onto the printer's platform until the final solid object is complete [8]. This innovative technology has the potential to replace conventional manufacturing, as it allows the fabrication of components and structures with complex geometries, it is operational flexible for on-demand and on-site production, and it can create functional end-use products without the need of special tools or machines. In addition, FDM's additive nature and working principle, restricts material usage and minimizes material waste during 3D printing, reduces production costs for small batches, and accelerates production compared to conventional manufacturing such as machining or injection molding.

As the maritime industry seeks to increase efficiency, reduce energy consumption and align with sustainability, the adoption of 3D printing has a significant potential to improve shipping and shipbuilding processes. First, the flexibility to create components on-demand and on-site using common 3D printers and feedstock material, without the need for expensive molds or tooling, makes 3D printing particularly attractive for ships, submarines and platform rigs in support of their operation and maintenance. Especially for marine spare parts that are required in case of malfunction or breakage, such as valves, bushings, bearings, rod ends, housings, etc., the use of 3D printing can shorten long supply chains and shipment time from remote suppliers and ensure uninterrupted and smooth operation even in the event of a critical failure [9]. In shipbuilding, additive manufacturing can be used to rapidly create prototypes, such as models of hulls, propellers, and other ship structures, and conduct hydrodynamic tests in actual towing tanks with the aim of optimizing ship design and performance [10]. Also, large format 3D printing can be used to create molds for the construction of plastic vessels, providing significant advantages such as freedom of design, reuse of the mold many times over, and reduction of the overall production cost and time [11,12]. In addition, the integration of AM technology with advanced materials, such as fiber-reinforced polymers, composite lattice core structures and carbon nanotubes, can lead to lightweight components and structures with enhanced durability, which can reduce the power required for propulsion and subsequently fuel consumption.

The paper is divided into six sections. In Section 2, the comprehensive history of the traditional yacht is described. In Section 3, the lines plan of the yacht is reproduced. In Section 4, the hydrostatic and hydrodynamic characteristics of the traditional yacht are calculated and presented. In Section 5, the 3D model of the hull is designed to scale and the hull mold prototype is manufactured via 3D printing. In Section 6, the glass reinforced polyester (GRP) hull of the vessel is constructed, and in Section 7, the main conclusions are drawn.

2 History of the traditional yacht Kostantis

Kostantis was a traditional boat built by the shipbuilders and owners Konstantinos Apostolou and Odysseus Apostolou at the Psilopatis shipyard in Kamatero, Salamina, in the spring of 1999 (Fig. 1a). Table 1 summarizes the main characteristics of the yacht [13].

Table 1. Main characteristics of Kostantis

Main dimension		Units
L_{OA}	23.95	m
L_{BP}	20.92	m
B_{max}	6.50	m
$D_{(B.L.)}$	2.83	m
$D_{(mld)}$	3.05	m
T	1.32	m

For its construction, the following types of wood were used:

- Pine of Mytilene, for the frames
- Pine of Samos, for the shell
- Pitch Pine, for the keel and the sternpost
- Plywood, for the superstructure and bulkheads

The yacht had two saloons, one of which was located on the Main Deck and the other in front of the engine room. In addition, it had two cabins to meet the crew's needs. In total, it was capable of carrying up to 187 passengers with a crew of 4, however, it was designed with the prospect of weekly cruises after appropriate retrofitting.

Kostantis was propelled by two 8-cylinder SCANIA D.S.14 engines with a horsepower of 343 BHP each. However, between 1999 and 2001 it also used two sails as an auxiliary means of propulsion, which were later removed (Fig. 1b). The yacht was cruising at a service speed of 10kn at 1600 rpm and the horsepower of each engine for this speed was about 280 HP.

From the spring of 1999 until 2001, Kostantis operated as a day ship based in Corfu. During this period, the vessel cruised to the following destinations: Paxos, Antipaxos, Sivota and Parga. From 2002 to 2014 it operated as a ferry on the route Salamis-Piraeus. From 2014 to 2017, the ferry continued to operate on the Thessaloniki-Perea-Neoi Epivates route. At the end of 2017 the vessel underwent a change in ownership but continued to fulfill the operational requirements of the same line until an unfortunate incident which occurred in 2022. During routine maintenance in a shipyard in Thessaloniki, a fire broke out, resulting in the complete destruction of Kostantis.

Fig. 1. The traditional yacht Kostantis (a) between 1999 and 2001, (b) after retrofitting and removal of the masts

The primary material used for constructing the hull of this yacht was pine wood. Initially, the keel was constructed using Pitch Pine. Then, the “akrapi” was created, a piece of wood approximately 4-5 centimeters thick, which was placed on top of the keel and nailed down with short nails. Its purpose was to seal the hull.

Additionally, it had notches of 2.5 centimeters, serving as guides for the placement of the frames. Next, the “stravoxyla” (crooked timbers), which are the frames, were constructed and placed into the notches made in the “akrapi”. The “stravoxyla” are double-layered. After the first pair of frames was placed on the “akrapi” on the starboard and port sides, it was aligned using the “alfadolasticho” (alignment rope). Then, the rest of the frames were positioned based on this alignment.

The next step was the installation of the longitudinal stiffeners. These stiffeners are categorised into several types: the “stragalias”, which consist of two planks; the “gyali koutouki” or “kourzeto” which is narrower than the “stragalias” but thicker than the “kamaria” (beams), which form the base for the “deck” and the “pikeries”, which are the deck longitudinal stiffeners.

Afterwards, the “trypito” (perforated strip) was installed, and subsequently, the planking, the “deck” and the “koupasti” (bulwark) were added. Then the “fraktes” (bulkheads) were constructed. Their construction materials include pine wood, exterior plywood, and “rock wool” for insulation. Once the “paniola” (floorboards) were placed, all other teams of craftsmen could begin their work, such as the installation of engine, shafts, rudders, electrical systems, and so on. Simultaneously, the superstructure was constructed and installed.

The midship section plan of the traditional yacht Kostantis is given in Fig. 2.

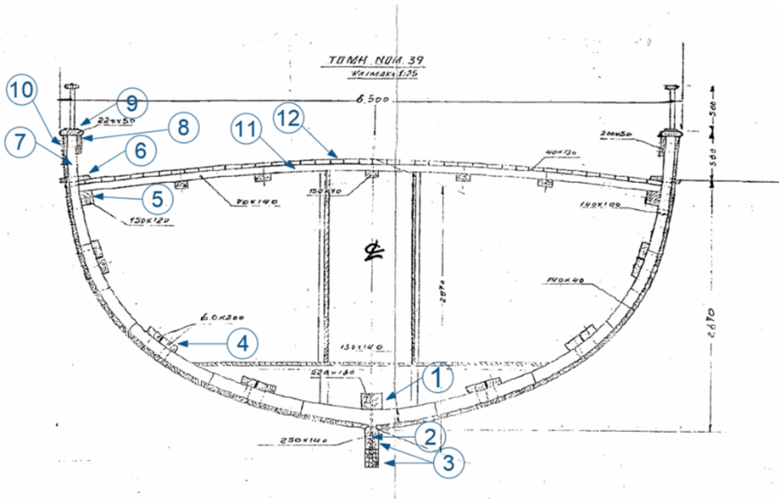

Fig. 2. Midship section plan of the traditional yacht Kostantis

More specifically:

1. “Sotropi” (Stemson)

A vertical timber that connects the keel to the stem, reinforcing the joint between these key structural elements

2. “Tsaveta” (Hook scarf or scarf joint key)

A wooden wedge or key inserted into a scarf joint to strengthen the connection between two joined timbers

3. “Karena and Kontra Karena” (Keel and false keel)

The keel is the main structural backbone running along the bottom of the hull, while the false keel is an additional timber fixed beneath it for protection and extra strength

4. “Stragialies” (Floors or floor timbers)

Horizontal timbers at the bottom of the hull that connect the port and starboard sides and support the vessel’s flooring

5. “Giali-koutouki”

Narrower, but thicker than floors

6. “Tripito” (Limber holes)

7. "Mantali" (Clamp or binding beam)

A wooden beam or temporary clamp used to hold or stabilize two parts of the structure during construction or assembly.

8. "Tsapa" (Adze)
9. "Koupasti" (Gunwale or bulwark rail)

The upper edge or rail of the boat's side, providing structural support and a barrier along the deck's perimeter

10. "Zonari" (Sheer strake or belt plank)

A long plank or series of planks running along the upper sides of the hull, tying the structure together and often marking the deck line

11. "Kamaria" (Beams, deck beams)

Horizontal timbers that span the width of the boat, supporting the deck and linking the sides of the hull

12. "Maderia" (Planks or timbers)

Wide wooden boards used to cover and clad the frame of the vessel, forming its external or internal skin

3 Creation of the Kostantis lines plan

The Rhinoceros program [14], which is based on the representation of curves and surfaces in 3D space using the Non-Uniform Rational B-Spline (NURBS) mathematical formulation, was used to design the hull of the traditional vessel. This commercial CAD program has a multitude of commands for line creation and editing and is the basis for modelling of vessels.

Initially, the original lines plan was imported into the appropriate projection plane. Then, the axis origin was defined, and the plan was shifted to this origin (Fig. 3).

The curvature of the lines was then checked, and the necessary smoothing (fairing) was applied where required. The smoothing process required special care to ensure that the curve did not deviate from the control points. It was therefore appropriate to limit the tolerance to a maximum of 0.02. The initial curve to be drawn was that of the profile.

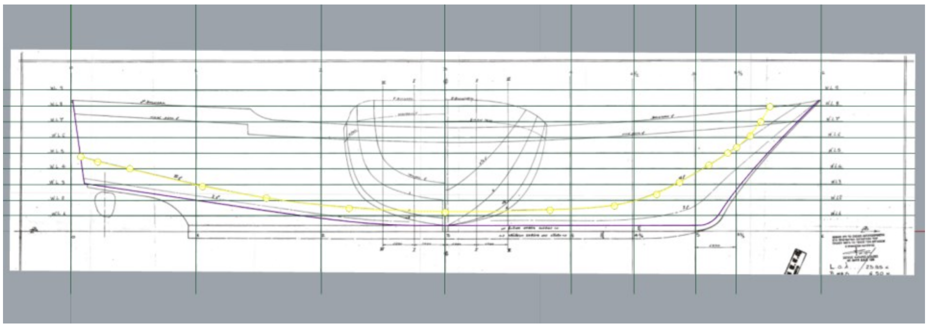

Fig. 3. Vertical design

The subsequent step was the smoothing of the curve, as illustrated in Figs 4 and 5 (before and after fairing).

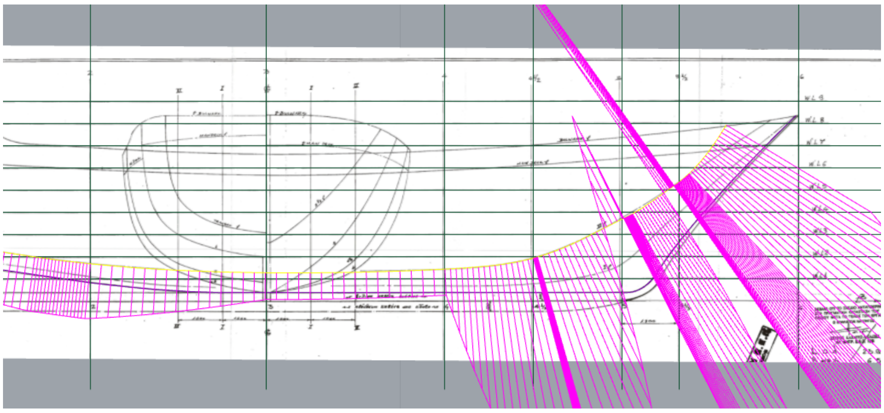

Fig. 4. Curve before smoothing

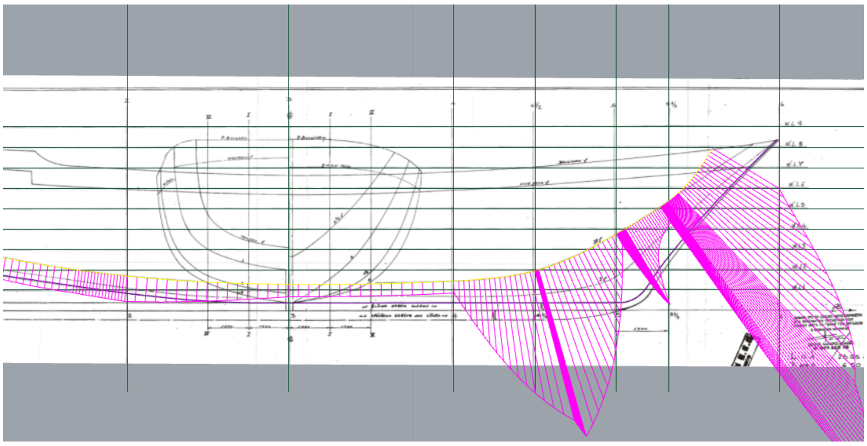

Fig. 5. Curve after smoothing

Then, the design and smoothing of the frames was undertaken. This process was conducted at the designated 'right' view of the ship (Fig. 6).

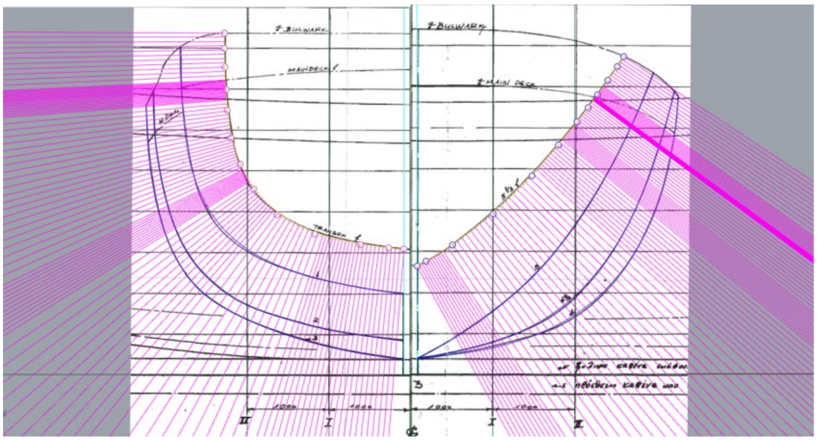

Fig. 6. Design and smoothing transom (left) and frame 5 1/3 (right)

The waterlines, main deck, bulkwark, verticals and karina were drawn on the same philosophy. At this point, all lines were placed correctly in position as shown in Fig. 7.

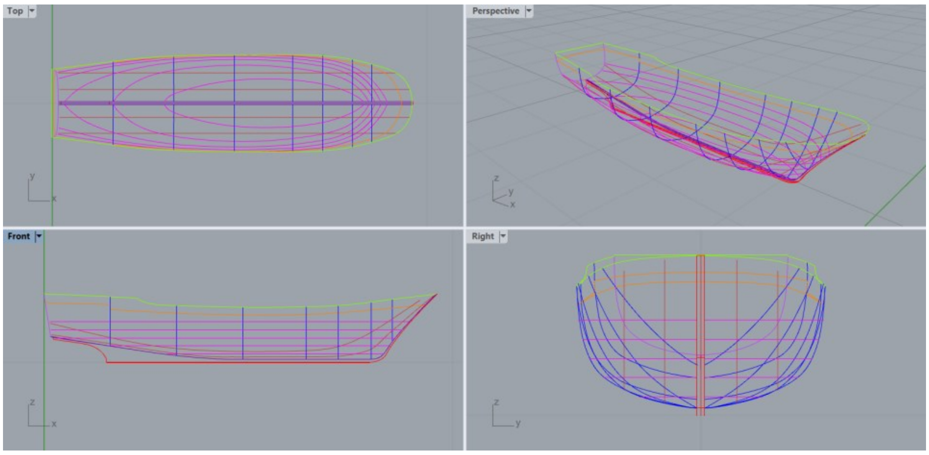

Fig. 7. Hull lines plan

The result of the body plan of the traditional hull is shown in Fig. 8.

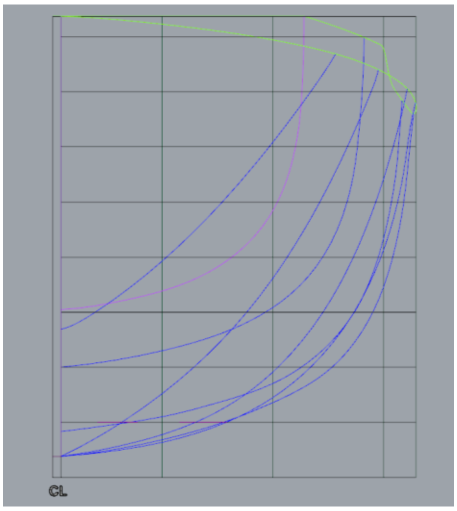

Fig. 8. Body plan of the traditional yacht Kostantis

4 Hydrostatic and hydrodynamic analysis

The calculation of hydrostatic and hydrodynamic quantities is essential because they constitute the ship's identity. A hydrostatic diagram is a graphical representation used in naval architecture to illustrate the hydrostatic properties of a ship at various drafts. These diagrams are crucial for understanding how a vessel behaves in water, particularly in terms of stability and buoyancy. They detail important parameters such as displacement, center of buoyancy, and metacentric height etc. By analyzing these curves, designers can optimize hull shapes to enhance stability and compliance with maritime regulations, ultimately contributing to safer and more efficient vessel operations [15]. Fig. 9 illustrates the hydrostatic diagram of the ship Kostantis. The calculations were performed using a dedicated hydrostatic and hydrodynamic program. More details can be found in [13].

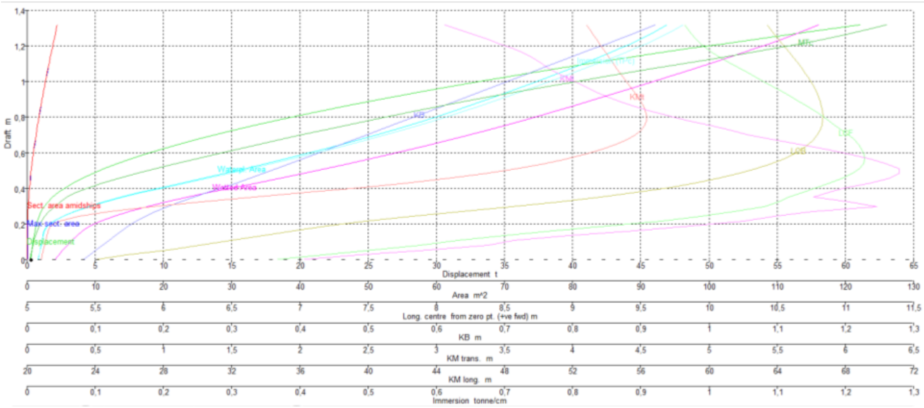

Fig. 9. Hydrostatic diagram

Table 2 compares the hydrostatic quantities from the simulations with those of the traditional yacht Kostantis.

Table 2. Comparison of the hydrostatic characteristics

	Konstantis	Simulations
∇ [t]	60.930	57.900
C_b [-]	0.325	0.282
LCF (from midship) [m]	1.400	1.320
LCB (from midship) [m]	0.687	0.668

The resistance curve, which includes both frictional (viscous) resistance and wave (residuary) resistance components, shows how the ship's resistance varies with its speed (Fig. 10). The horizontal axis (x-axis) shows the speed (in kn), while the vertical axis (y-axis) shows the resistance (in kN).

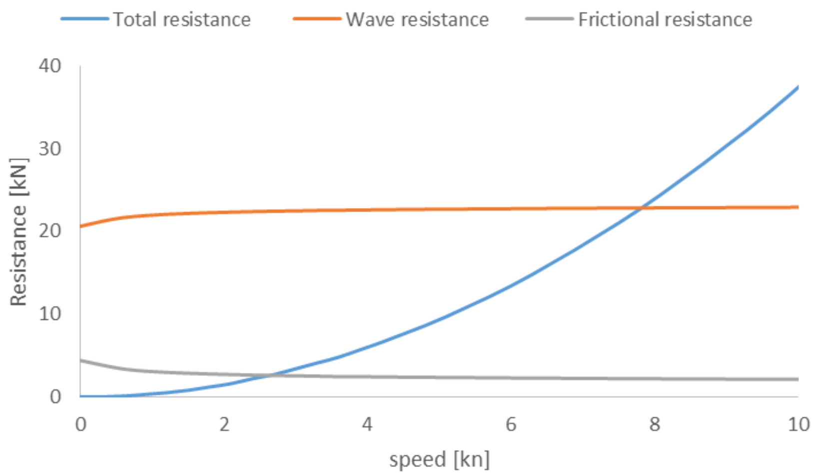

Fig. 10. Resistance-velocity diagram for the Kostantis traditional yacht

The HP curve shows the power required by the engine to achieve a specific speed (Fig. 11). The horizontal axis (x-axis) represents the ship's speed (in knots), while the vertical axis (y-axis) shows the required power (in HP).

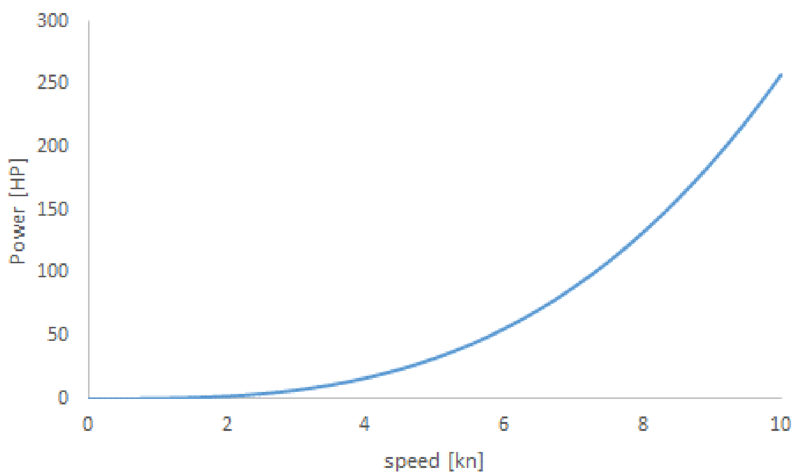

Fig. 11. Power vs velocity diagram for the Kostantis traditional yacht

The wave pattern refers to the distribution and formation of waves around a ship as it moves through the water [16]. It appears due to the refraction and reflection of the water as the ship passes through it. This pattern shows areas with higher and lower waves and typically includes the bow waves (leading waves) and stern waves (behind the ship), as well as areas where vortices are created (Figs. 12-15).

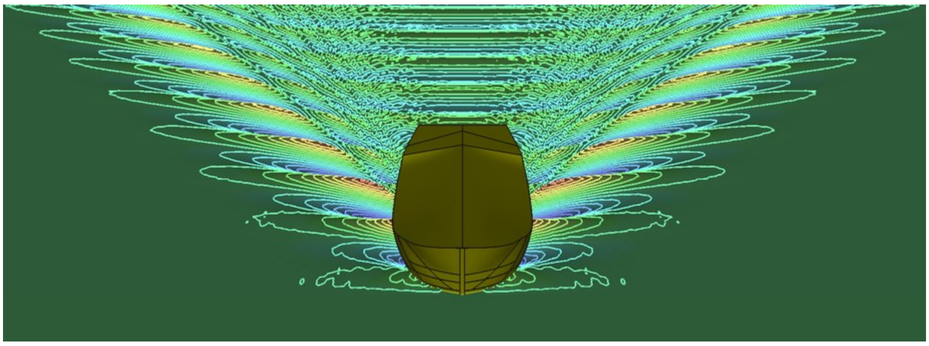

Fig. 12. Contour of the free wave surface for a speed of V=7 kn

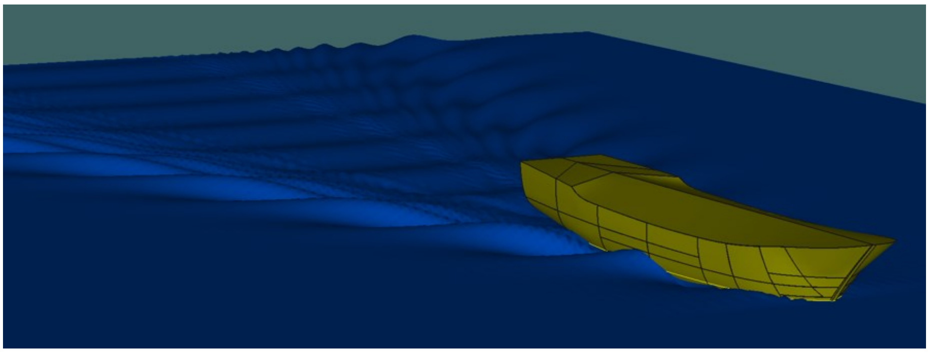

Fig. 13. Wave elevation around the ship for forward speed V=7 kn

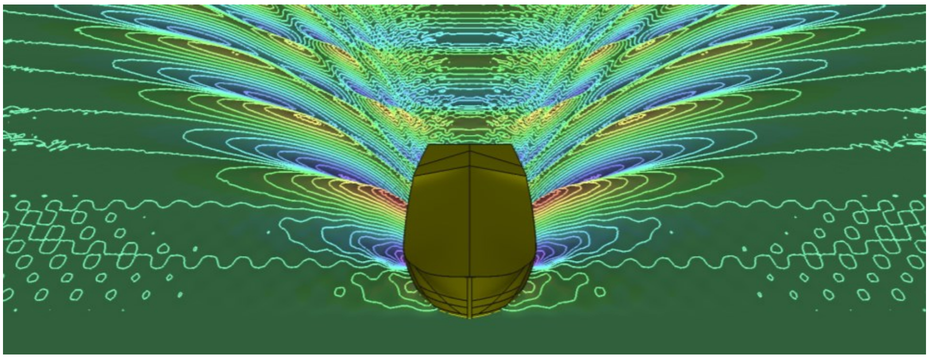

Fig. 14. Contour of the free wave surface for a speed of V=10 kn

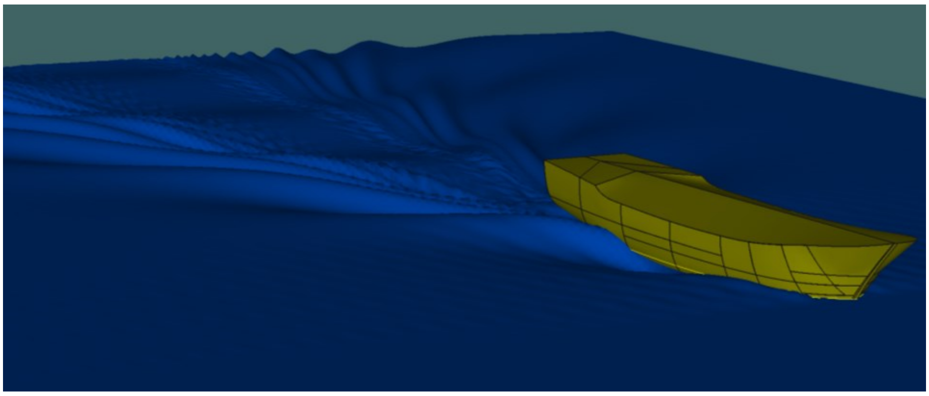

Fig. 15. Wave elevation around the ship for forward speed V=10 kn

5 Design and 3D printing of the hull mold prototype

The common process for the construction of plastic vessels includes three main steps: the creation of the hull mold, the use of a lay-up technique on the internal or external surface of the mold, and the detachment of the hull from the mold. In this work, the scale hull mold of the traditional boat of Kostantis was created using the FDM 3D printing technique. To proceed with the printing process, it was necessary to design the 3D solid model of the hull to scale.

Starting with the half hull lines plan of Figure 6, the surfaces that form the 3D model of the hull were designed in Rhinoceros using NetworkSrf, PlanarSrf, Loft and Join commands. Some gaps at the joints of the surfaces were repaired, while the continuity of tangential surfaces was checked using the Zebra command. The surface model of the hull is shown in Fig. 16.

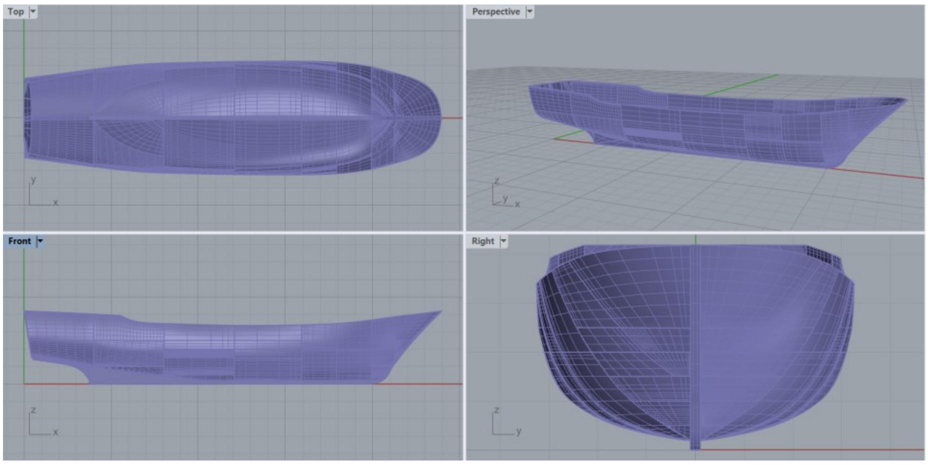

Fig. 16. The surface model of the hull of Kostantis

The next step was to scale the 3D model into an appropriate size, considering multiple parameters, such as the dimensions of the towing tank and the total manufacturing time and cost required to 3D print the hull.

The surface model was scaled in Rhinoceros using the uniform 1:15 scale and then converted into a solid model using the Offset command and selecting Distance = 0.005, Corner = Round, Solid = Yes and FlipAl. The thickness of the hull was set to 5 mm in order to ensure that the 3D printed hull prototype would be strong enough as a mold without the risk of breakage or deformation during the subsequent construction process. The solid model was also checked for inconsistent geometry, such as discontinuities or holes between the generated faces.

The solid model of the hull, with dimensions L_{OA} = 1.60 m, L_{BP} = 1.40 m and B = 0.43 m, was then divided into 14 parts, considering the available build volume of the 3D printer Ultimaker S5 (330 mm in width, 240 mm in depth, 300 mm in height). Fig. 17 shows the solid model of the hull separated into fourteen (14) parts.

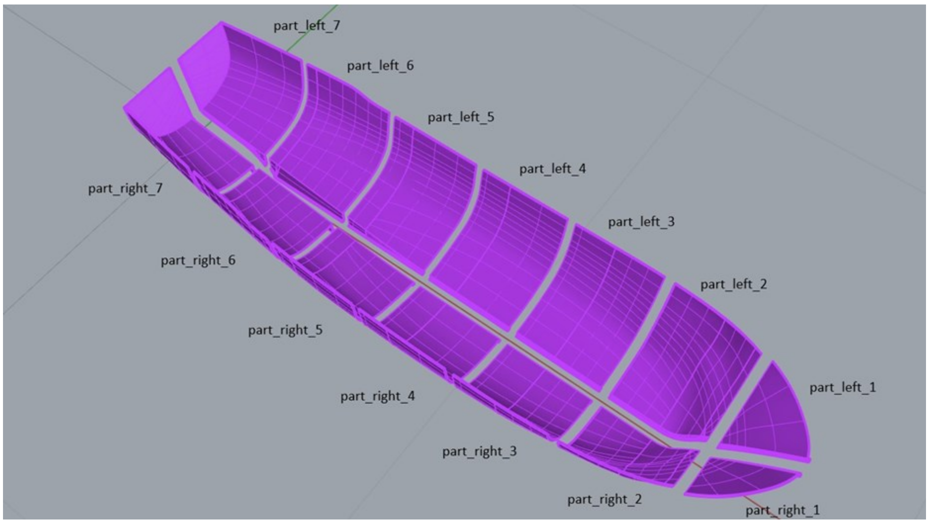

Fig. 17. The solid model of the hull separated into 14 parts

To define the printing parameters, simulate the printing process and produce the G-code, the Ultimaker Cura slicing software was used [17]. First, the optimum build orientation of each part on the bed platform was defined in such a way to minimize the need of support and reduce manufacturing time and cost. To ensure rigidity and durability of the 3D printed parts, Tough PLA (polylactic acid) was selected as the printing filament, while the basic parameters of the printing process include 0.2mm layer height, 0.4mm raster width, two outer wall skins, triangle infill pattern, and 20% infill density. Fig. 18 illustrates (a) the build orientation of "part-right-4" on the bed platform, (b) a detail of the printing simulation where the infill density can be clearly observed, and (c) the 3D printed "part-right-4".

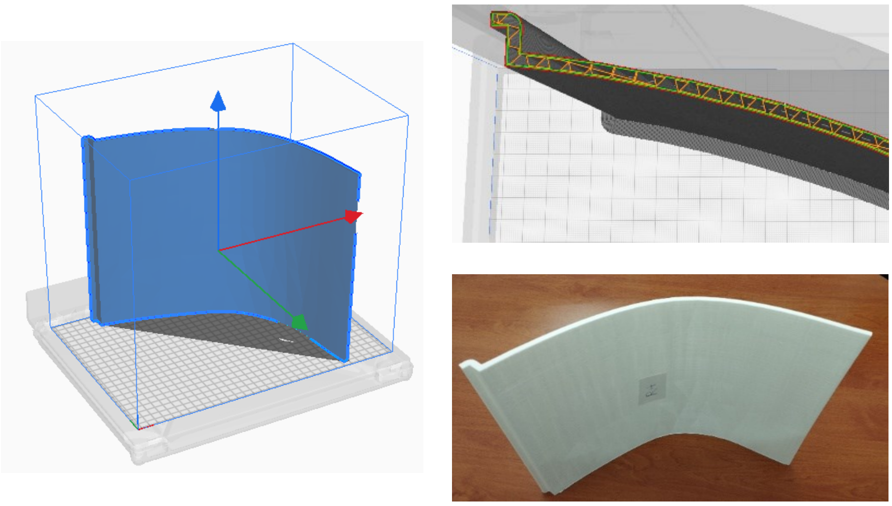

Fig. 18. The build orientation (left), detail of the printing simulation (top right) and the 3D printed “part-right-4” (bottom right)

The 3D printing process was quite successful with smooth extrusion of the material and good adhesion between the layers, while all 3D printed parts exhibited good surface quality and dimensional accuracy. The post-processing of the 3D printed parts and their assembly into two halves of the mold (the left and the right) was achieved through the following steps:

Step 1: The supports were carefully removed from each part. These areas, as well as some surfaces imperfections, e.g. convex areas, were smoothed with sandpaper (Fig. 19 left).

Step 2: The 3D printed parts were joined together to form the two halves of the mold using epoxy adhesive and tool holders (Fig. 19 center).

Step 3: Stucco was applied to concave areas (small imperfection due to 3D printing) and at the points where the parts were joined together, both in interior and exterior surfaces (Fig. 19 right).

Step 4: The surfaces of the hull mold were smoothed with emery paper (sandpaper).

Fig. 19. The preparation and assembly of the 3D printed parts

Fig. 20 shows the 3D printed hull mold of Kostantis with overall dimensions L_{OA} = 1.60 m, L_{BP} = 1.40 m, and B = 0.43 m, with the two halves temporarily supported together.

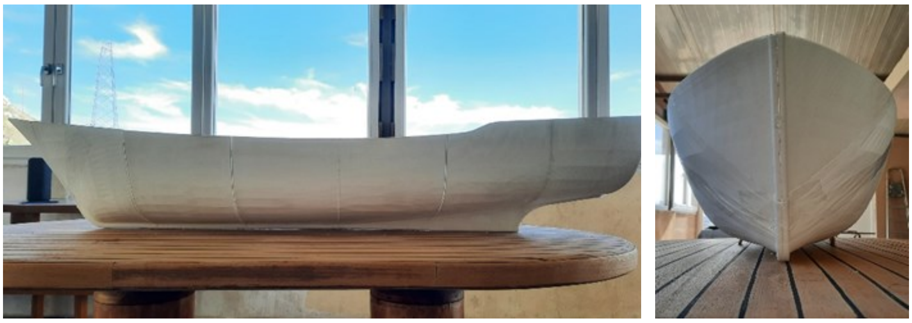

Fig. 20. The 3D printed hull prototype of Kostantis, built to 1:15 scale

6 Construction of the glass reinforced polyester hull of the vessel

To construct the GRP hull model of the vessel Kostantis, layers of polyester resin and fiberglass fabric will be added to the inner surface of each half of the mold using the hand lay-up technique.

The first step was to apply Gel Coat to each part of the mold, which will form the outer coating of the polyester model (Fig. 21). Gel Coat was applied with a brush and partially cured in 2-3 hours, while full curing occurred after 12-24 hours, depending on temperature and humidity.

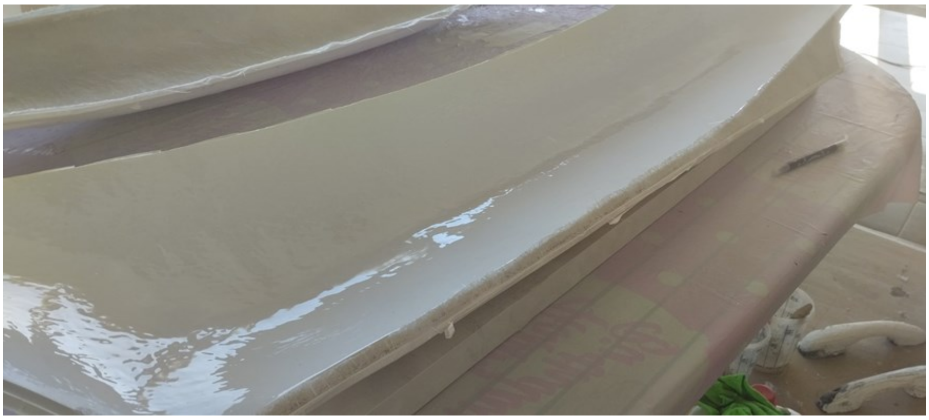

Fig. 21. The inner surface of the mold after applying Gel Coat

The second step was to prepare the polyester resin/catalyst mixture in the correct proportions. The mixture must be used within a short period of time before it hardens. A small amount of polyester was then applied to the entire surface of the mold (Fig. 22). Then the fiberglass fabric and the mixture were placed carefully layer by layer, while a plastic roller was used to remove trapped air (Fig. 23).

Fig. 22. Coating of polyester resin on the surface of the mold

Fig. 23. Removal of trapped air bubbles

A different process was used for the keel section, which was considered more effective. A spatula was used to apply polyester glue to the entire section (Fig. 24).

Fig. 24. Placement of polyester glue in the keel

The process of applying layers of polyester and fiberglass was repeated a total of three times on each half of the mold. When the polyester dried well, the fiberglass reinforced polyester pattern was removed from the mold (Fig. 25, 26). Special care was required at this stage to avoid damaging the outer surface of the GRP hull model. Excess pieces of polyester and glass fabric that protruded from the model outline were removed using a rotary multi-tool and a roller sander (Fig. 27).

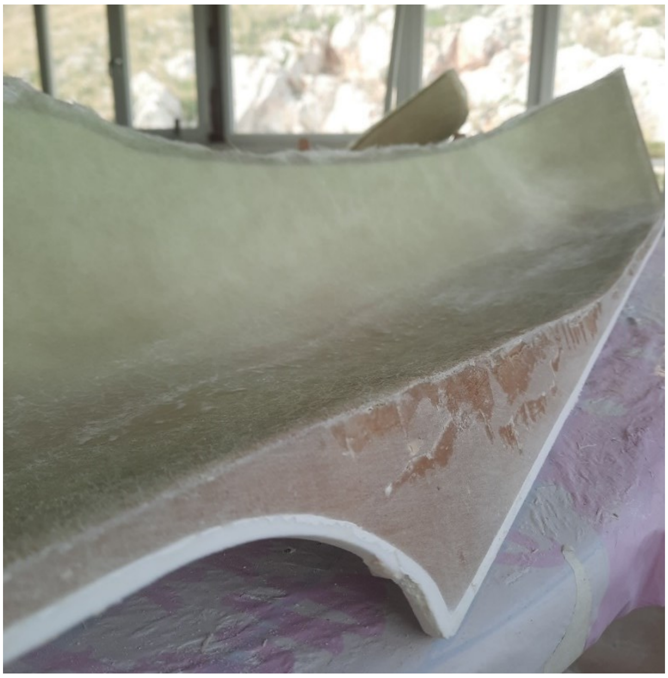

Fig. 25. The GRP hull model 24 hours after hand lay-up application

Fig. 26. The process of removing the GRP hull model from the mold

Fig. 27. Removal of excess polyester and glass fabric with rotary multi-tool and roller sander

The next step was to join the two parts of the GRP hull model (left and right) using polyester glue (Fig. 28).

Fig. 28. Application of polyester glue to join the two parts of the GRP model

The glued hull model was covered internally with a final layer of polyester and fiberglass, in order to evenly cover both parts of the model, especially in the joint, and also increase its strength (Fig. 29).

Fig. 29. Application of a final layer of polyester and fibreglass on the inner surface of the hull model

Then, some minor modifications were made to the surface of the model by applying stucco and smoothing with sandpaper. Finally, an acrylic primer was applied to improve the adhesion of the paint and protect the surface from wear, as well as acrylic paint. The completed GRP hull model of the Kostantis traditional boat is shown in Fig. 30.

Fig. 30. Bow (top left), stern (top right) and right view (bottom) of the GRP hull model

7 Conclusions

The paper presents a broad approach to support maritime decarbonization through the adoption of new practices for the design and construction of small vessels. First, the integration of 3D modelling and hydrostatic/ hydrodynamic analysis of the vessel's hull, using modern user-friendly software tools, provides the opportunity to further optimize the hull design. According to the derived hydrostatic and hydrodynamic characteristics, the hull shape can be remodeled with the intention to improve the water flow around the forward and aft parts of the hull, and reduce friction and wave resistance. These modifications can lead to optimized hull geometry and a reduction in the propulsive power required to maintain a given speed. As a result, fuel consumption can be reduced, helping to minimize fuel emissions and the environmental impact of the vessel's operation.

In addition, the use of additive manufacturing technology to create the mold which will be used for the construction of the fiberglass reinforced plastic vessel, can further improve the efficiency of the overall production process. The 3D printed mold, made of materials of appropriate strength, can be reused many times to construct plastics vessels from different composite materials using the hand lay-up technique. Various composite materials can be used for the hull, and their hydrodynamic behavior can be tested in a towing tank. The proposed strategy of integrating additive manufacturing into the construction of plastic vessels can contribute to the identification of advanced optimal materials and hull designs. Compared to conventional molding processes, the proposed strategy can reduce the time, cost and carbon footprint of the overall manufacturing process, contributing to an extent to decarbonization in the manufacturing and shipbuilding industry.

Regarding the selection of the printing material for the mold, it depends on the number of times it is expected to be used as a mold, as well as on the parameters and conditions of the construction technique (hand lay-up, vacuum bag, vacuum infusion, etc.). For high temperatures and pressures, advanced high-strength printing materials such as carbon fiber-reinforced polymers, can be used for the mold.

In conclusion, the future prospects of the proposed approach, which consist of (a) digitizing and documenting the hull model of the case vessel, (b) creating the 3D printed mold, (c) constructing a scale hull using different composite materials, (d) testing the hulls in a towing tank, and (e) comparing the hydrodynamic behavior of the hulls to the simulation results, can provide useful information regarding the impact of the different materials on the performance of the vessel and also proceed to design optimization. Furthermore, the employment of modern materials, such as carbon nanotubes composites or sandwich structures with lattice core, can lead to lighter components and structures and faster ships, reducing fuel consumption and emissions and enabling decarbonization and sustainability in shipping.

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